Computer Networking : Principles, Protocols and Practice

Part 3 : Transport Layer

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Module 3 : Transport Layer

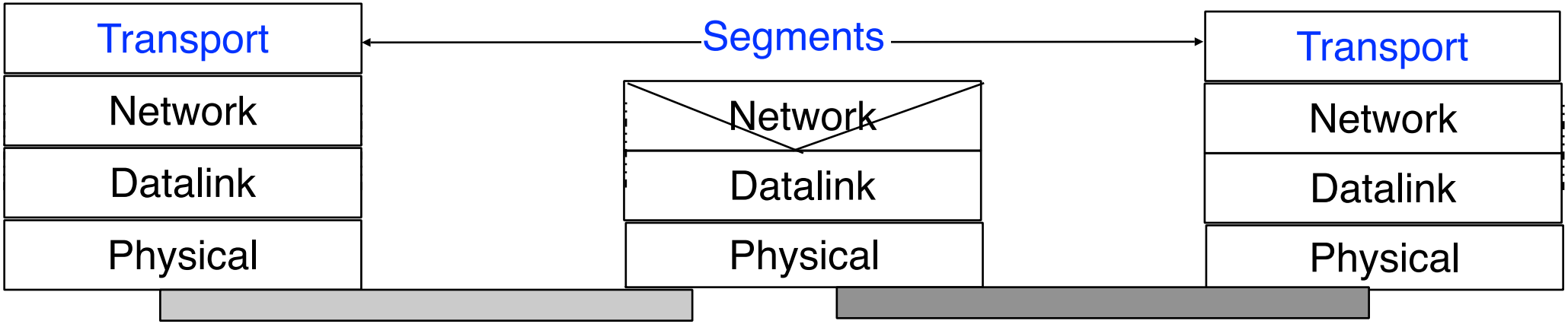
→ Basics

Building a reliable transport layer
- Reliable data transmission
- Connection establishment
- Connection release

UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

The transport layer



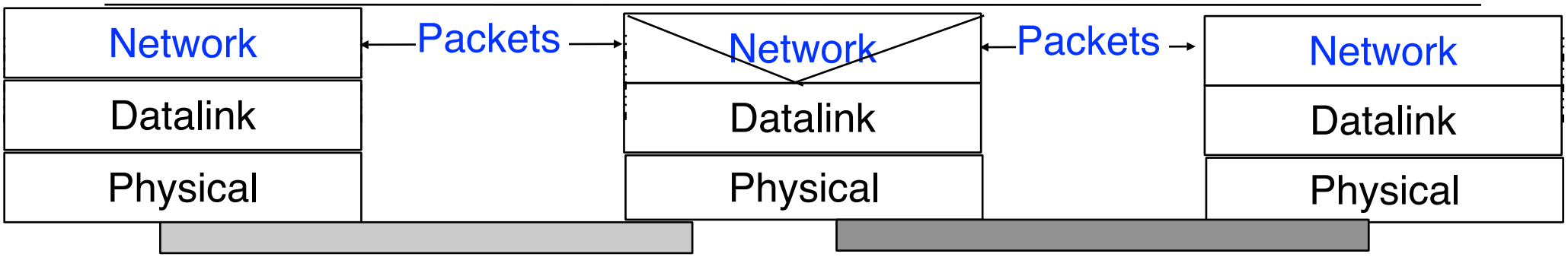
Goals

- Improves the service provided by the network layer to allow it to be useable by applications
  - reliability
  - multiplexing

Transport layer services

- Unreliable connectionless service
- Reliable connection-oriented service

The network layer



Network layer service in Internet

- Unreliable connectionless service
  - Packets can be lost
  - Packets can suffer from transmission errors
  - Packet ordering is not preserved
  - Packet can be duplicated
  - Packet size is limited to about 64 KBytes

How to build a service useable by applications ?

The transport layer

Problems to be solved by transport layer

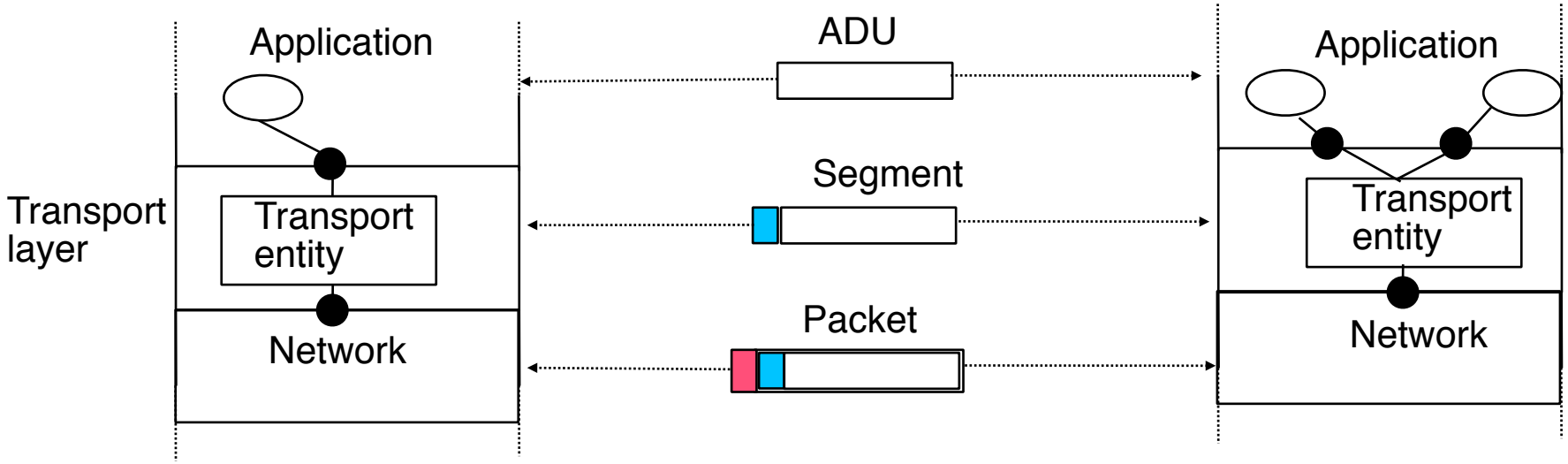
- Transport layer must allow two applications to exchange information
  - This requires a method to identify the applications
- The transport layer service must be useable by applications
  - detection of transmission errors
  - correction of transmission errors
  - recovery from packet losses and packet duplications
  - different types of services
    - connectionless
    - connection-oriented
    - request-response

The transport layer (2)

Internal organisation

The transport layer uses the service provide by the network layer

Two transport layer entities exchanges segments



Module 3 : Transport layer

Basics

Building a reliable transport layer

- Reliable data transmission
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- Connection release

UDP : a simple connectionless transport protocol

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Transport layer protocols

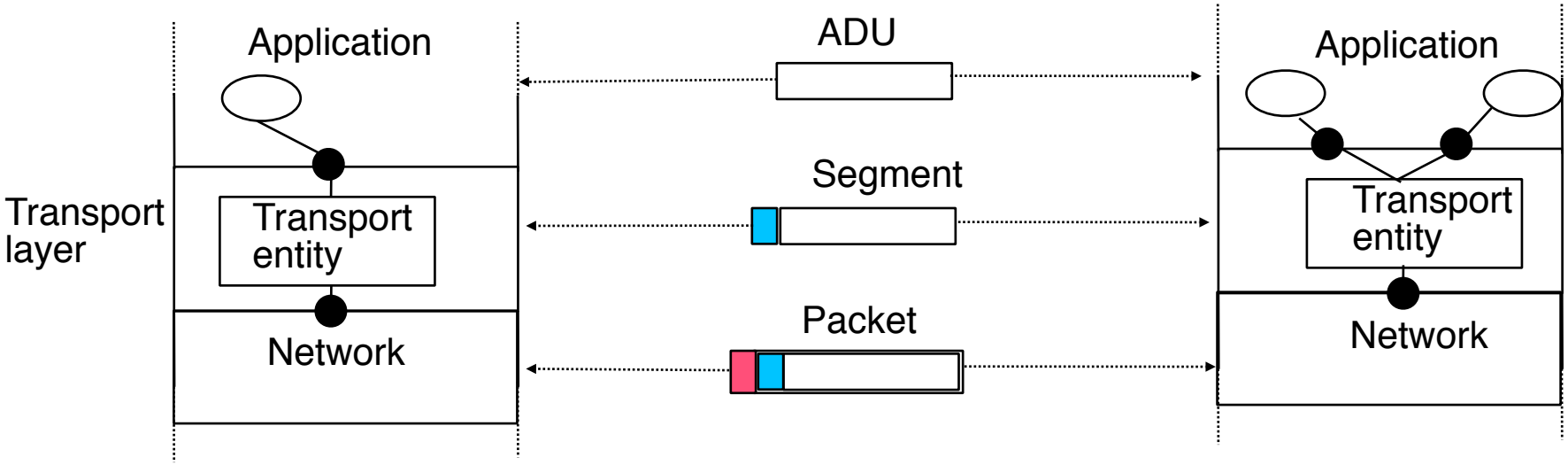
How can we provide a reliable service in the transport layer

Hypotheses

1. The application sends small SDUs
2. The network layer provides a perfect service
   1. There are no transmission errors inside the packets
   2. No packet is lost
   3. There is no packet reordering
   4. There are no duplications of packets
3. Data transmission is unidirectional

Transport layer protocols (2)

Reference environment

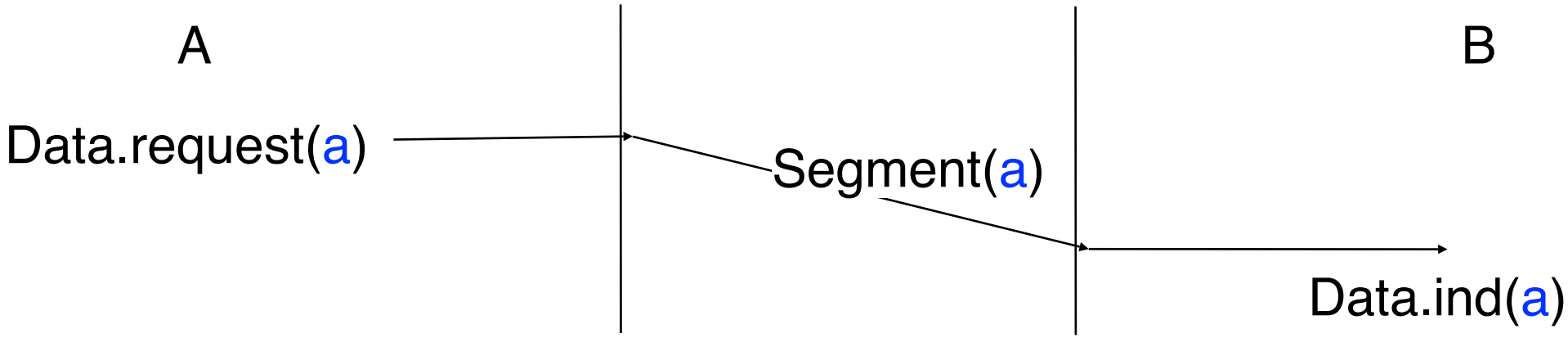


Notations

`data.req` and `data.ind` primitives for application/ transport interactions

`recv()` and `send()` for interactions between transport entity and network layer

Protocol 1 : Basics



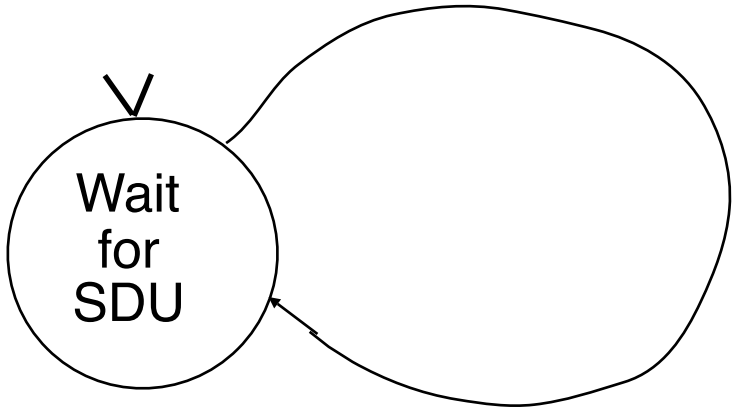
Principle

Upon reception of `data.request(SDU)`, the transport entity sends a segment containing this SDU through the network layer (`send(SDU)`)

Upon reception of the contents of one packet from the network layer (`recv(SDU)`), transport entity delivers the SDU found in the packet to its user by using `data.ind(SDU)`

Protocol 1 as a FSM

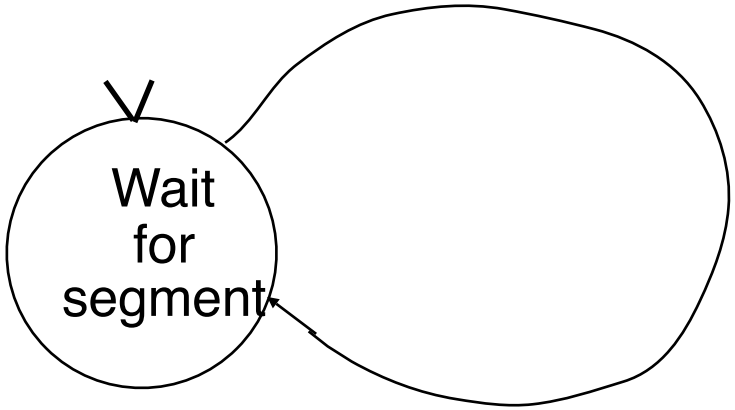
Sender



Data.req(SDU)

`send(SDU)`

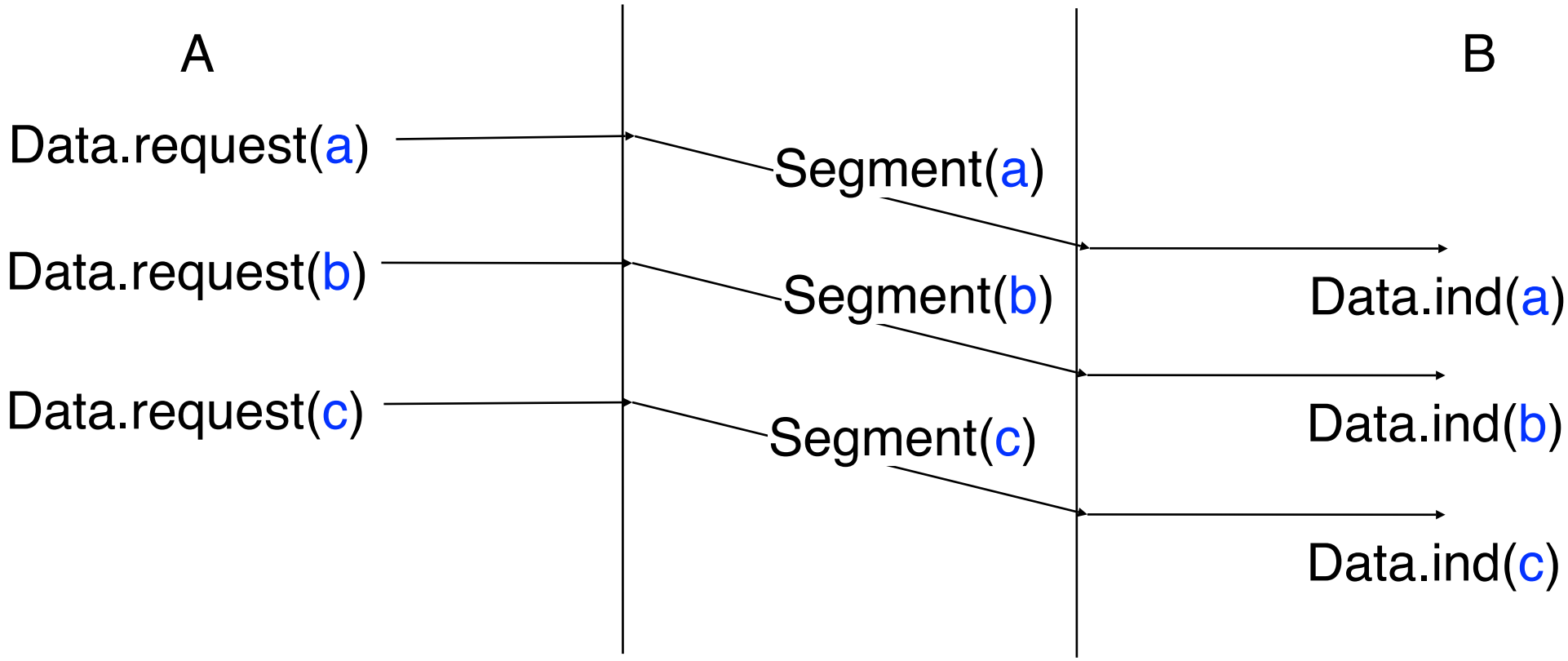
Receiver



`recvd(SDU)`

Data.ind(SDU)

Protocol 1 : Example



Issue

What happens if the receiver is much slower than the sender ?

e.g. receiver can process one segment per second while sender is producing 10 segments per second ?

Protocol 2

Principle

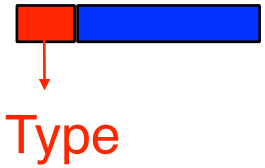
Use a control segment (OK) that is sent by the receiver after having processed the received segment

creates a feedback loop between sender and receiver

Consequences

Two types of segments

- Data segment containing on SDU
  - Notation : D(SDU)
- Control segment
  - Notation : C(OK)

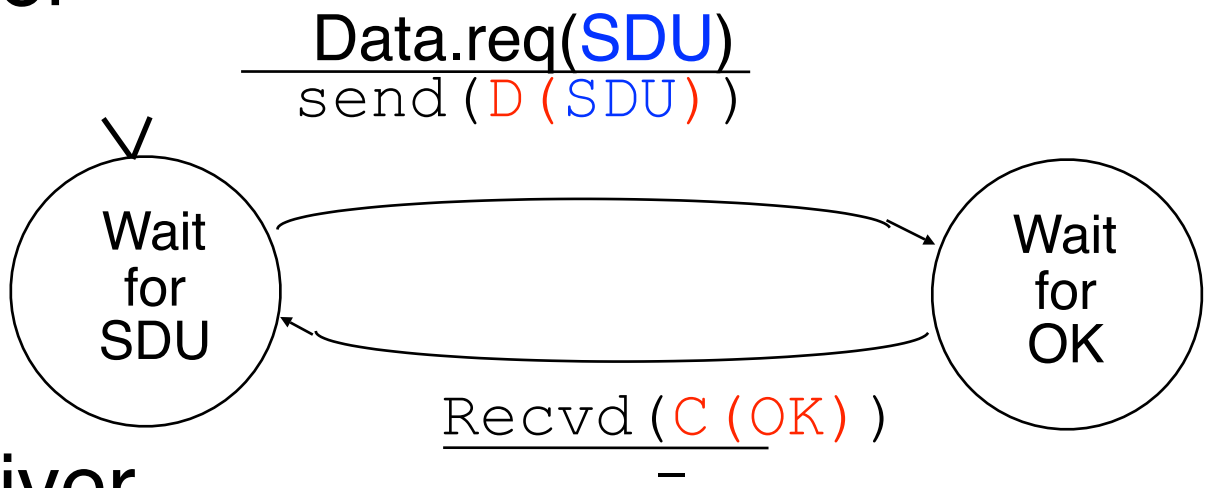


Segment format

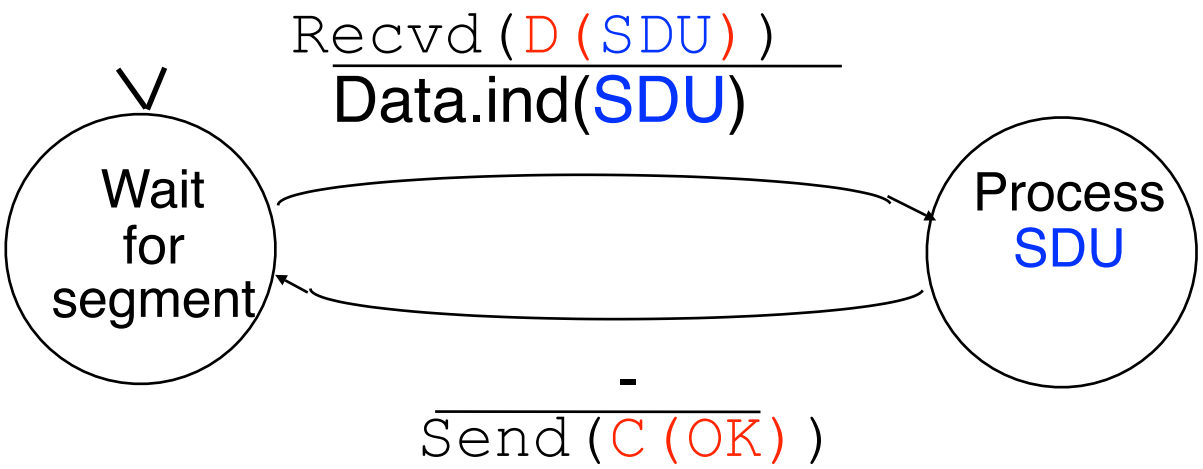
At least one bit in the segment header is used to indicate the type of segment

Protocol 2 (cont.)

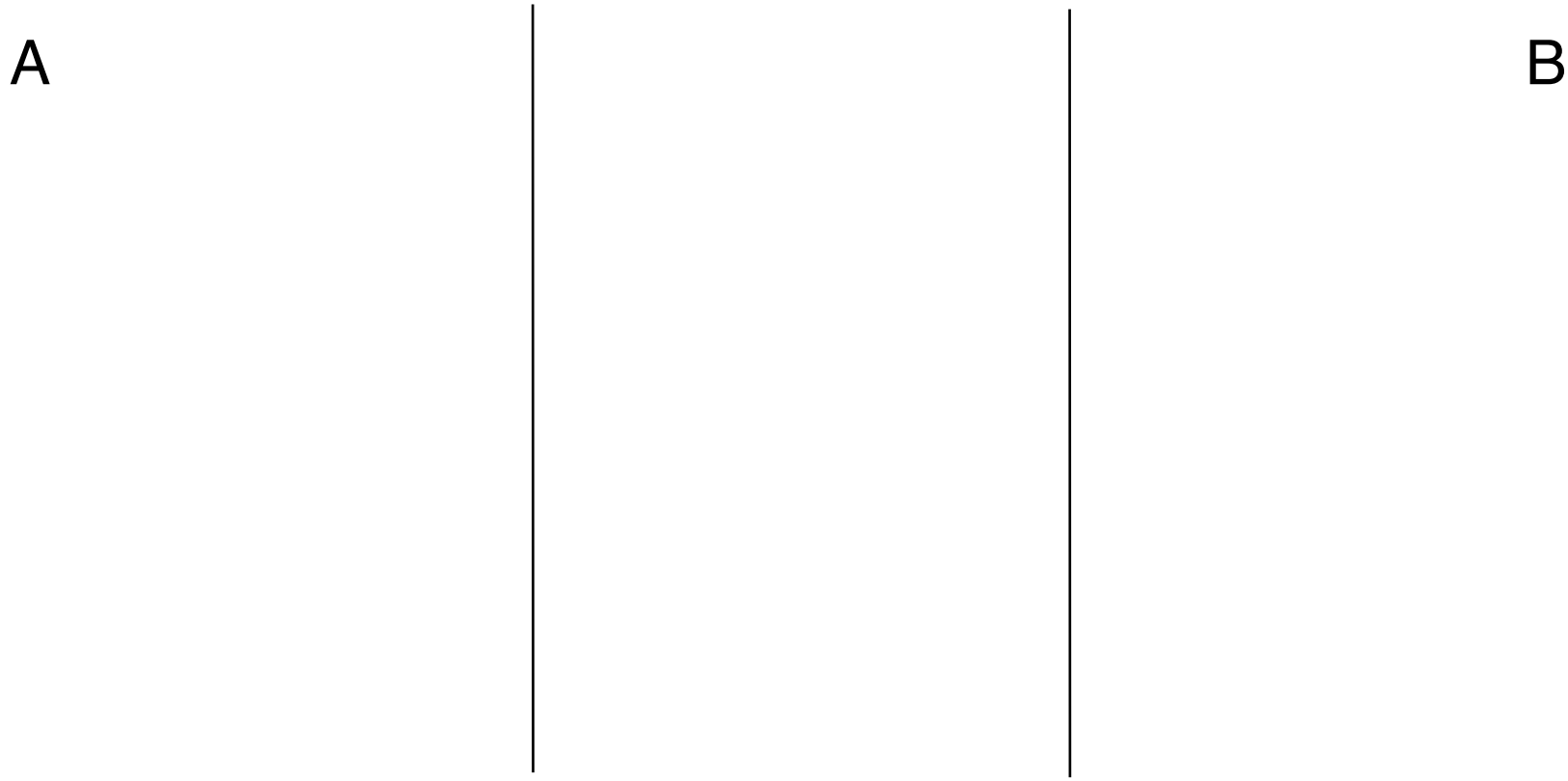
Sender



Receiver

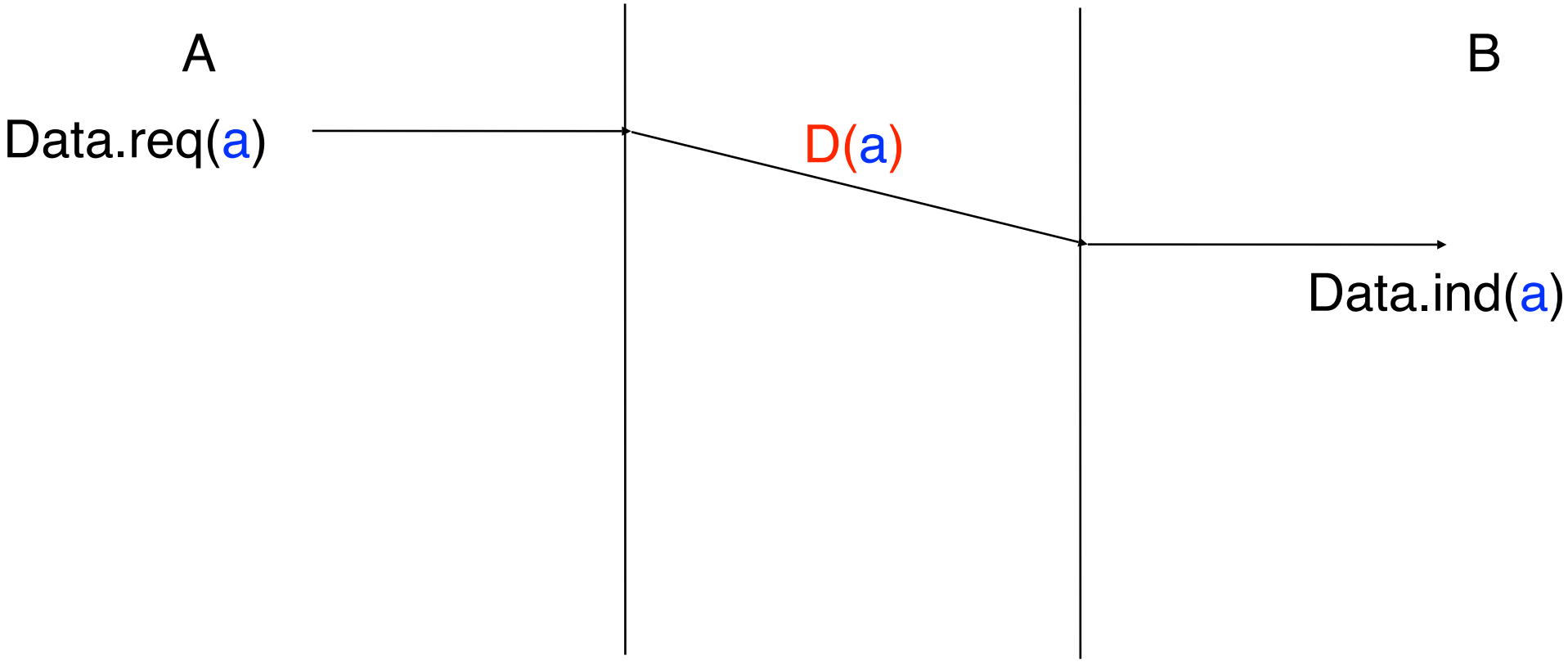


Protocol 2 : Example



The sender only sends segments when authorised by the receiver

Protocol 2 : Example



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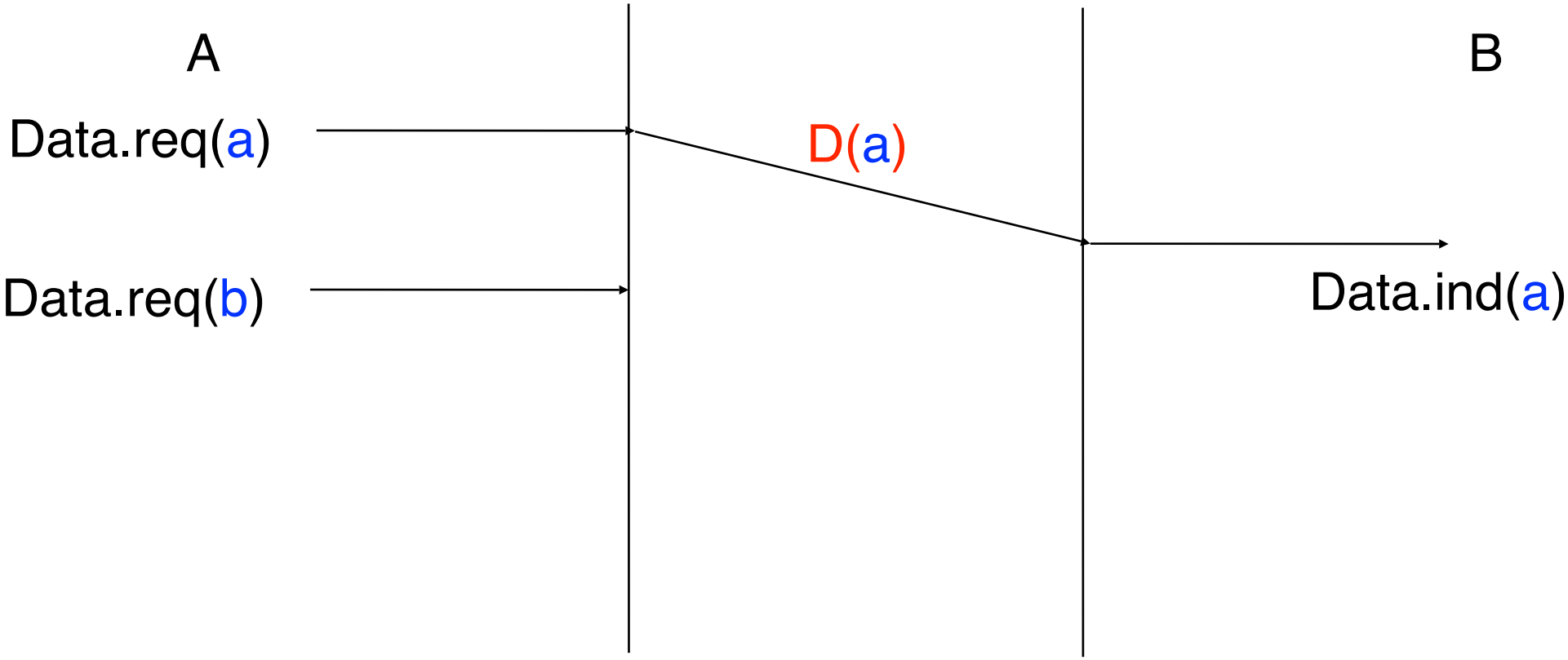

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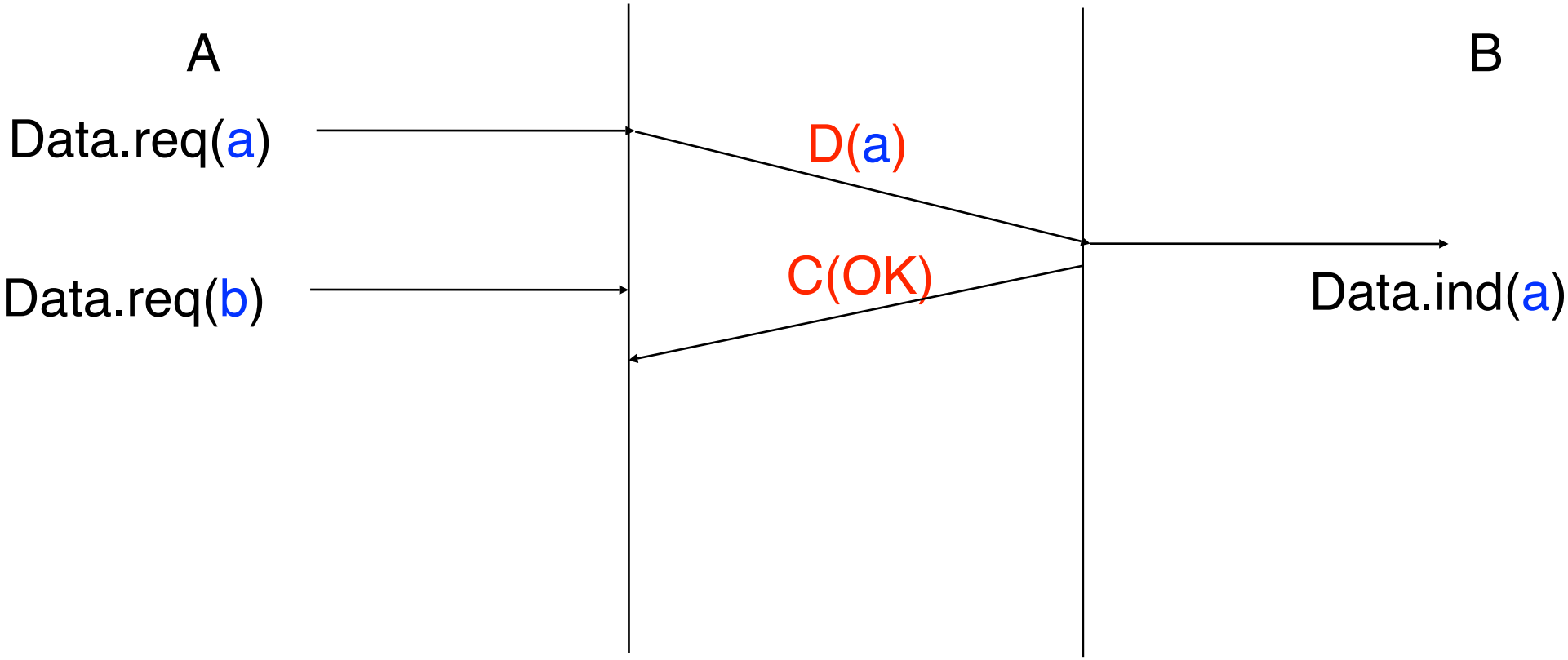

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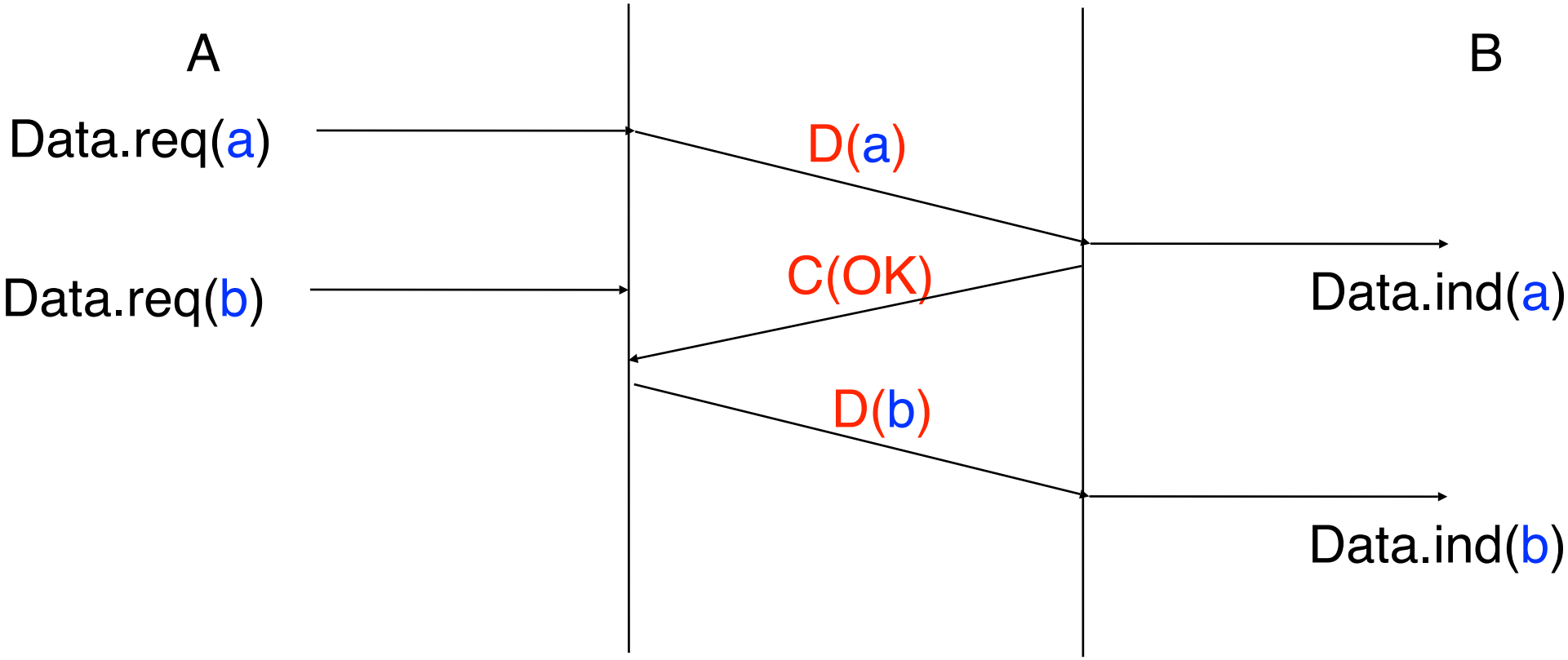

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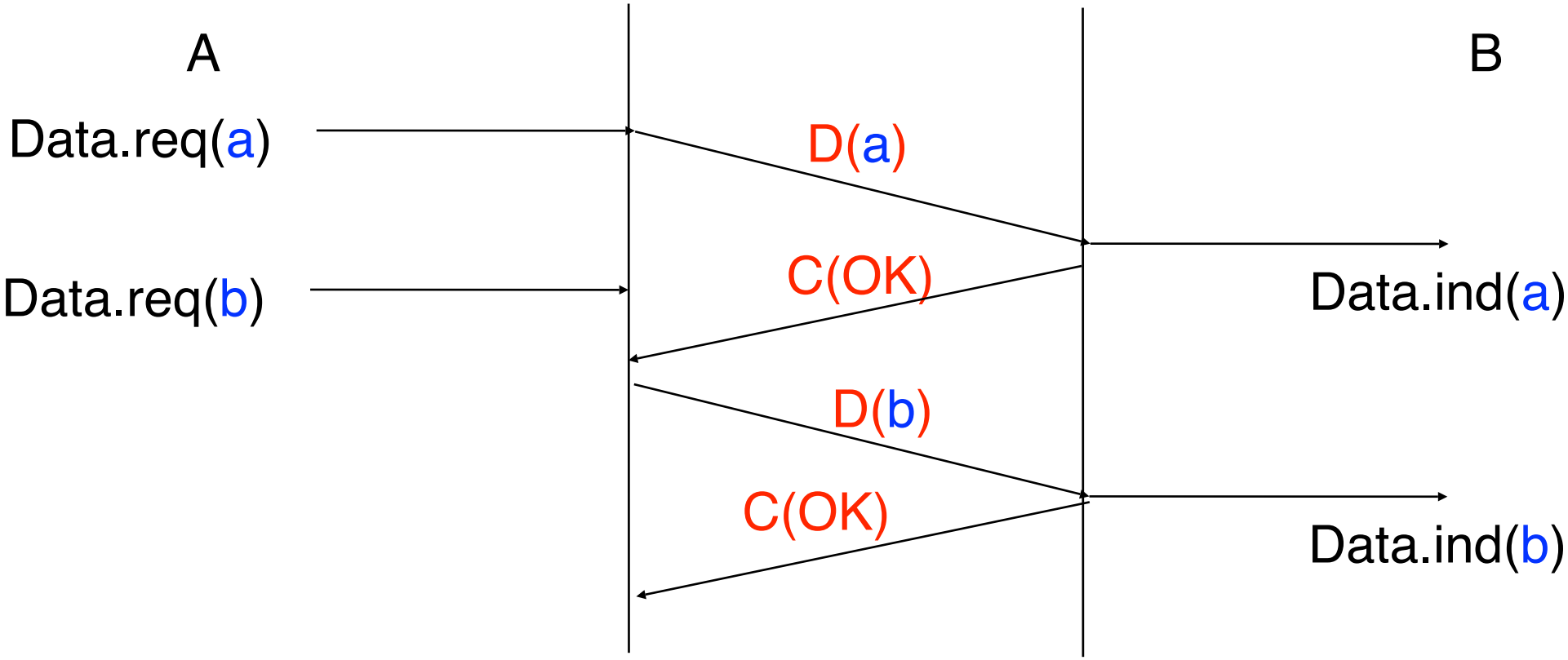


The sender only sends segments when authorised by the receiver

Protocol 3

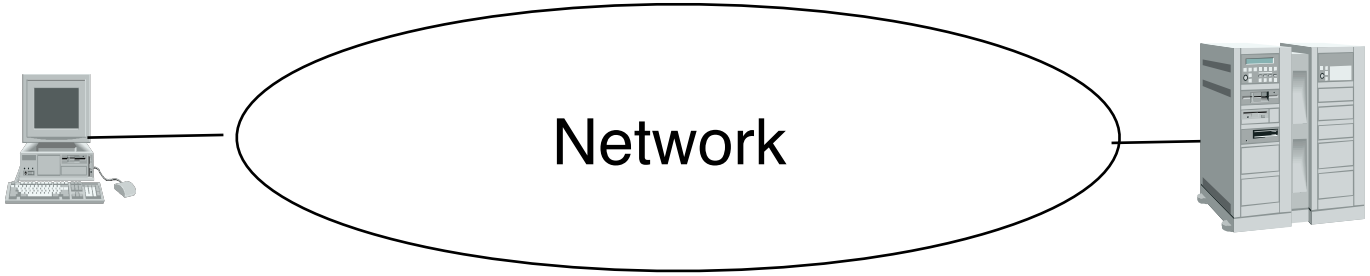
How can we provide a reliable service in the transport layer

Hypotheses

1. The application sends small SDUs
2. The network layer provides a perfect service
   1. Transmission errors are possible
   2. No packet is lost
   3. There is no packet reordering
   4. There are no duplications of packets
3. Data transmission is unidirectional

Transmission errors

Which types of transmission errors do we need to consider in the transport layer ?

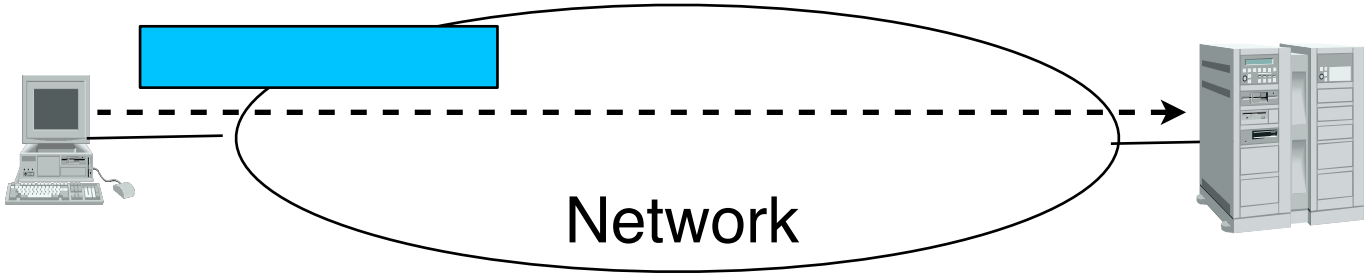


Physical-layer transmission errors caused by nature

- Random isolated error
  - one bit is flipped in the segment
- Random burst error
  - a group of n bits inside the segment is errored
    - most of the bits in the group are flipped

Security issues versus transmission errors

Information sent over a network may become corrupted for other reasons than transmission errors



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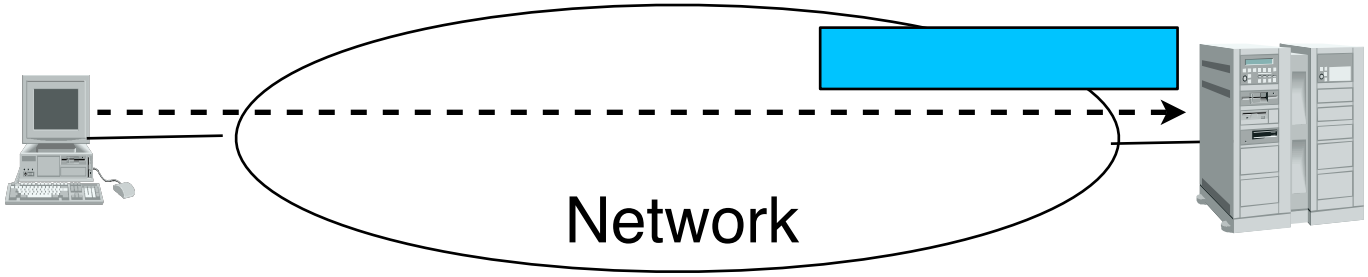

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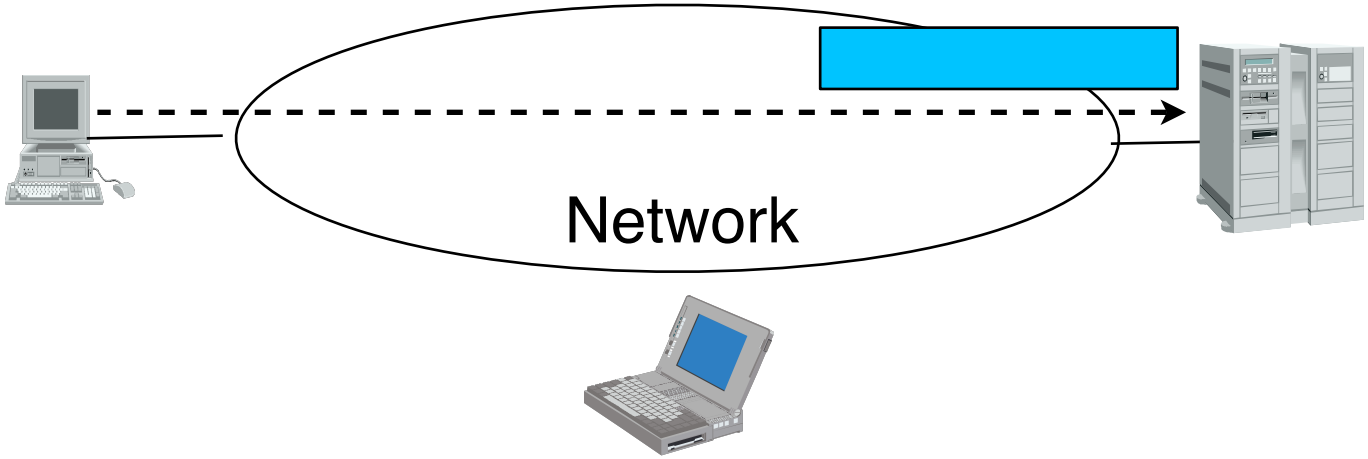

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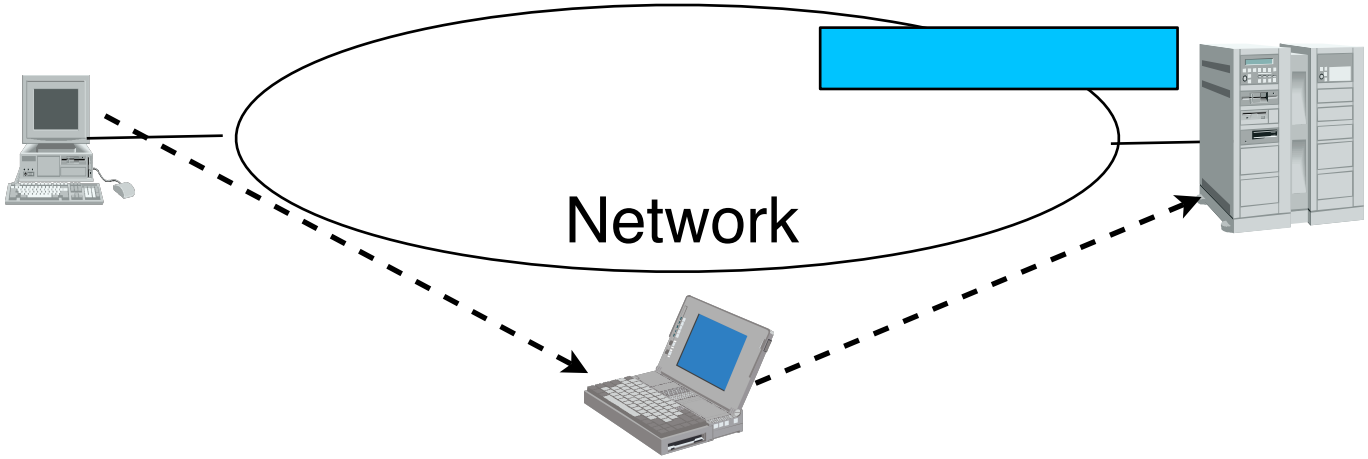

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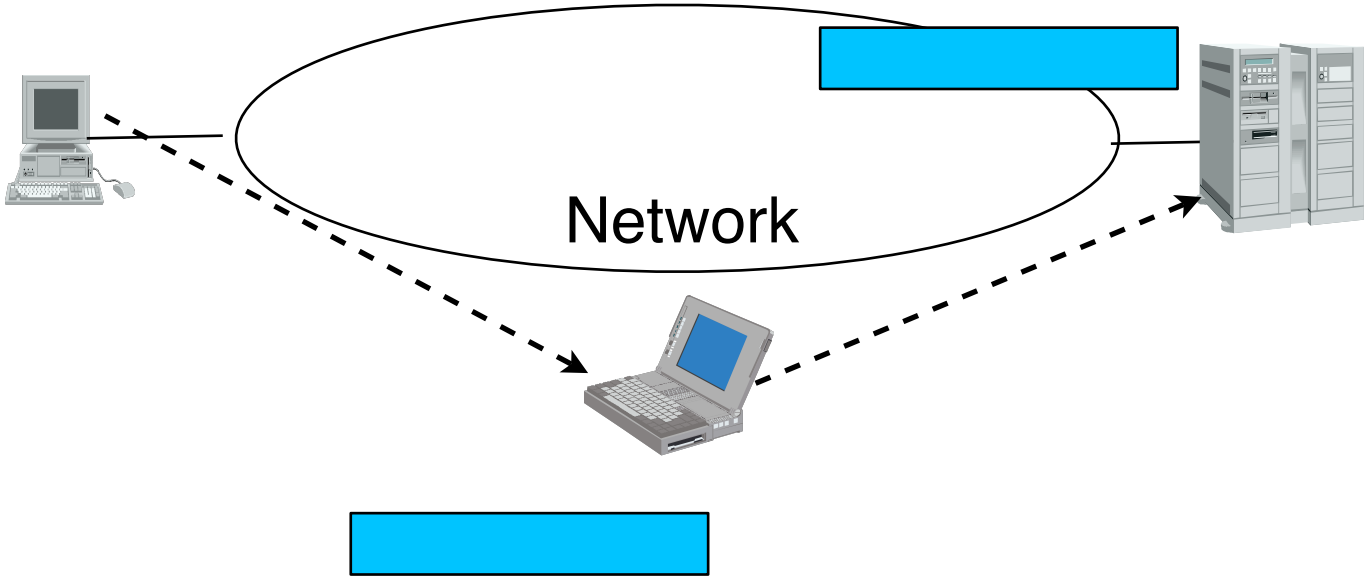

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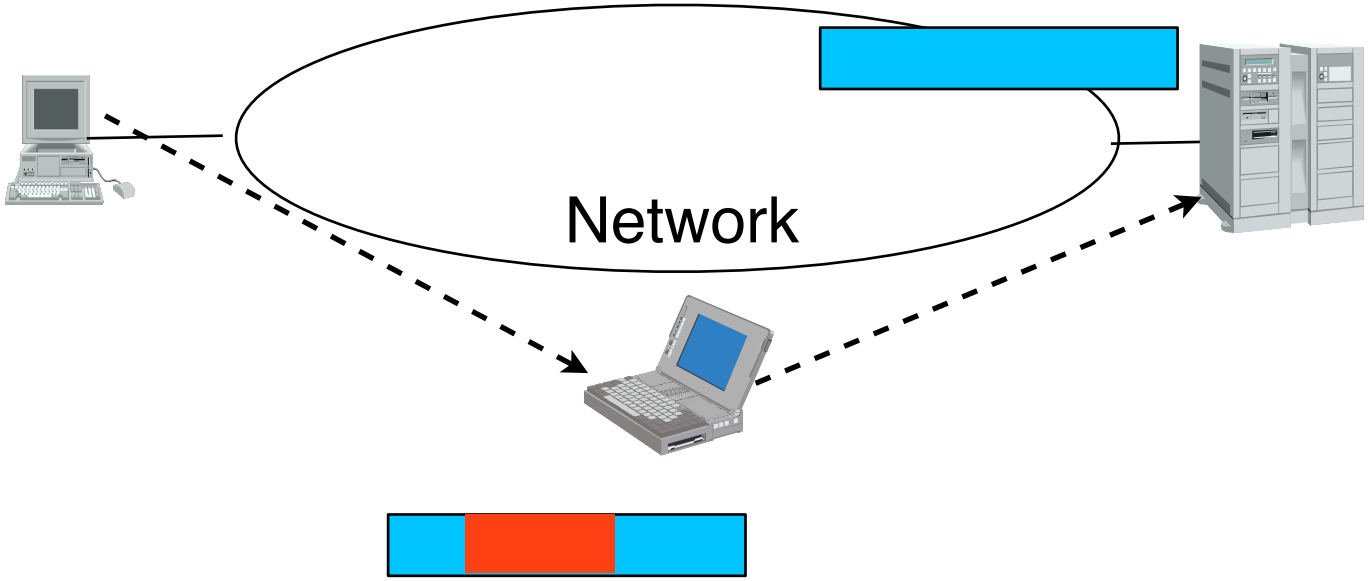

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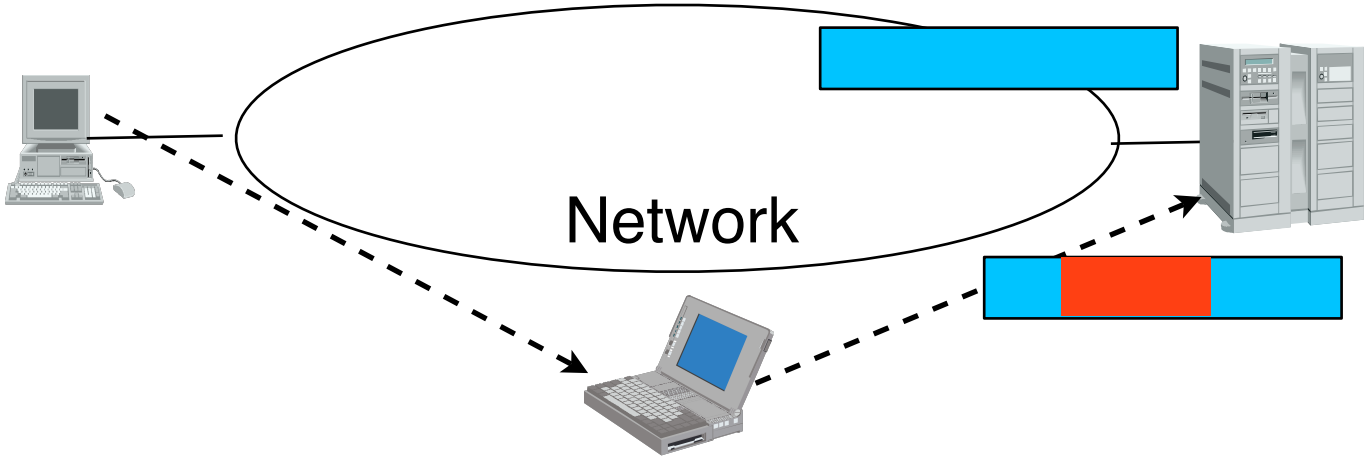

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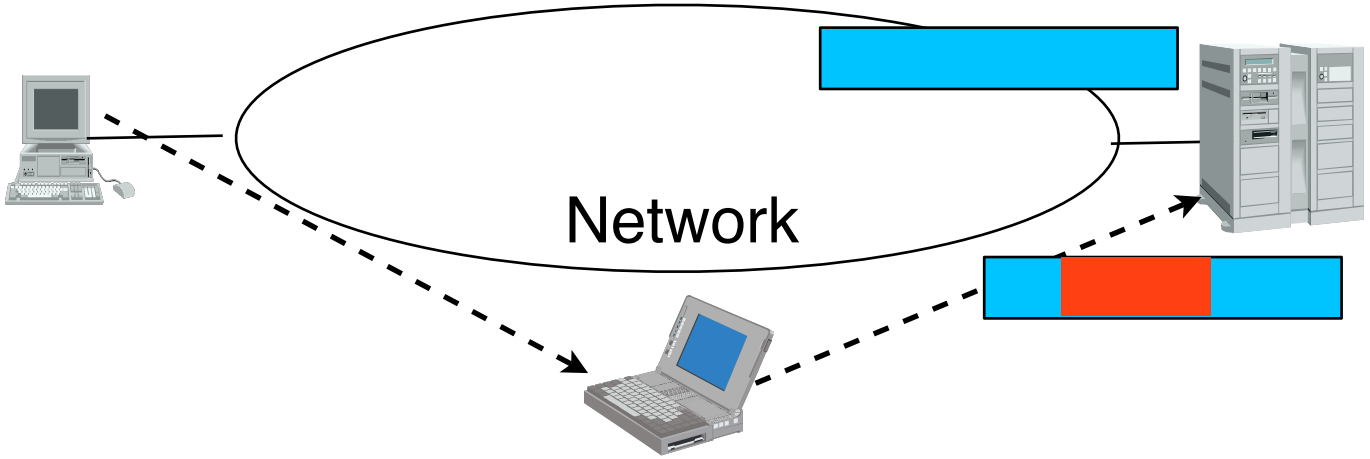

These attacks are dealt by using special security protocols and mechanisms outside the transport layer

How to detect transmission errors ?

Principle

Sender adds some control information inside the segment

control information is computed over the entire segment and placed in the segment header or trailer

Receiver checks that the received control information is correct by recomputing it

Parity bits

Simple solution to detect transmission errors

Used on slow-speed serial lines

e.g. modems connected to the telephone network

Odd Parity

For each group of n bits, sender computes the n+1th bit so that the n+1 group contains an odd number of bits set to 1

Examples

```
0011010          1101100
```

Even Parity

Parity bits

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Examples

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Even Parity

Internet checksum

Motivation

Internet protocols are implemented in software and we would like to have efficient algorithms to detect transmission errors that are easy to implement

Solution

Internet checksum

Sender computes for each segment and over the entire segment the 1s complement of the sum of all the 16 bits words in the segment

Receiver recomputes the checksum over each received segment and verifies that it is correct. Otherwise, the

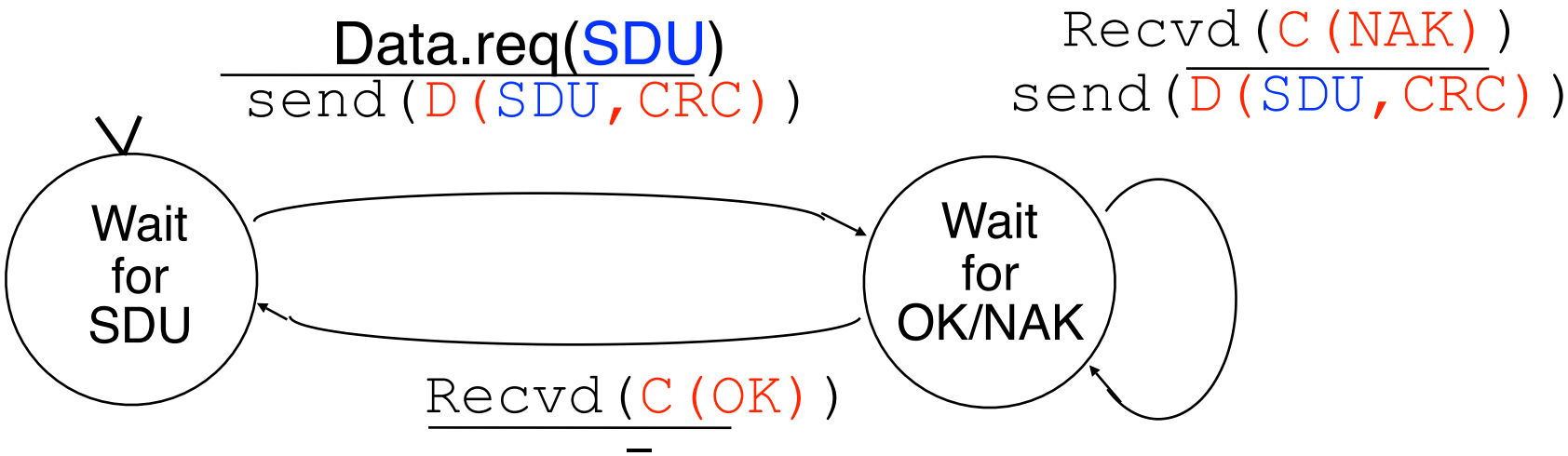
Detection of transmission errors (2)

Behaviour of the receiver

- If the checksum is correct
  - Send an OK control segment to the sender to
    - confirm the reception of the data segment
    - allow the sender to send the next segment
- If the checksum is incorrect
  - The content of the segment is corrupted and must be discarded
  - Send a special control segment (NAK) to the sender to ask it to retransmit the corrupted data segment

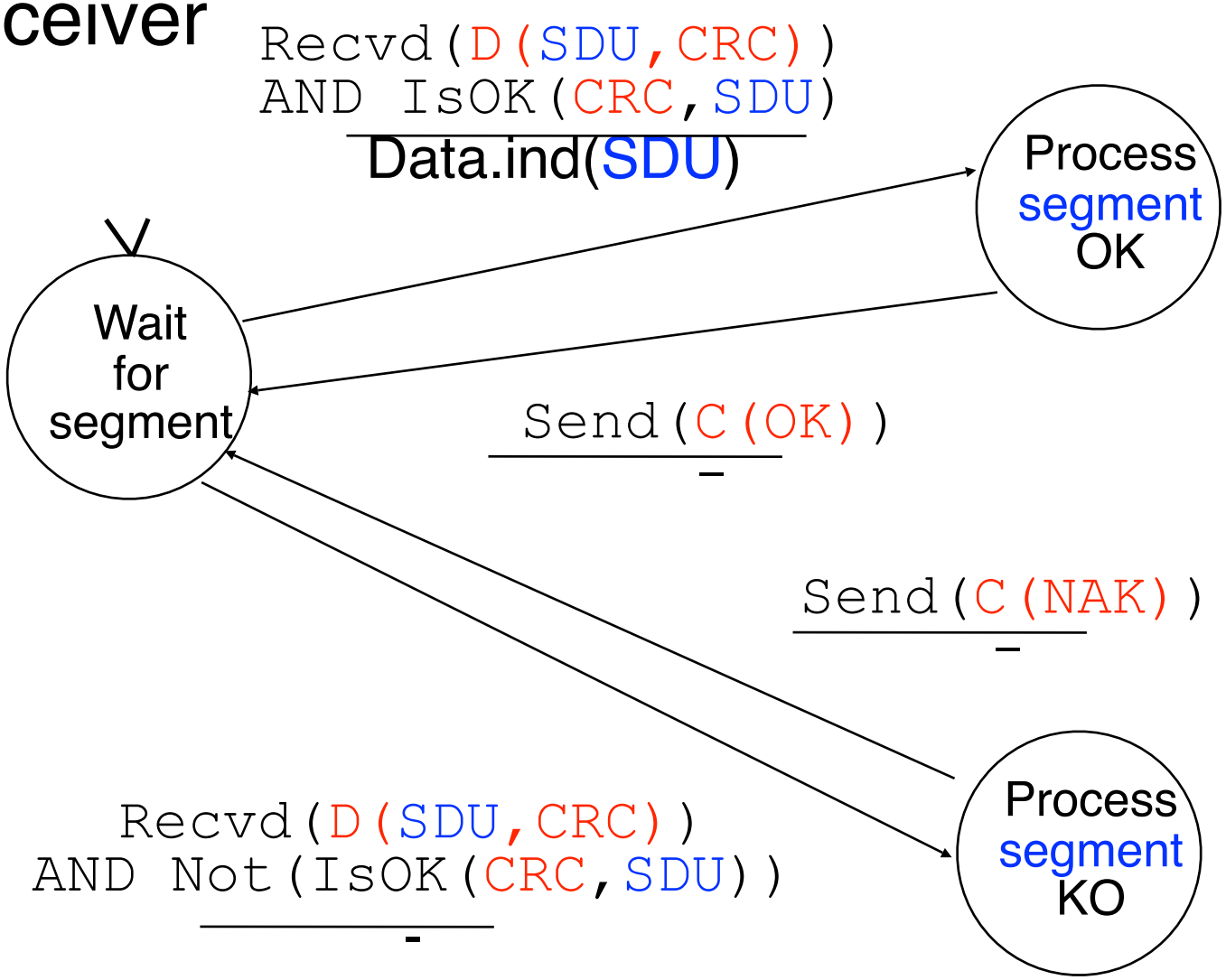
Protocol 3a : Sender

Sender



Protocol 3a : Receiver

Receiver

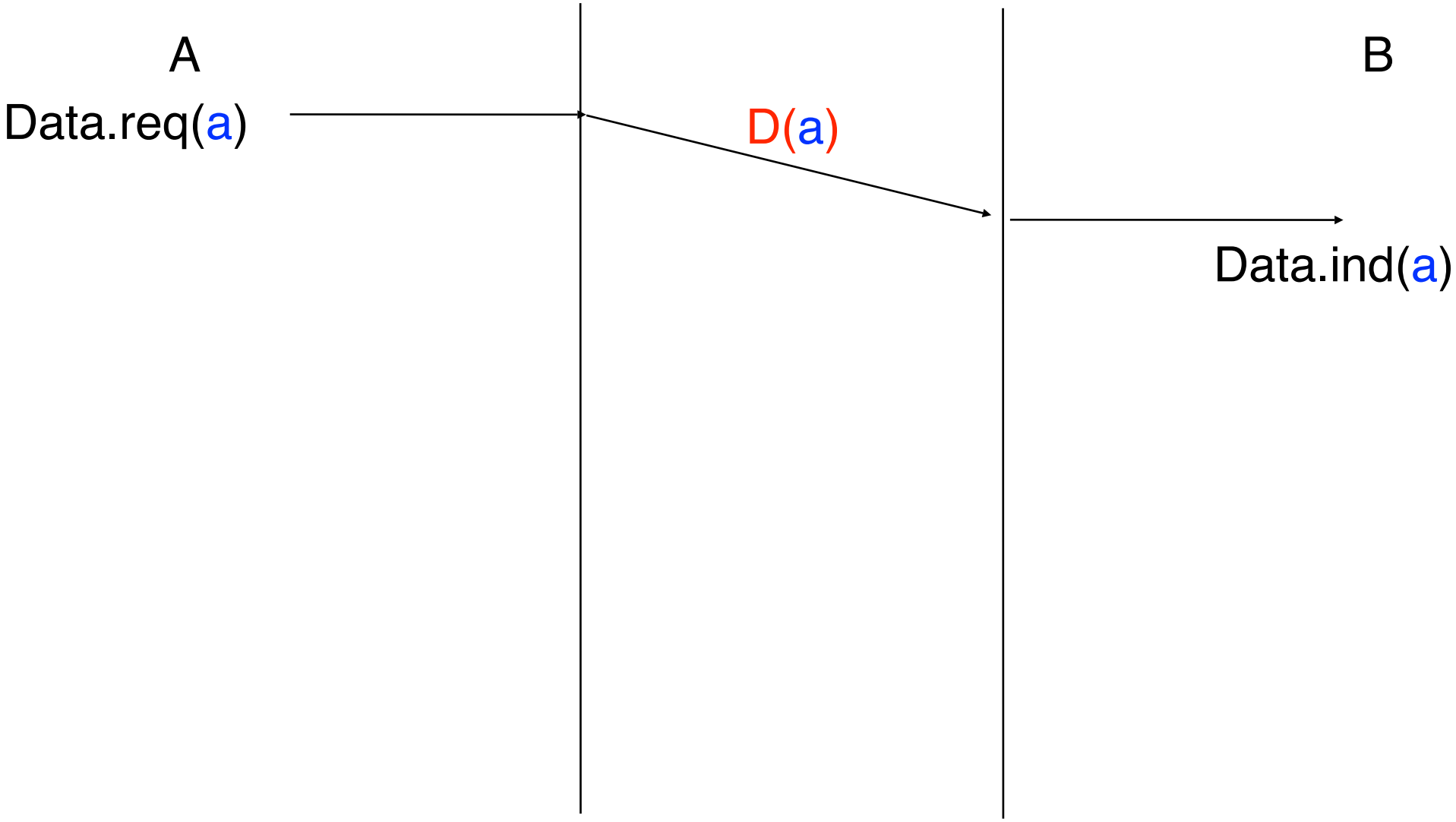


Protocol 3a : Example

A

B

Protocol 3a : Example



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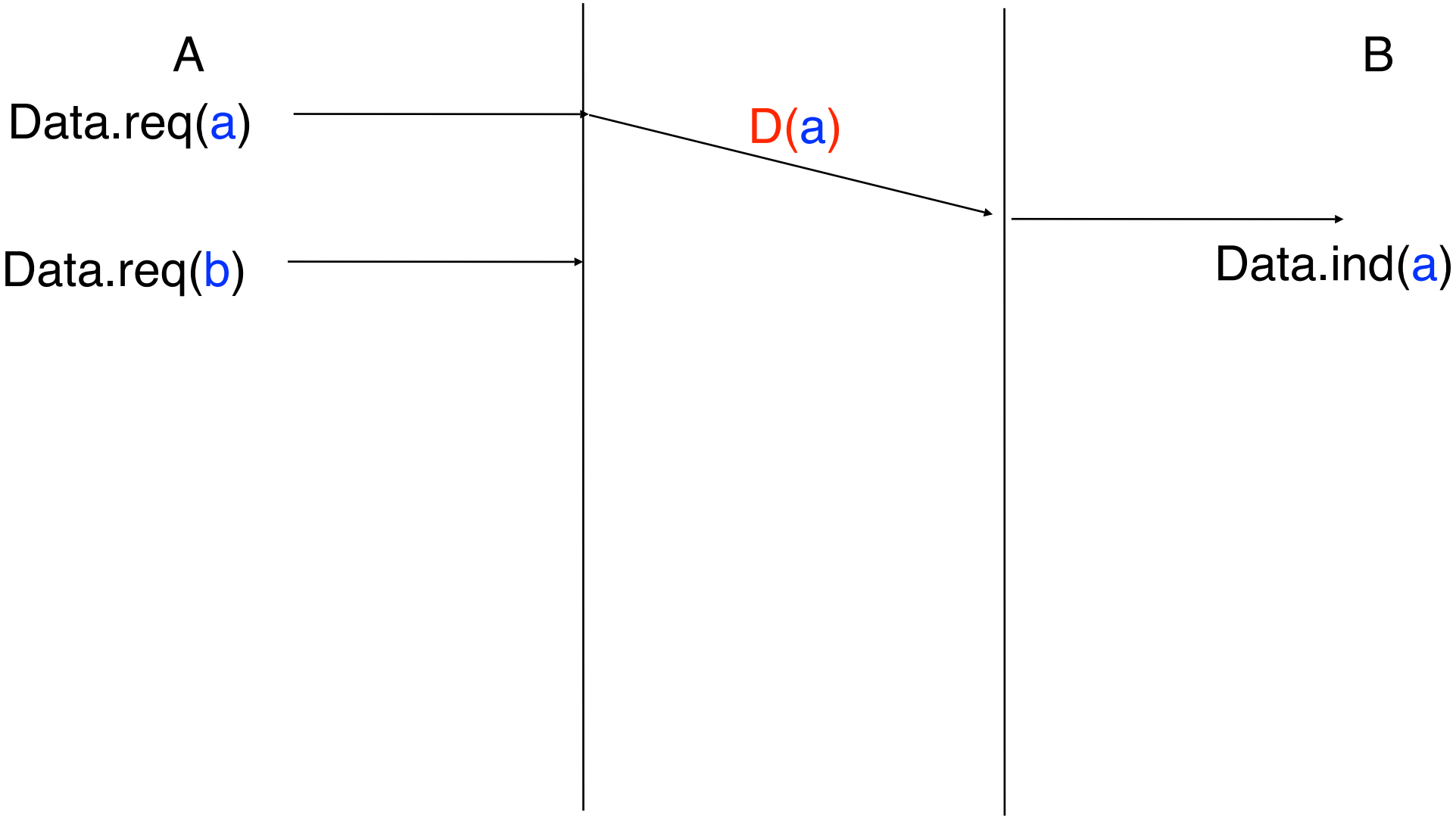

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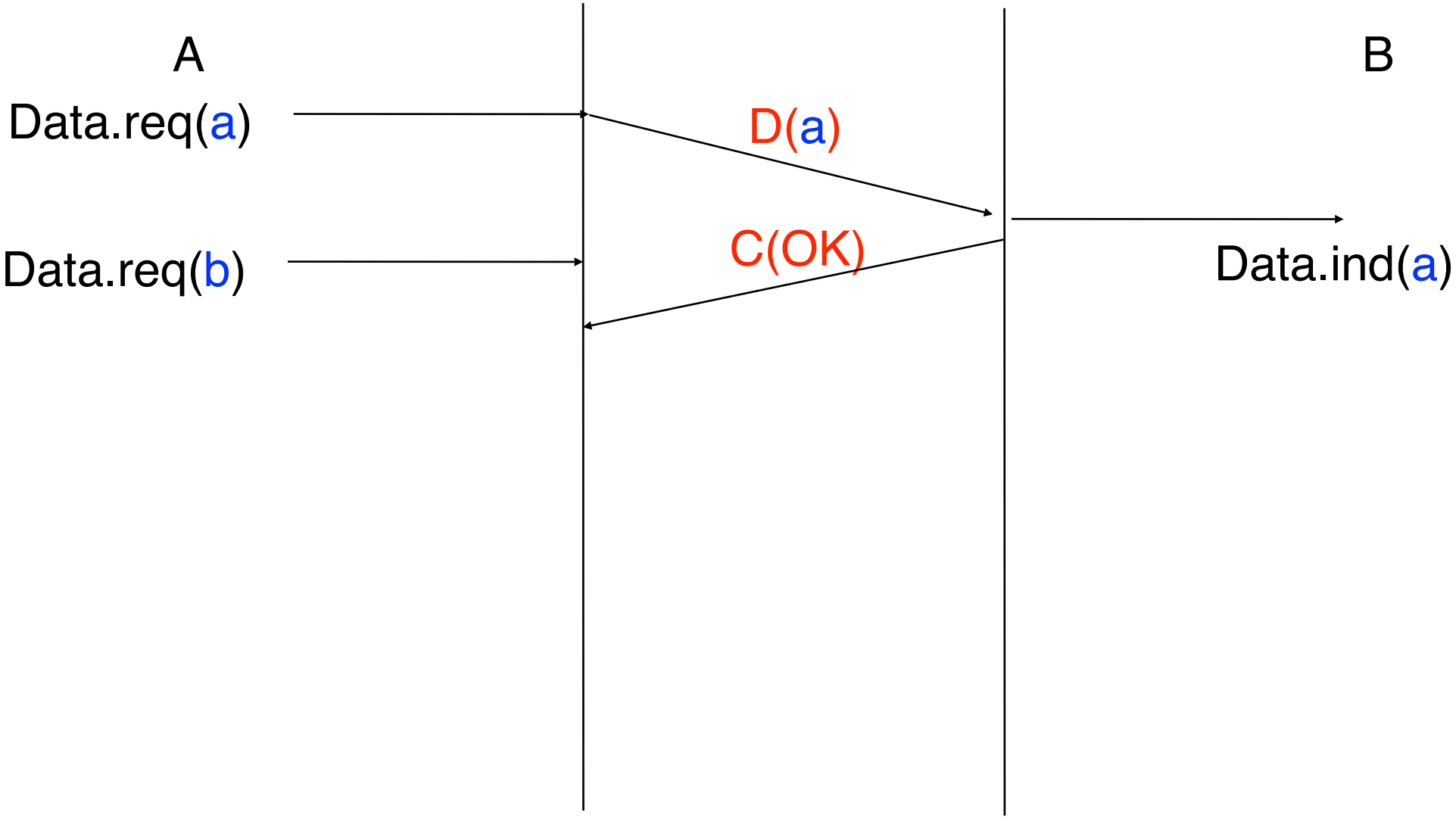

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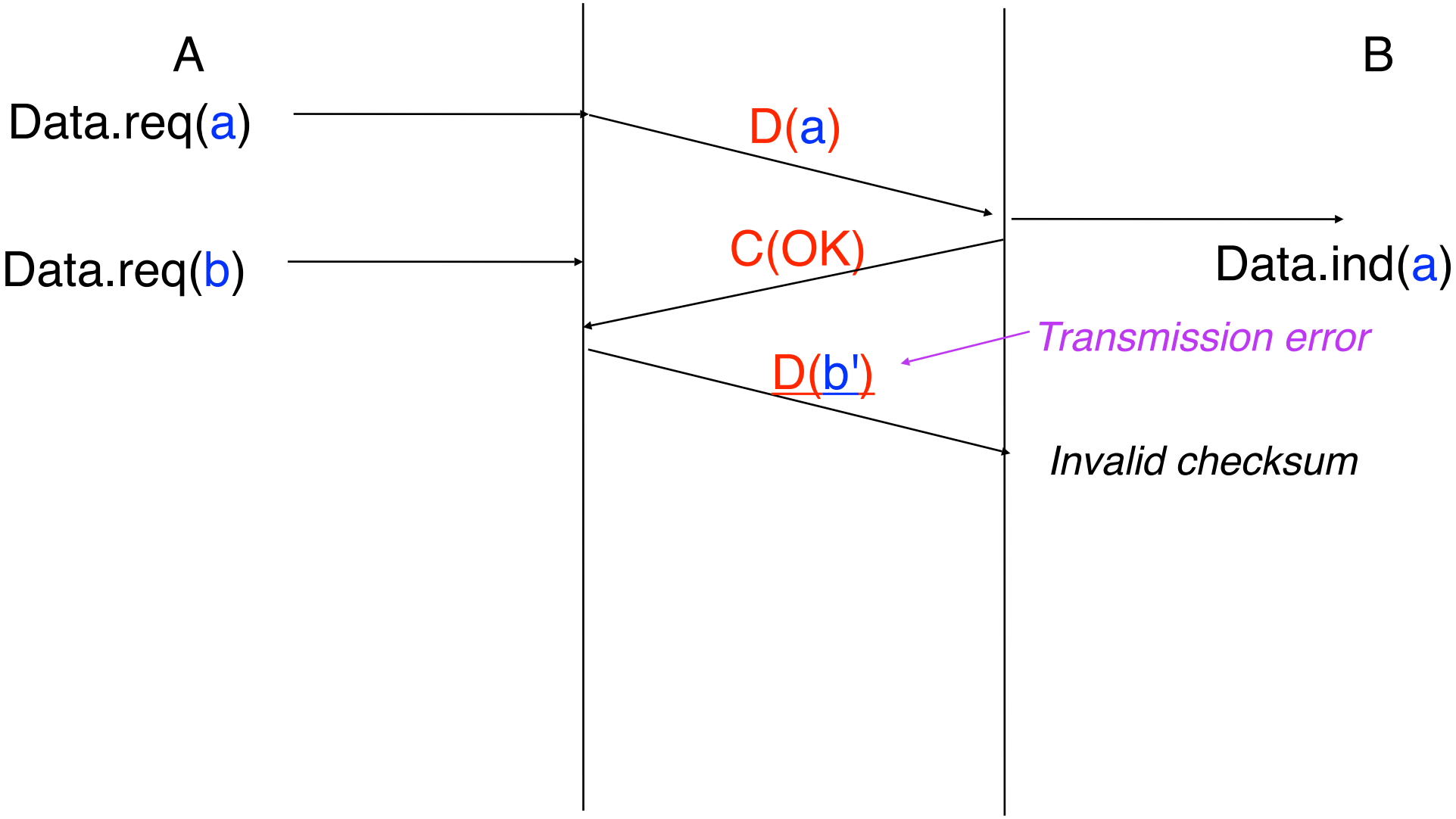

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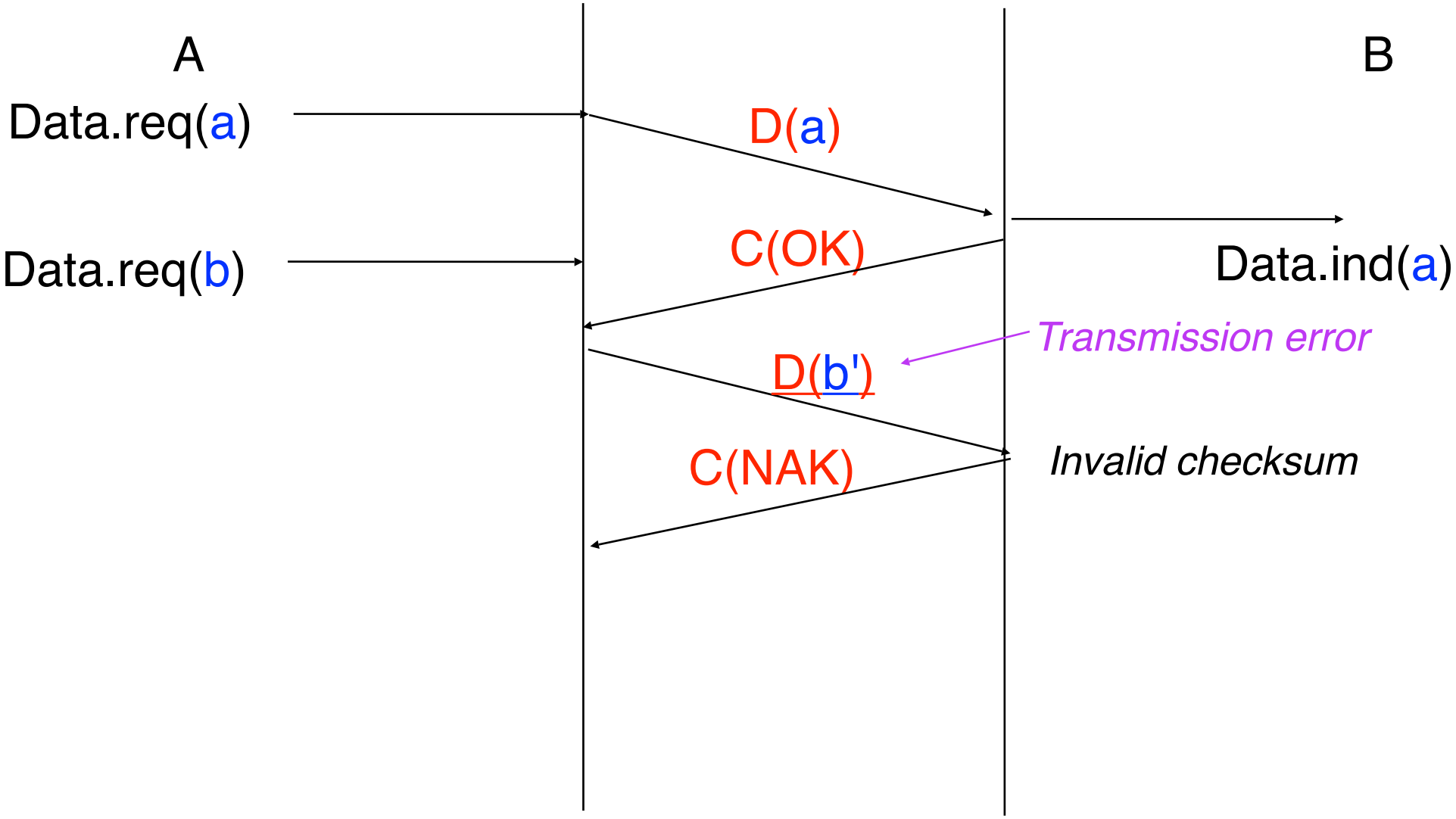

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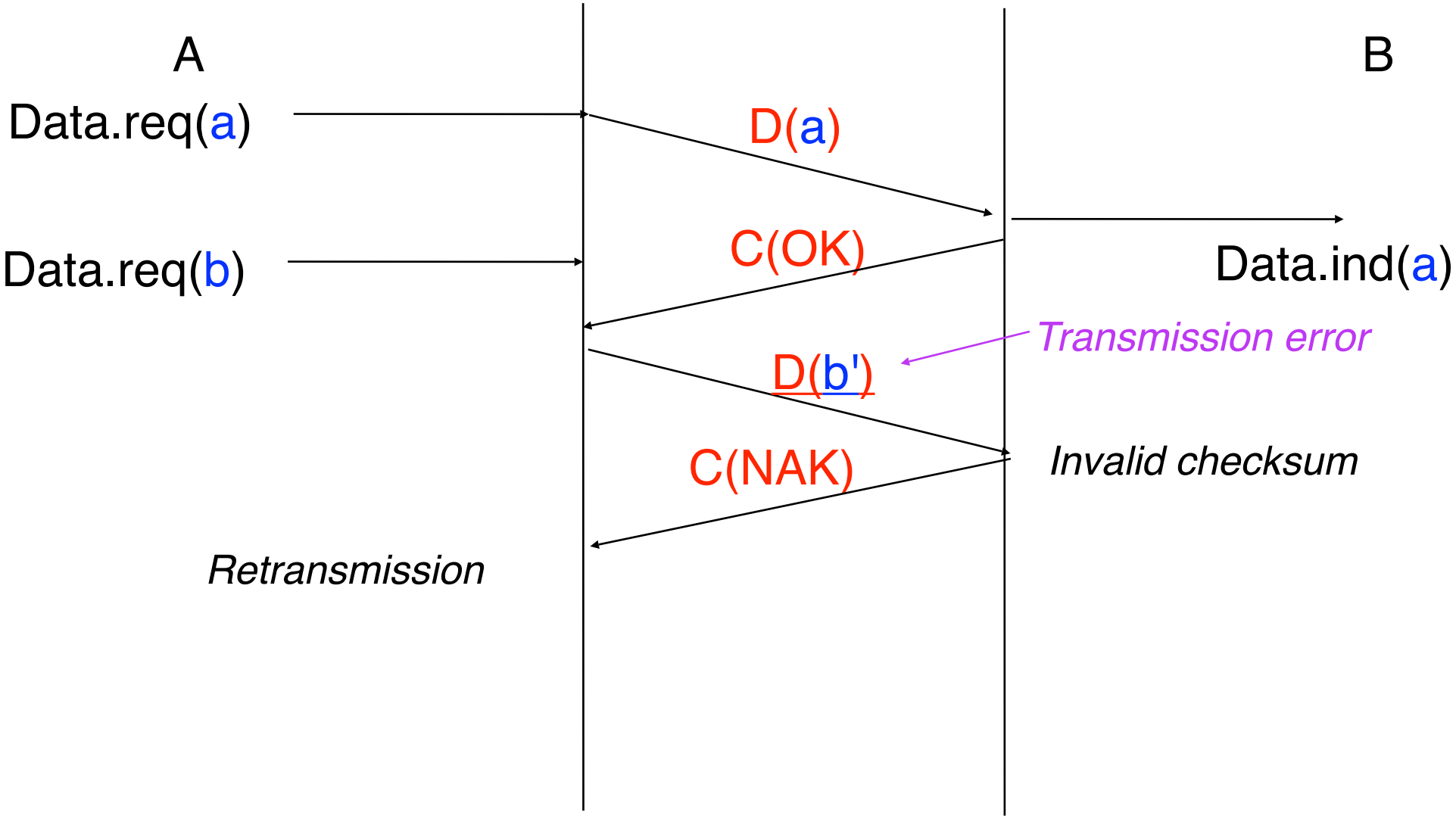

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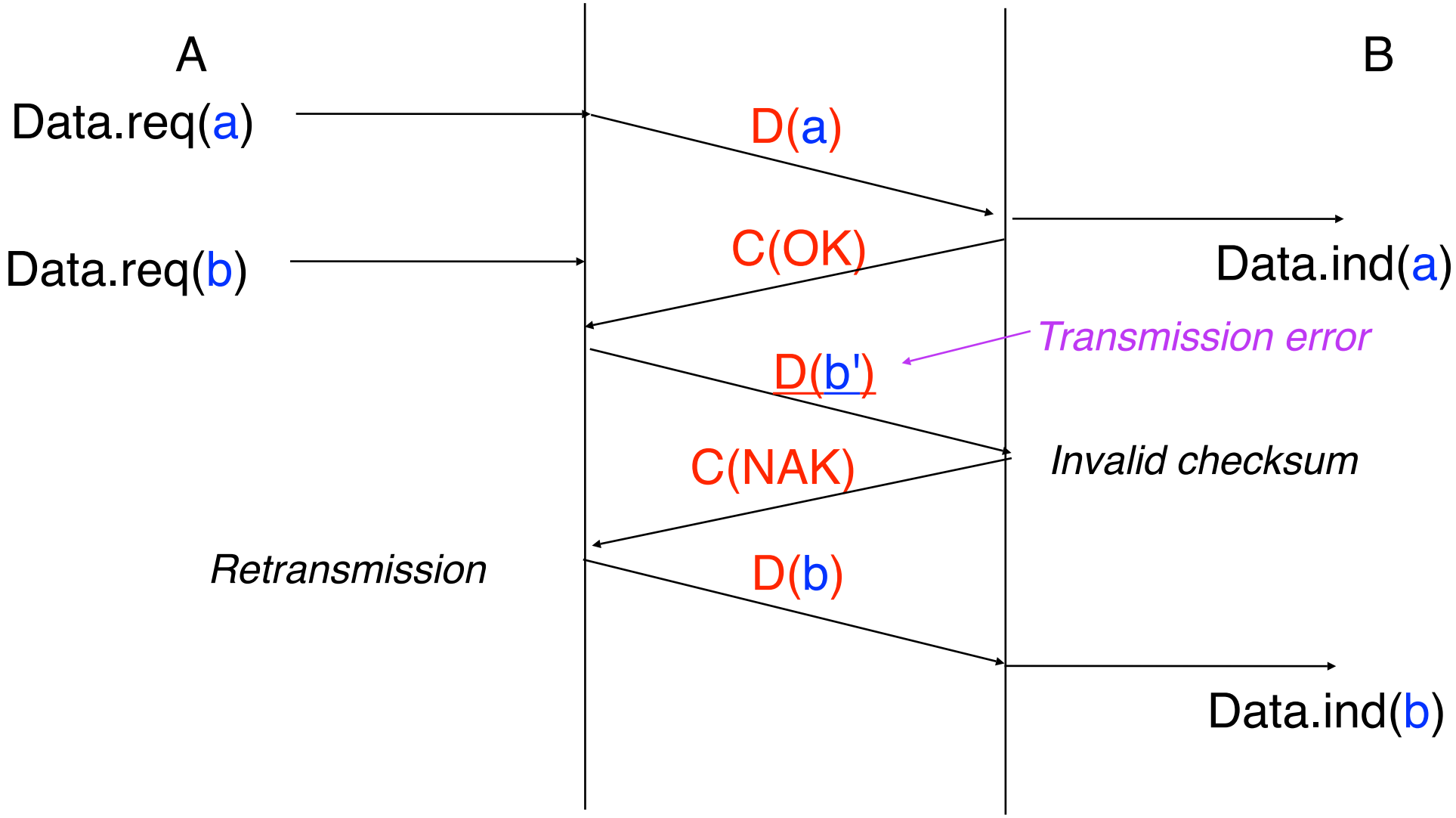

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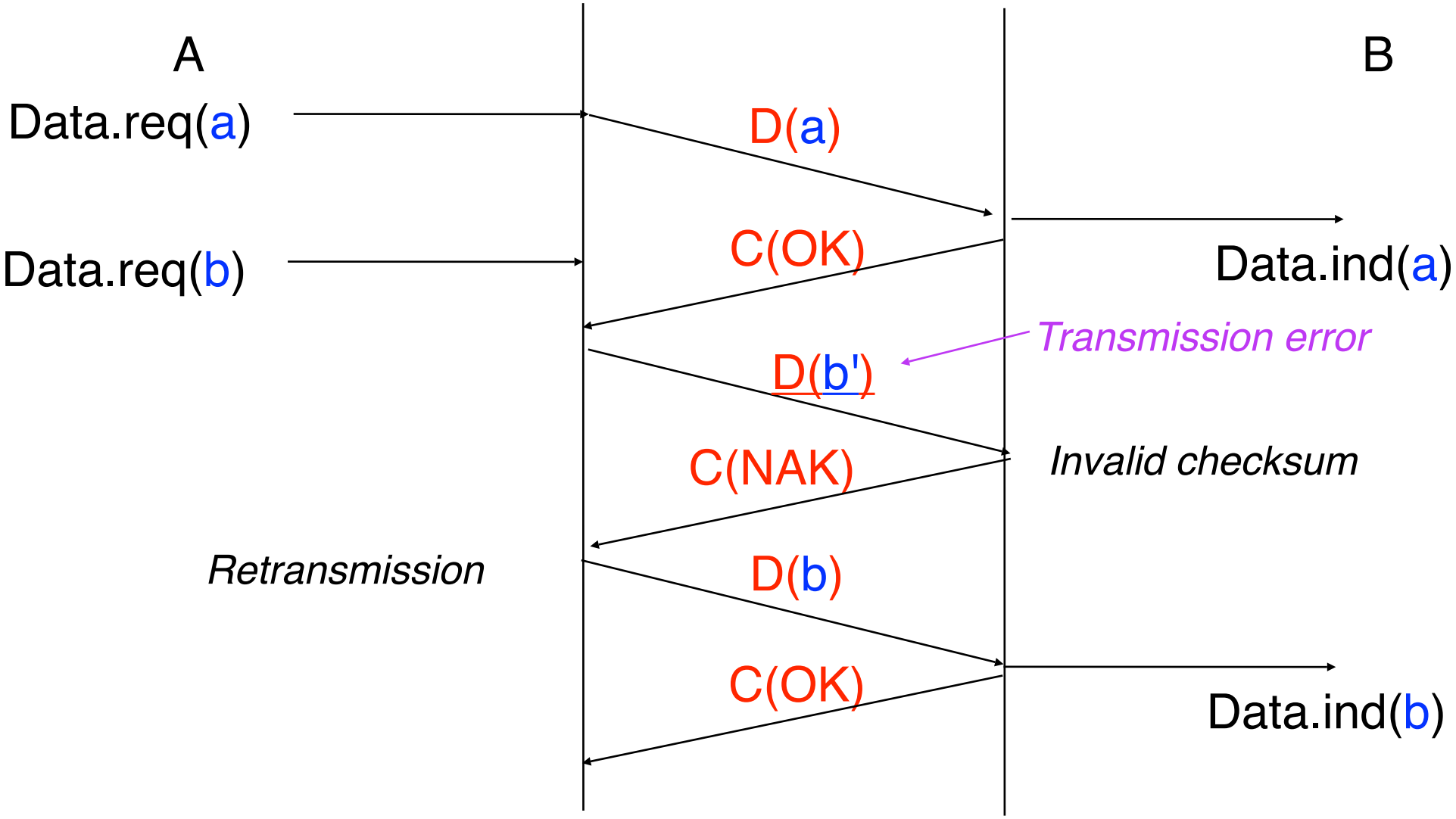
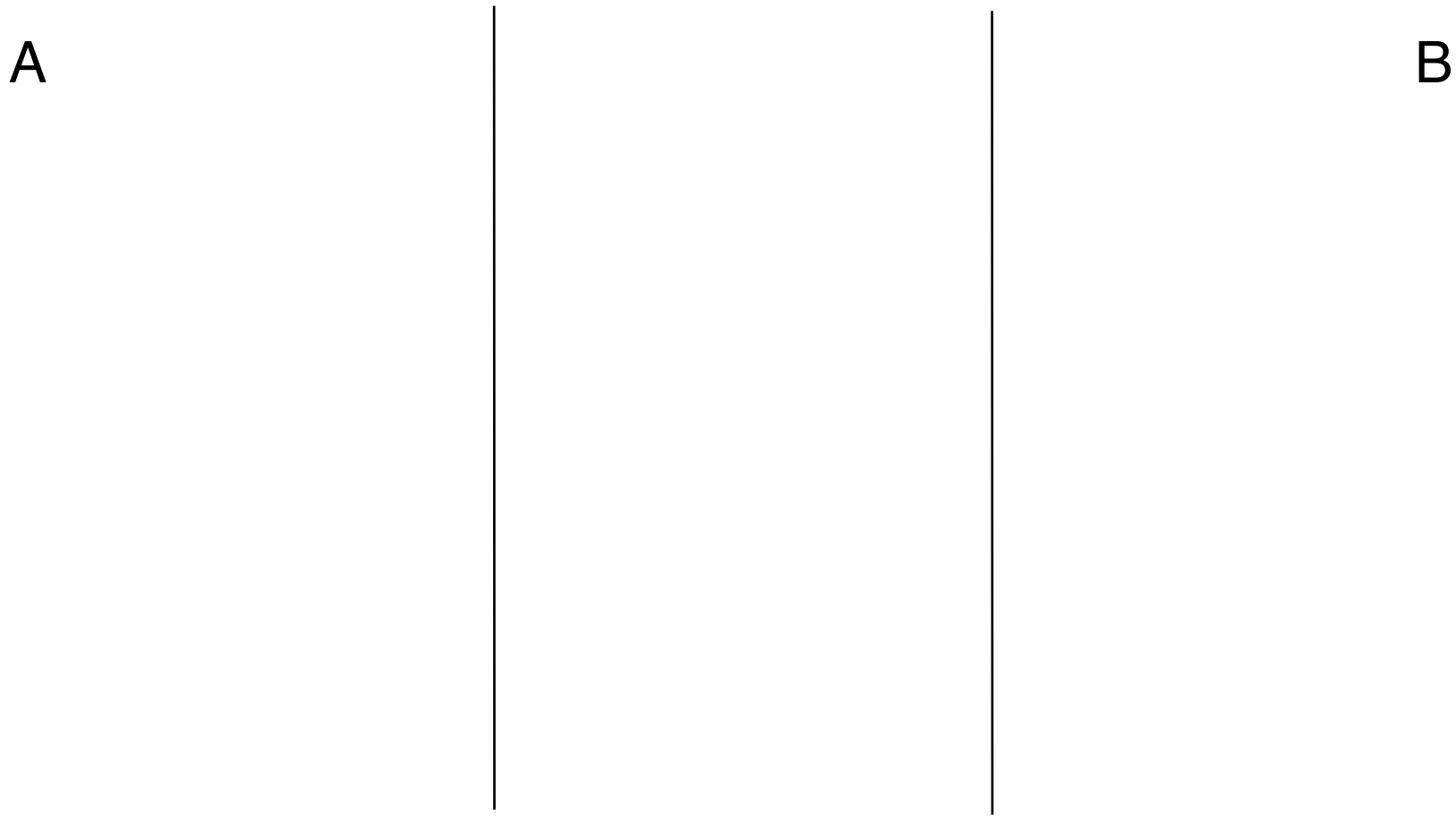


Protocol 3a and segment losses

How do segment losses affect protocol 3a ?



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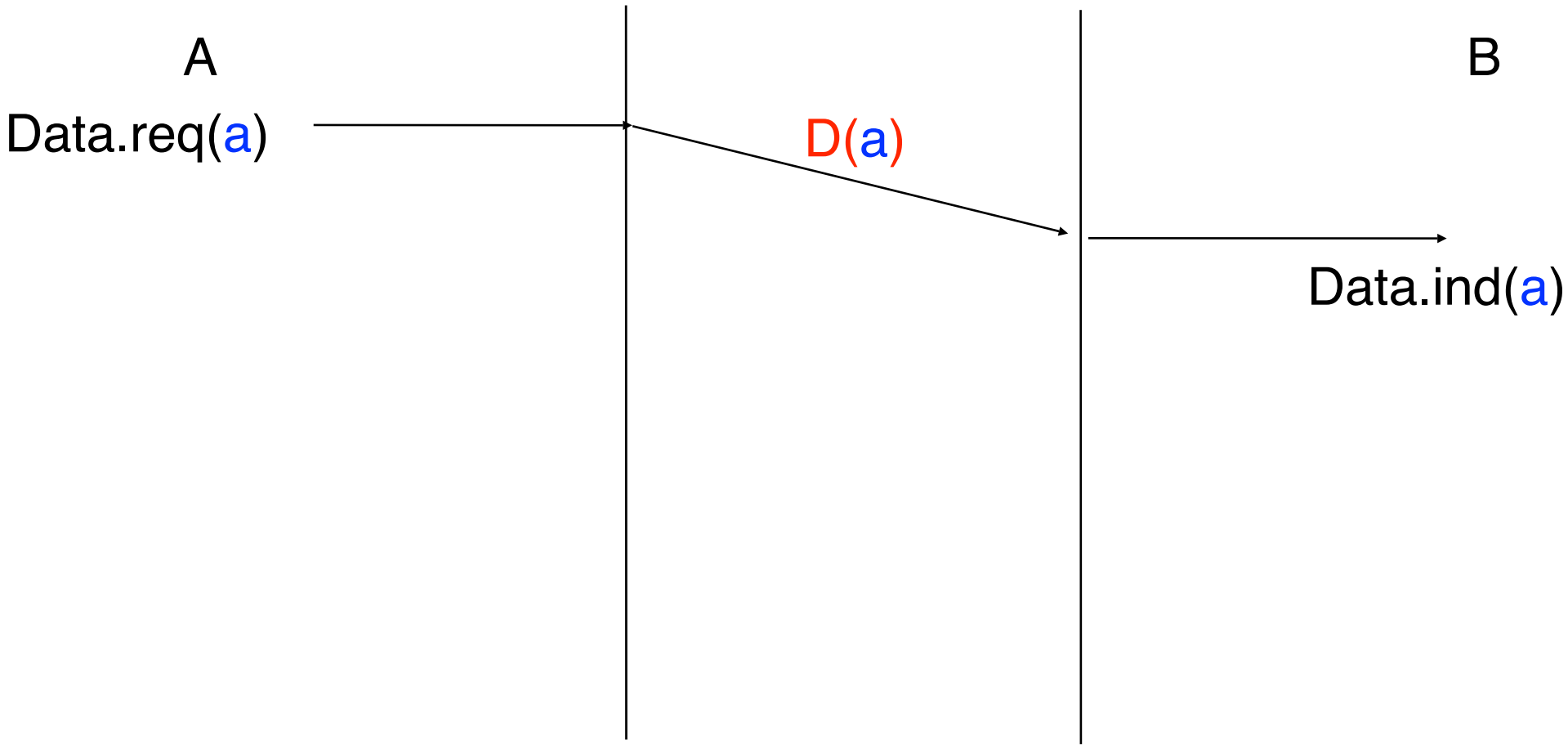

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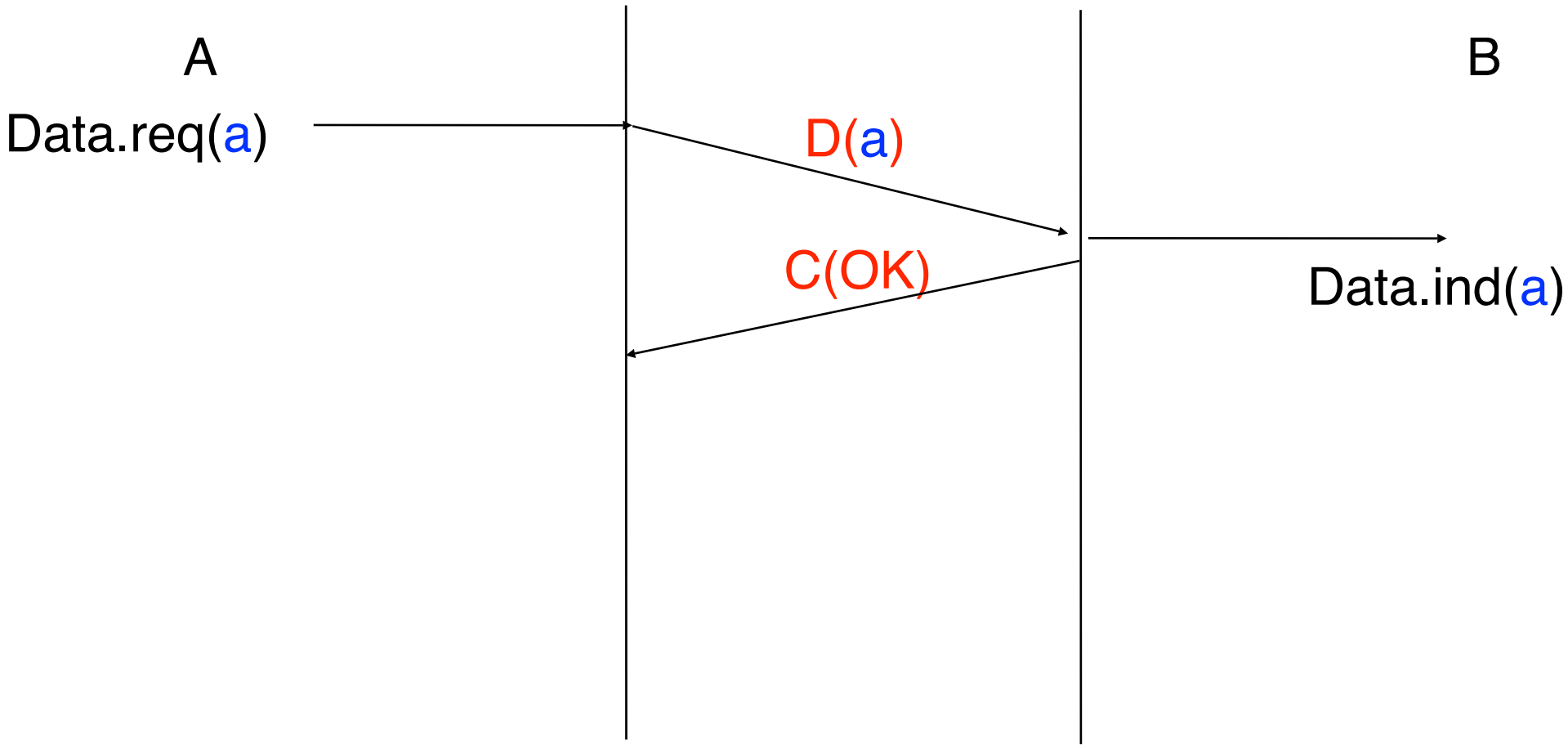

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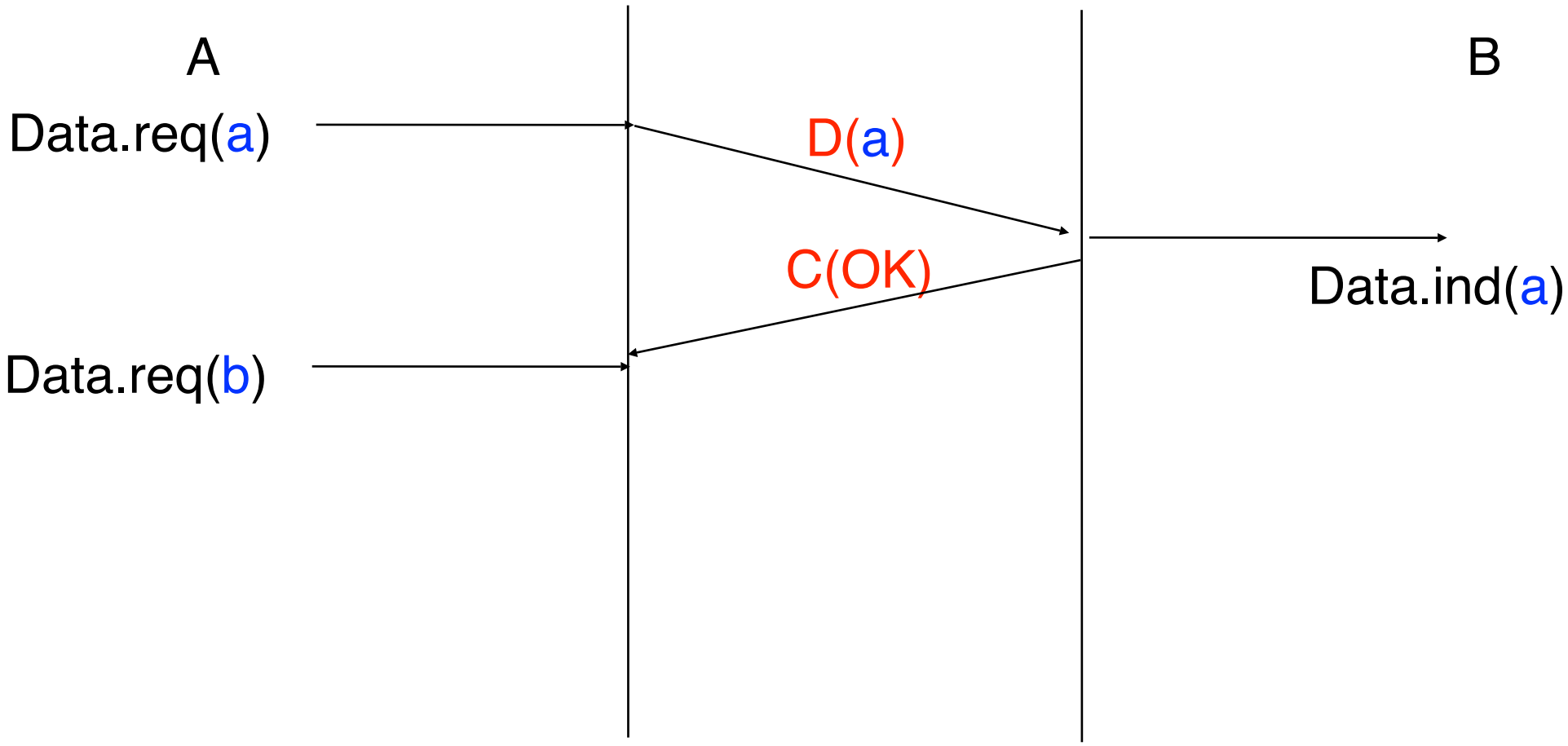

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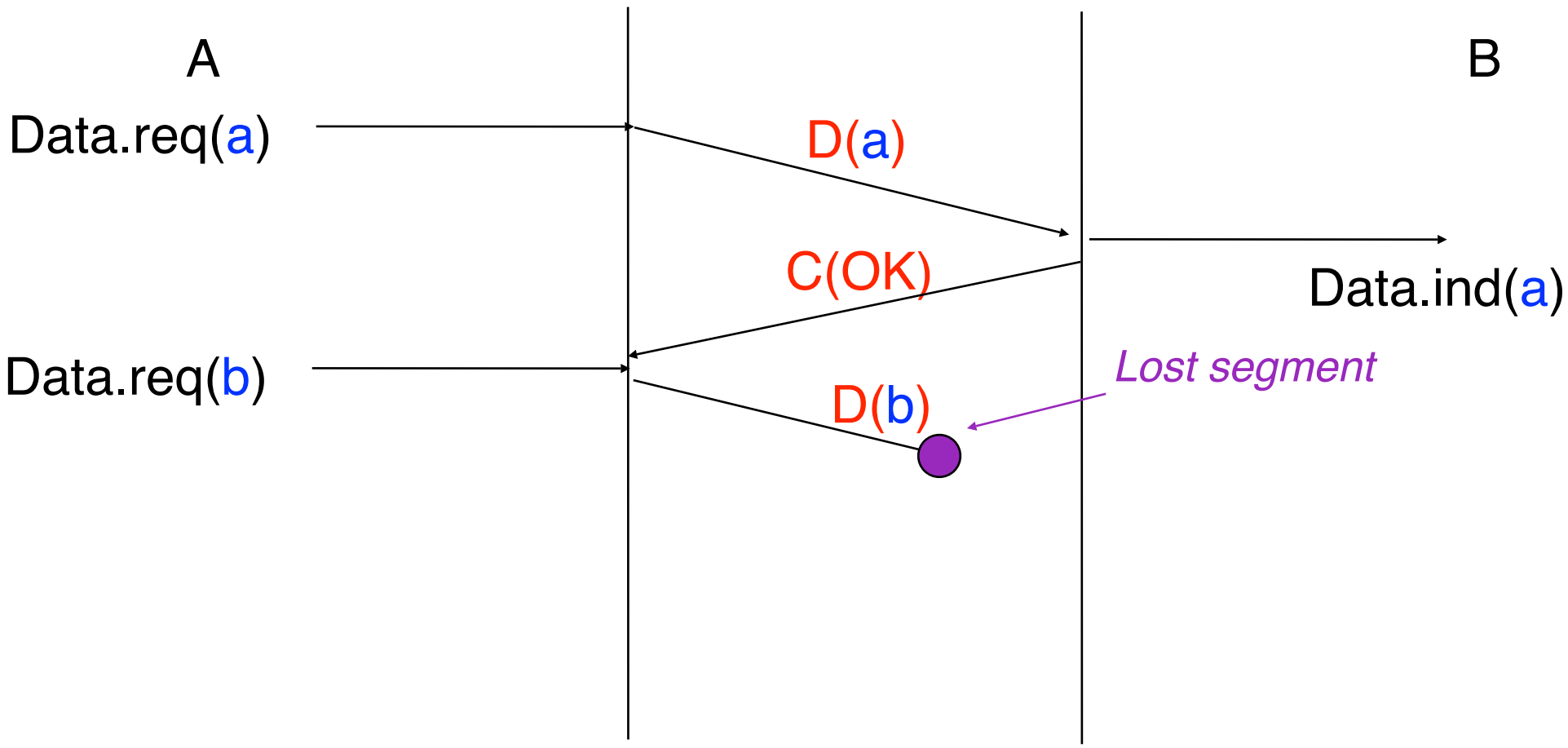

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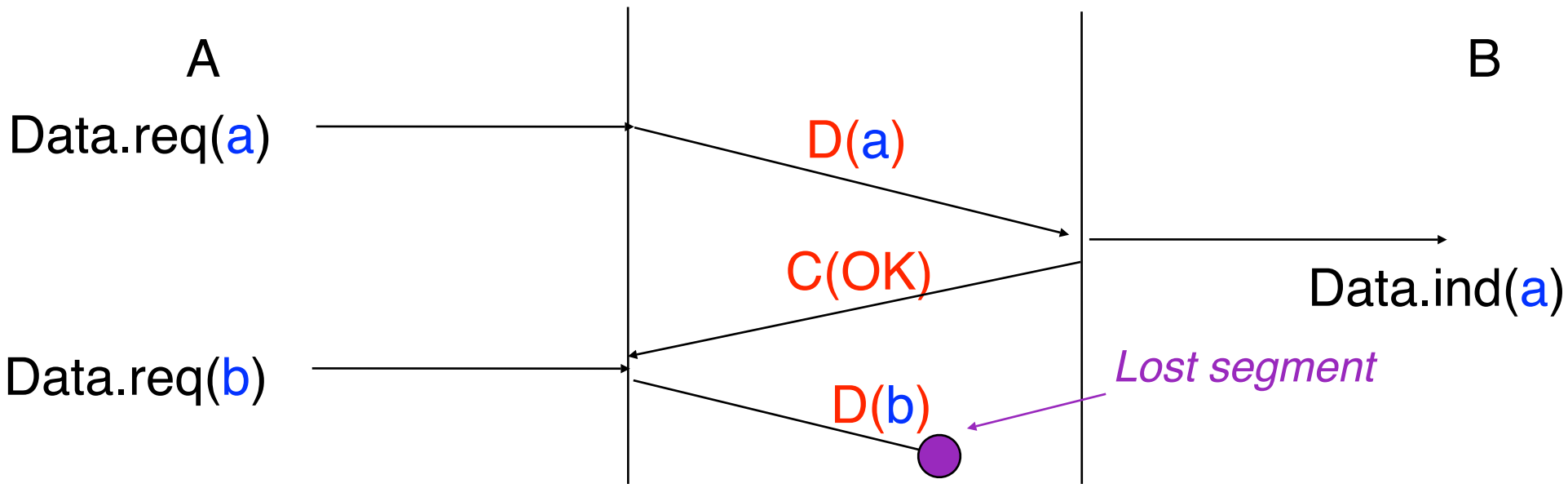


DEADLOCK

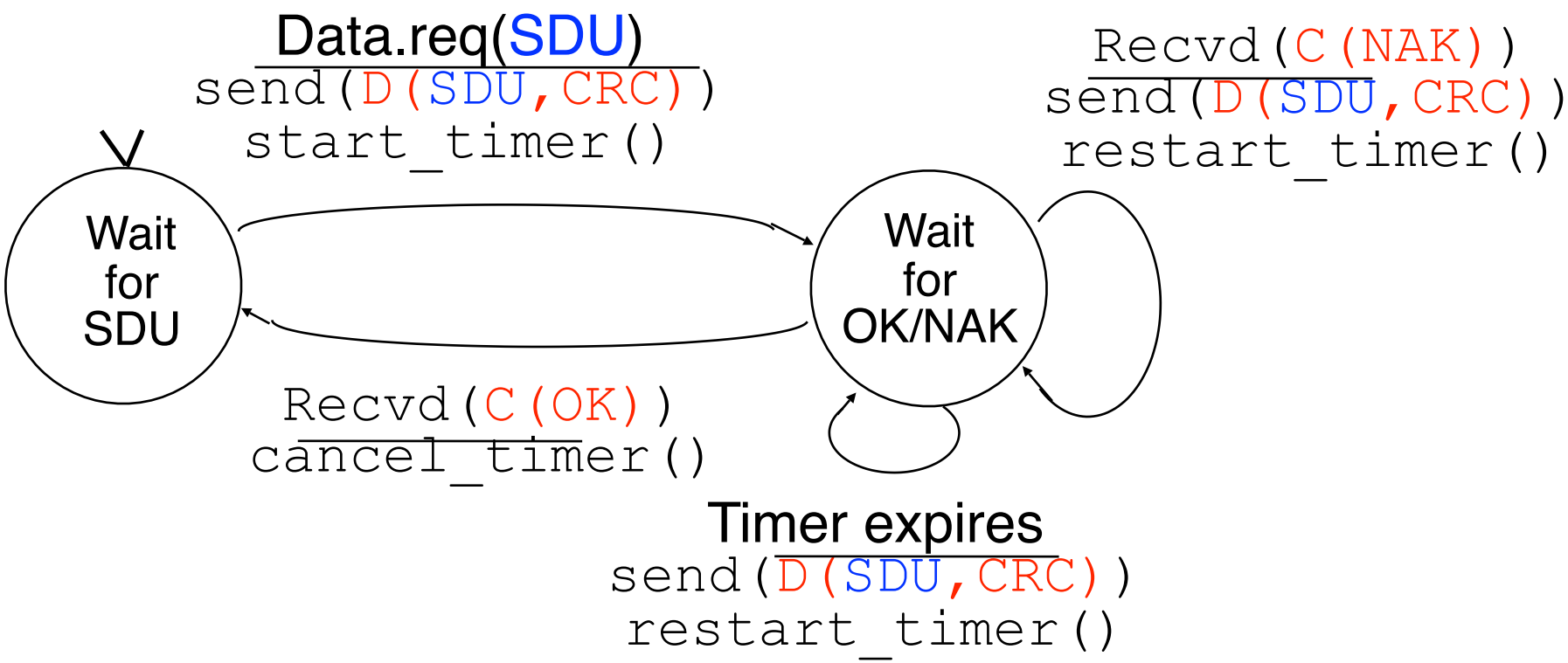
A is waiting for a control segment

B is waiting for a data segment

Protocol 3b

Modification to the sender

Add a retransmission timer to retransmit the lost segment after some time



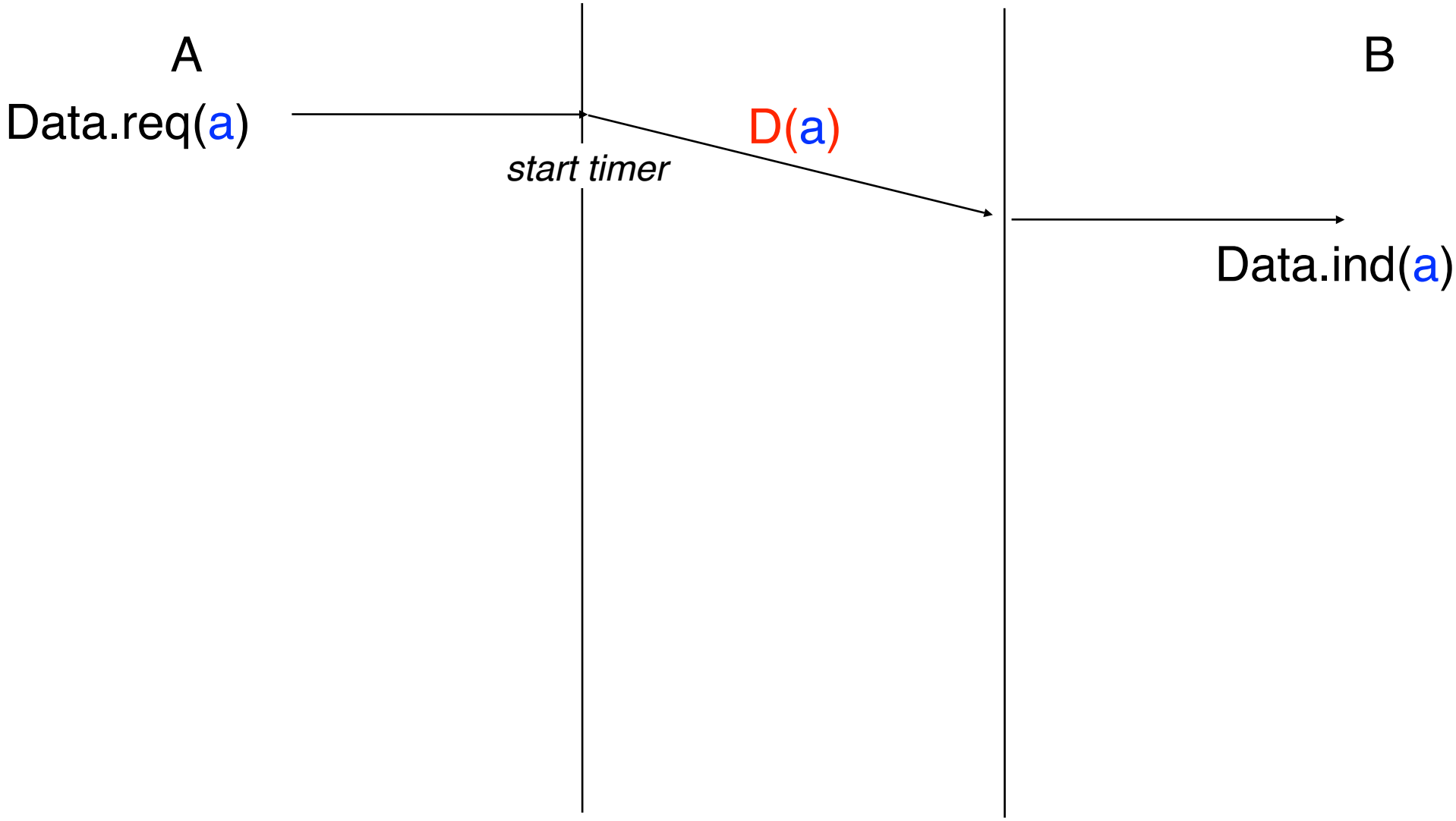
No modification to the receiver

Protocol 3b : Example

A

B

Protocol 3b : Example



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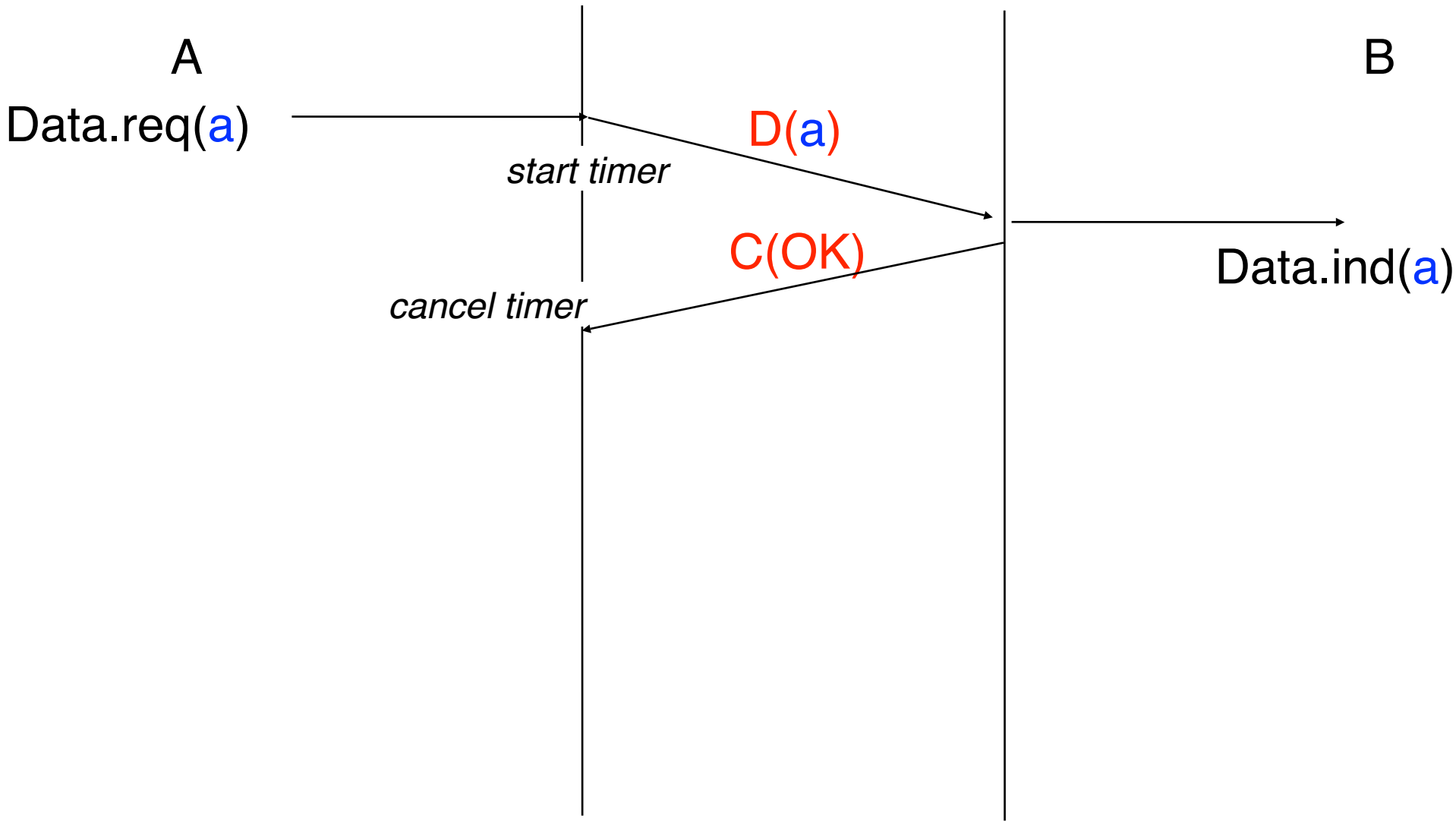

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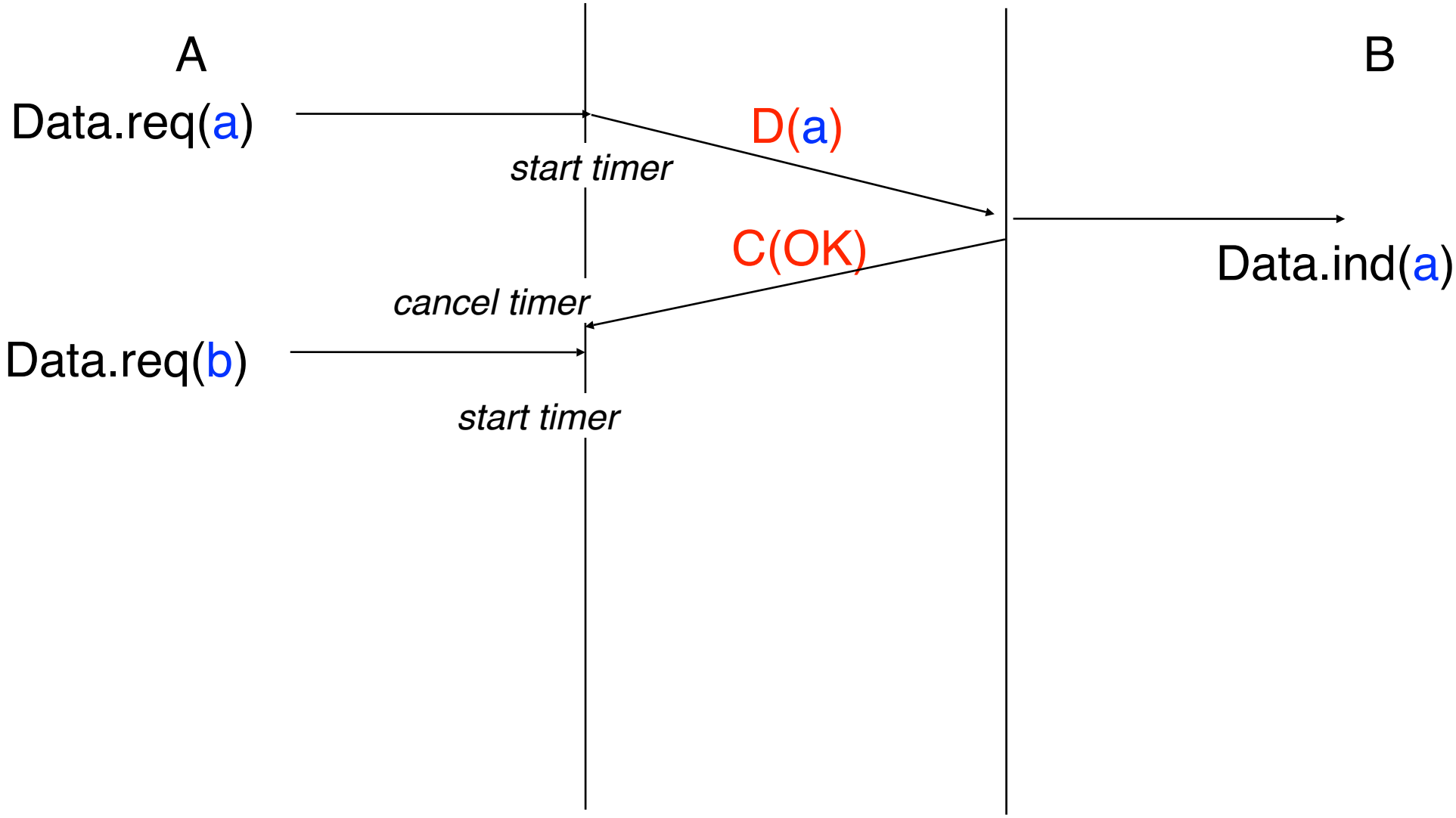
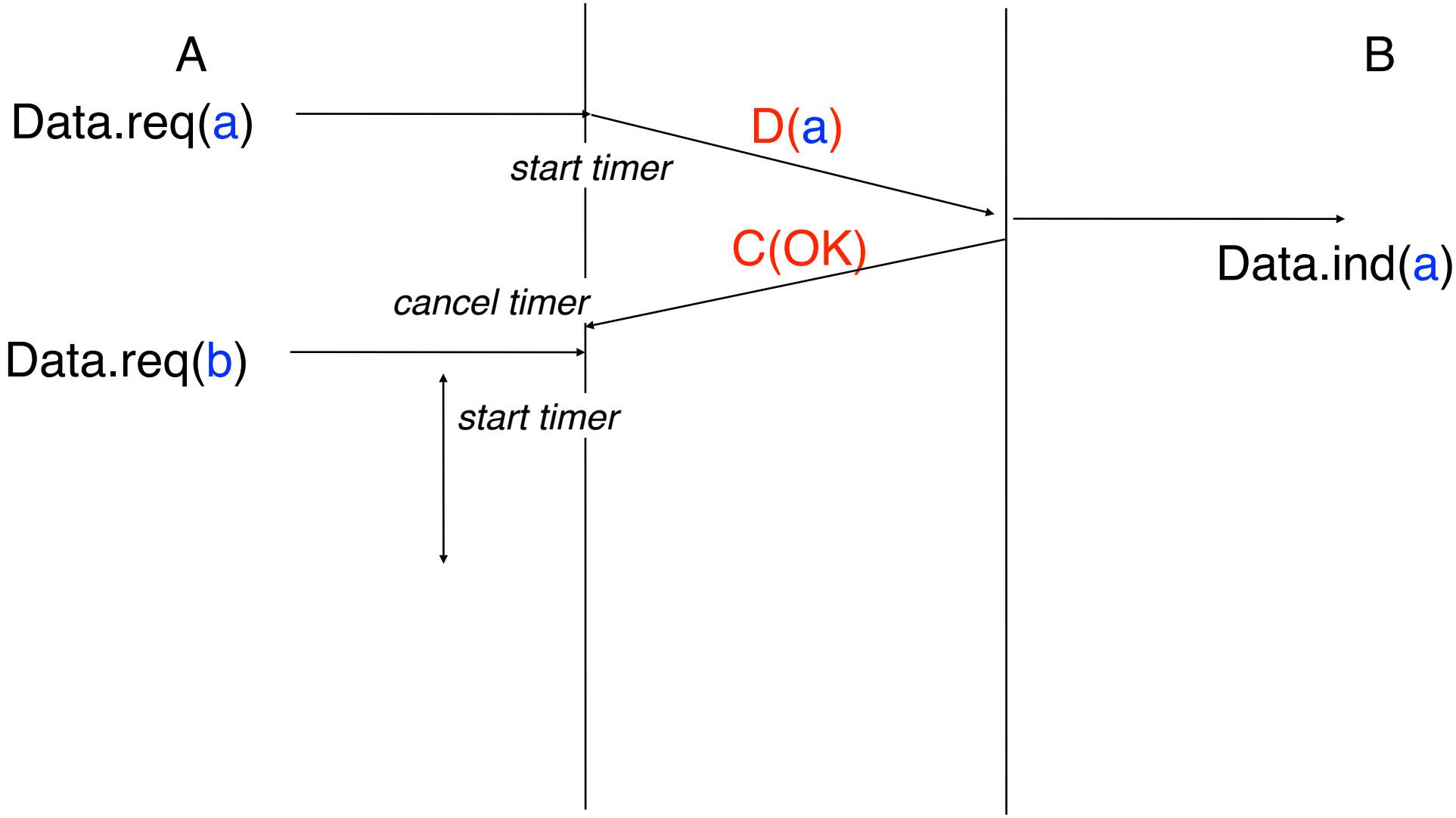
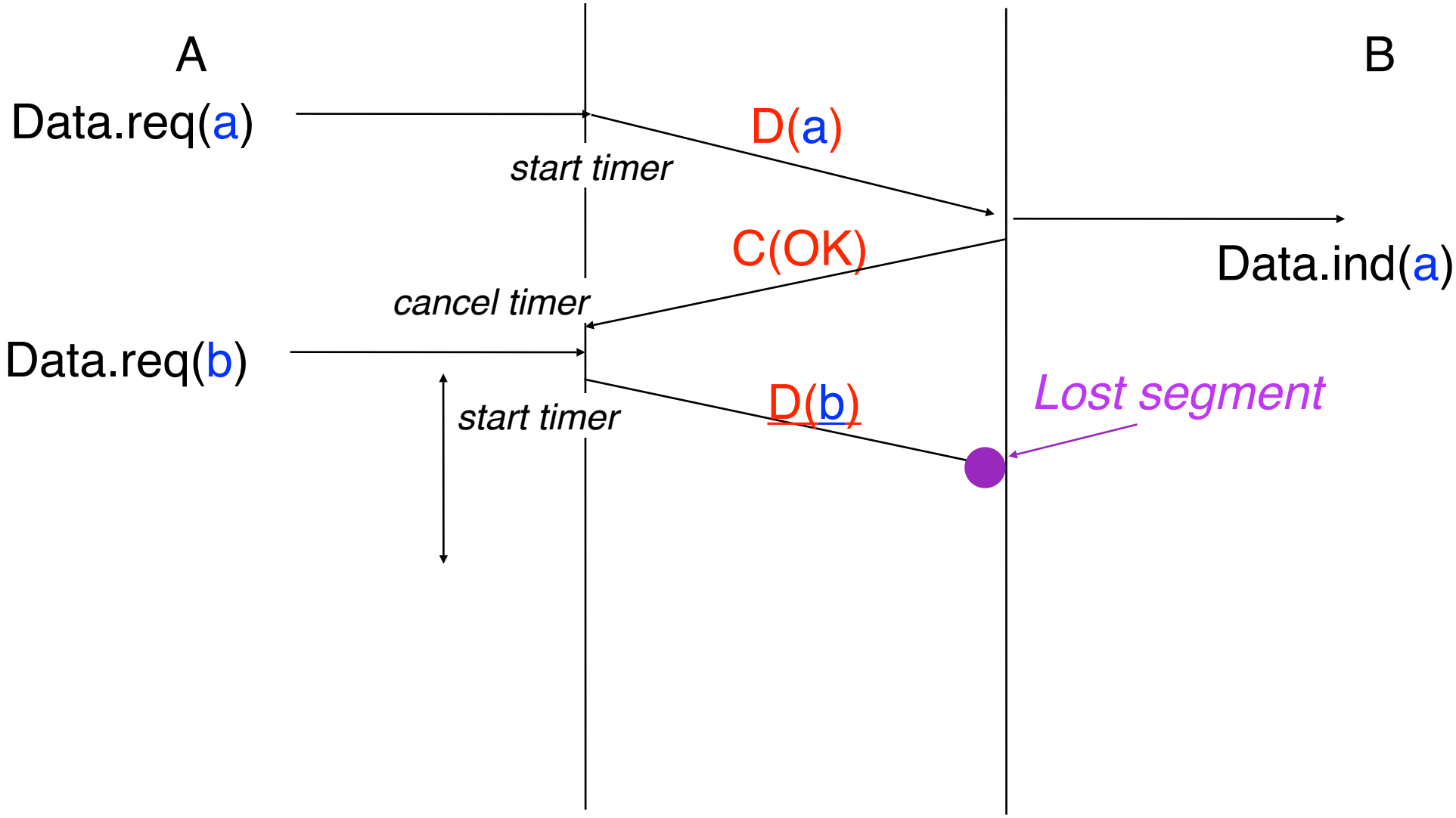


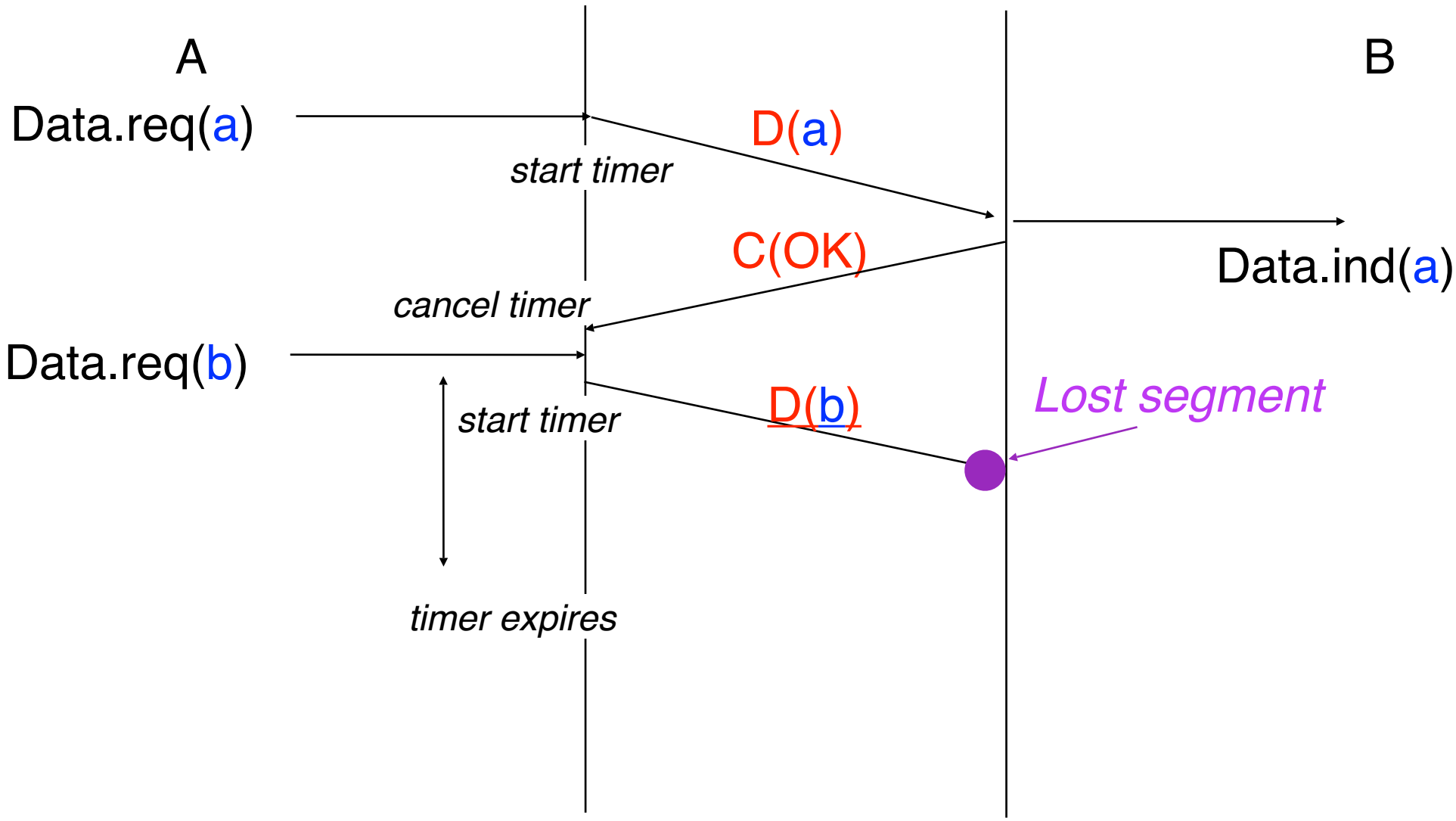
Protocol 3b : Example



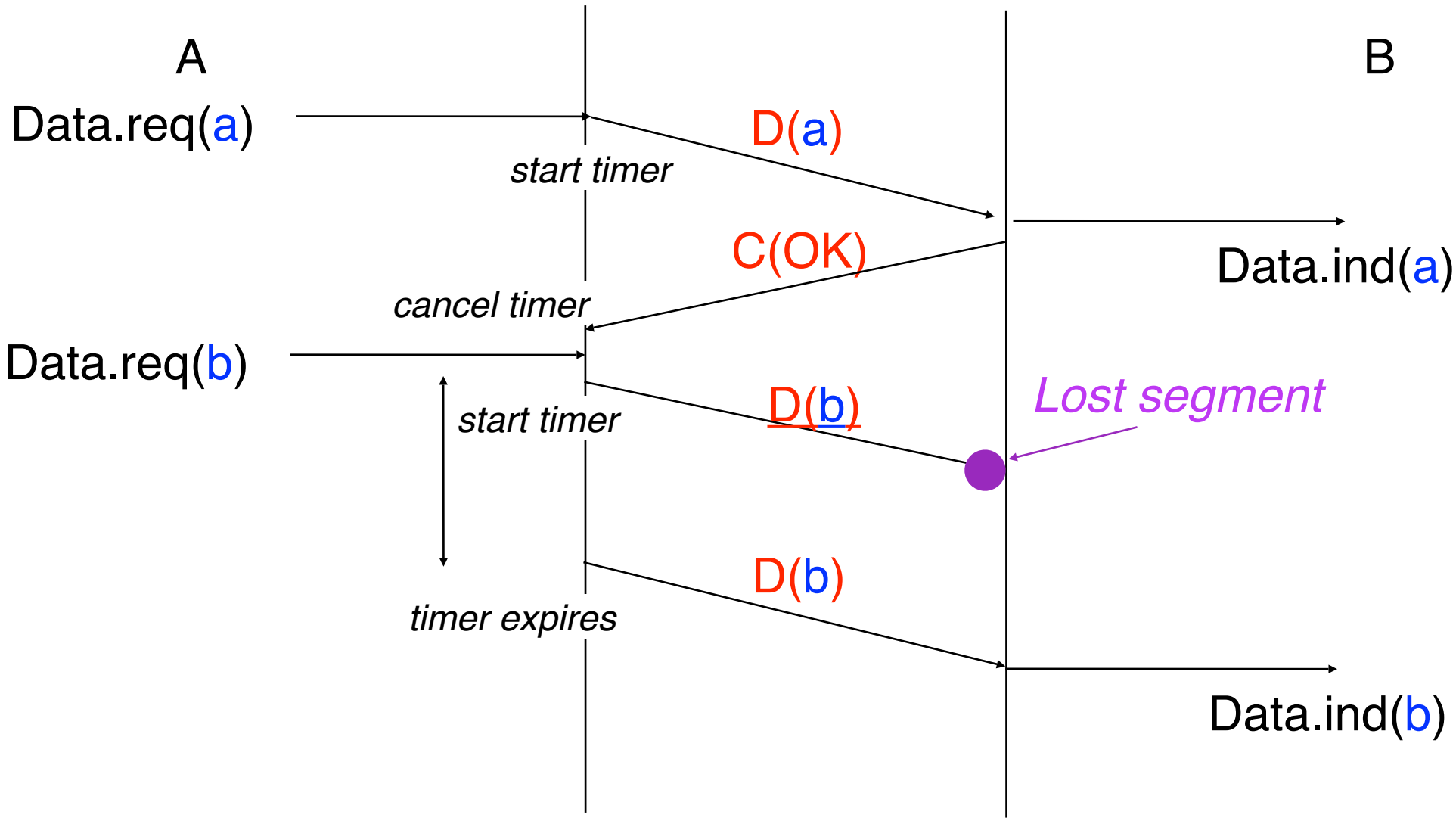
Protocol 3b : Example



Protocol 3b : Example



Protocol 3b : Example



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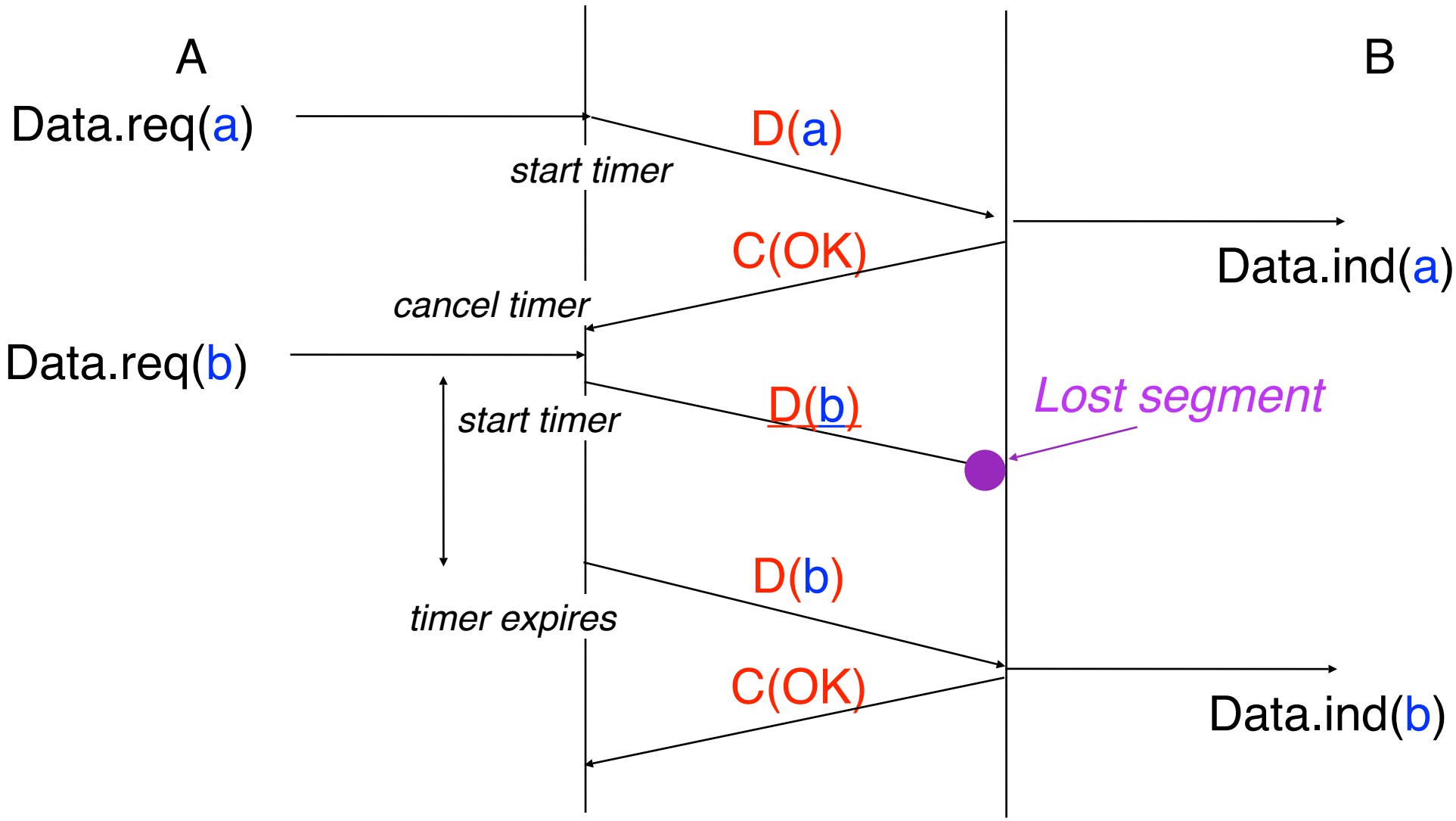

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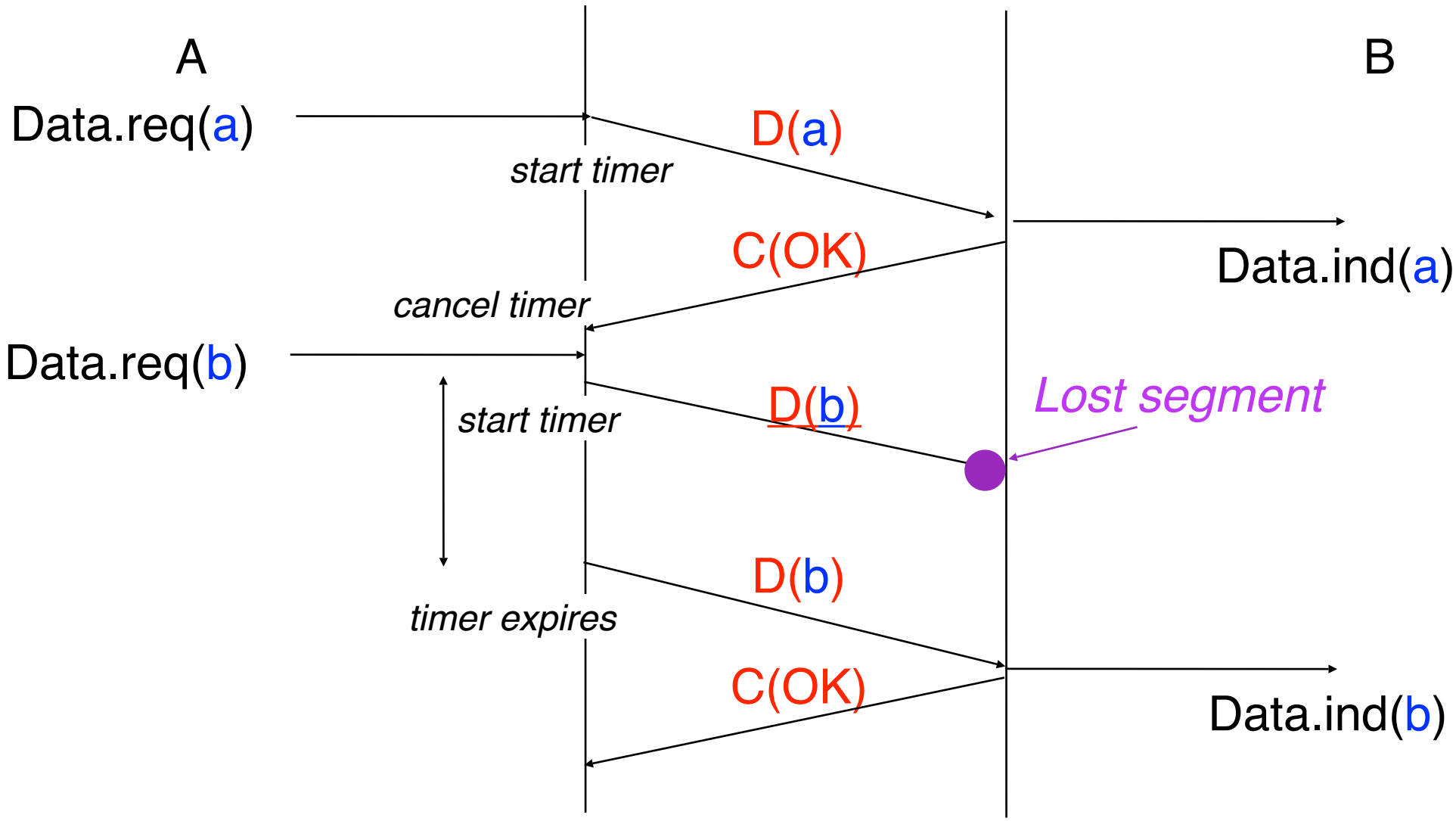


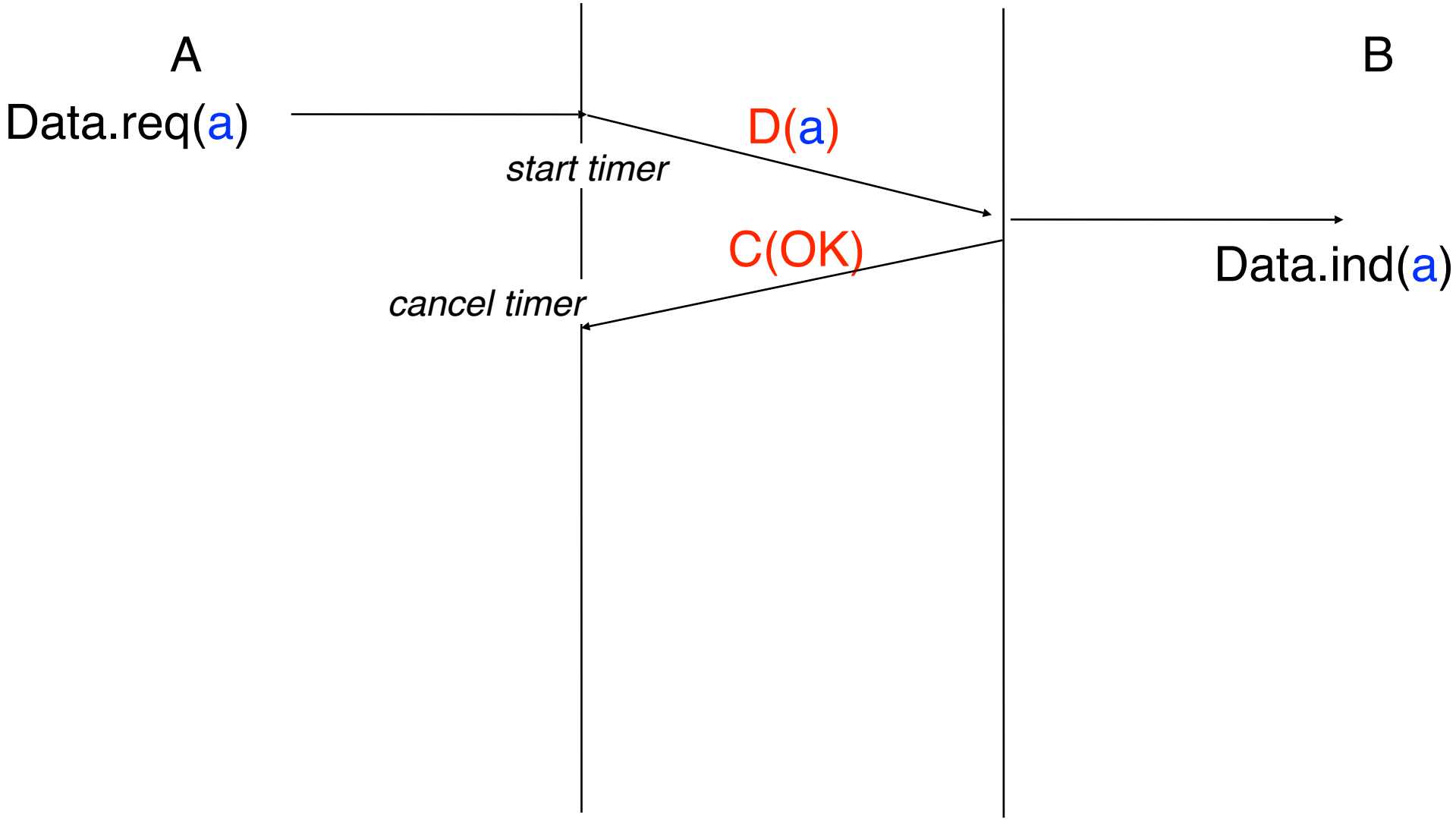
Does this protocol always work ?

Protocol 3b : Example

A

B

Protocol 3b : Example



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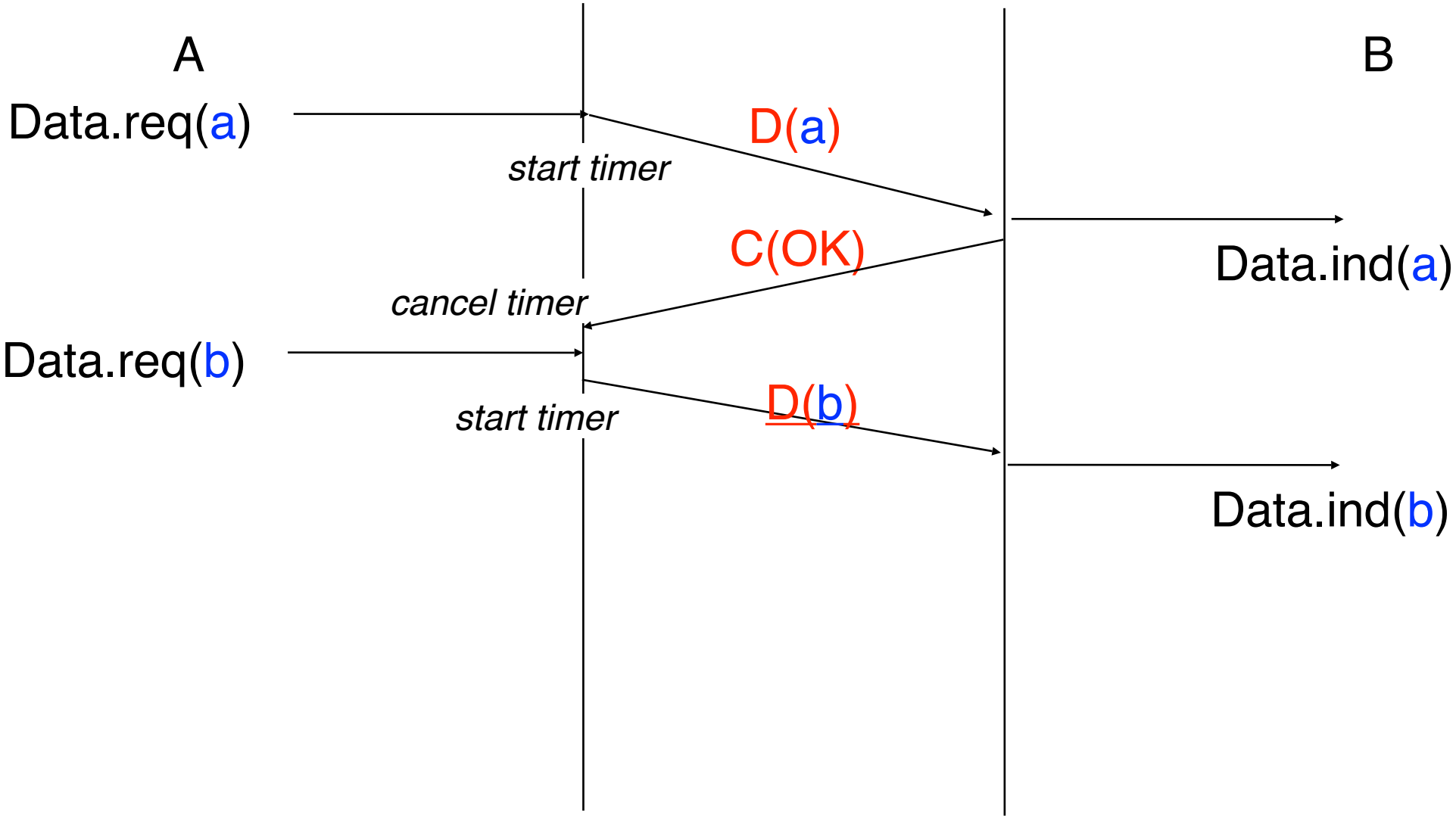

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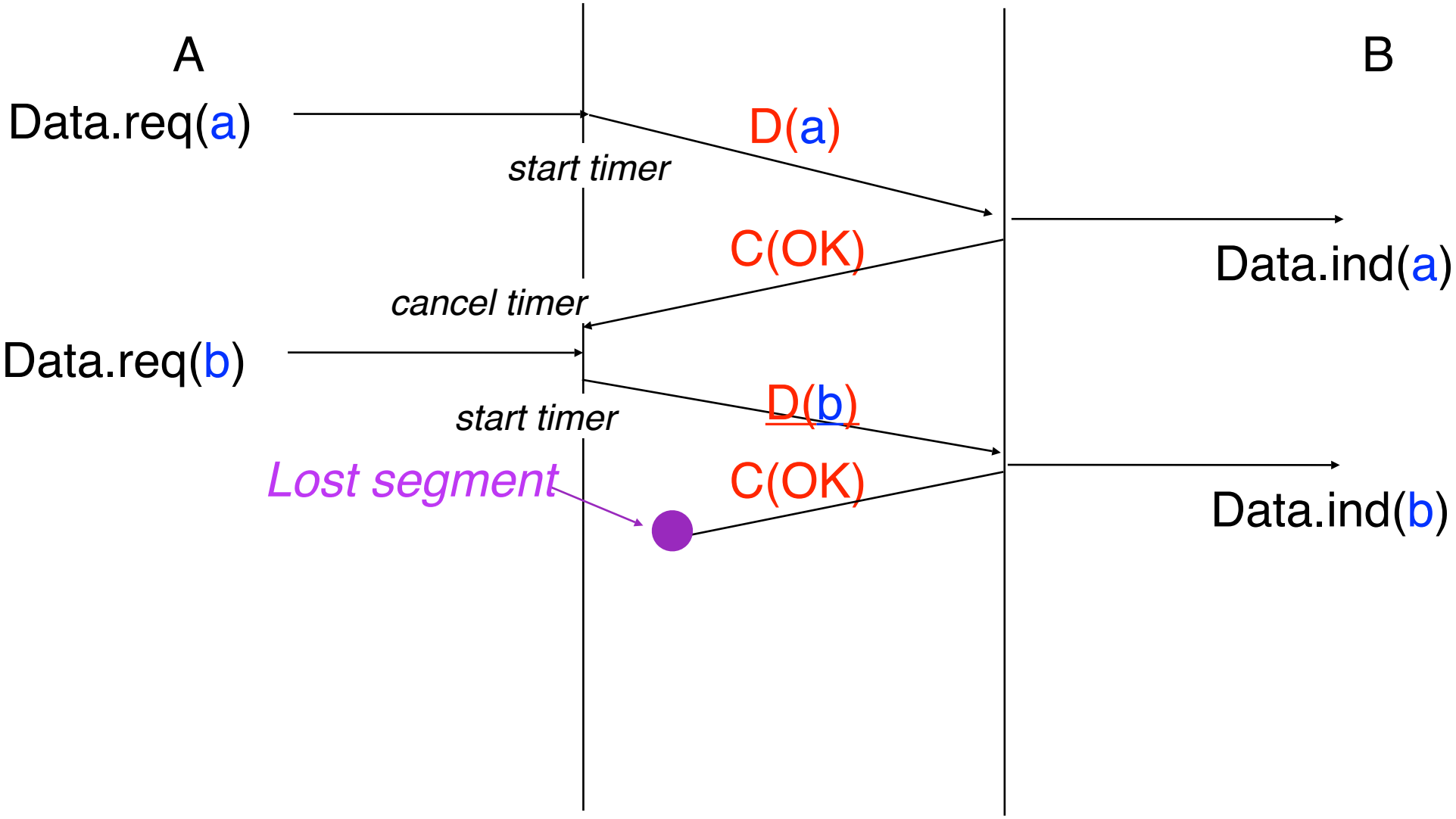

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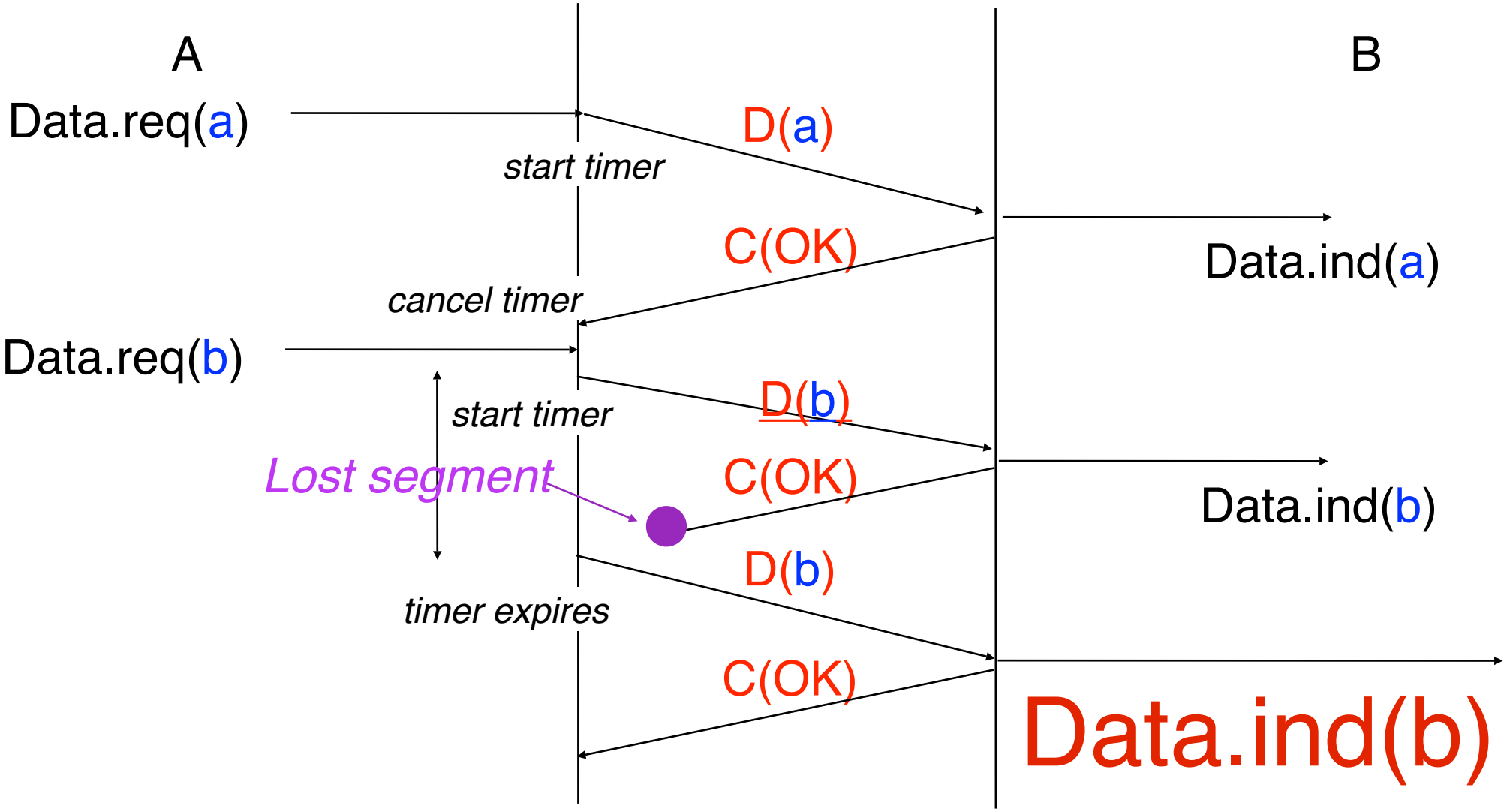

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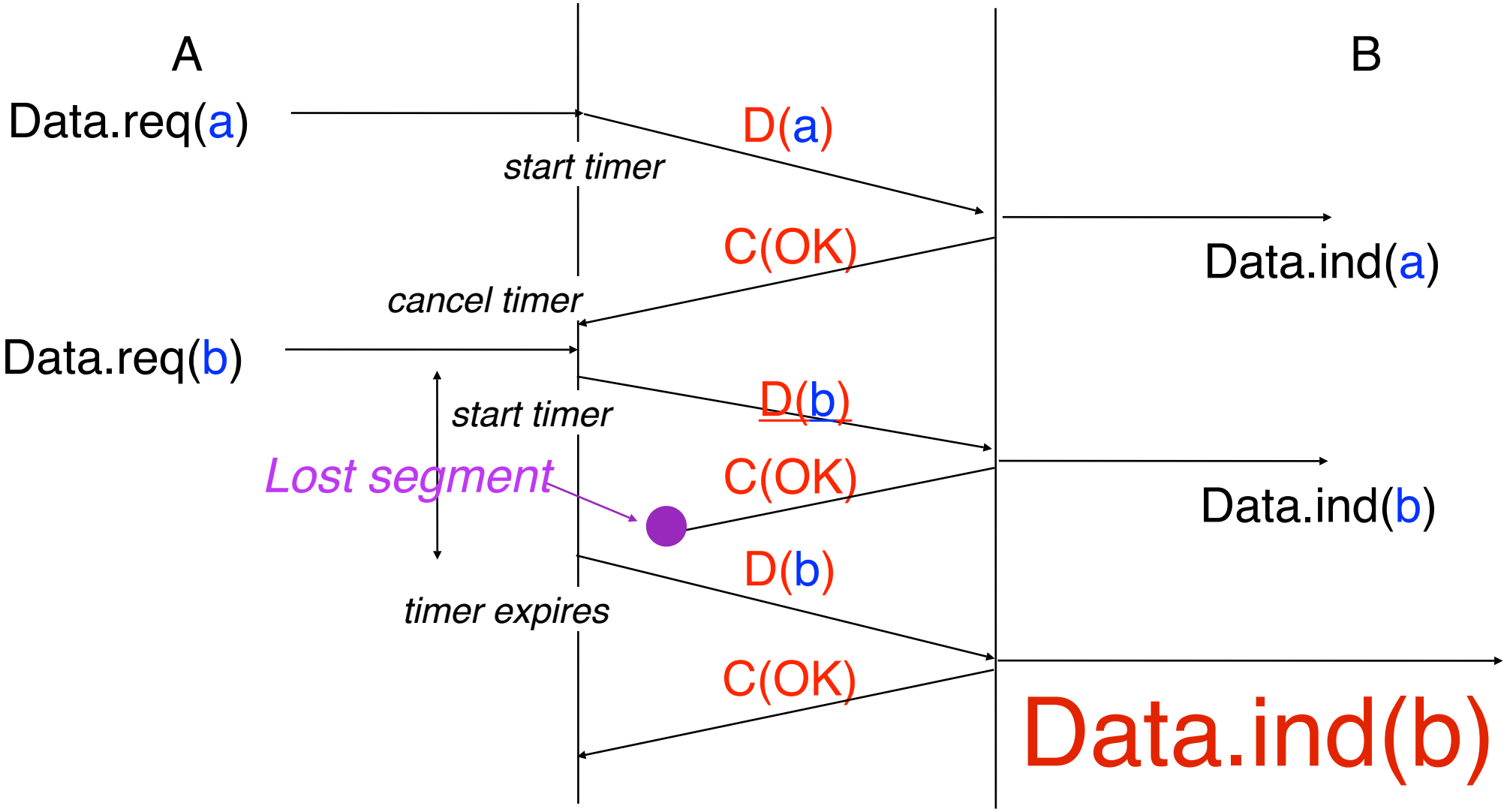


How to solve this problem ?

Protocol 3b

How can we provide a reliable service in the transport layer ?

Hypotheses

1. The application sends small SDUs
2. The network layer provides a perfect service
   1. Transmission errors are possible
   2. Packets can be lost
   3. There is no packet reordering
   4. There are no duplications of packets
3. Data transmission is unidirectional

2. How to deal with these problems ?

Alternating bit protocol

Principles of the solution

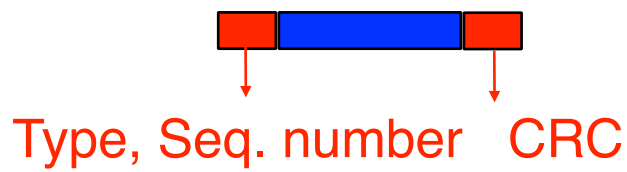
Add sequence numbers to each data segment sent by sender

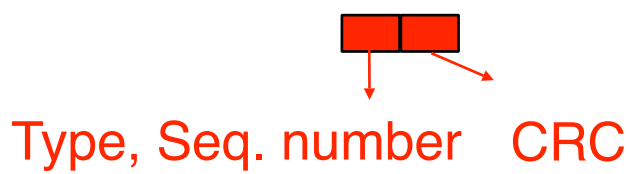
By looking at the sequence number, the receiver can check whether it has already received this segment

Contents of each segment

Data segments

Control segments

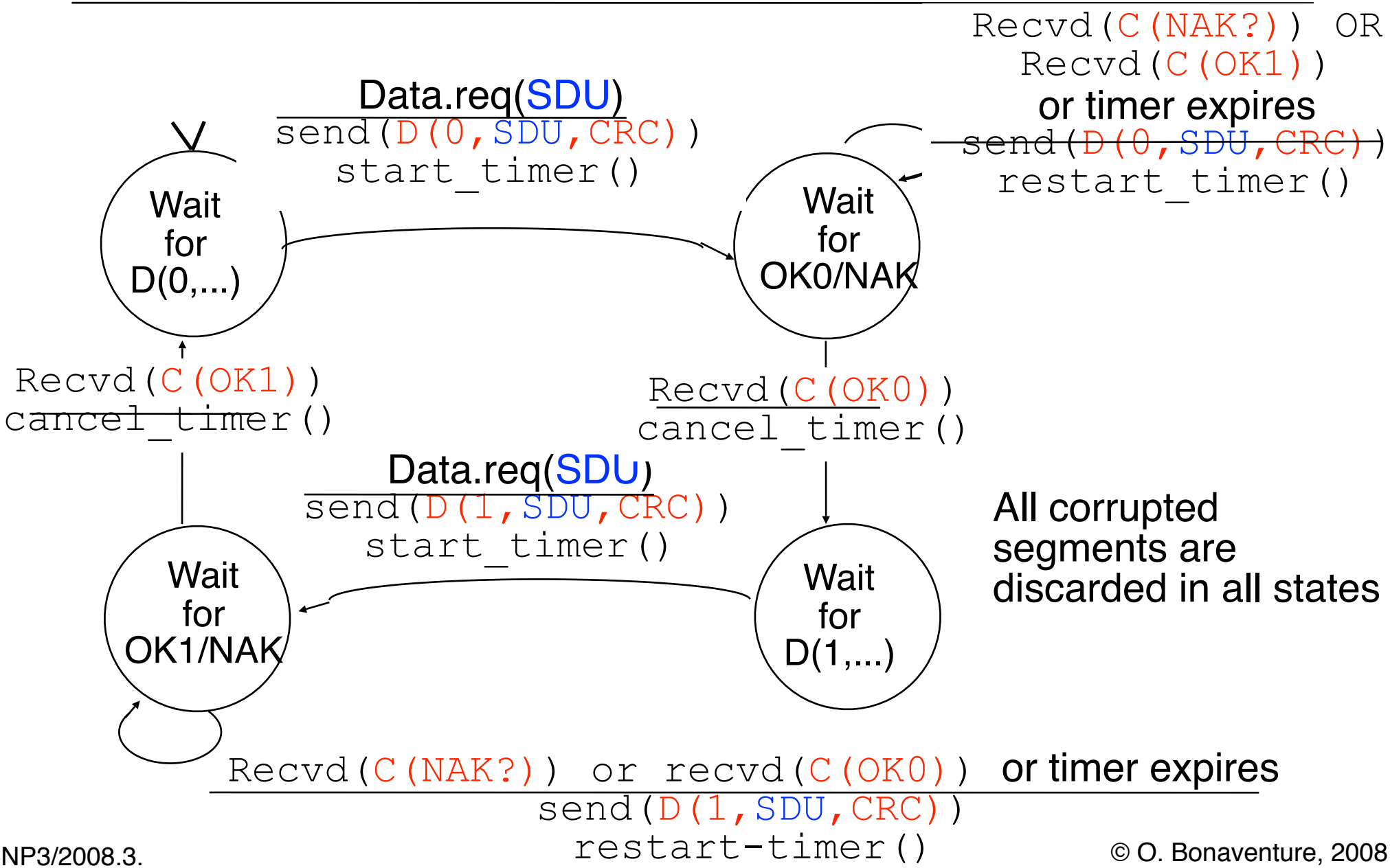




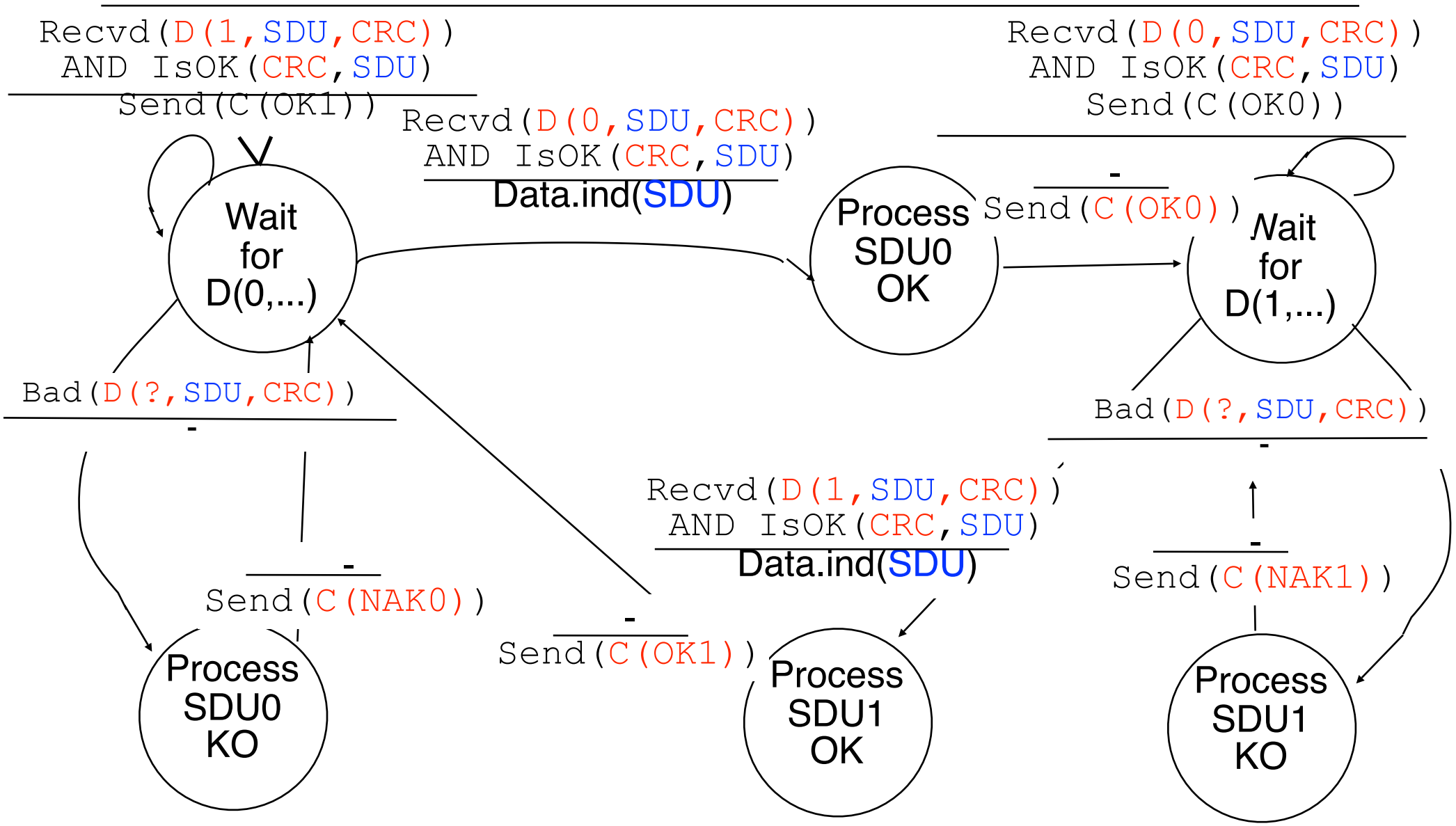
How many bits do we need for the sequence number?

a single bit is enough

Alternating bit protocol Sender



Alternating bit protocol Receiver

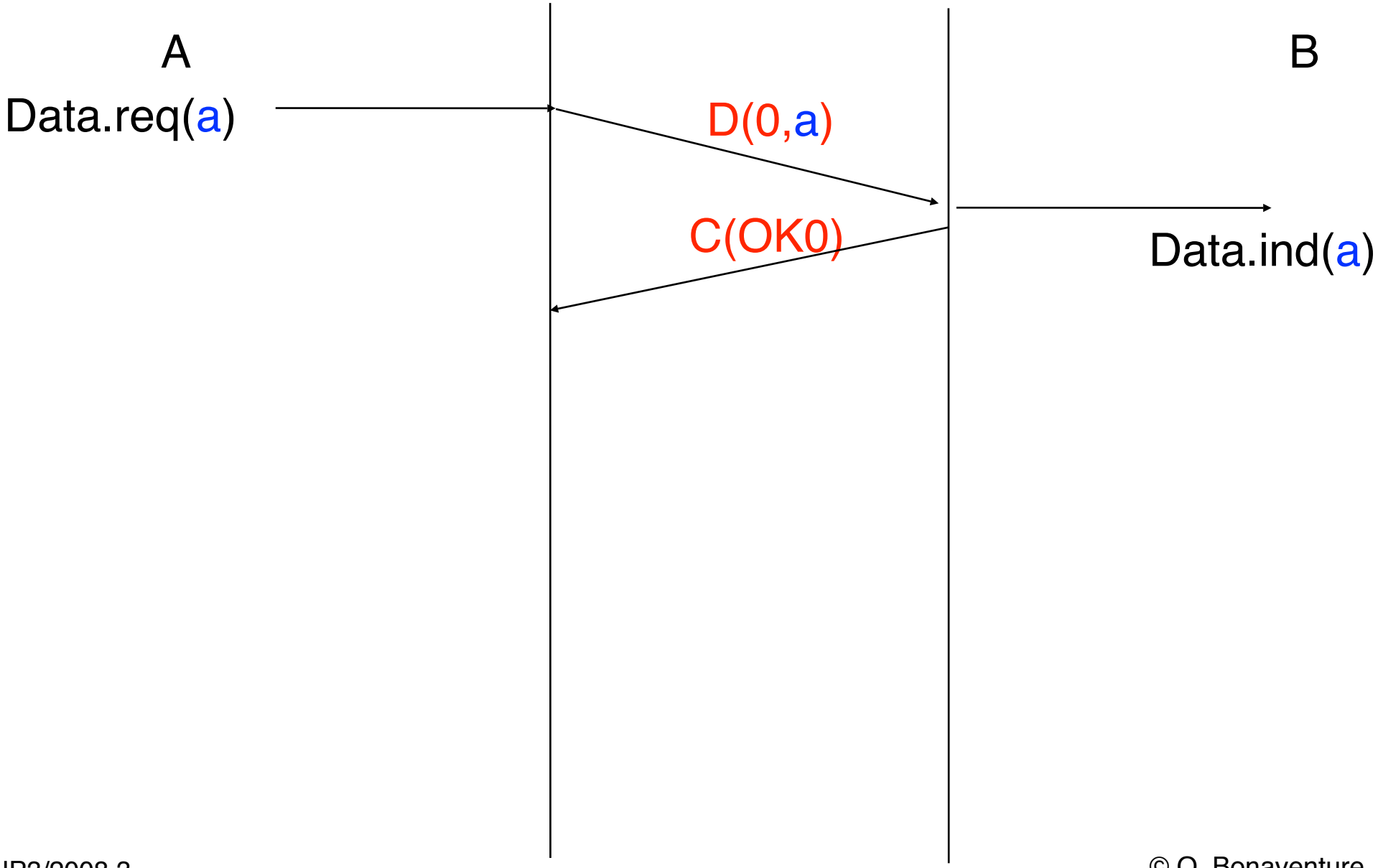


Alternating bit protocol Example

A

B

Alternating bit protocol Example



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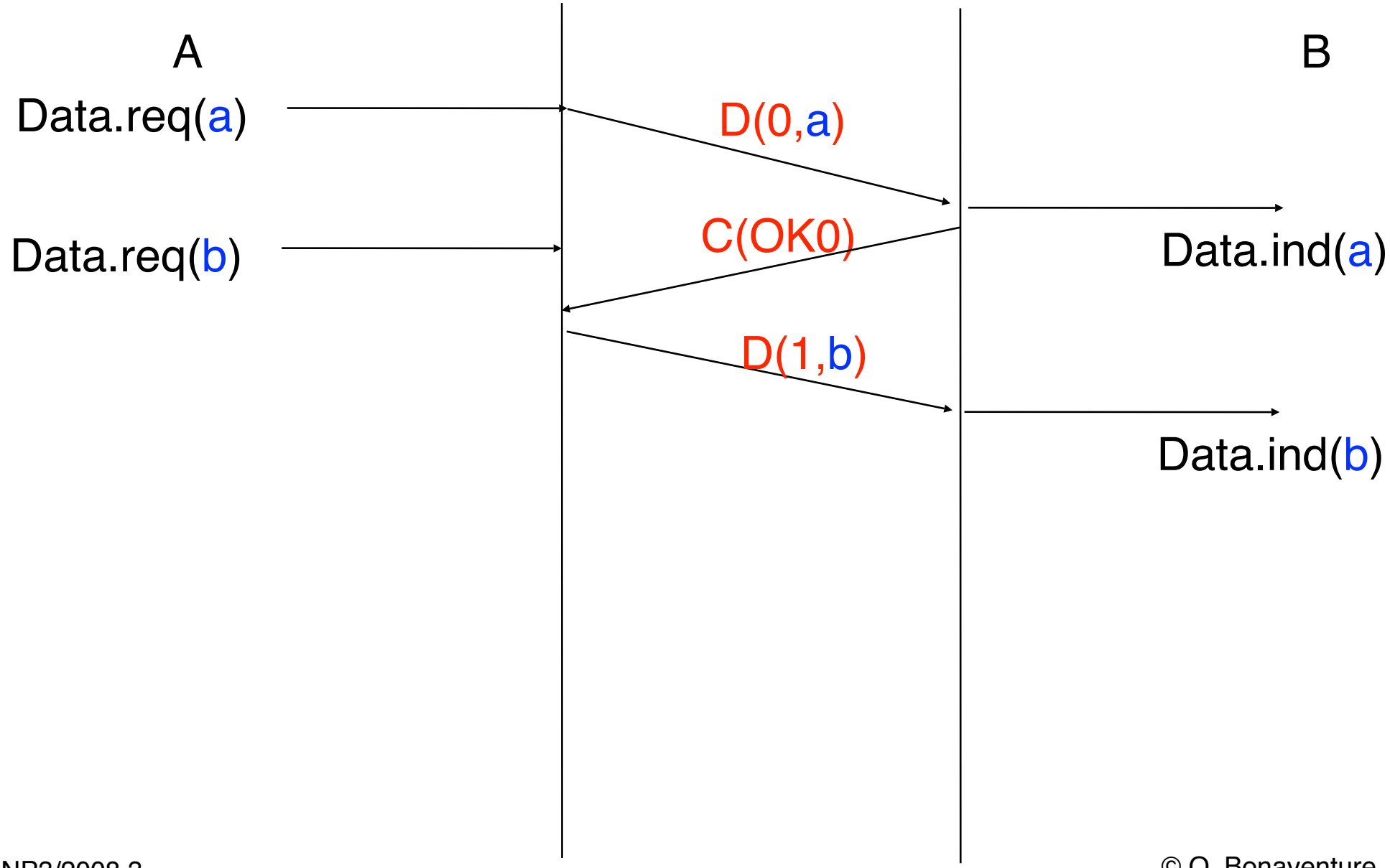

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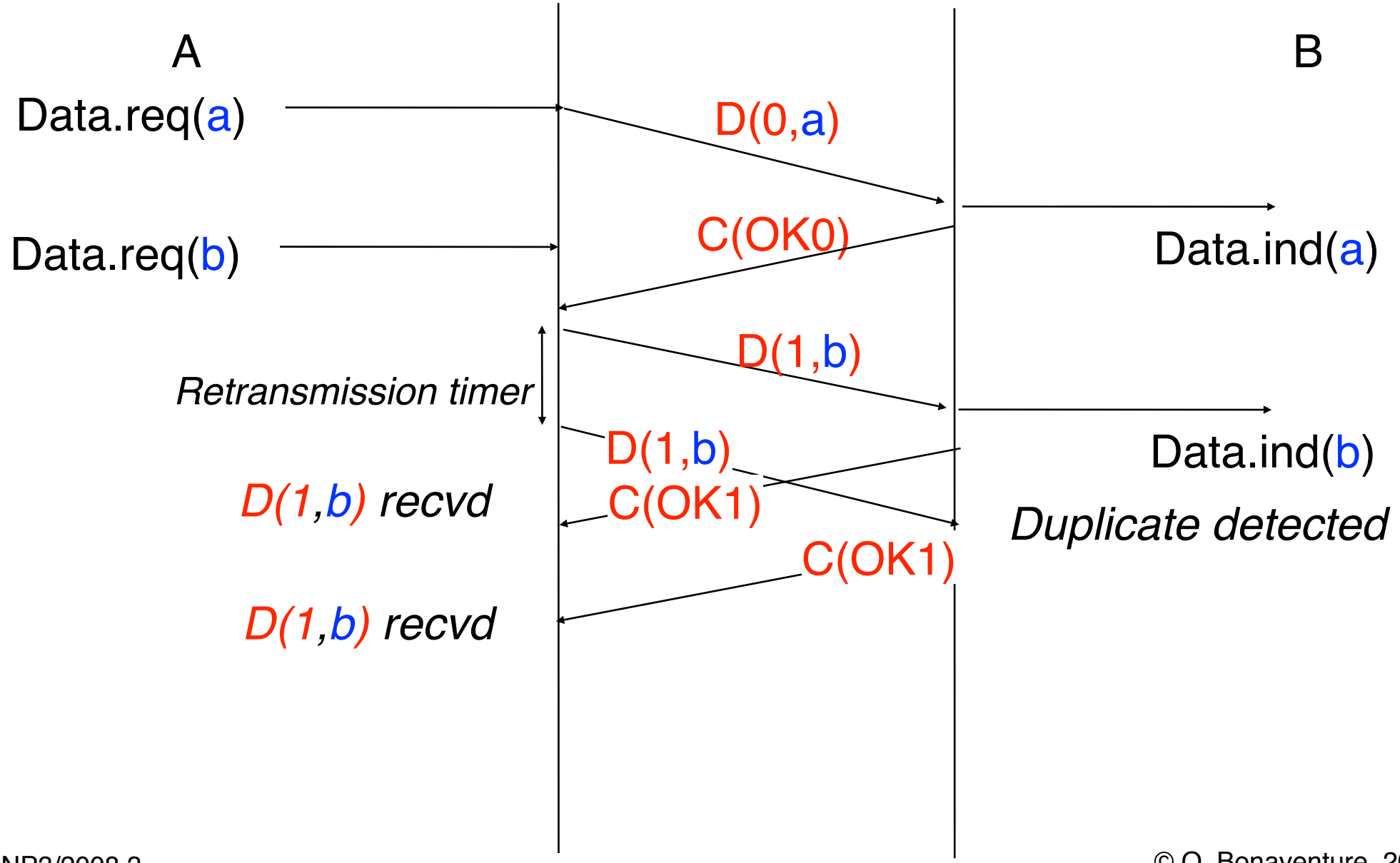

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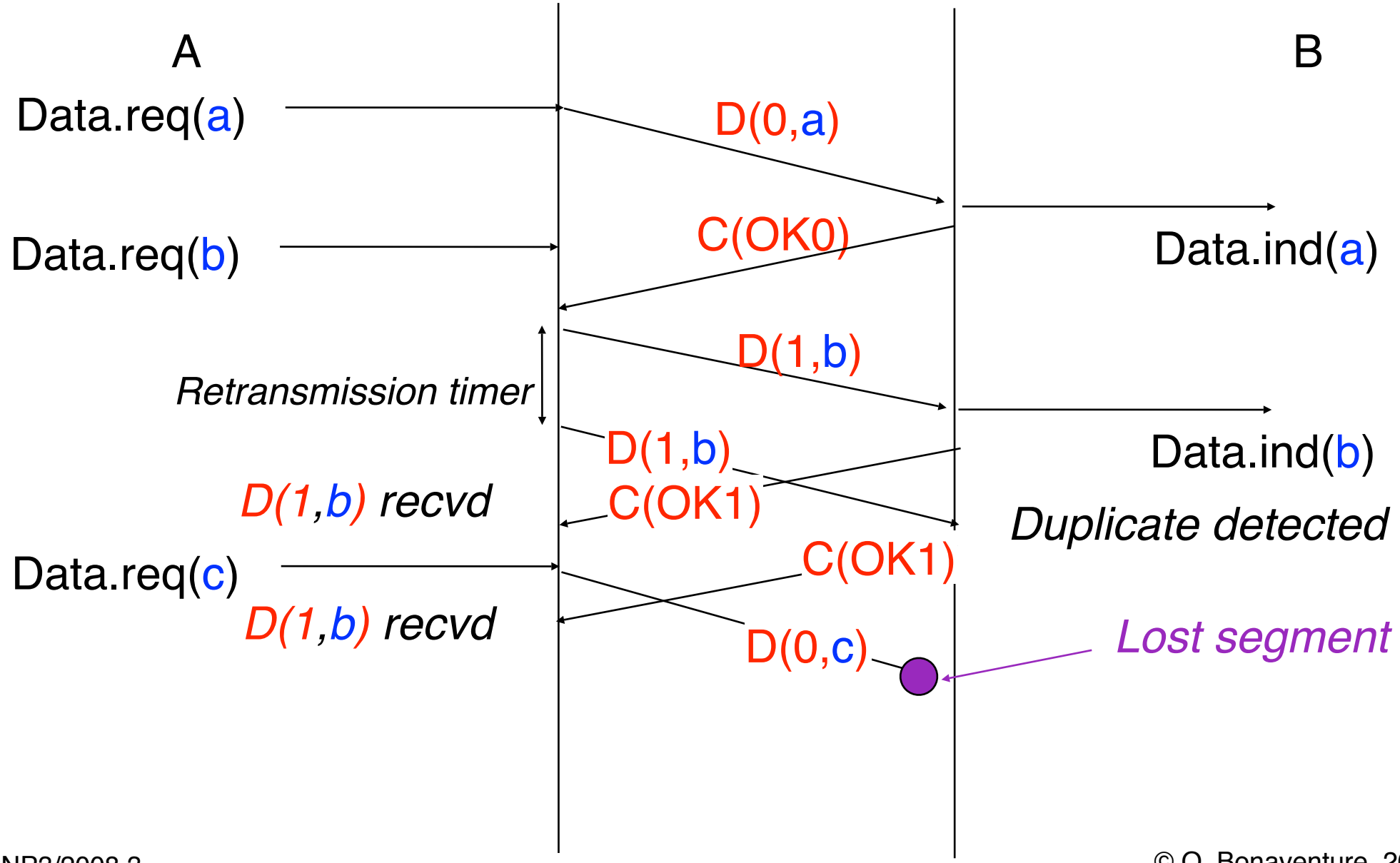

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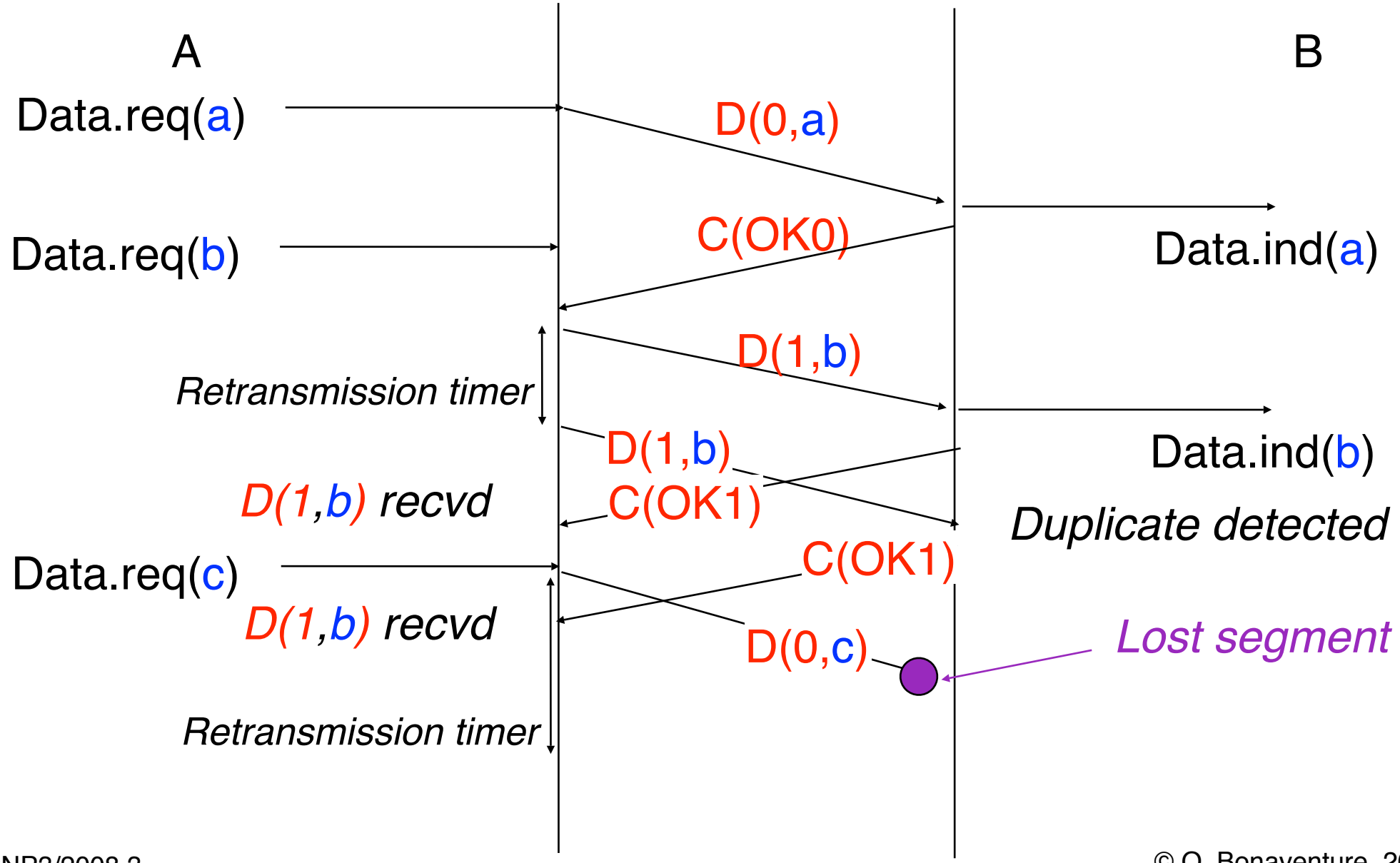
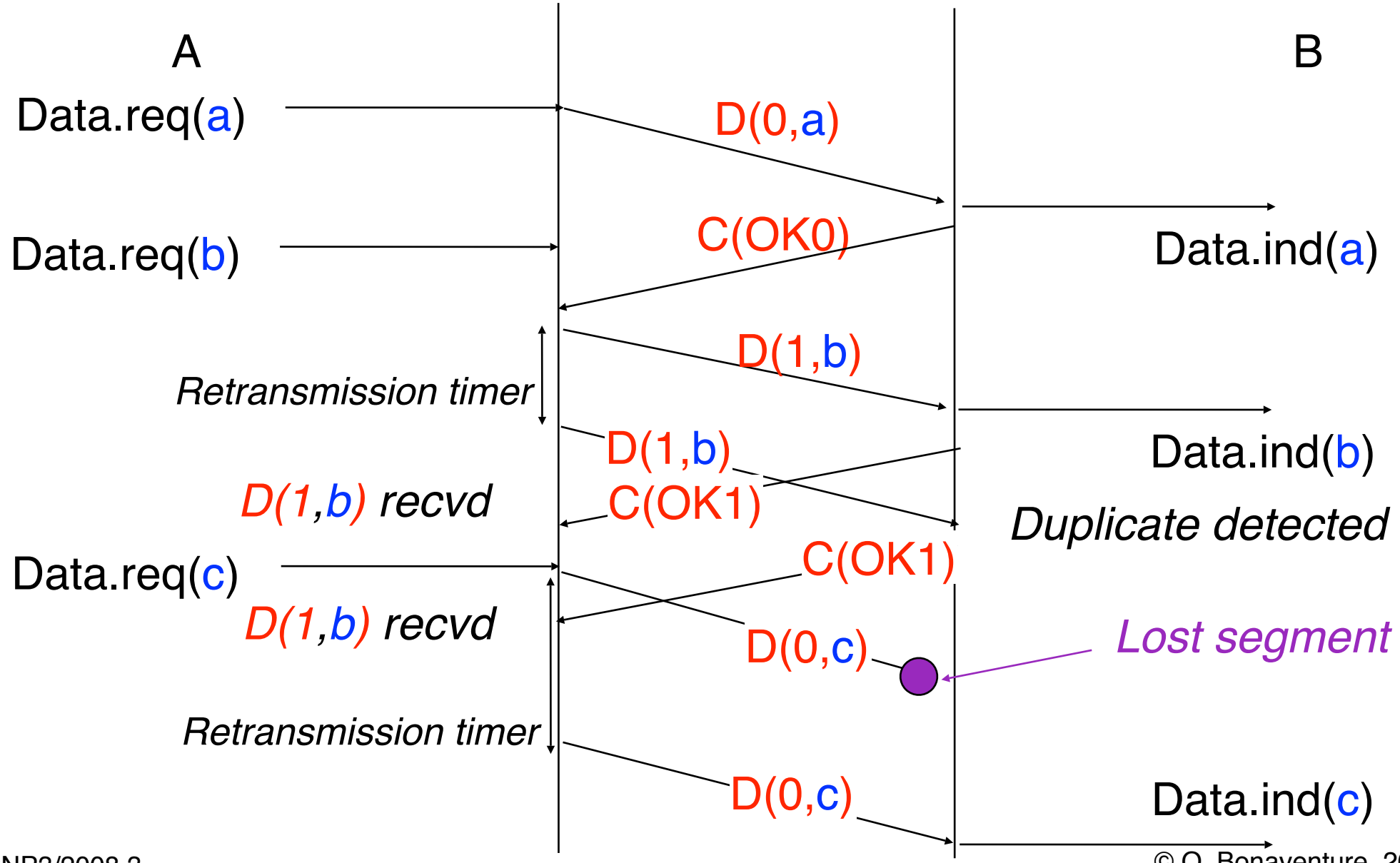


Alternating bit protocol Example



Performance of the alternating bit protocol

What is the performance of the ABP in this case

- One-way delay : 250 msec
- Physical layer throughput : 50 kbps
- segment size : 1000 bits

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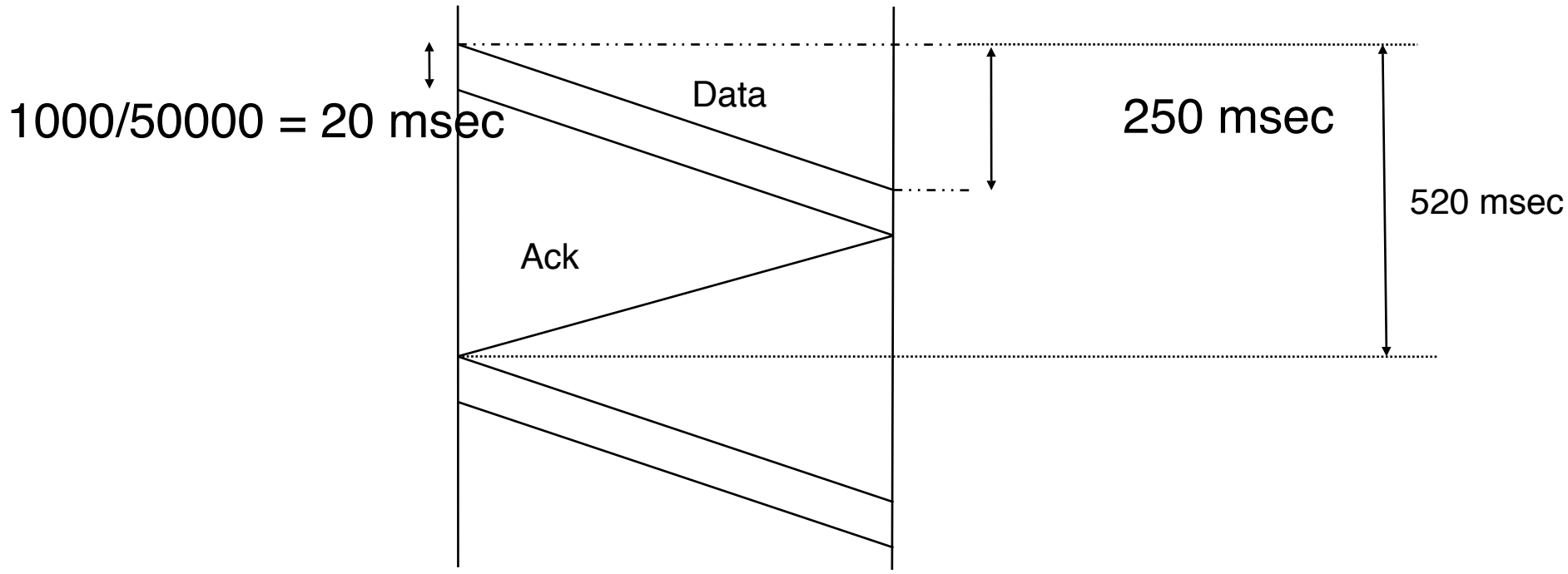

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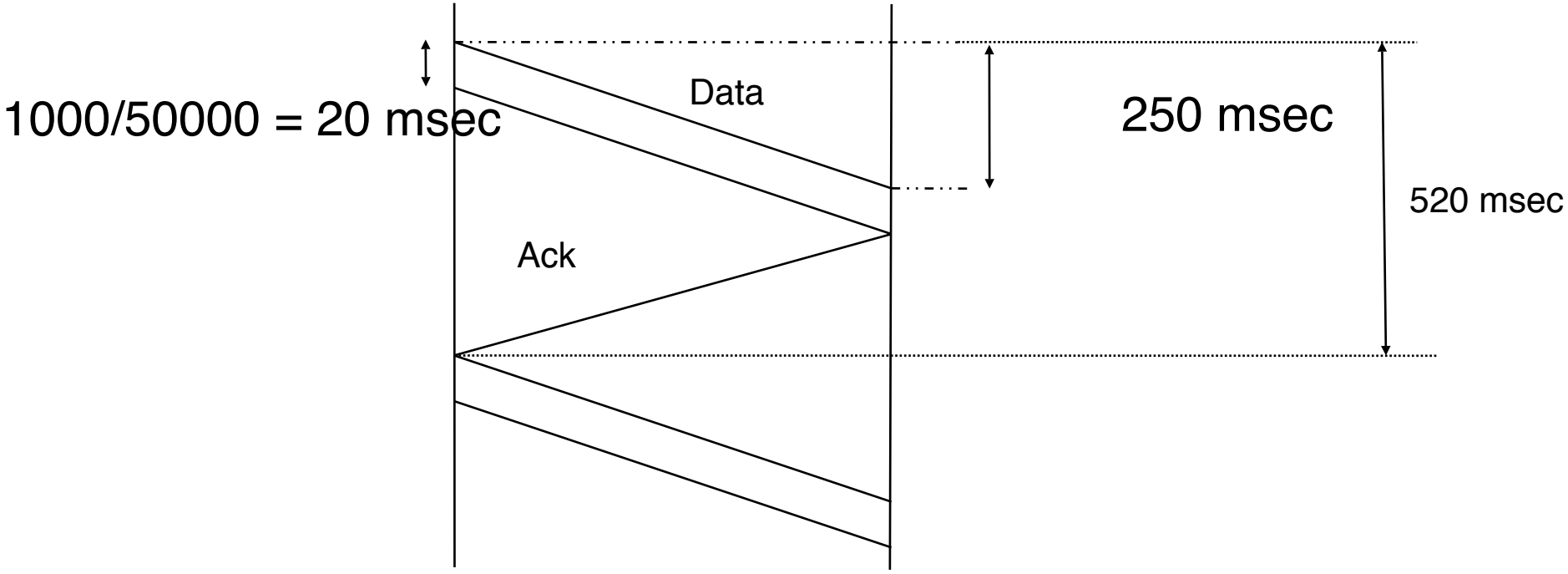

-> Performance is function of

*bandwidth * round-trip-time*

How to improve the alternating bit protocol ?

Use a pipeline

Principle

The sender should be allowed to send more than one segment while waiting for an acknowledgement from the receiver

How to improve the alternating bit protocol ?

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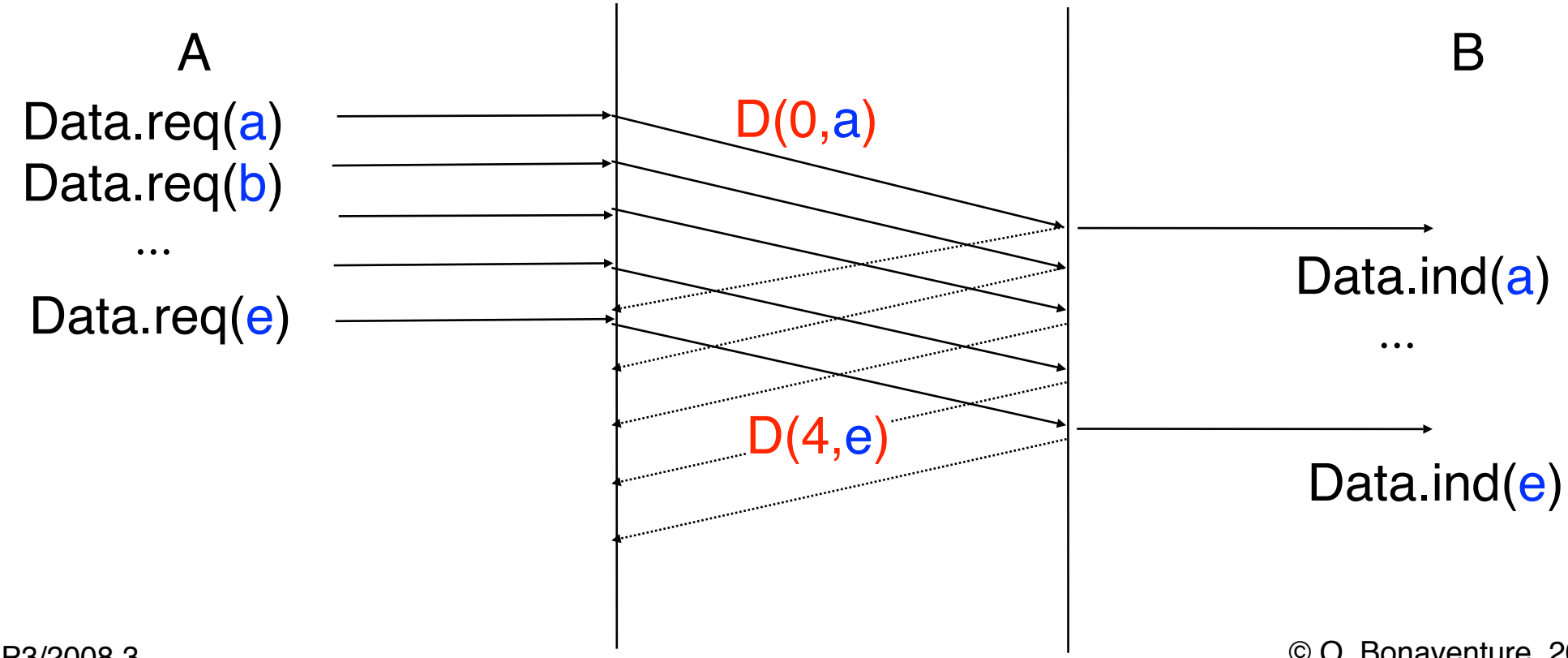
The sender should be allowed to send more than one segment while waiting for an acknowledgement from the receiver



How to improve the alternating bit protocol ? (2)

Modifications to alternating bit protocol

- Sequence numbers inside each segment
  - Each data segment contains its own sequence number
  - Each control segment indicates the sequence number of the data segment being acknowledged (OK/NAK)
- Sender
  - Needs enough buffers to store the data segments that have not yet been acknowledged to be able to retransmit them if required
- Receiver
  - Needs enough buffers to store the out-of-sequence segments

How to improve the alternating bit protocol ? (2)

Modifications to alternating bit protocol

Sequence numbers inside each segment

Each data segment contains its own sequence number
Each control segment indicates the sequence number of the data segment being acknowledged (OK/NAK)

Sender

Needs enough buffers to store the data segments that have not yet been acknowledged to be able to retransmit them if required

Receiver

Needs enough buffers to store the out-of-sequence segments

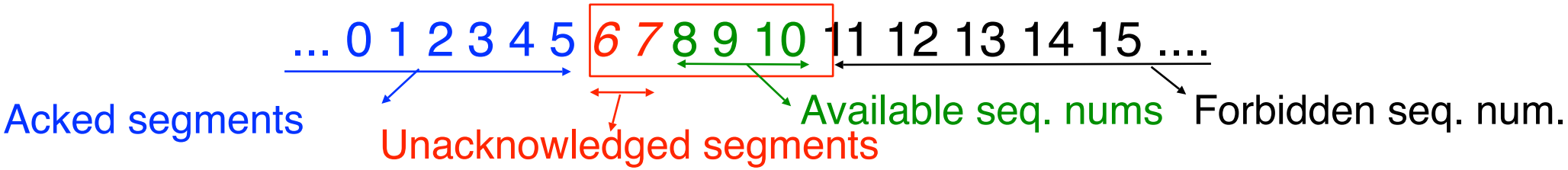
How to avoid an overflow of the receiver's buffers ?

Sliding window

Principle

Sender keeps a list of all the segments that it is allowed to send

`sending_window`



Receiver also maintains a receiving window with the list of acceptable sequence number

receiving_window

Sender and receiver must use compatible windows

sending_window ≤ receiving window

For example, window size is a constant for a given protocol or negotiated during connection establishment phase

Sliding windows : example

Sending and receiving window : 3 segments

A

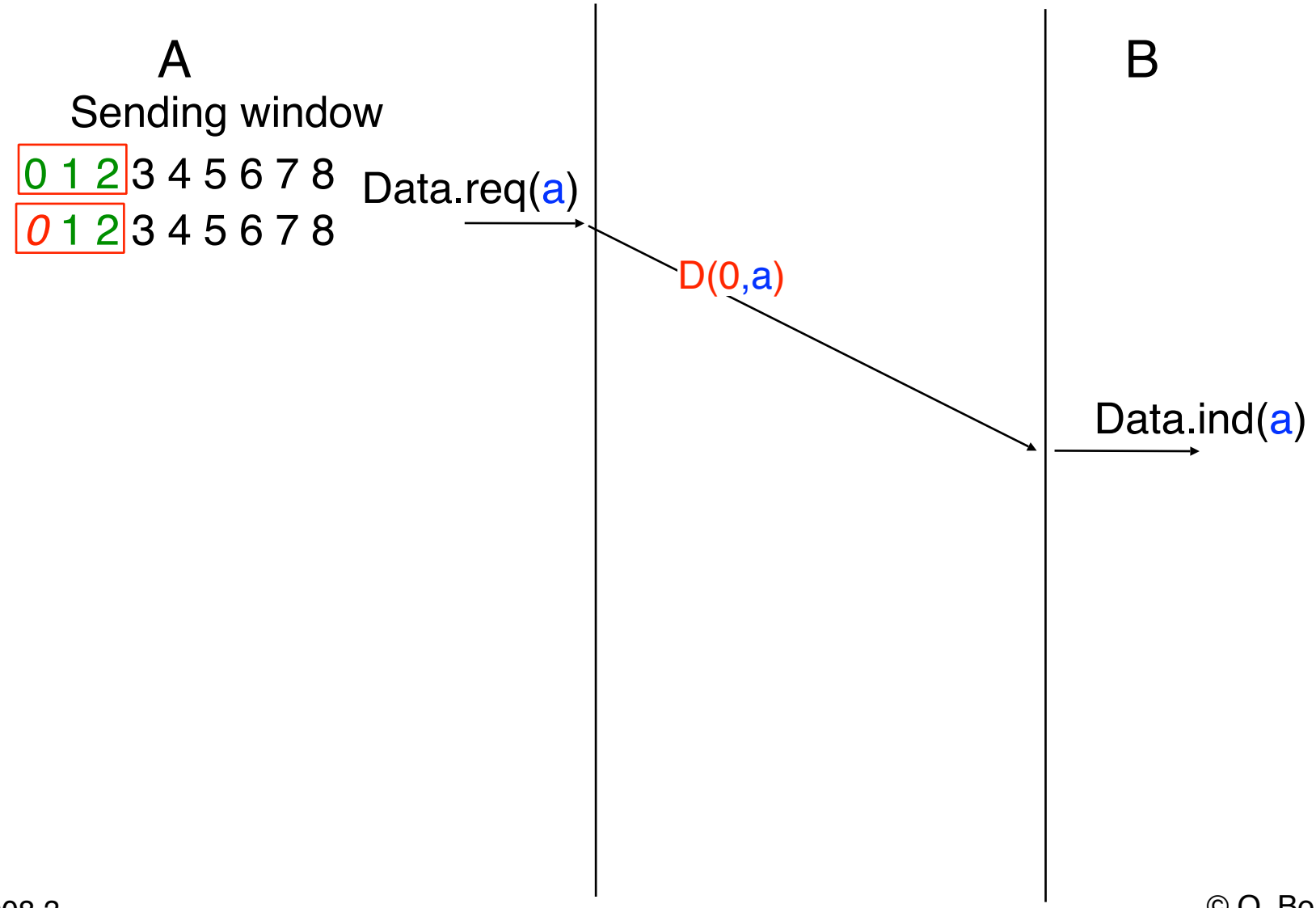
Sending window

0 1 2 3 4 5 6 7 8

B

Sliding windows : example

Sending and receiving window : 3 segments



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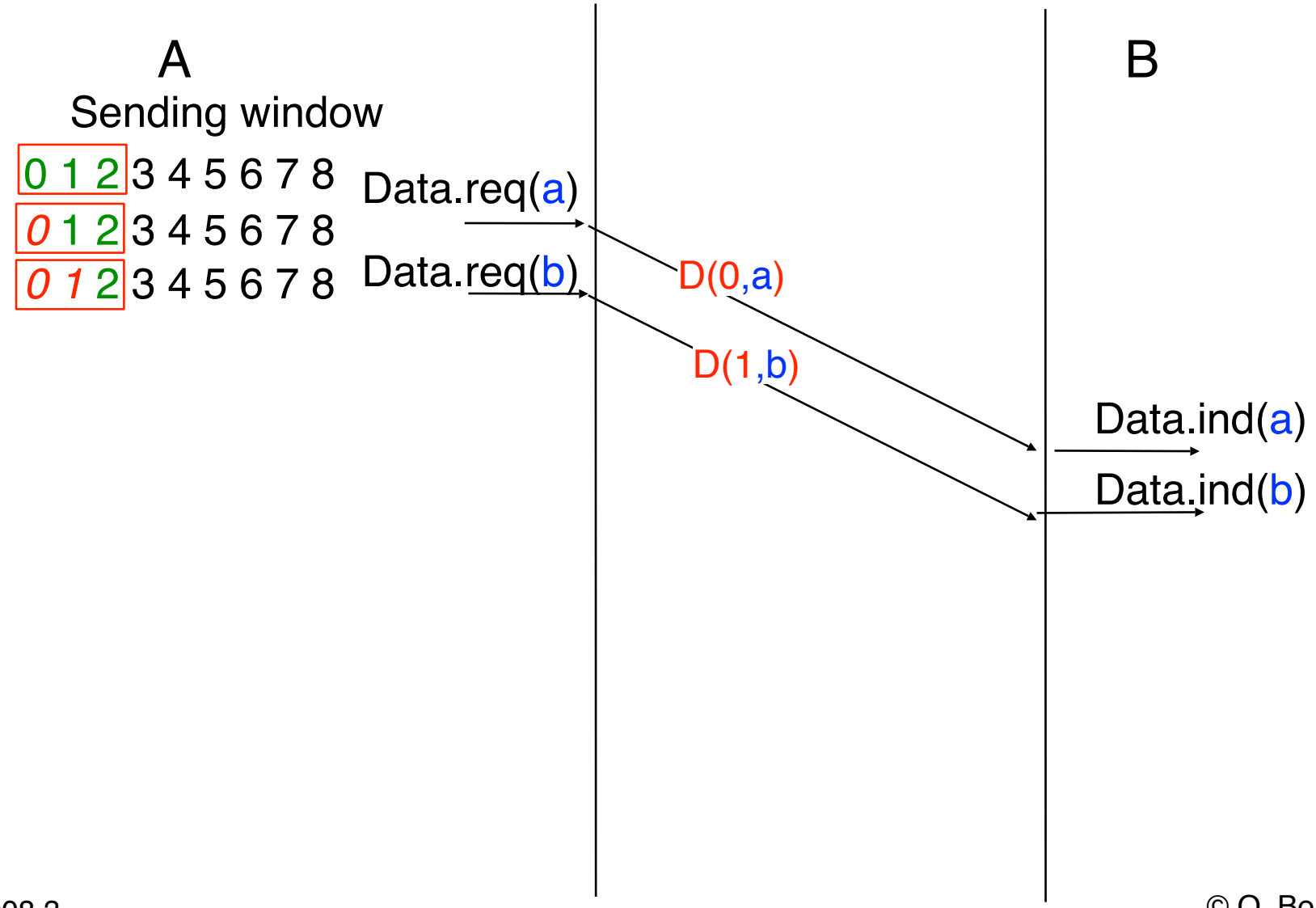
Sending and receiving window : 3 segments



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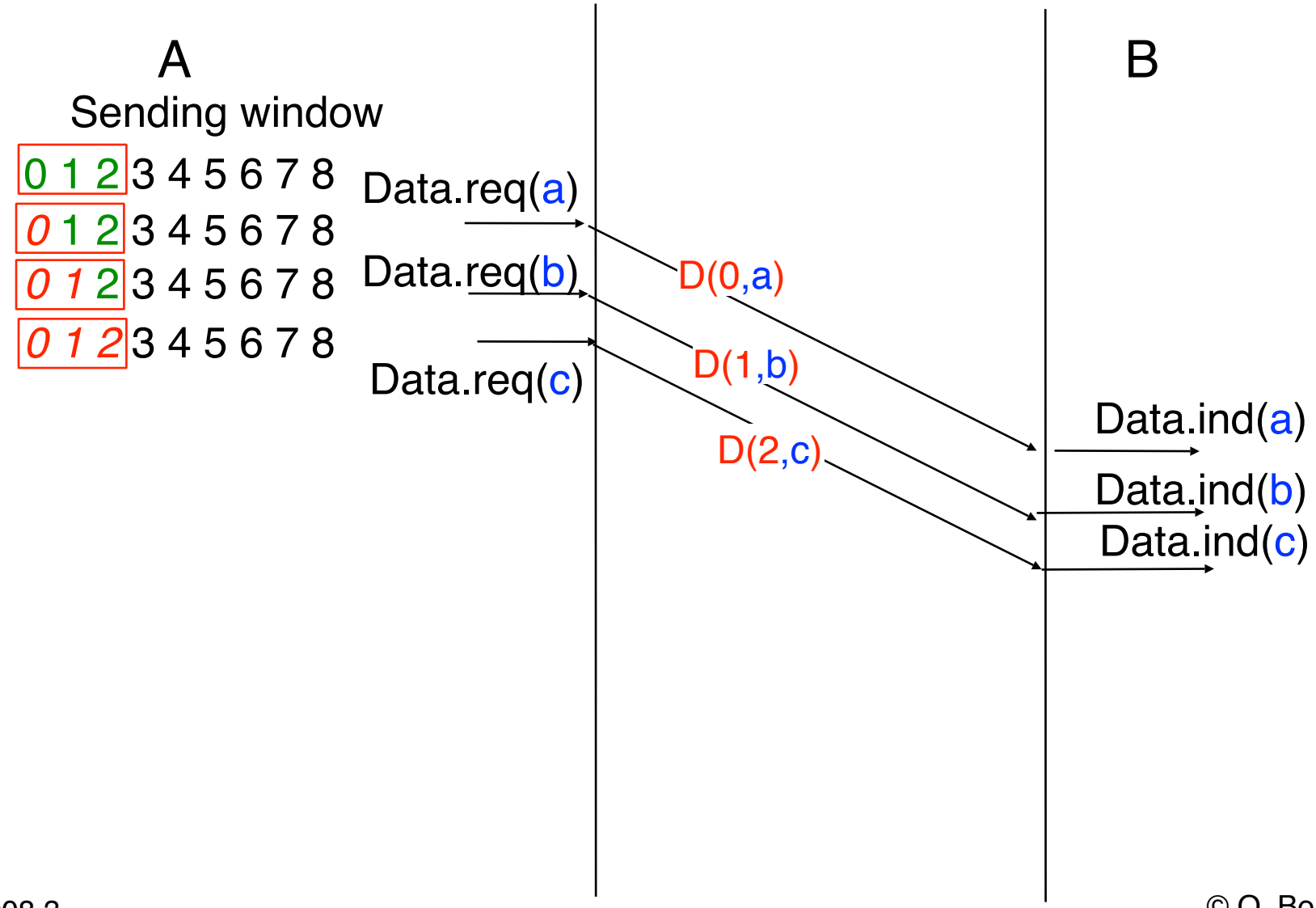

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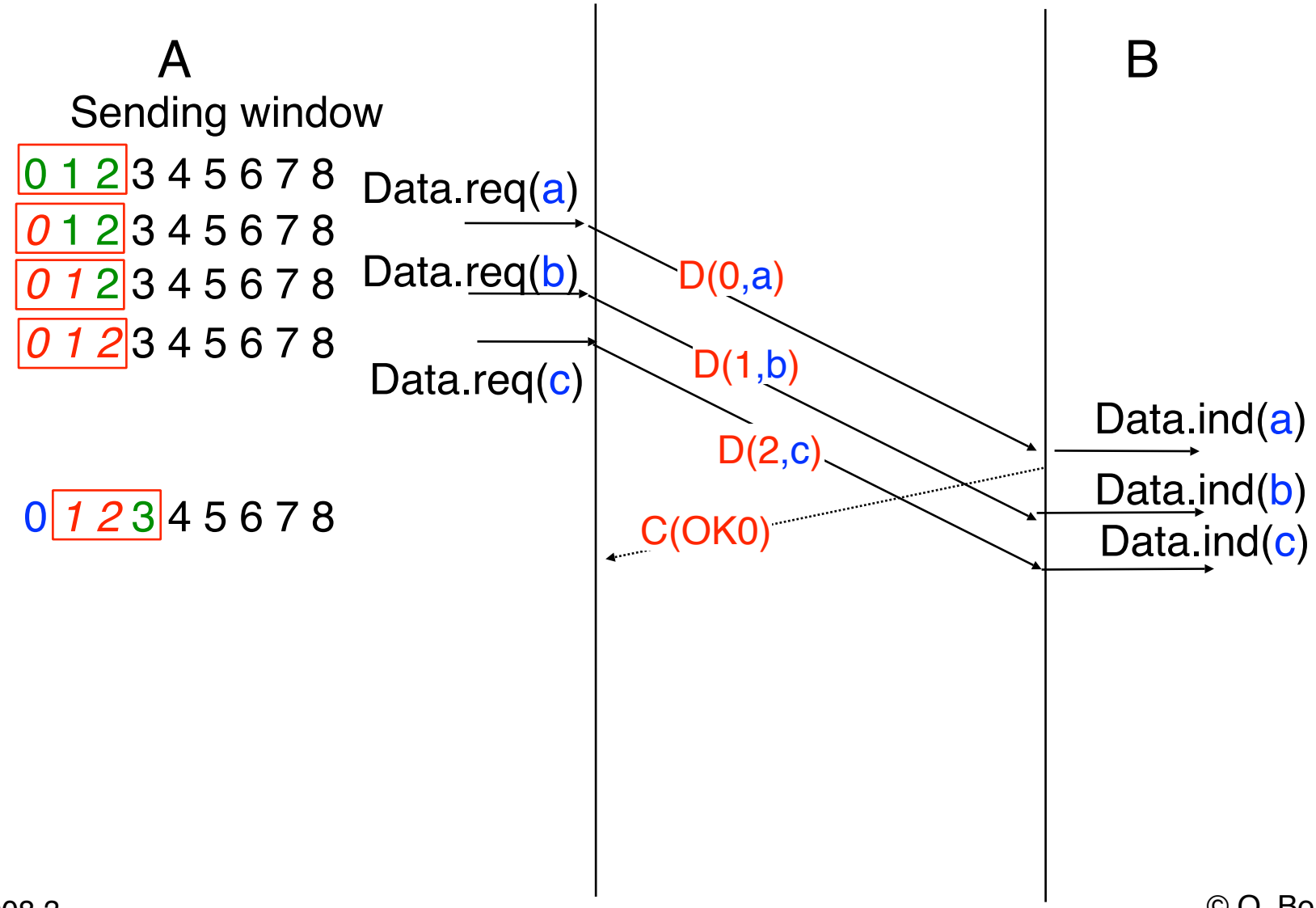

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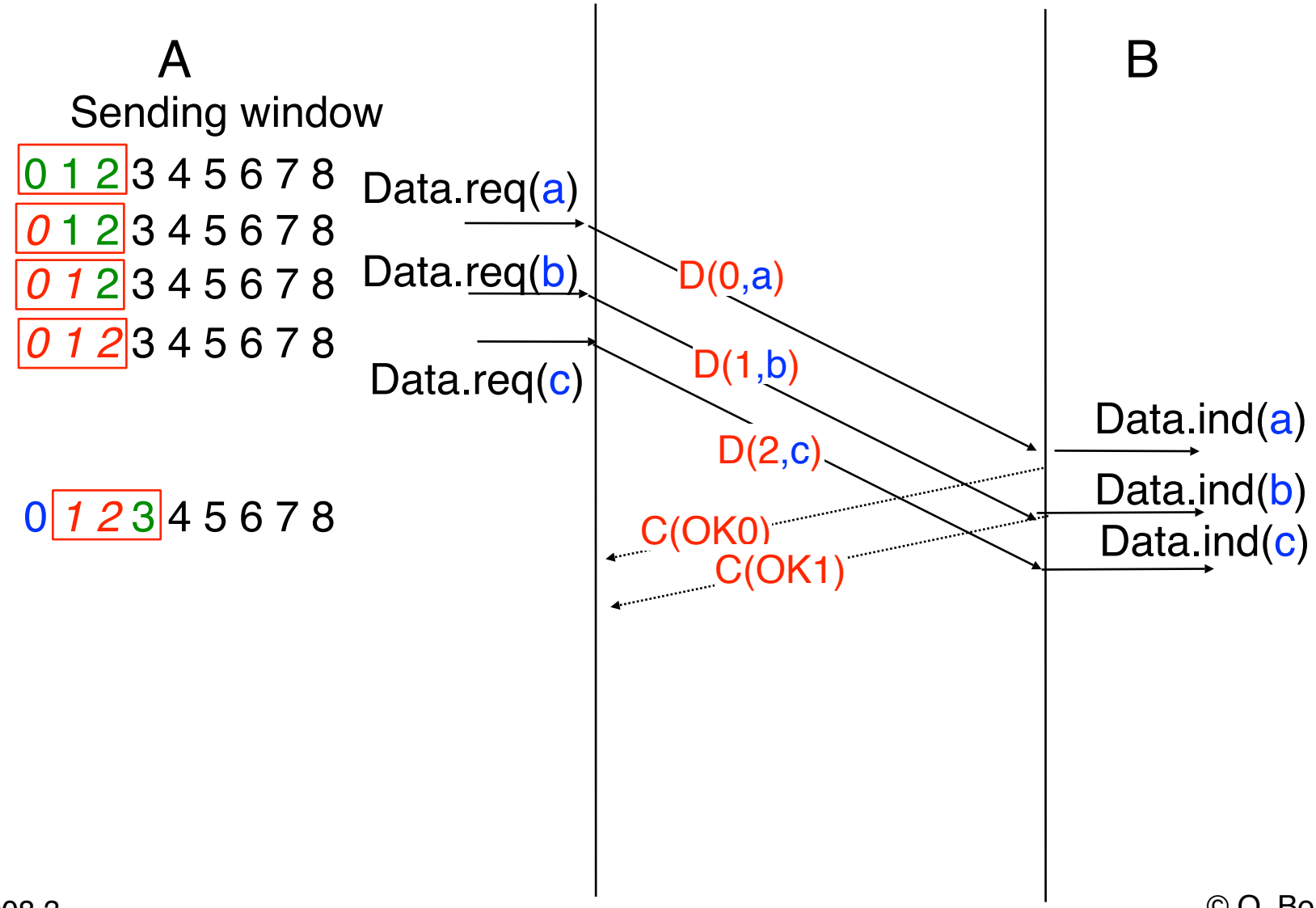

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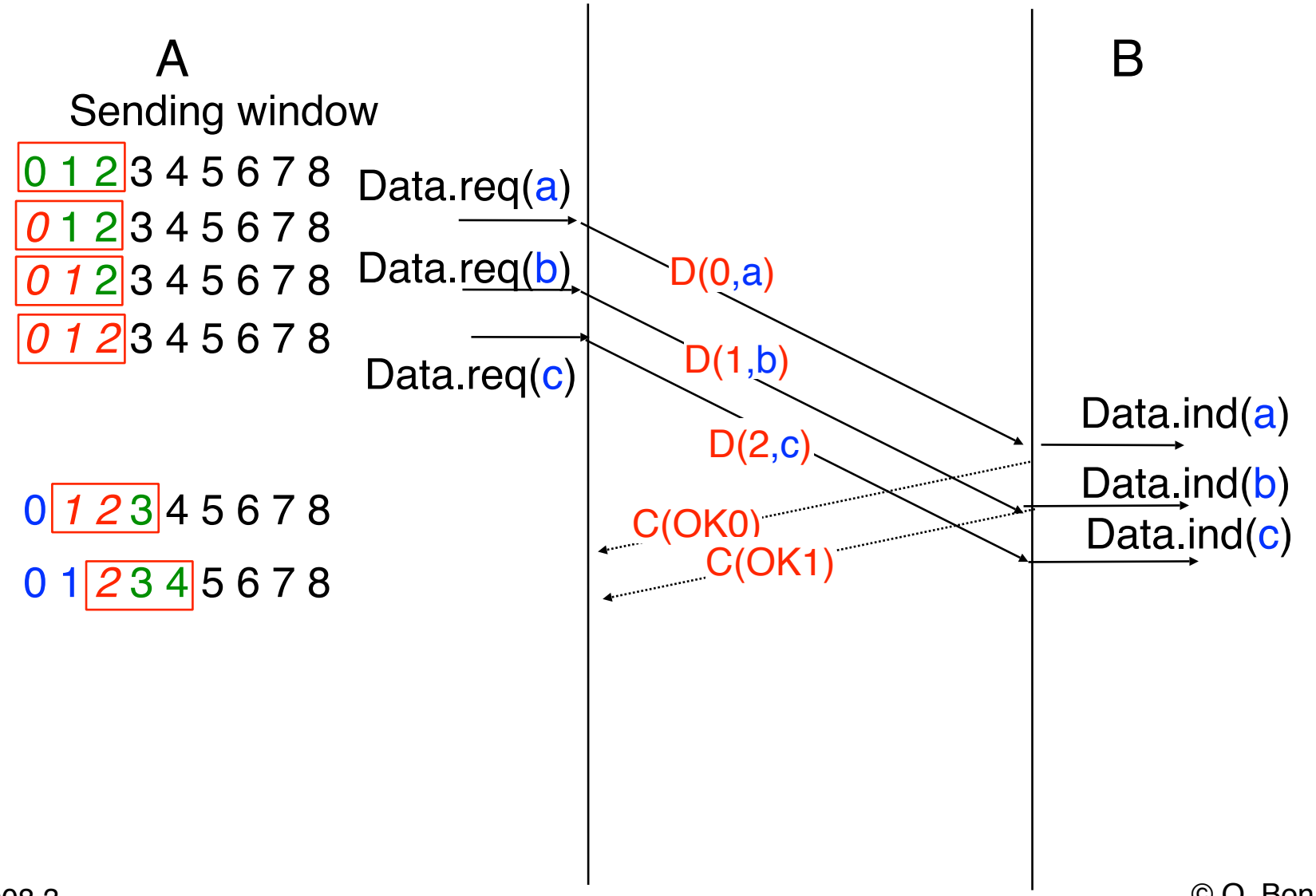

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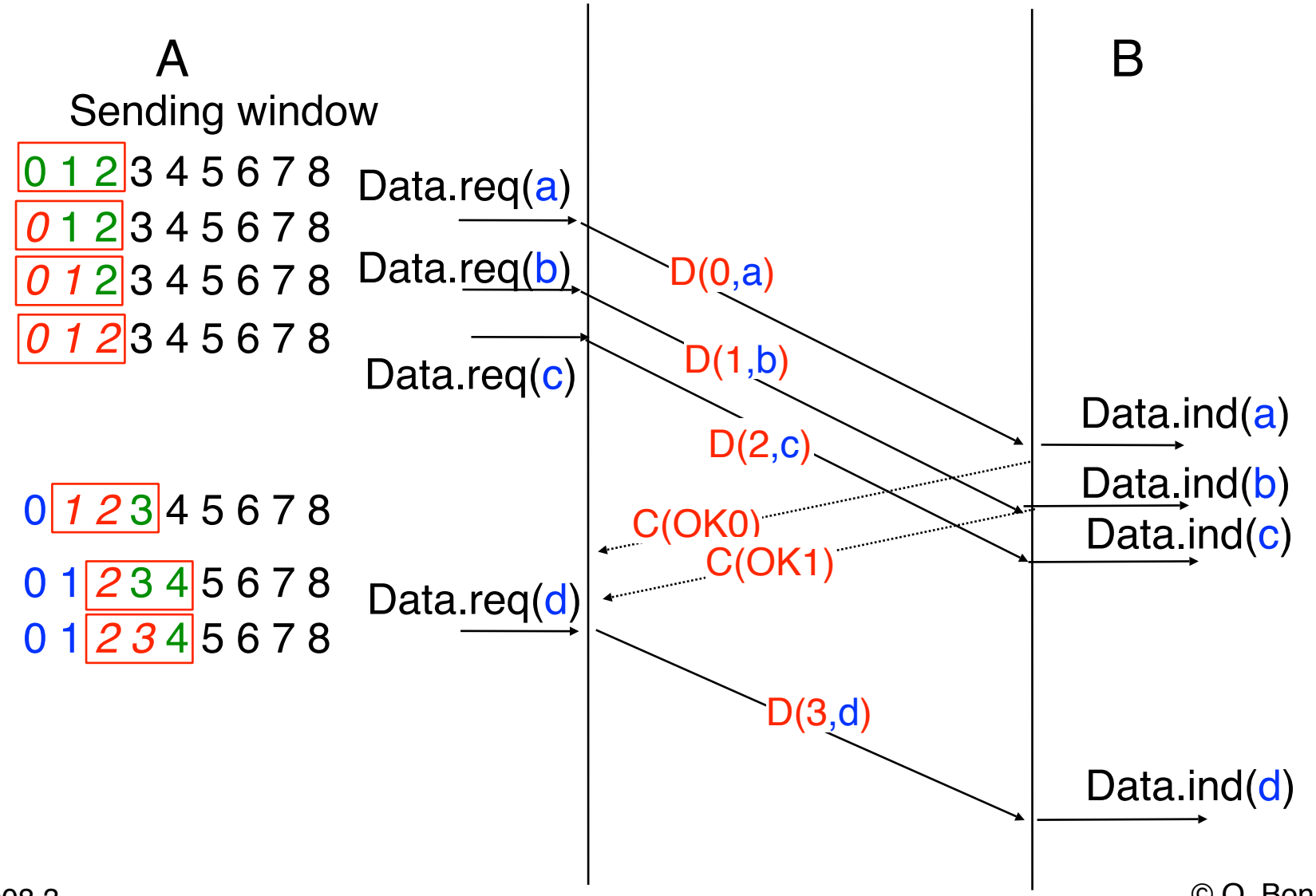

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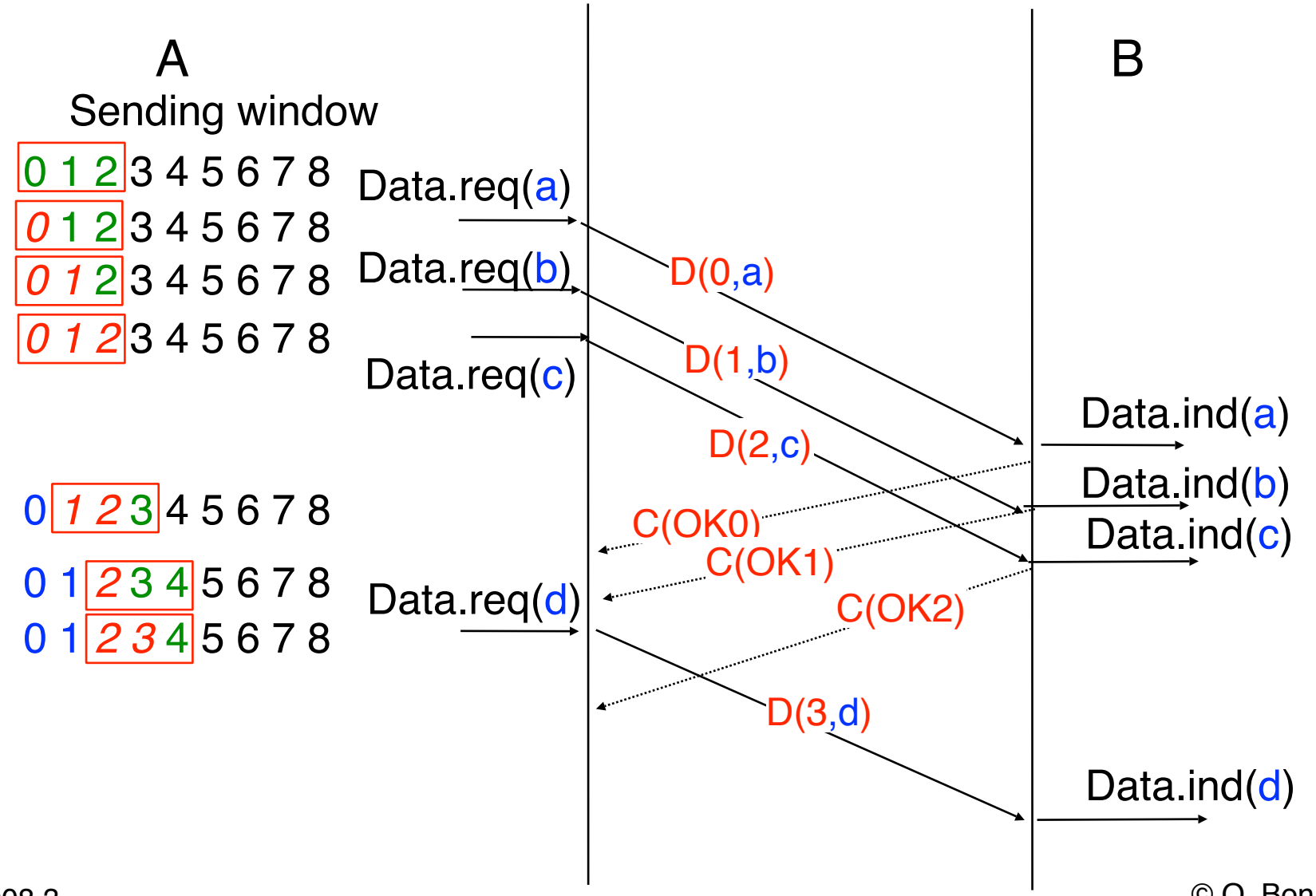

Sliding windows : example

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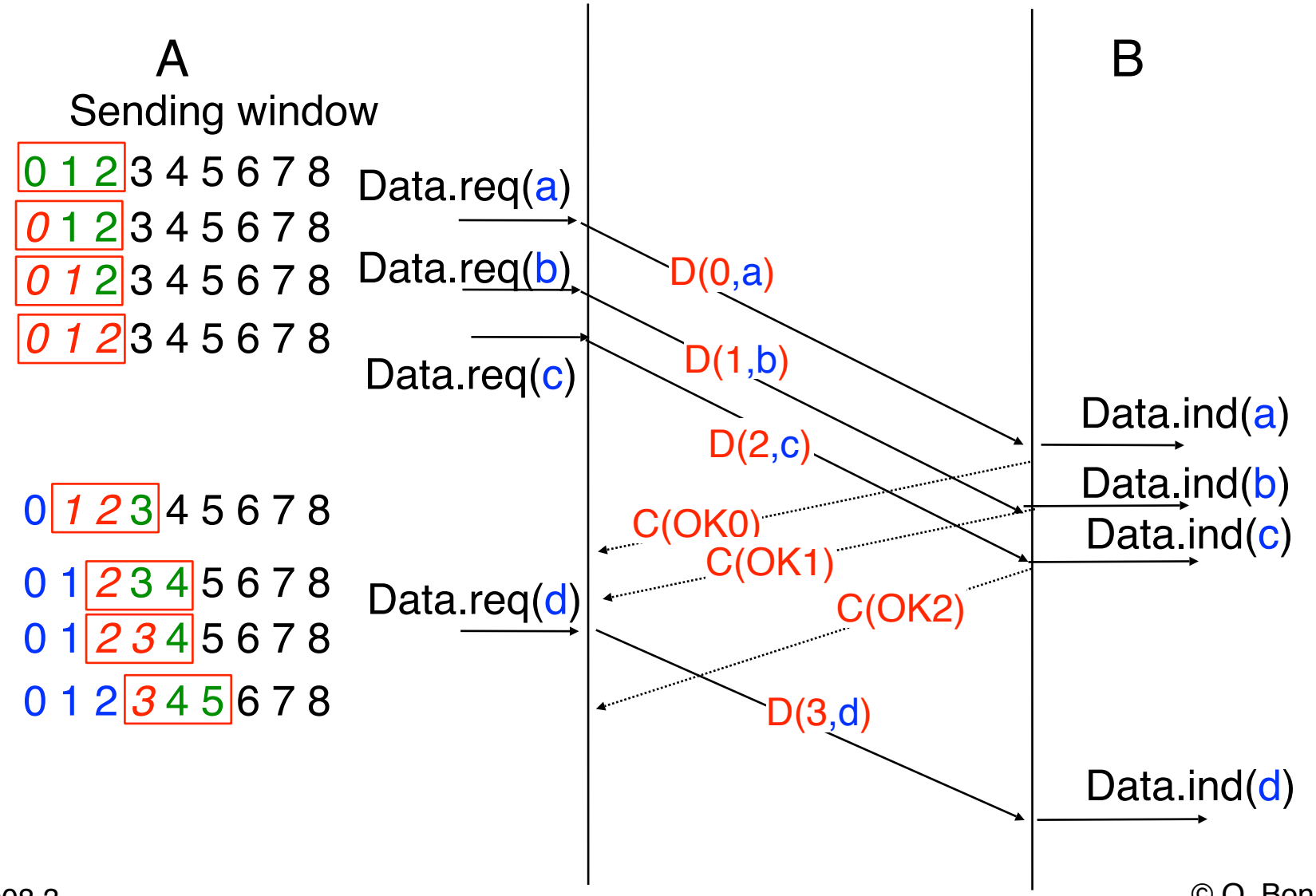

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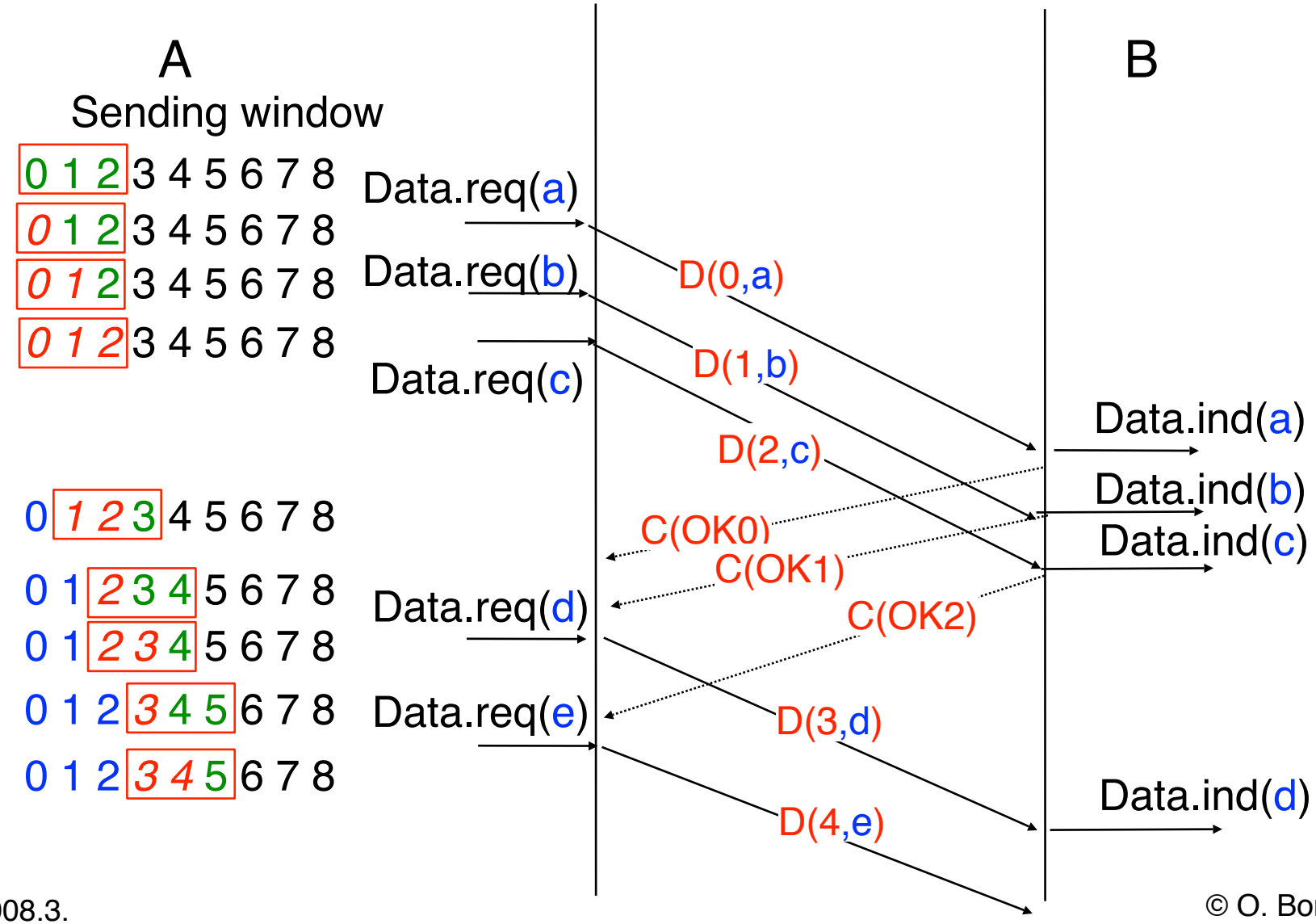


Encoding sequence numbers

Problem

How many bits do we have in the segment header to encode the sequence number

- N bits means 2^N different sequence numbers

Solution

place inside each transmitted segment its sequence number modulo 2^N

The same sequence number will be used for several different segments

- be careful, this could cause problems...

Sliding window

- List of consecutive sequence numbers (modulo 2^N) that the sender is allowed to transmit

Sliding window : second example

3 segments sending and receiving window

Sequence number encoded as 2 bits field

A

Sending window

0 1 2 3

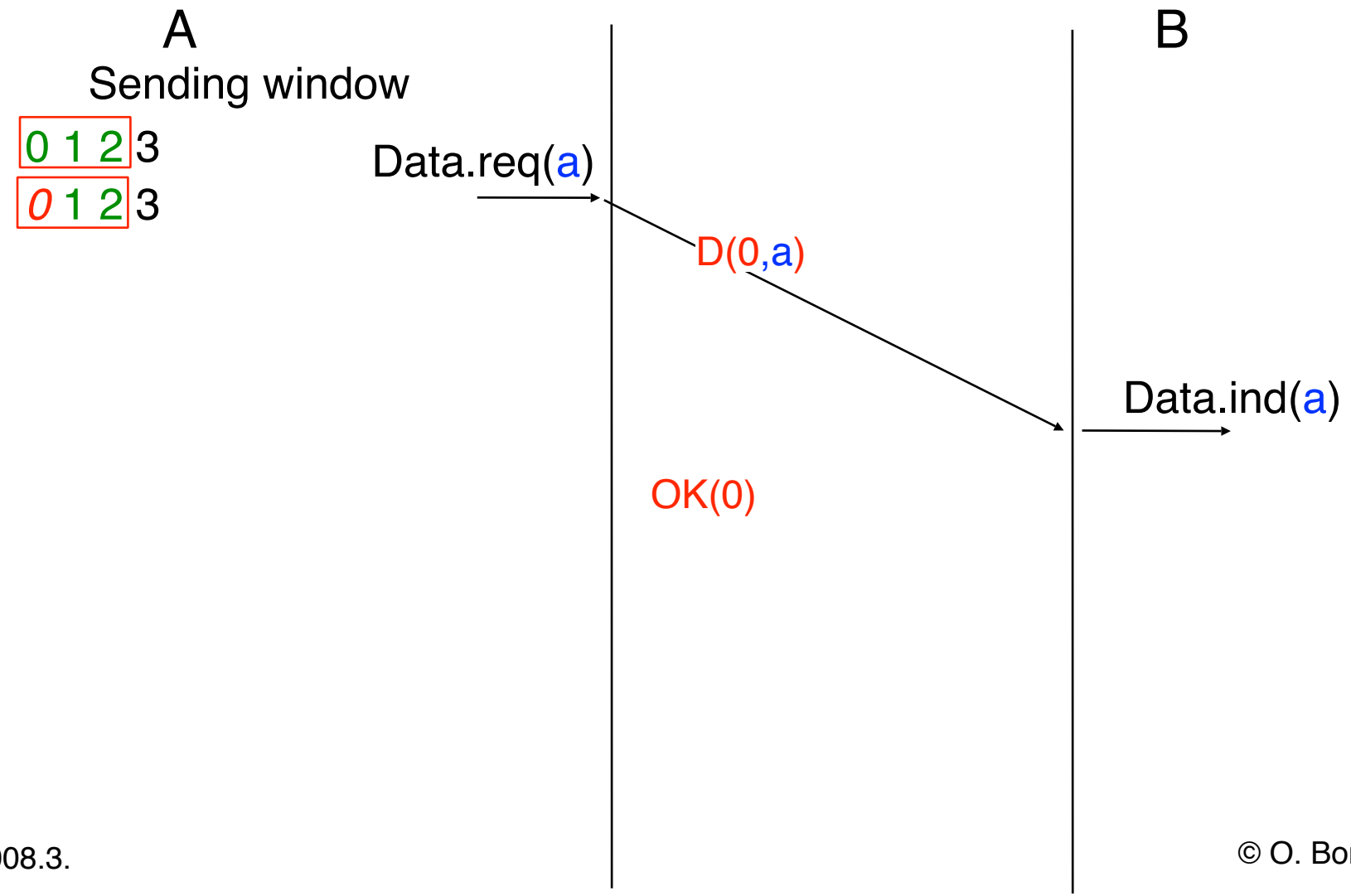
B

OK(0)

Sliding window : second example

3 segments sending and receiving window

Sequence number encoded as 2 bits field



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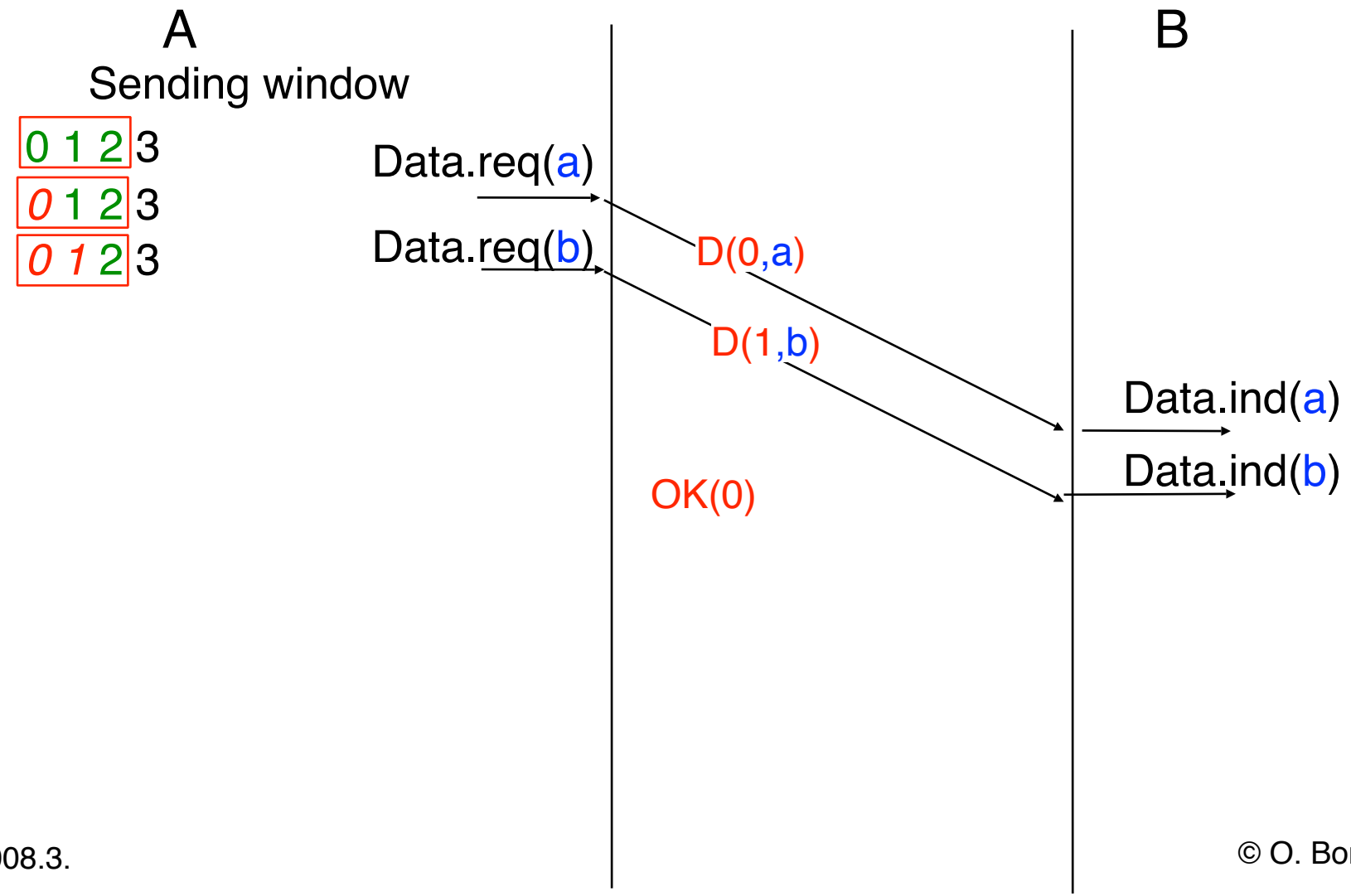

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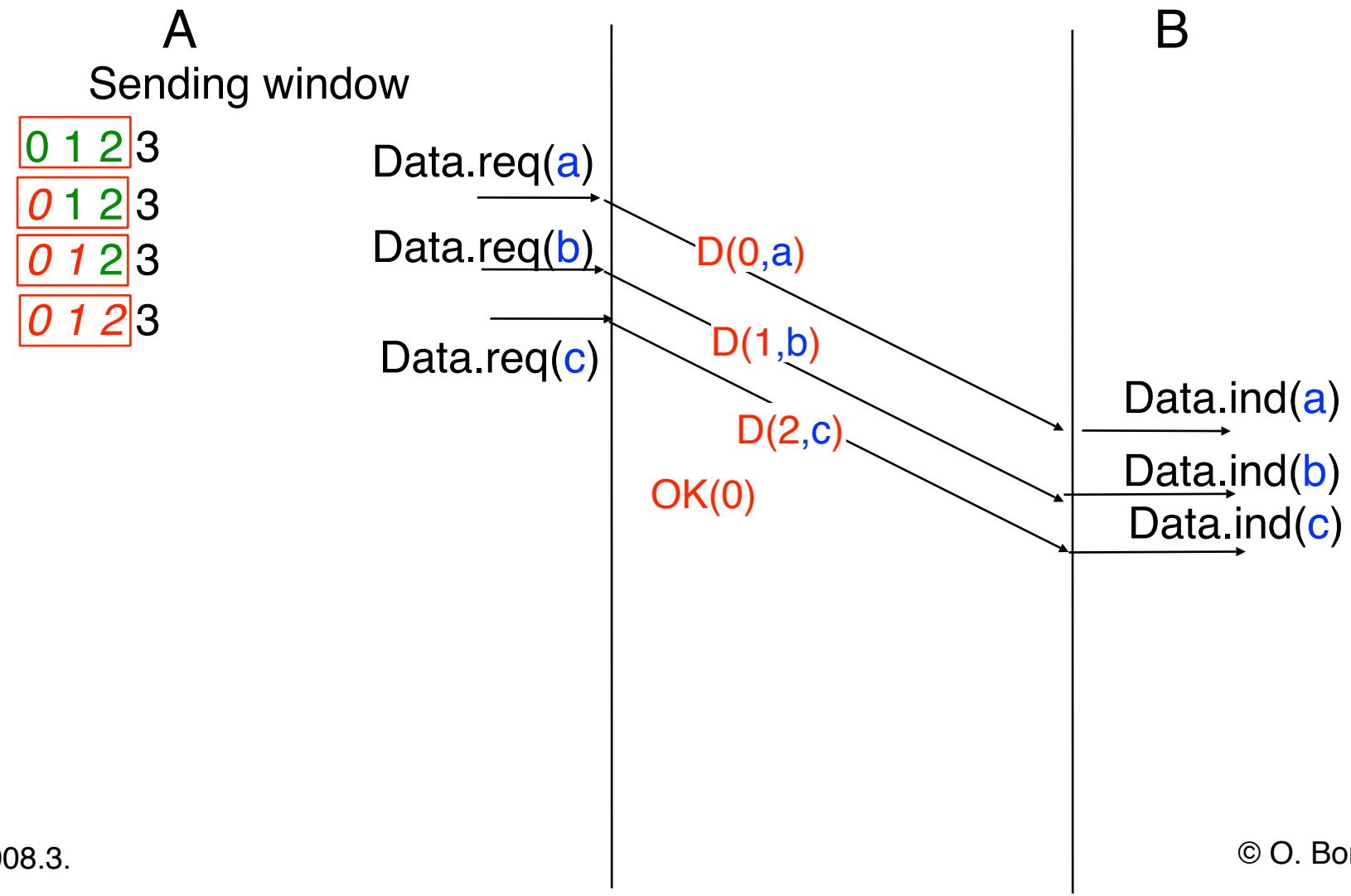

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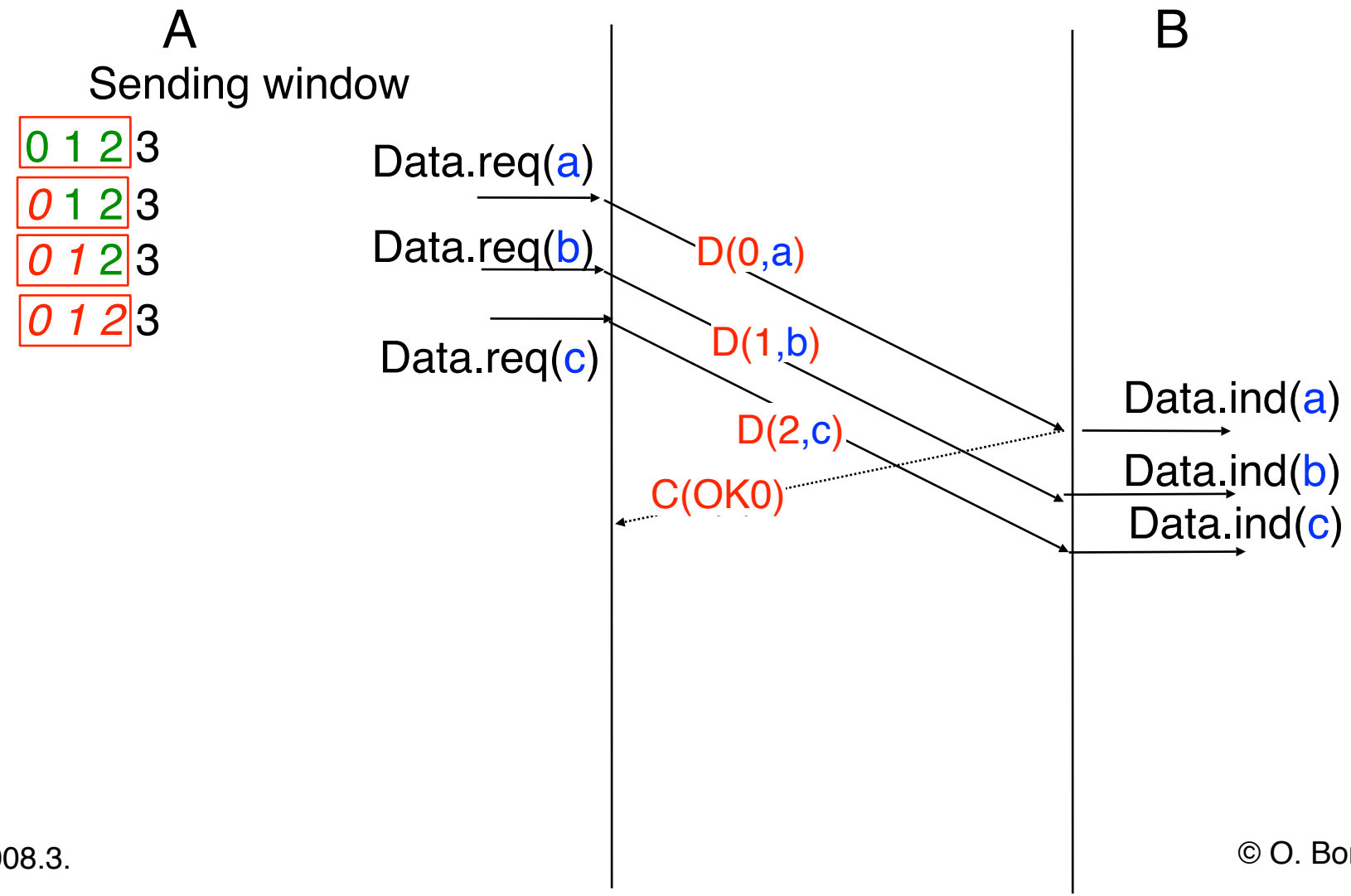

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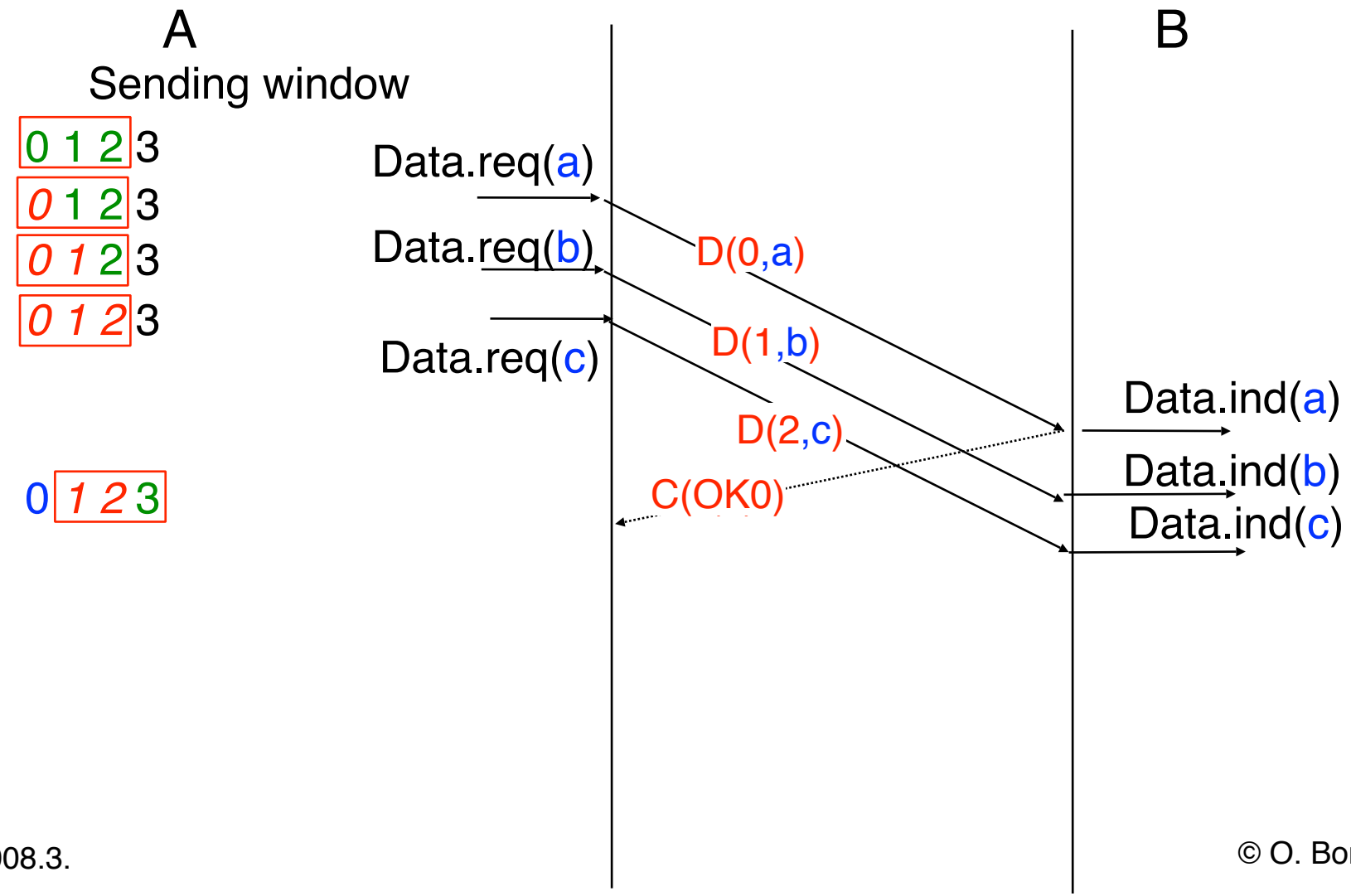

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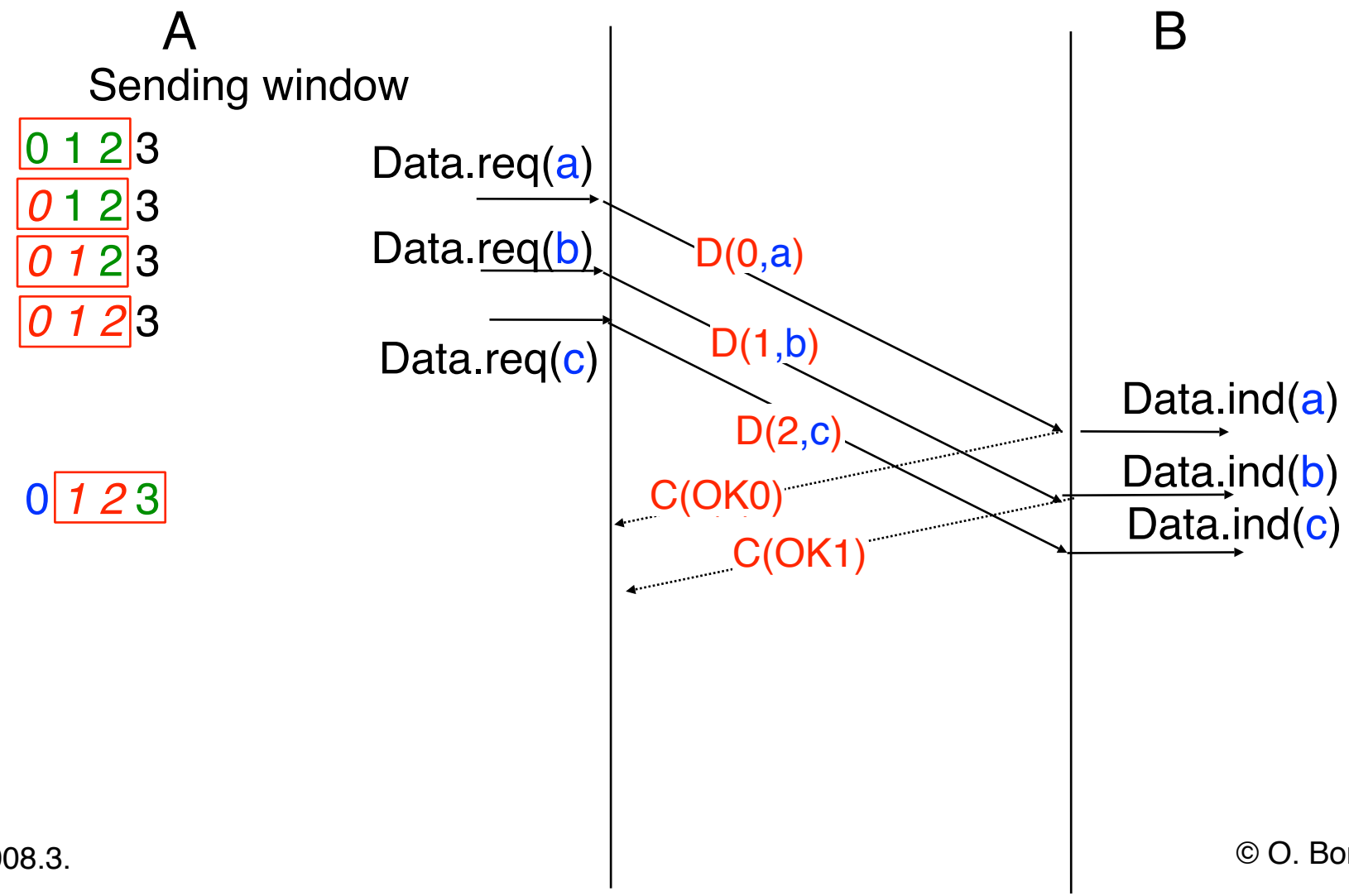

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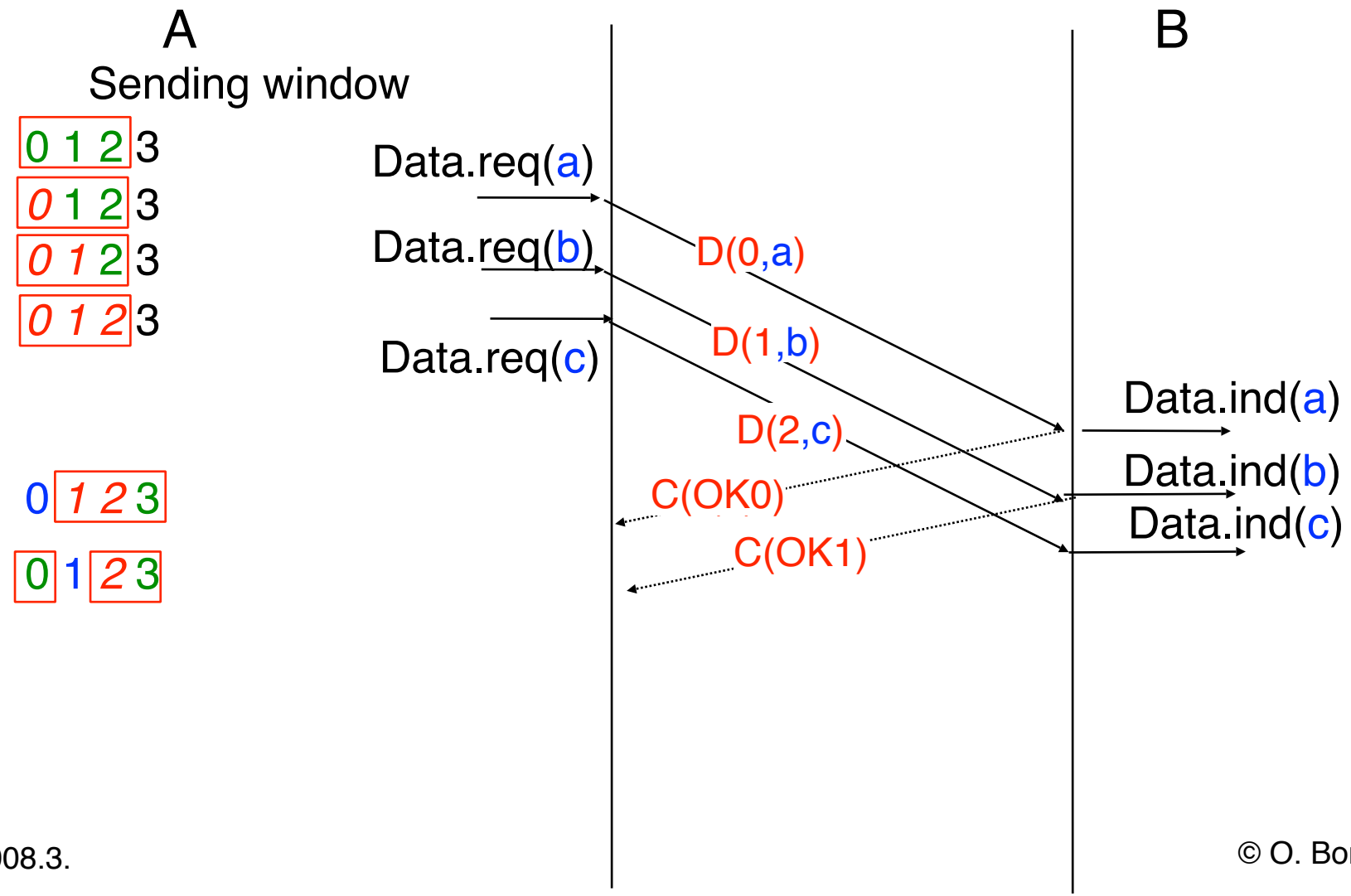

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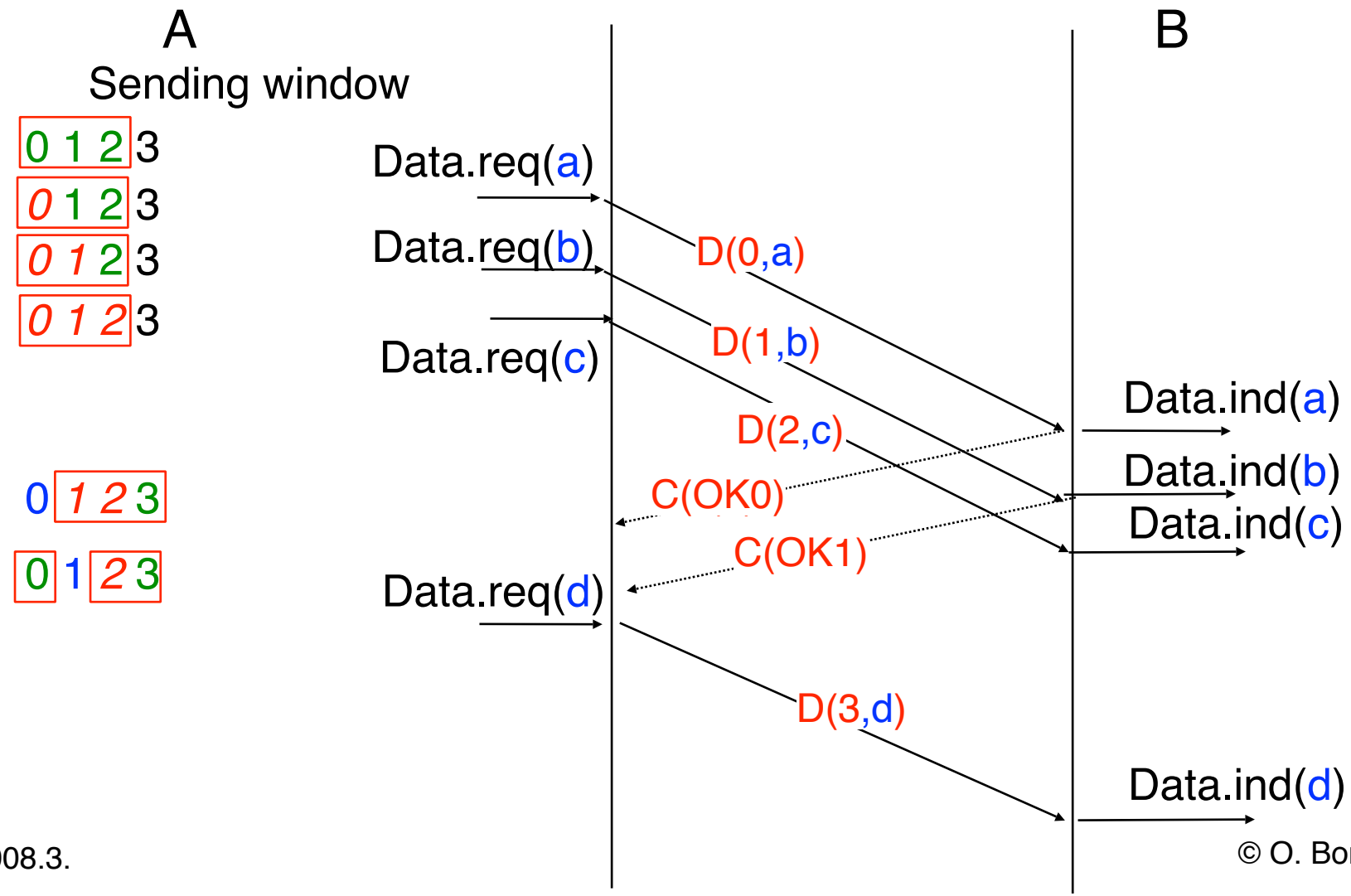
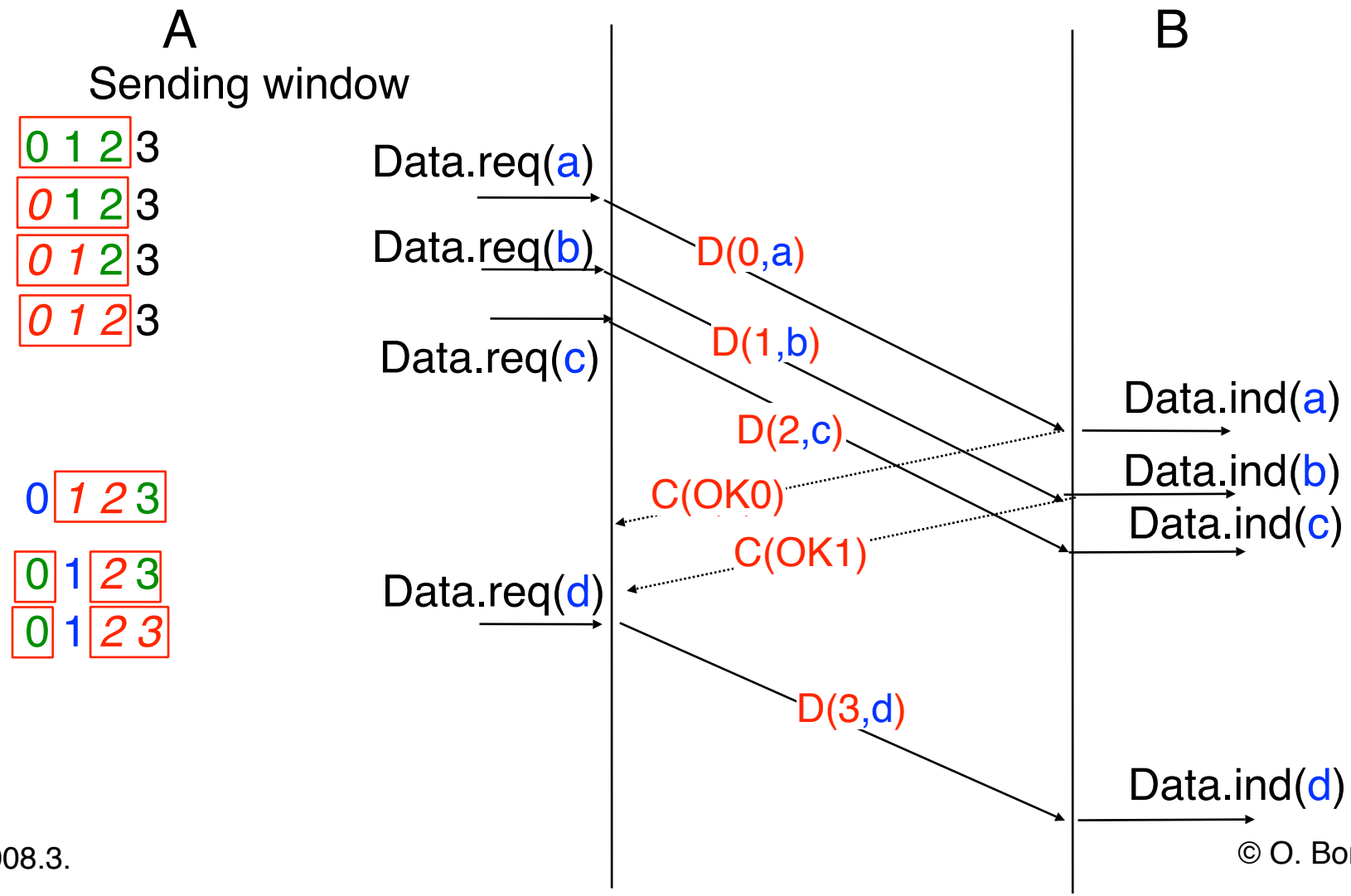


Sliding window : second example

3 segments sending and receiving window
Sequence number encoded as 2 bits field



Sliding window : second example

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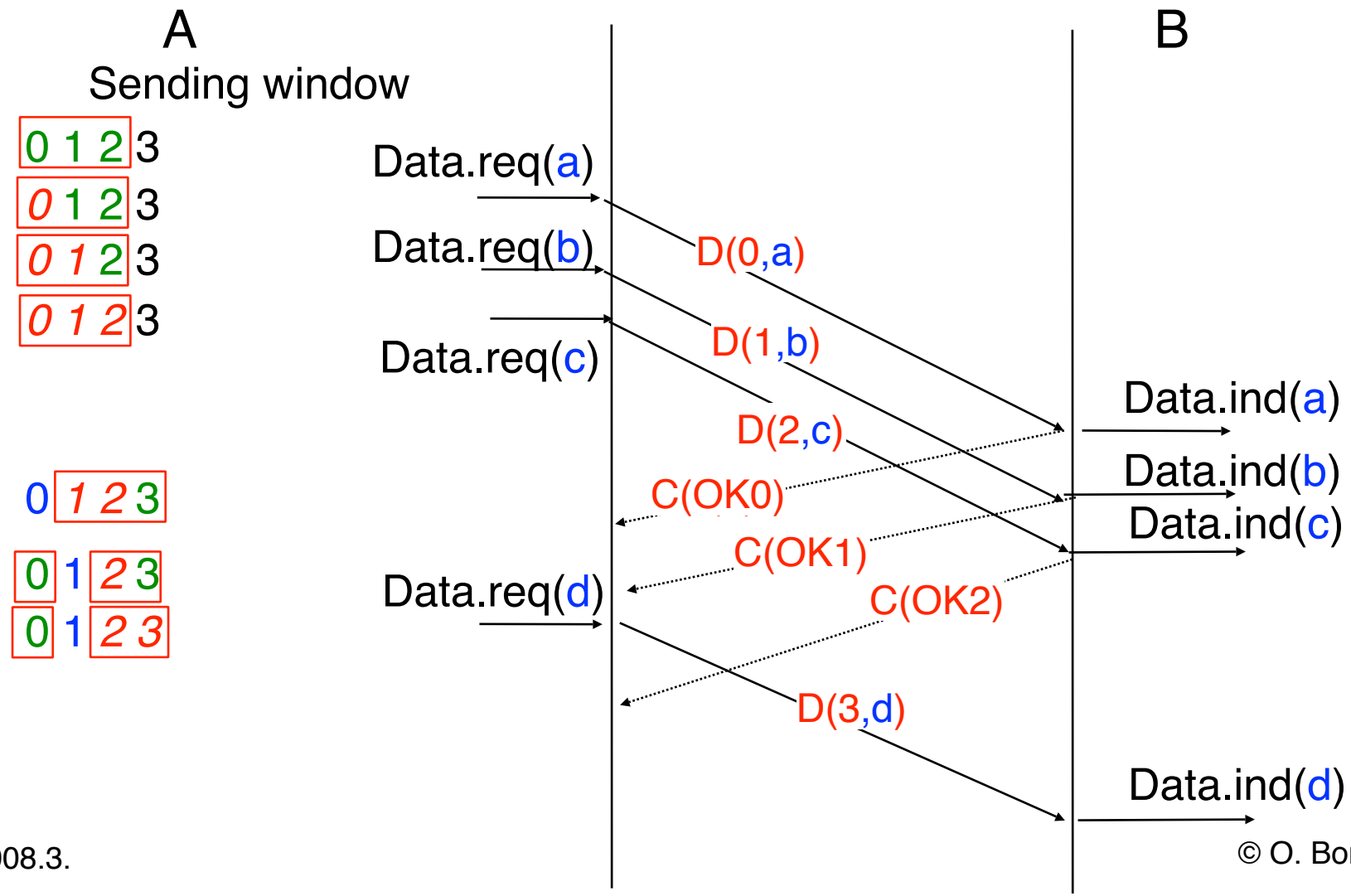

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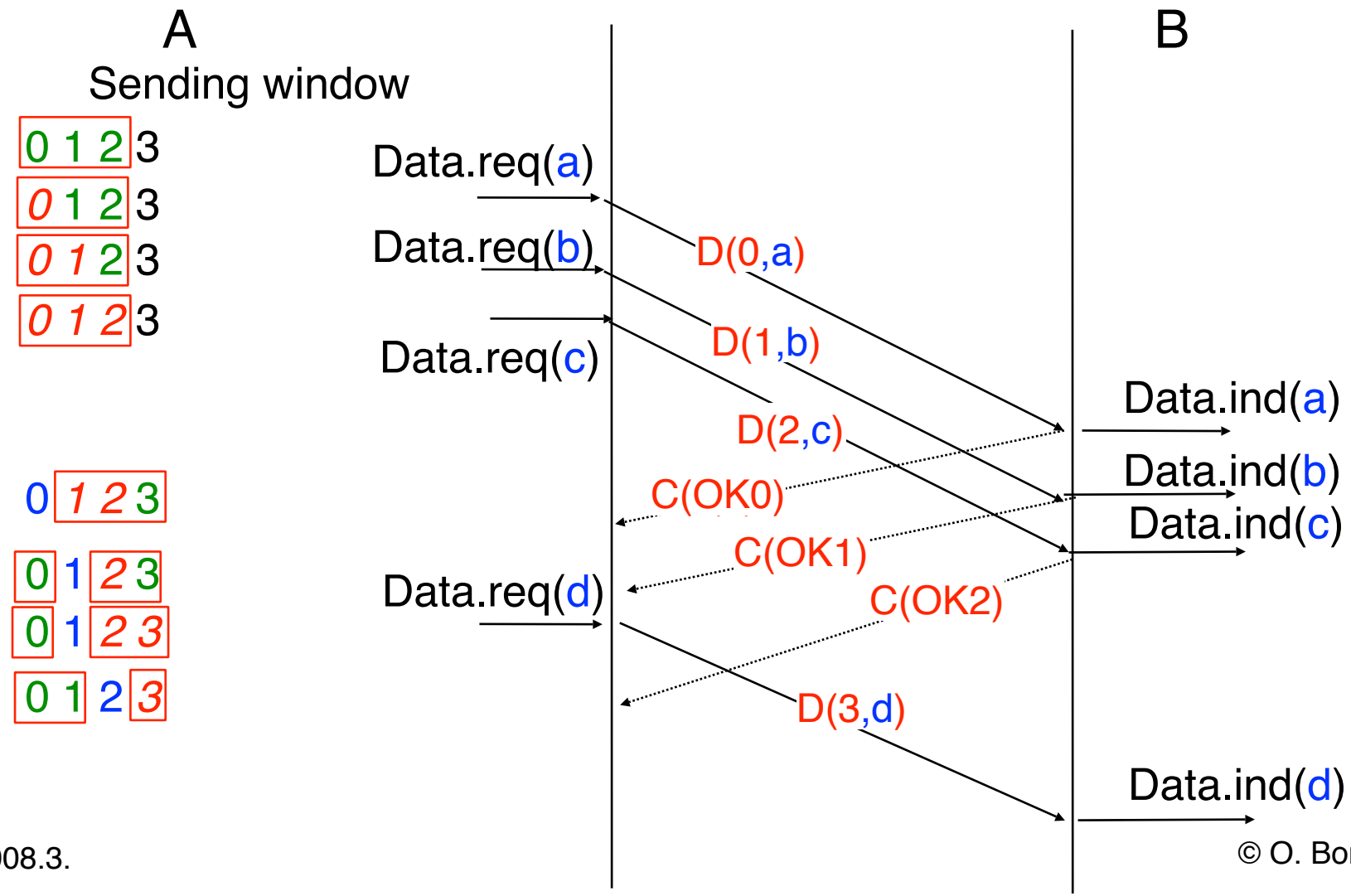

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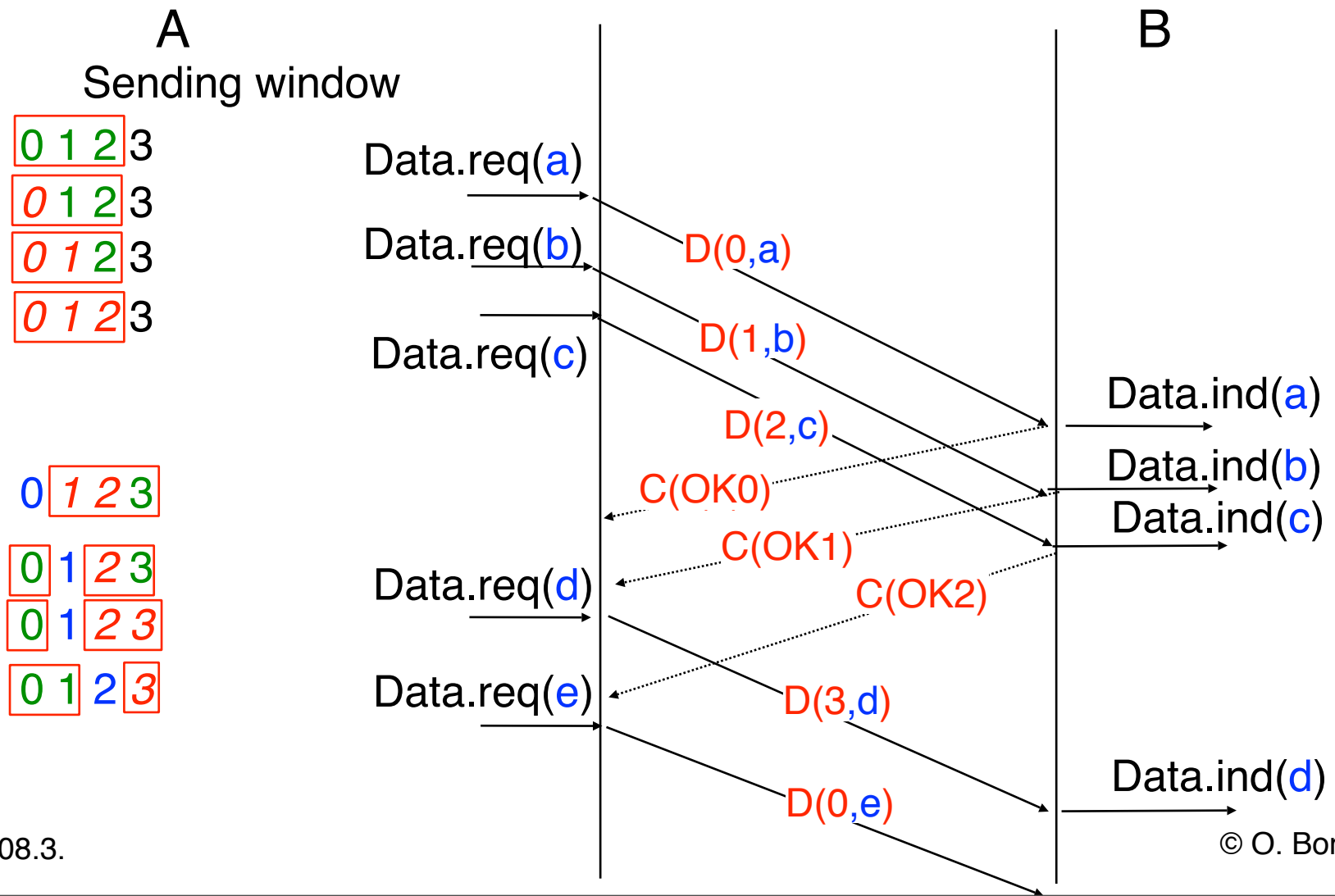

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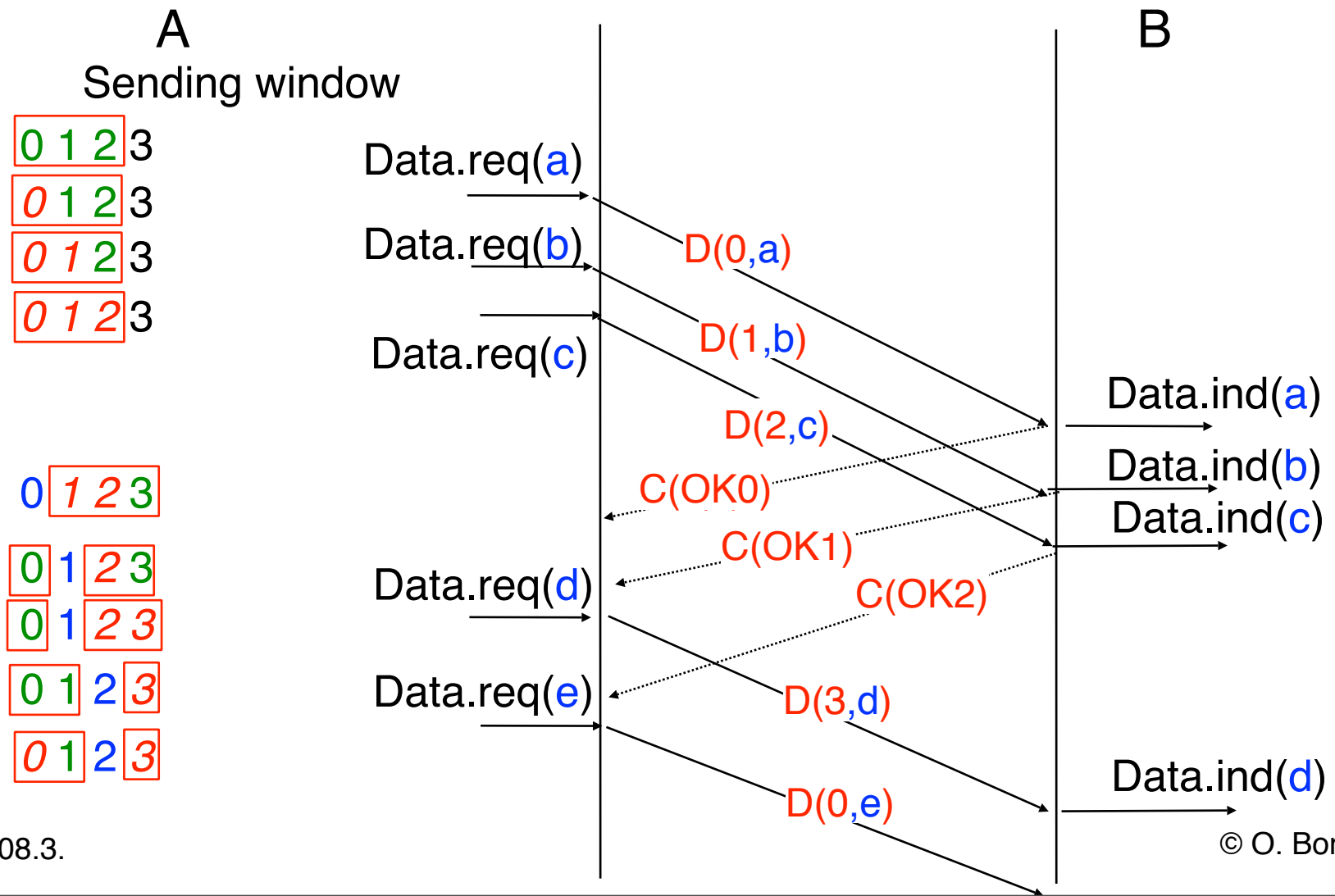


Reliable transfer with a sliding window

- How to provide a reliable data transfer with a sliding window
  - How to react upon reception of a control segment ?
  - Sender's and receiver's behaviours
- Basic solutions
  - Go-Back-N
    - simple implementation, in particular on receiving side
    - throughput will be limited when losses occur
  - Selective Repeat
    - more difficult from an implementation viewpoint
    - throughput can remain high when limited losses occur

GO-BACK-N

Principle

Receiver must be as simple as possible

Receiver

- Only accepts consecutive in-sequence data segments
- Meaning of control segments
  - Upon reception of data segment
    - OKX means that all data segments, up to and including X have been received correctly
    - NAKX means that the data segment whose sequence number is X contained an error or was lost

Sender

- Relies on a retransmission timer to detect segment losses
- Upon expiration of retransmission time or arrival of a NAK segment : retransmit all the unacknowledged data segments
  - the sender may thus retransmit a segment that was already received correctly but out-of-sequence at destination

Go-Back-N : Example

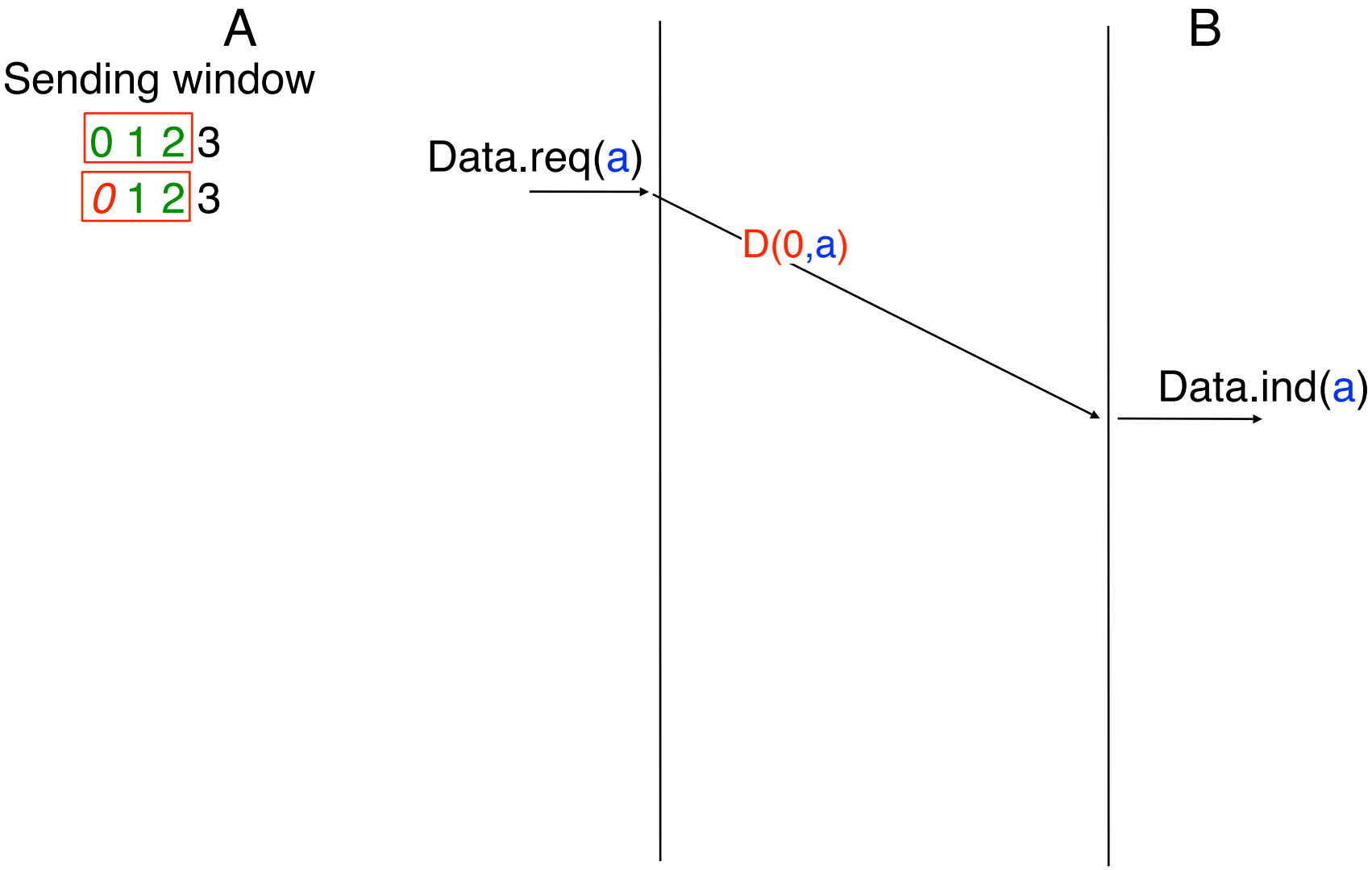
A

Sending window

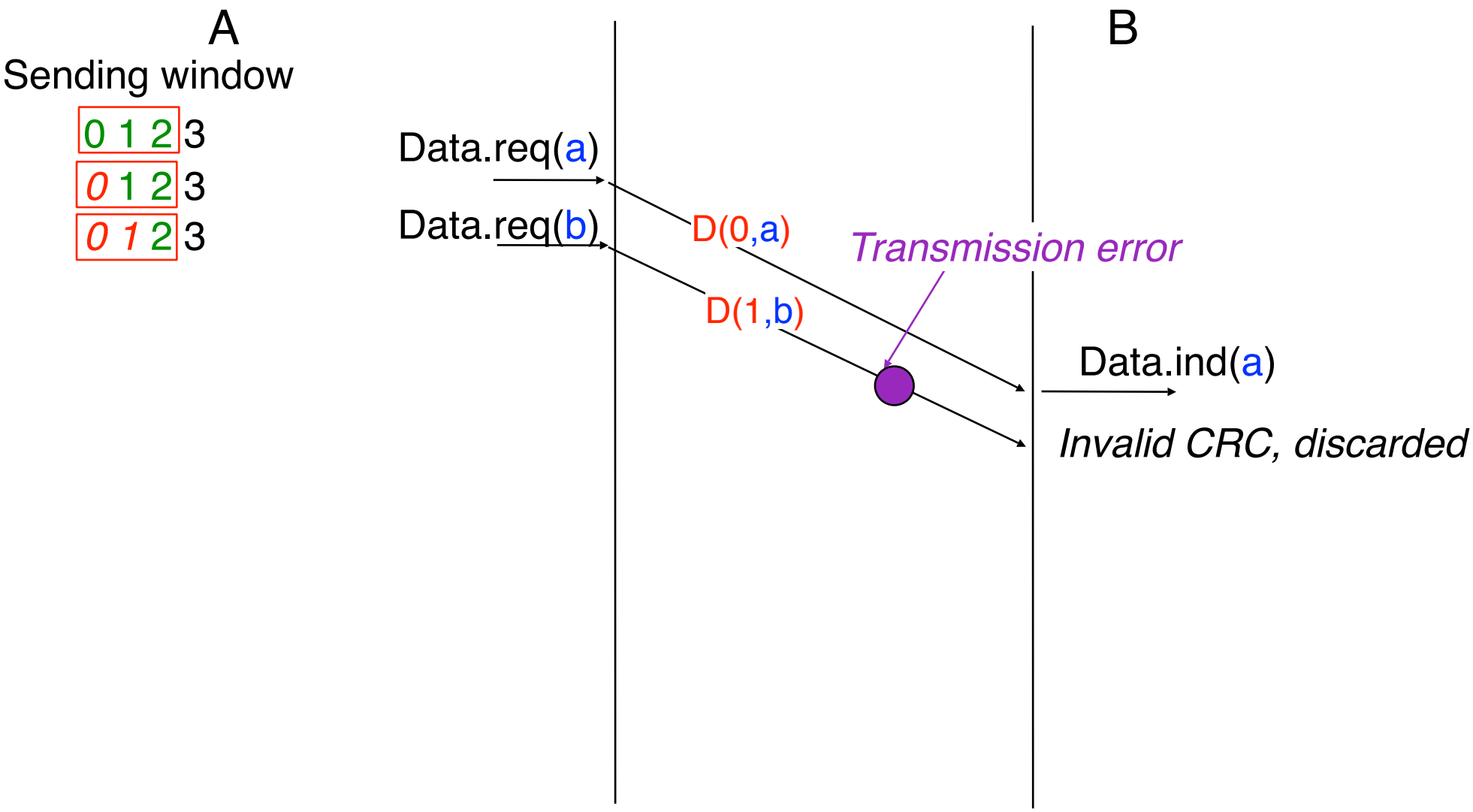
0 1 2 3

B

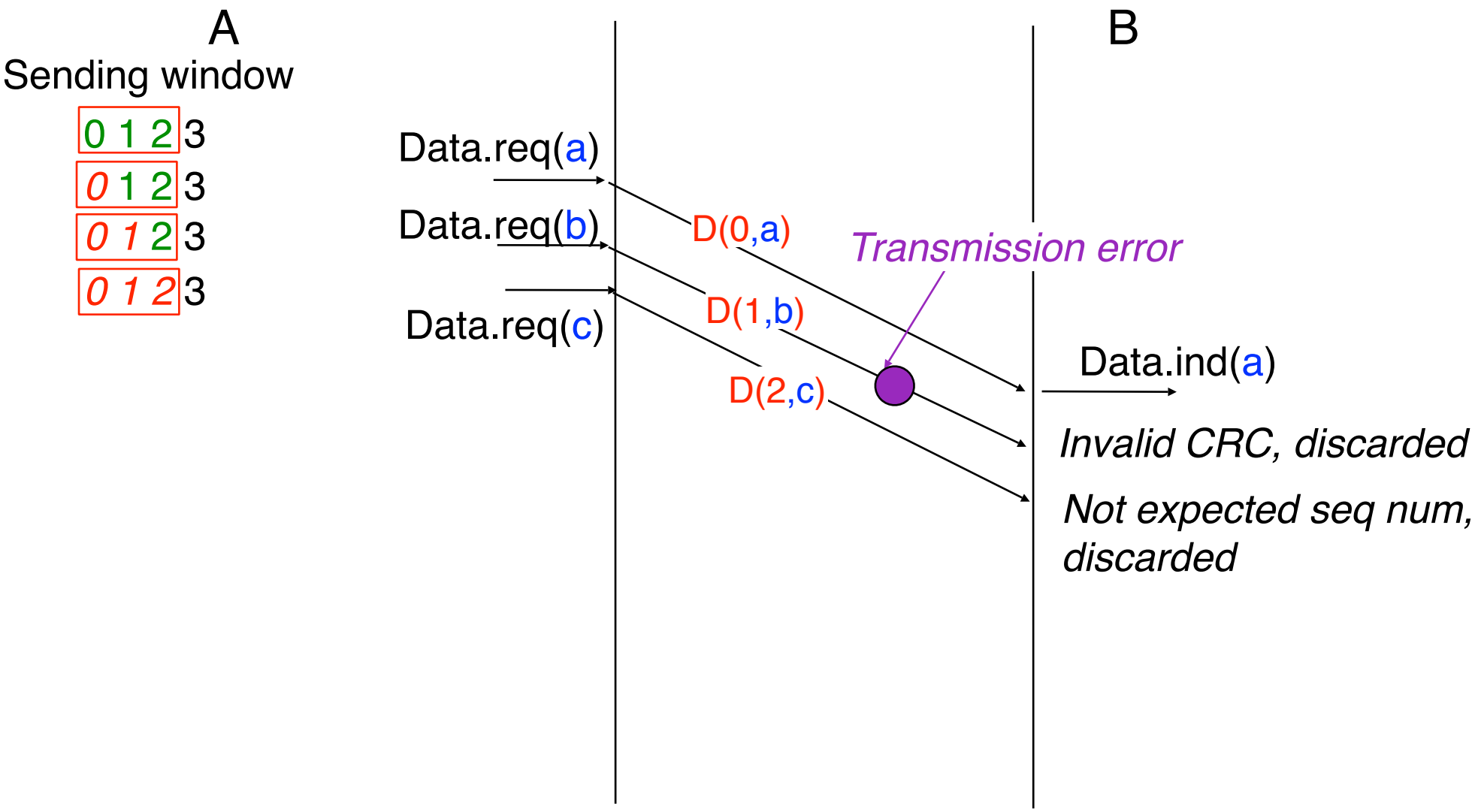
Go-Back-N : Example



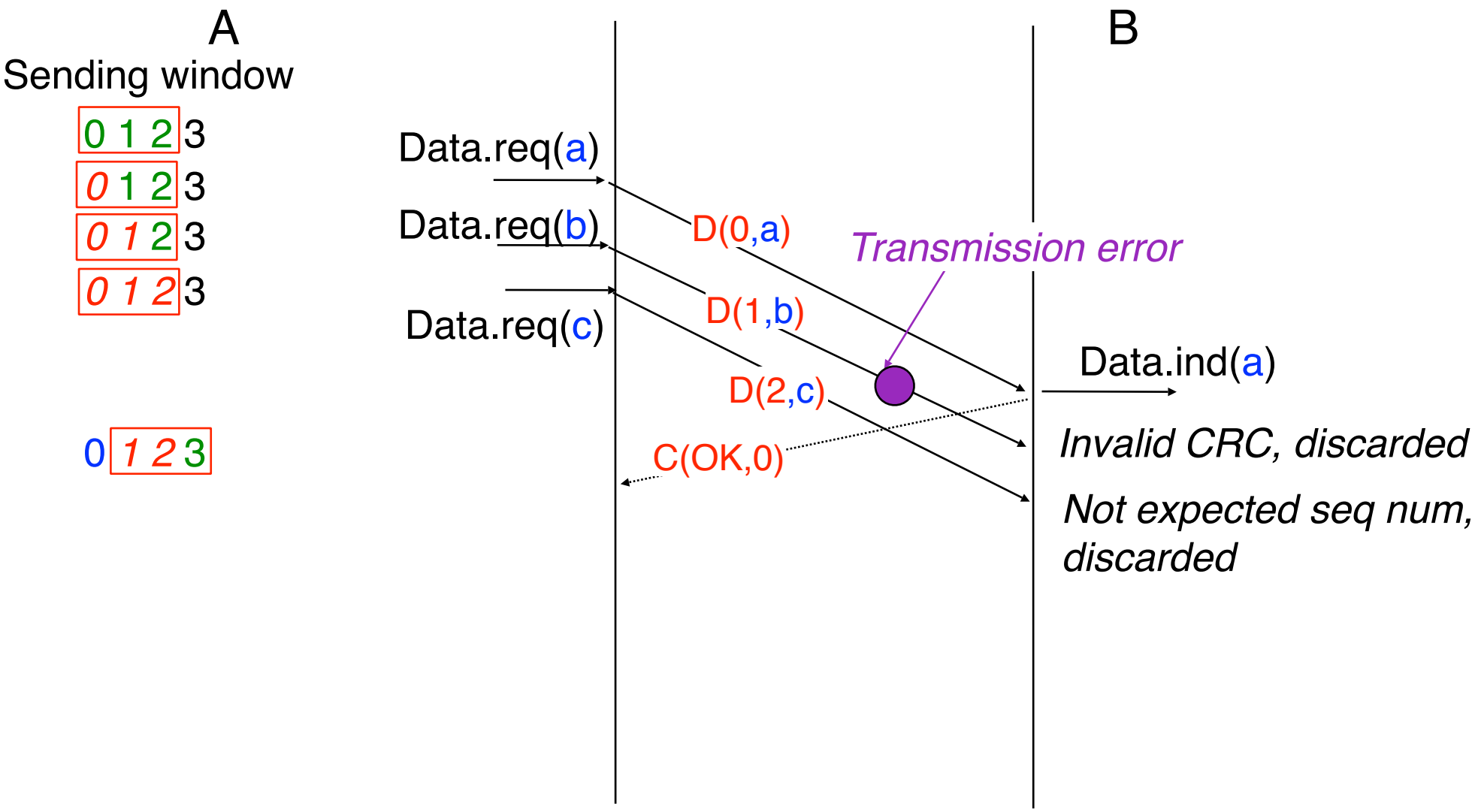
Go-Back-N : Example



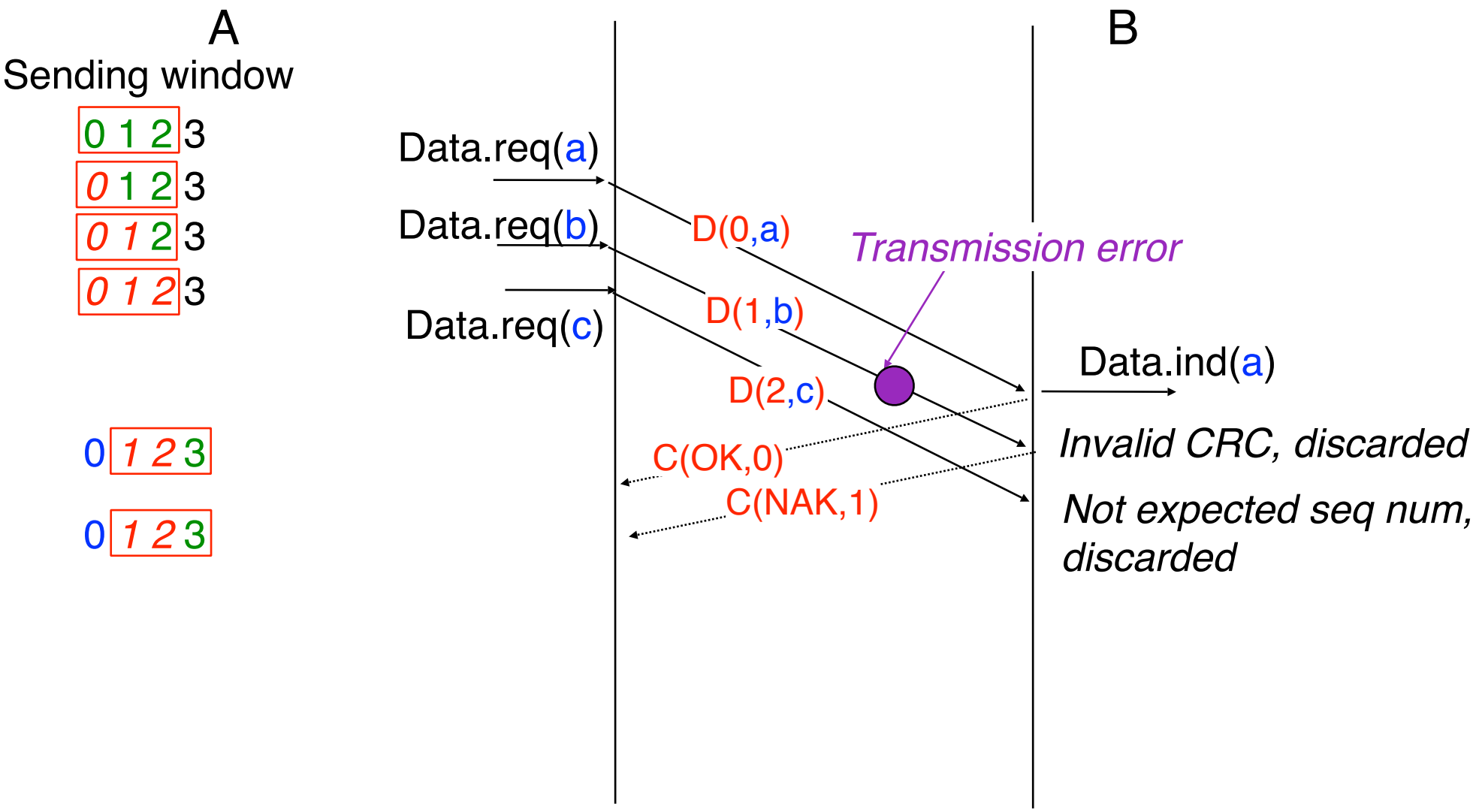
Go-Back-N : Example



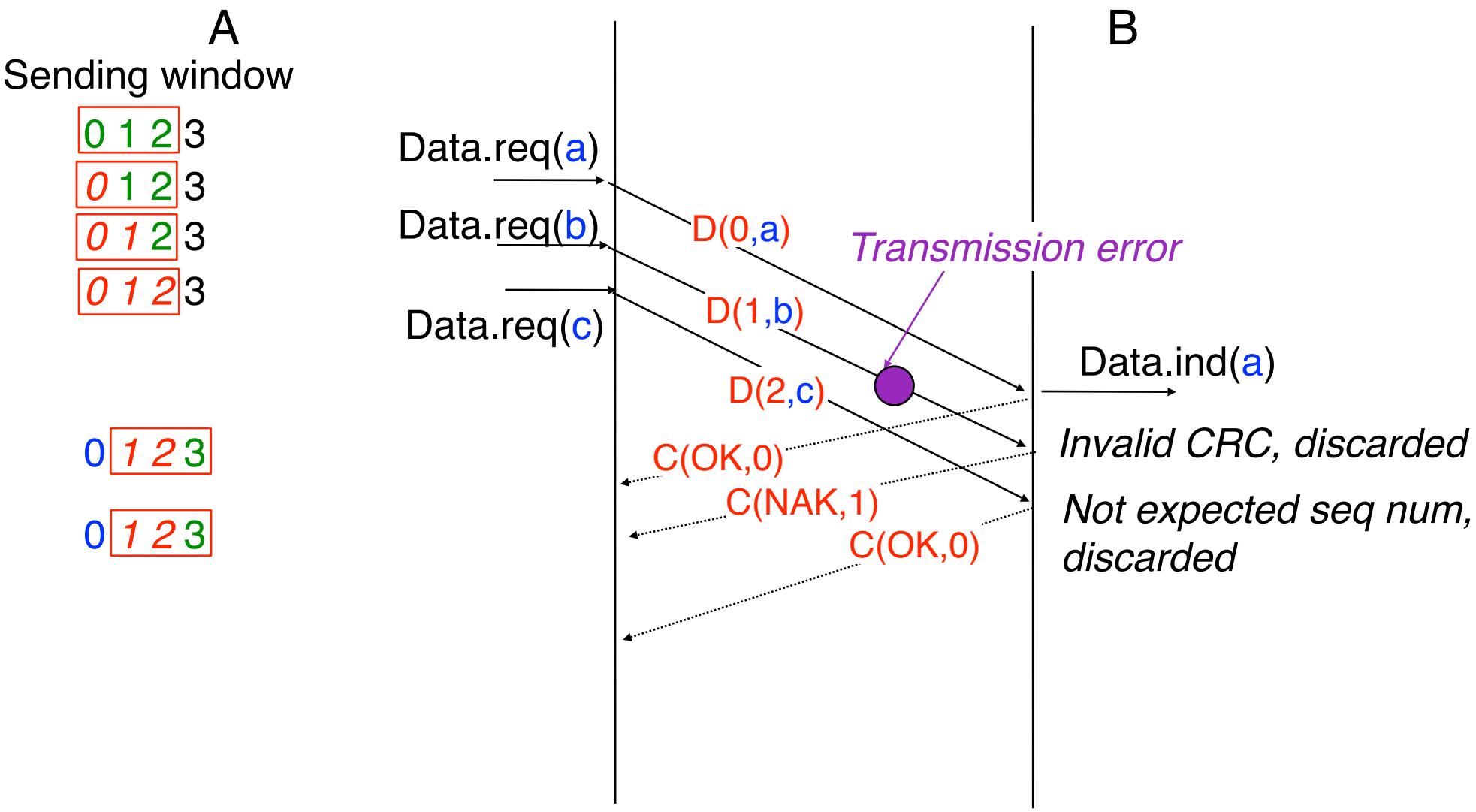
Go-Back-N : Example



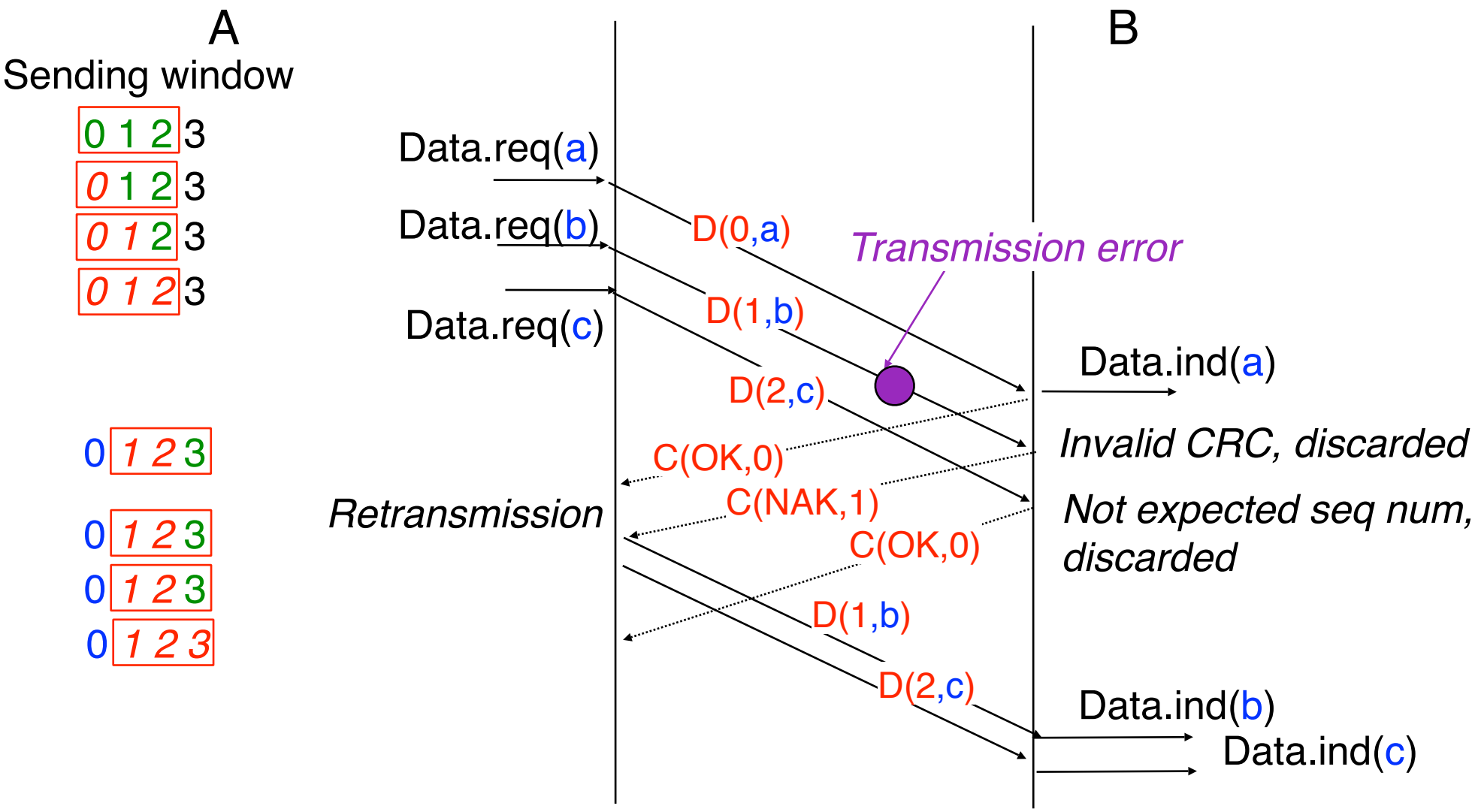
Go-Back-N : Example



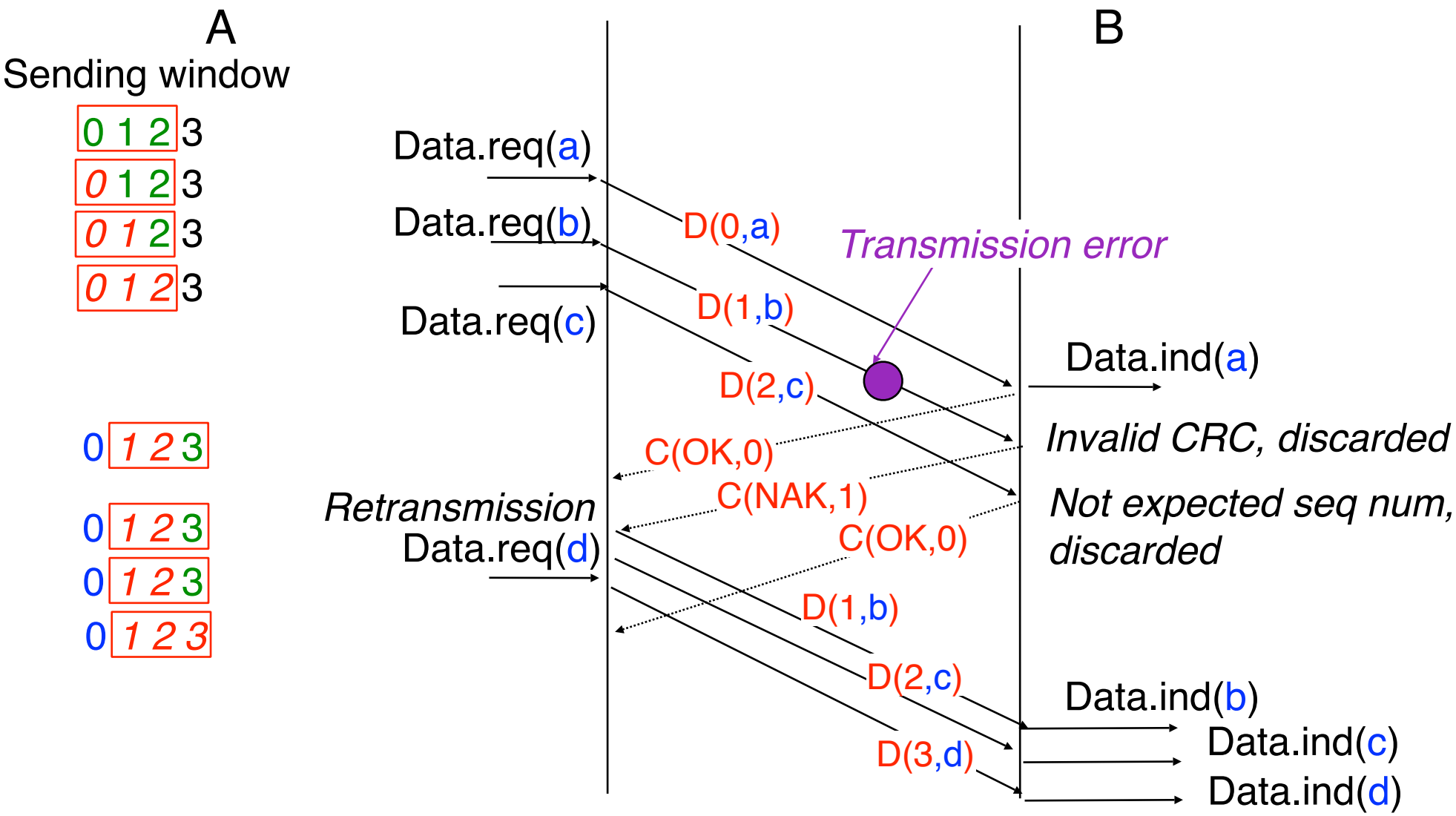
Go-Back-N : Example



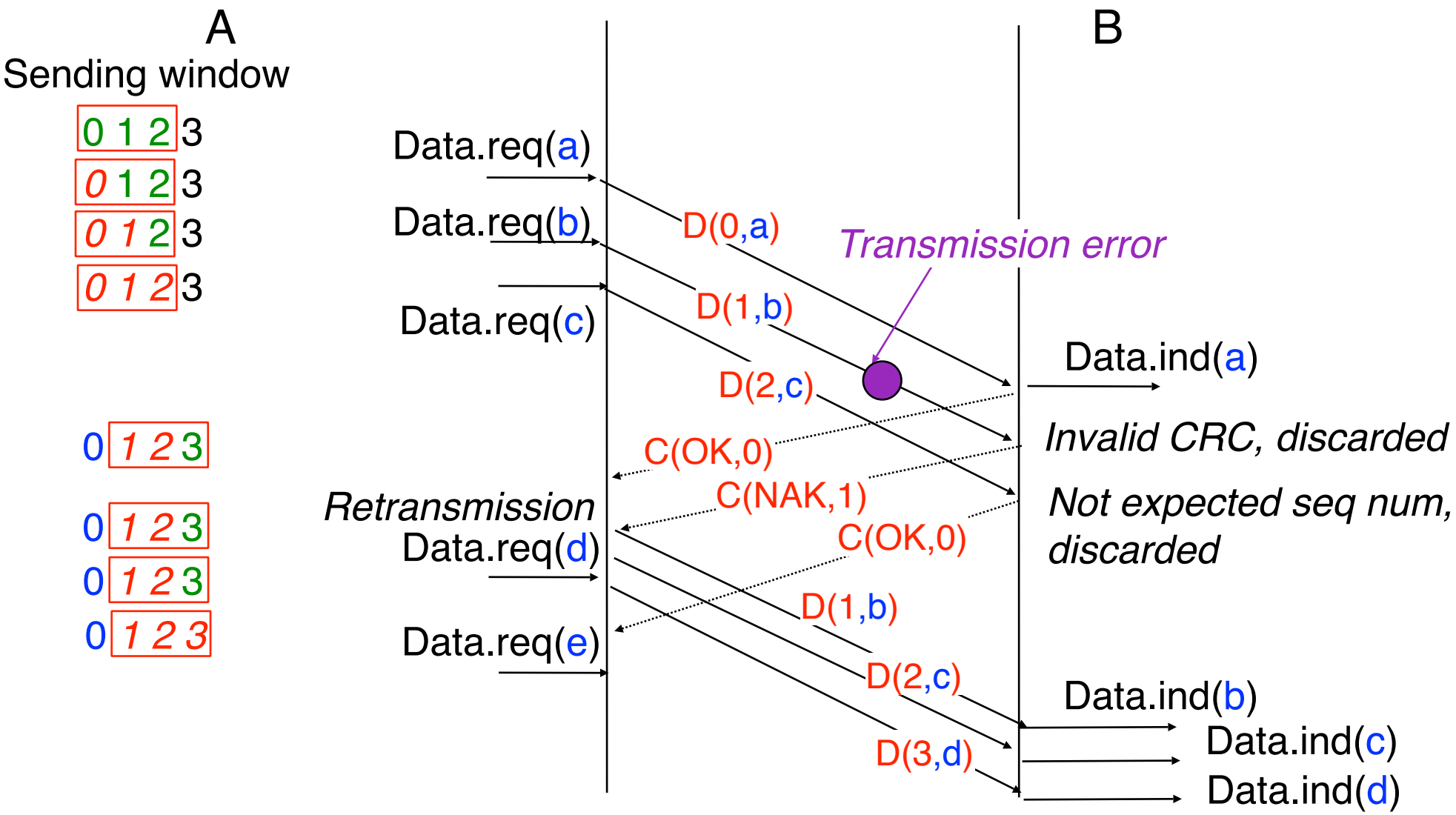
Go-Back-N : Example



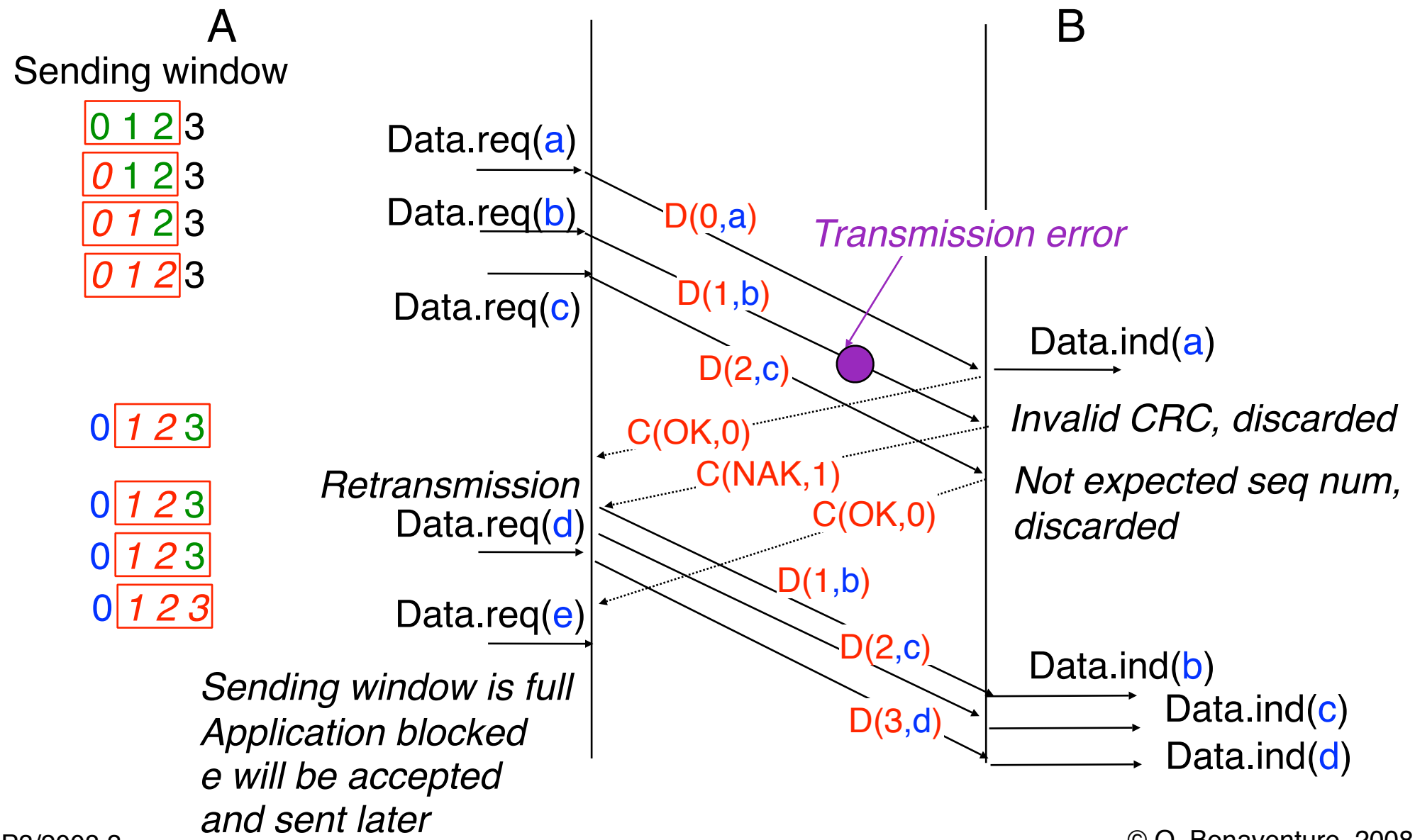
Go-Back-N : Example



Go-Back-N : Example



Go-Back-N : Example



Go-Back-N : Example (2)

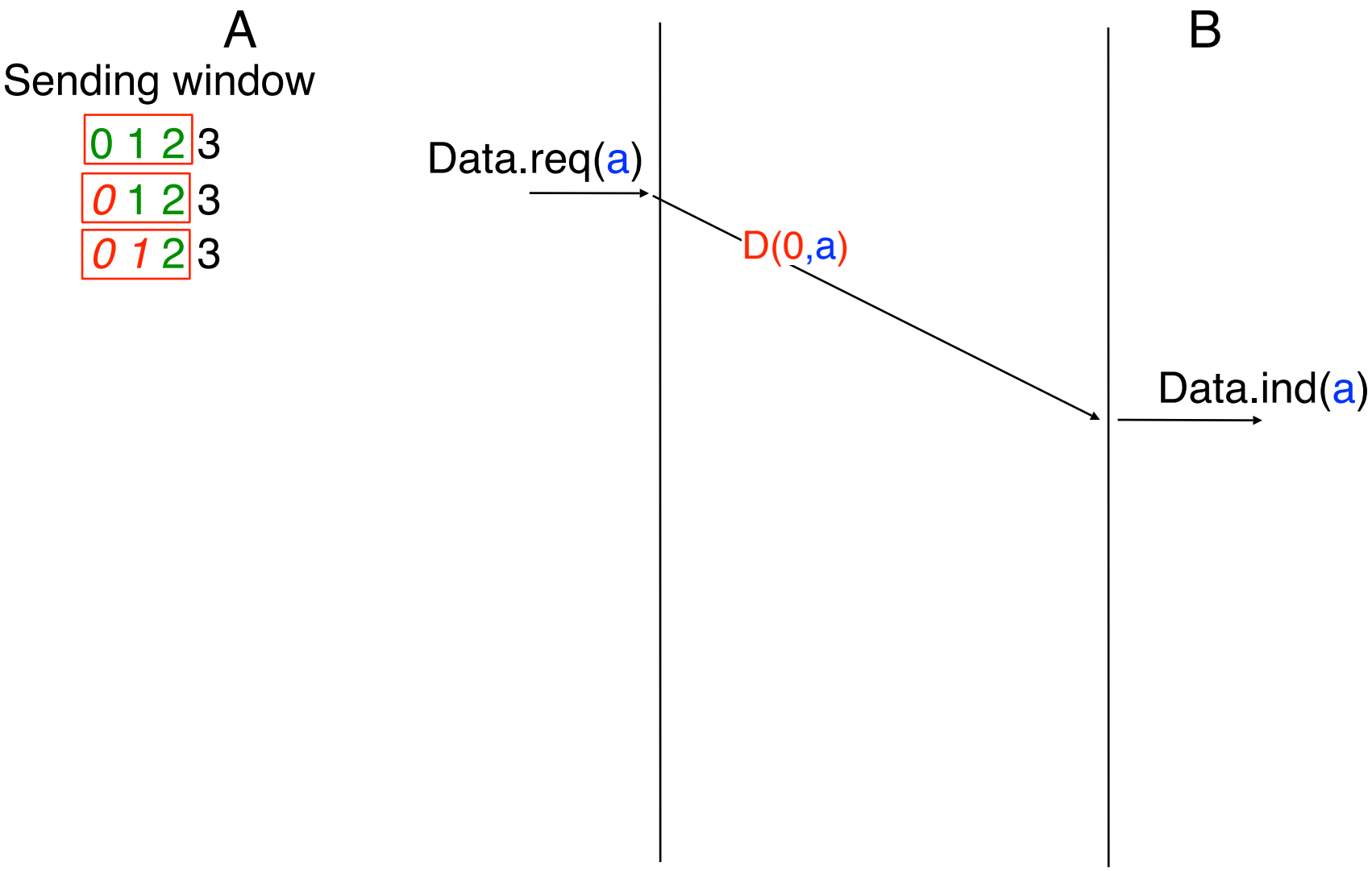
A

Sending window

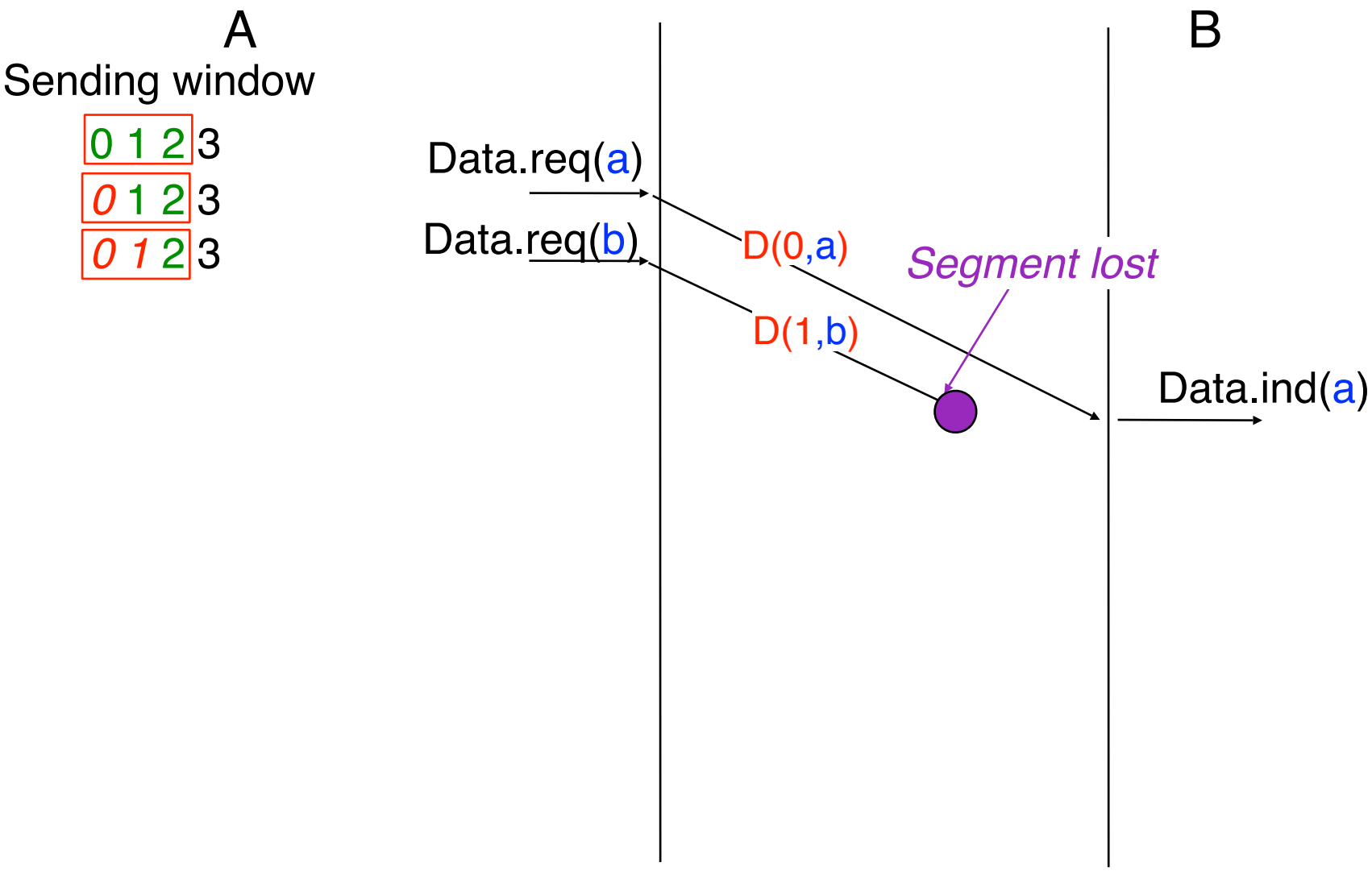
0 1 2 3

B

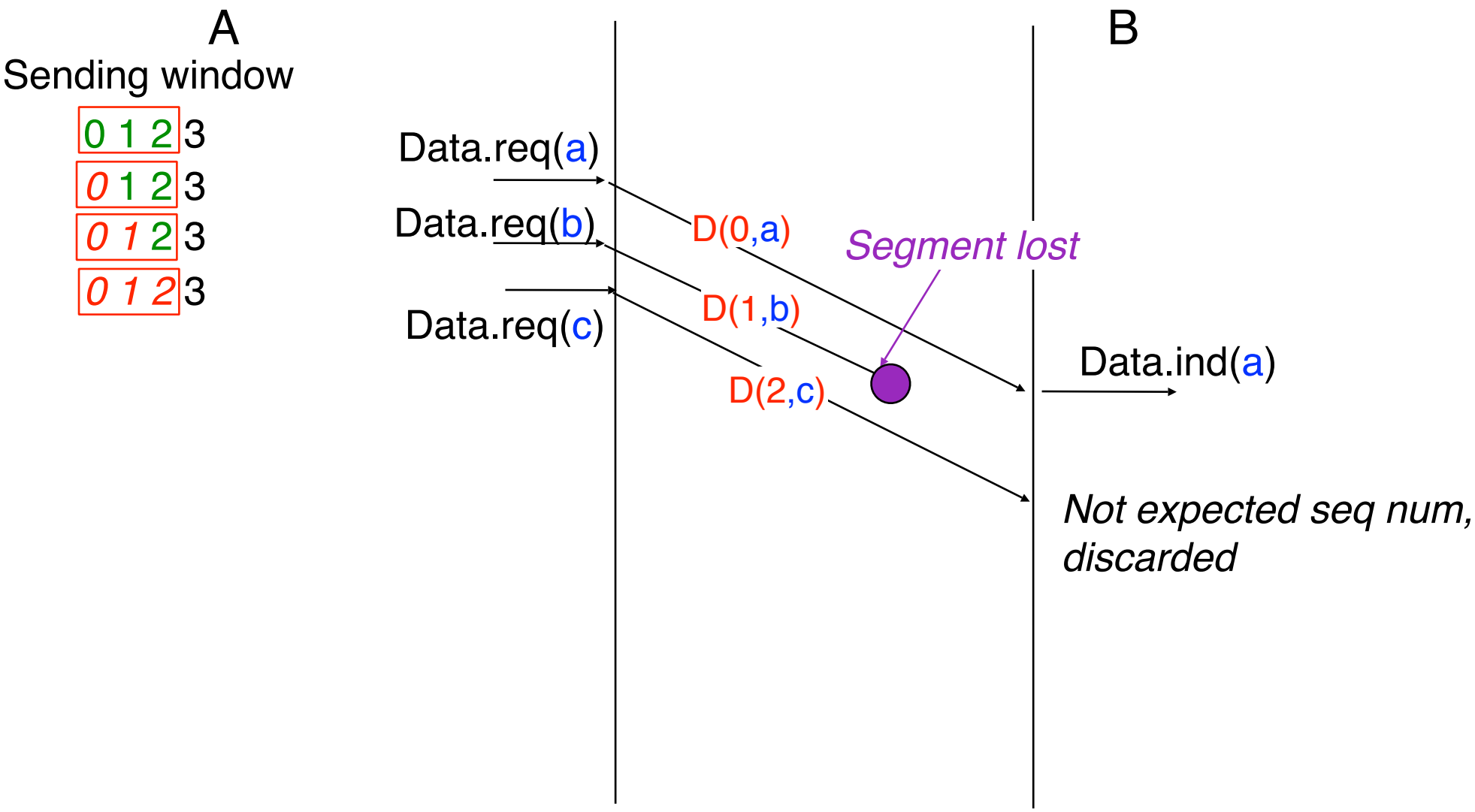
Go-Back-N : Example (2)



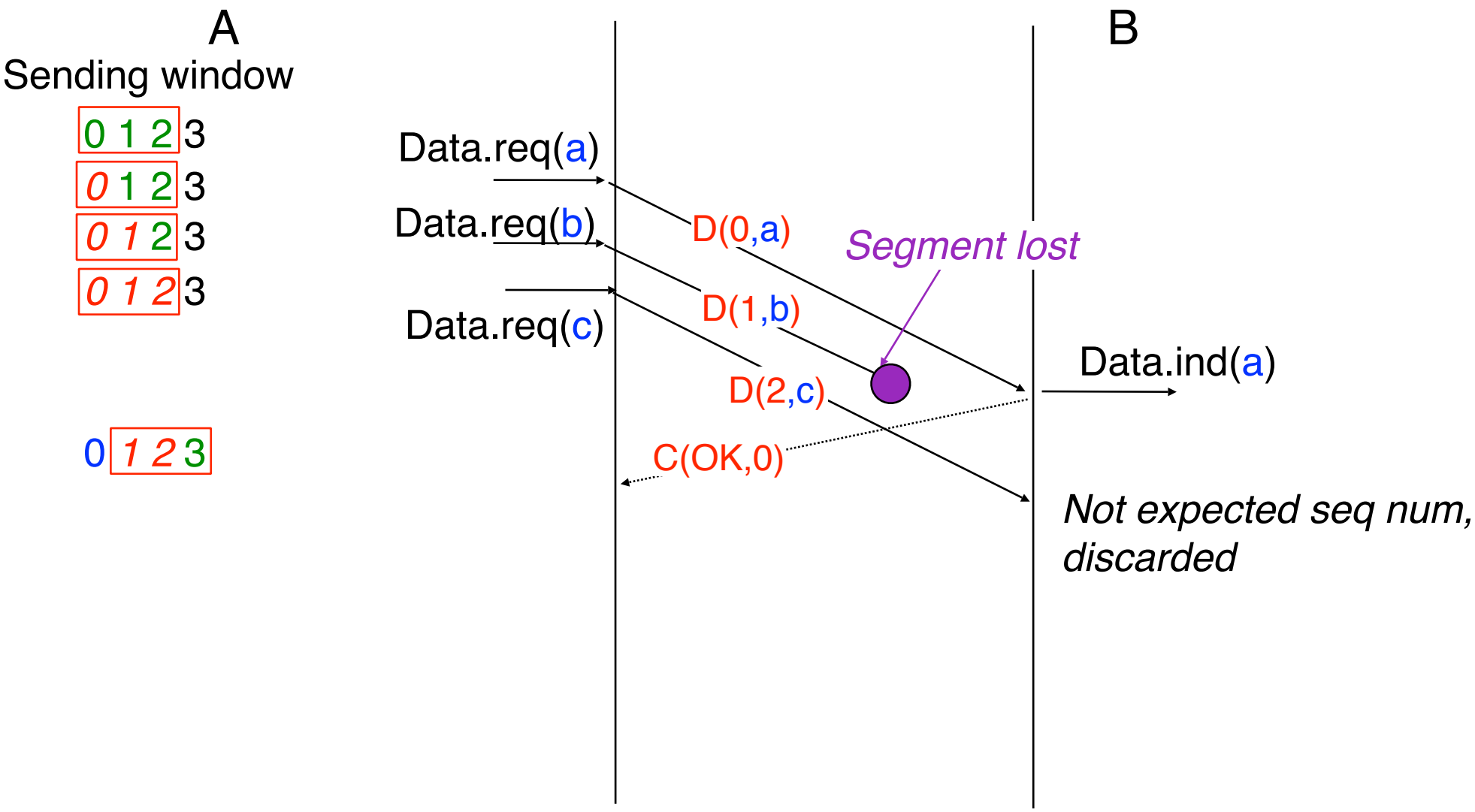
Go-Back-N : Example (2)



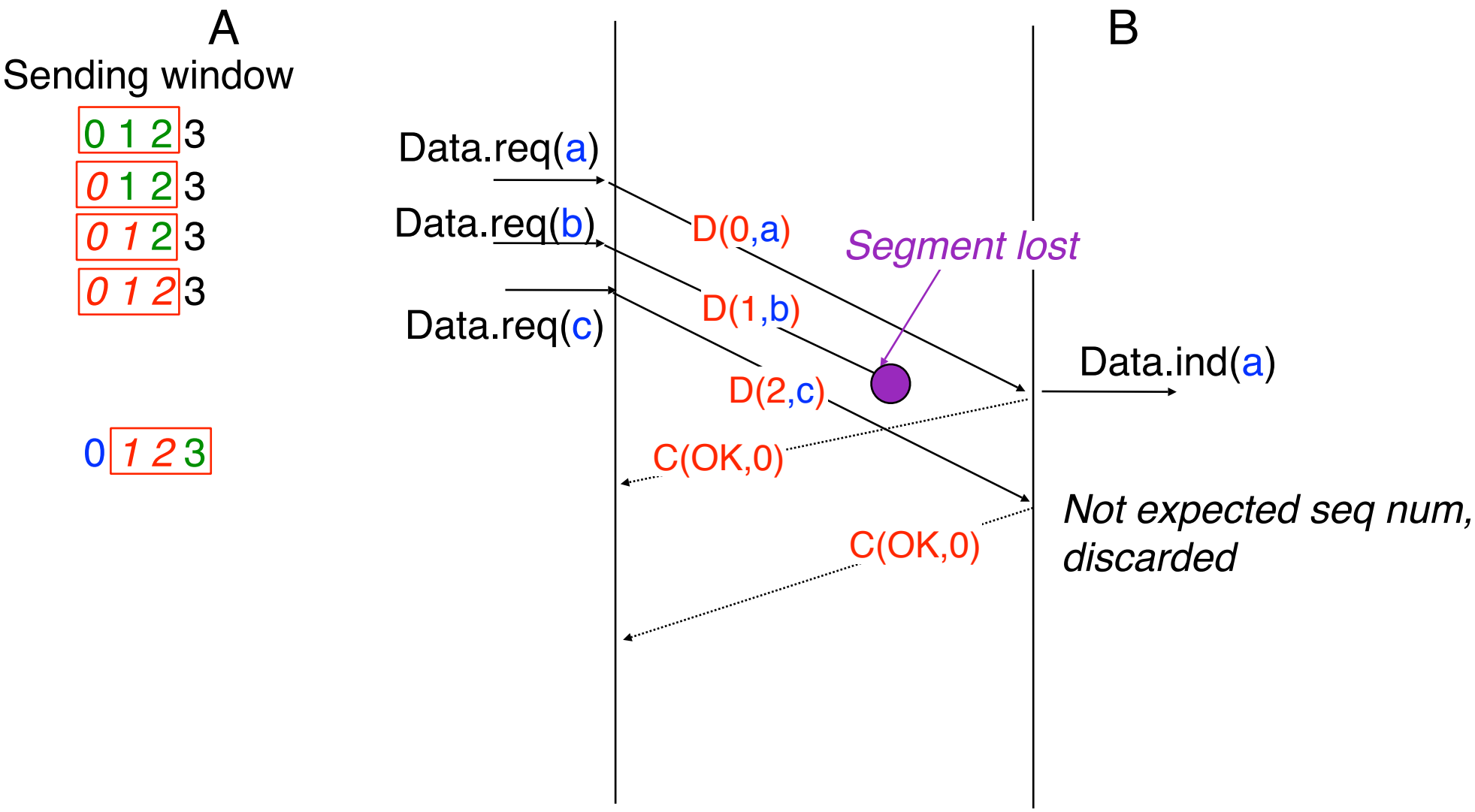
Go-Back-N : Example (2)



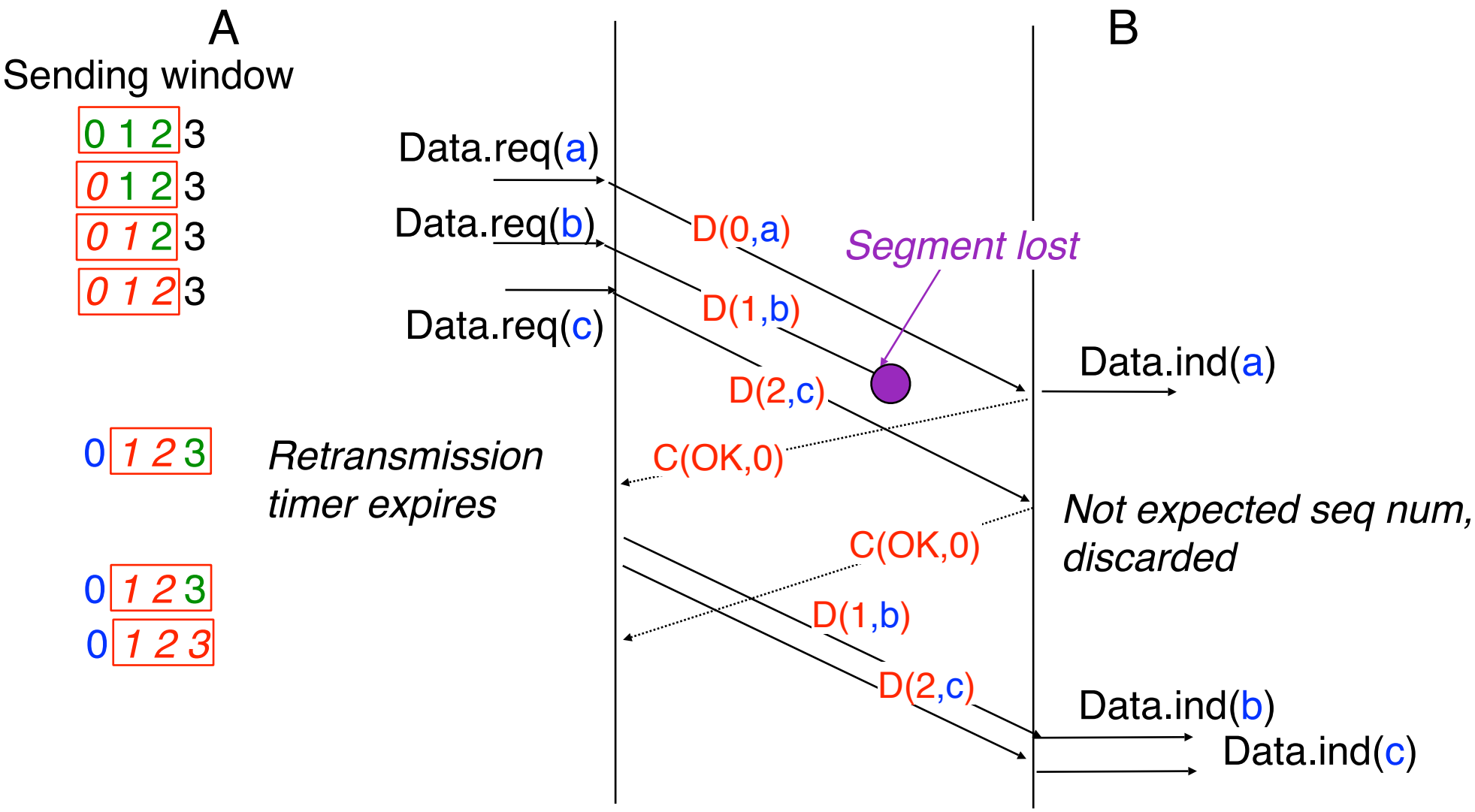
Go-Back-N : Example (2)



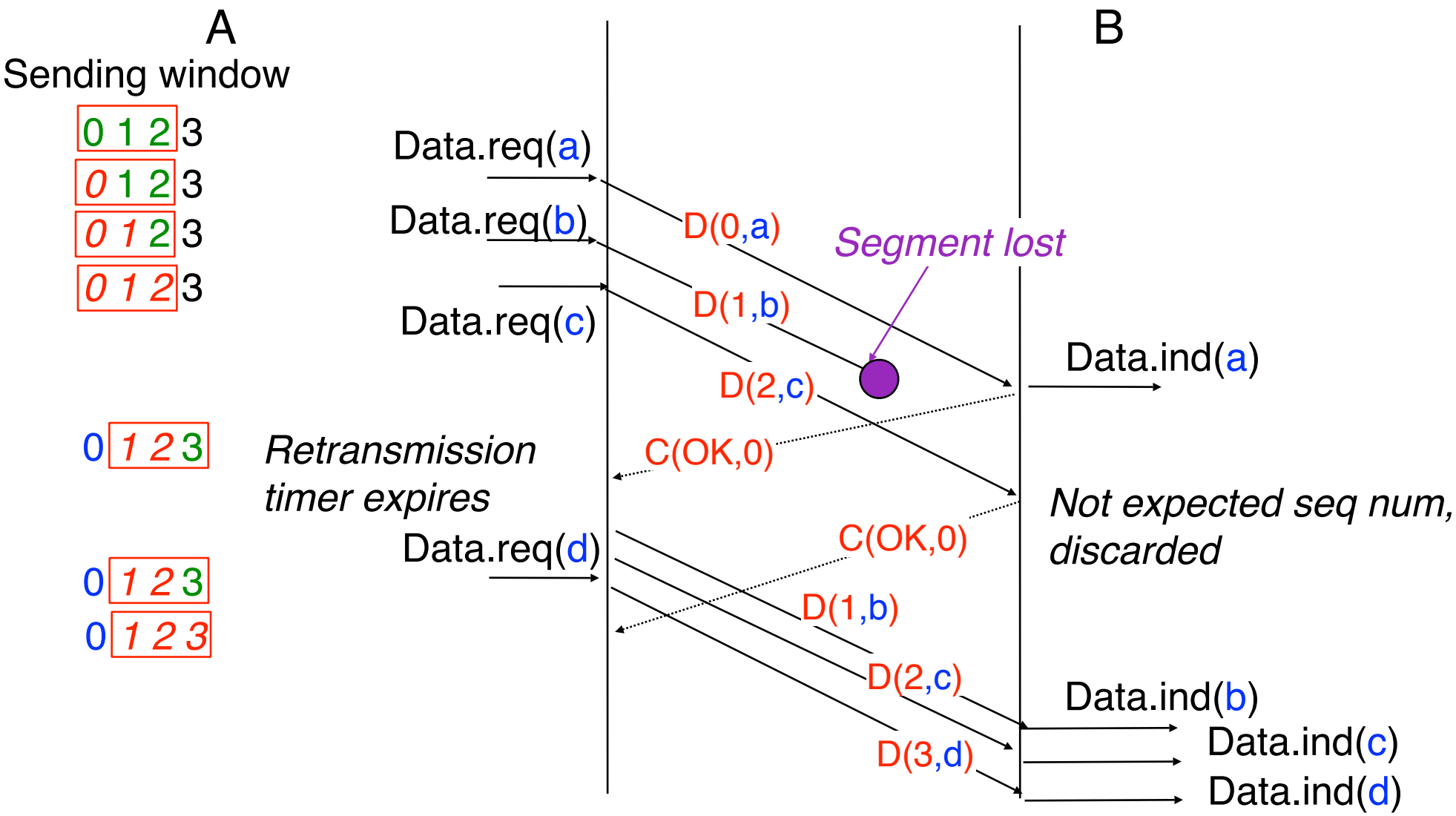
Go-Back-N : Example (2)



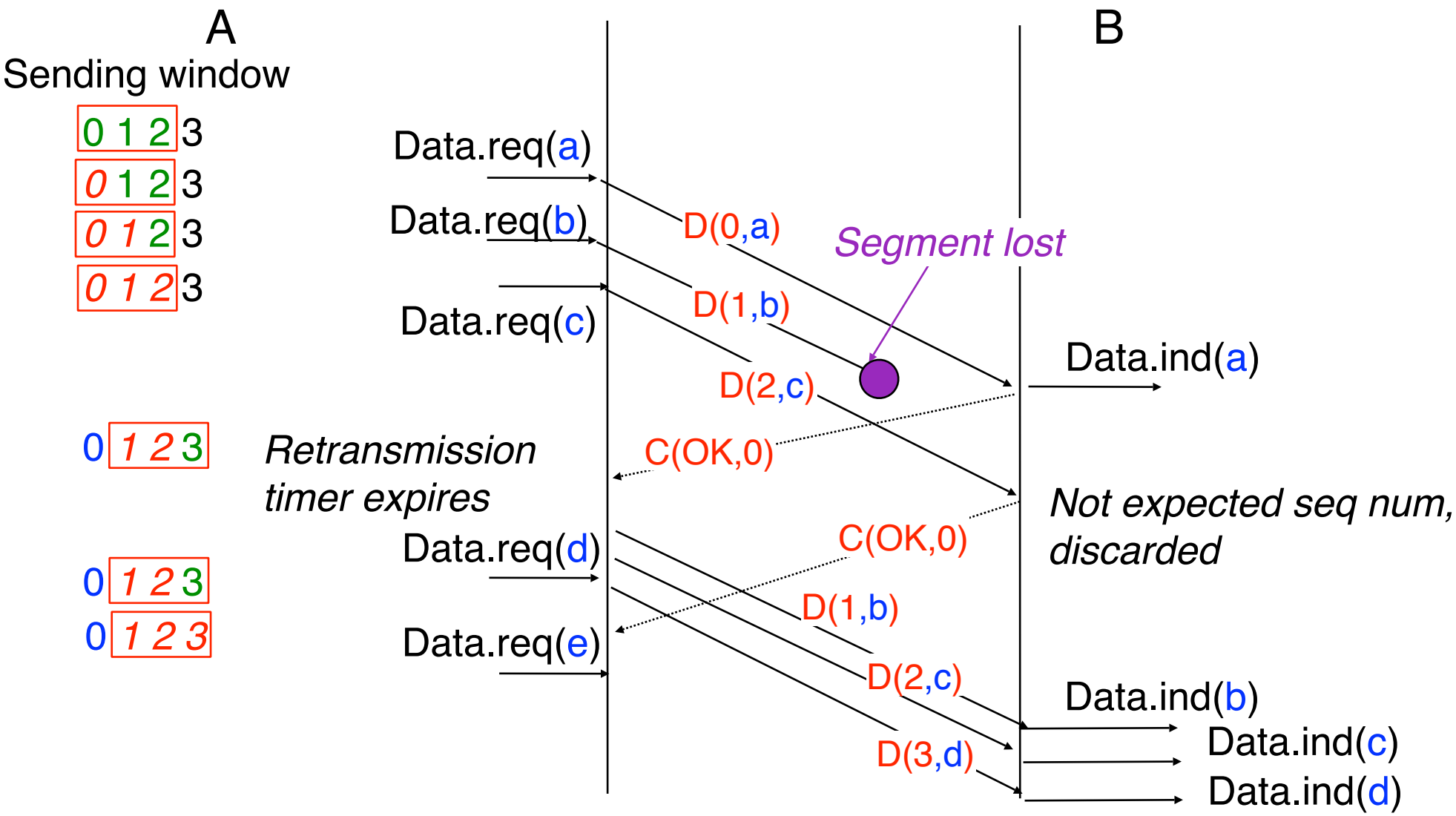
Go-Back-N : Example (2)



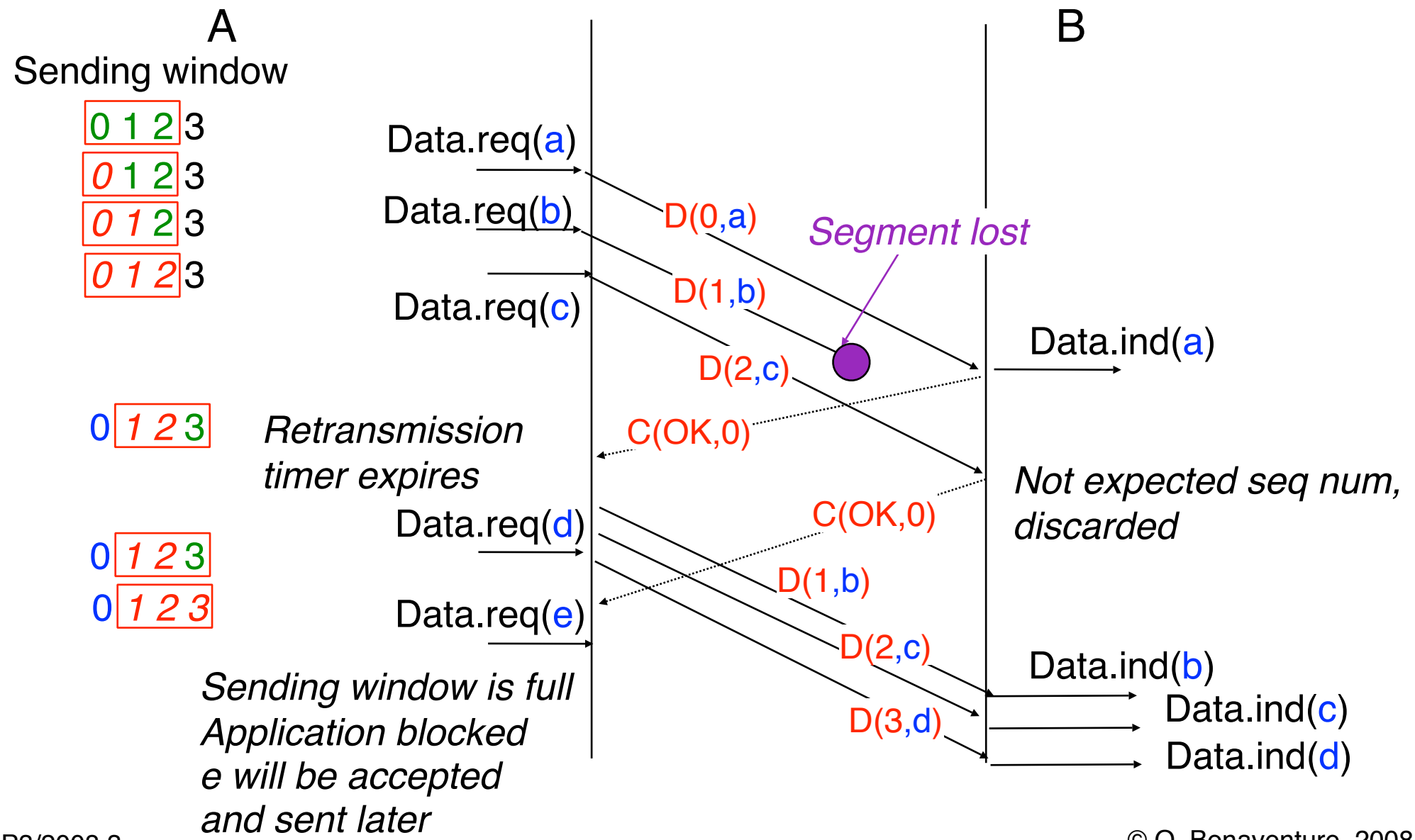
Go-Back-N : Example (2)



Go-Back-N : Example (2)



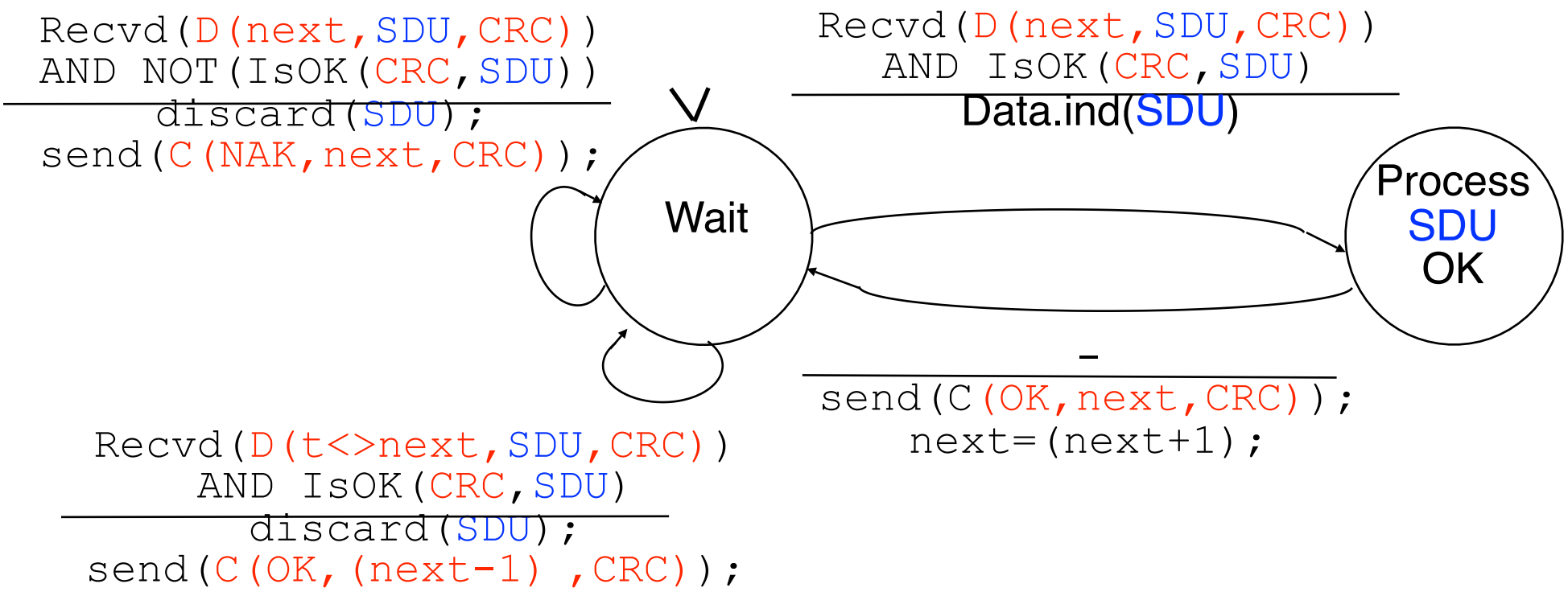
Go-Back-N : Example (2)



Go-Back-N : Receiver

State variable

`next` : sequence number of expected data segment



Go-Back-N : Sender

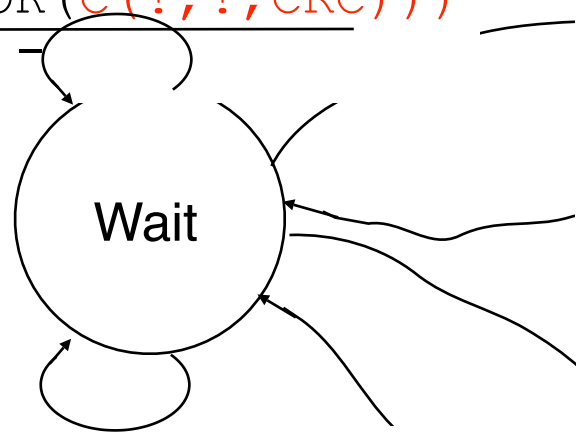
State variables

- `base` : sequence number of oldest data segment
- `seq` : first available sequence number
- `W` : size of sending window

```
Recvd(C(?,?,CRC))
and NOT( CRCOK(C(?,?,CRC)))
```

Data.req(SDU)

```
AND ( seq < (base+w) )
if (seq==base) { start_timer ; }
insert_in_buffer(SDU);
send(D(seq,SDU,CRC));
seq=seq+1 ;
```




```
[ Recvd(C(NAK,?,CRC))
and CRCOK(C(NAK,?,CRC))]
```

or timer expires

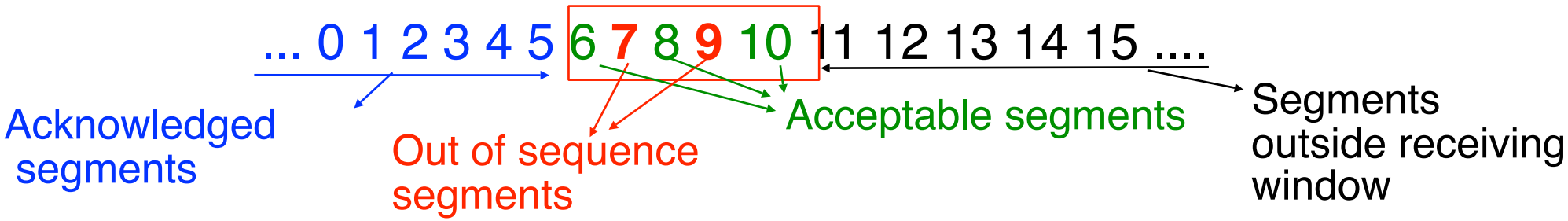
```
for (i=base;i<seq; i=i+1)
{ send(D(i,SDU,CRC)); }
restart_timer();
```

```
Recvd(C(OK,t,CRC))
and CRCOK(C(OK,t,CRC))
base=(t+1);
if (base==seq)
{ cancel_timer();}
else
{ restart_timer(); }
```

Selective Repeat

Receiver

- Uses a buffer to store the segments received out of sequence and reorder their content
- Receiving window

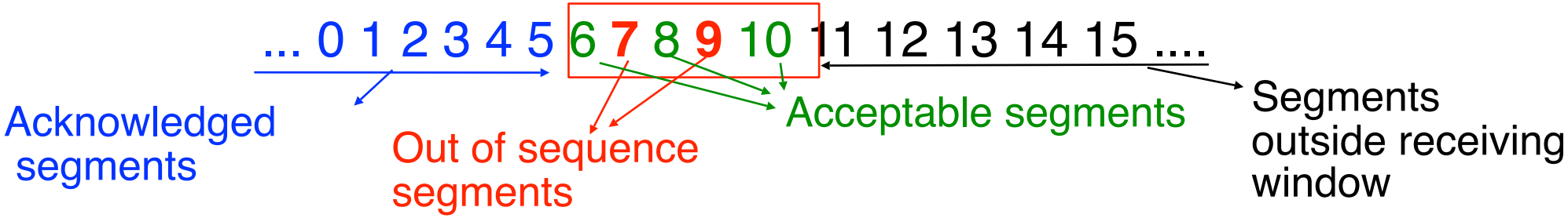


Selective Repeat

Receiver

Uses a buffer to store the segments received out of sequence and reorder their content

Receiving window



Semantics of the control segments

- OKX
  - The segments up to and including sequence number X have been received
- NAKX
  - The segment with sequence number X was errored

Sender

Upon detection of an errored or lost segment, sender retransmits only this segment

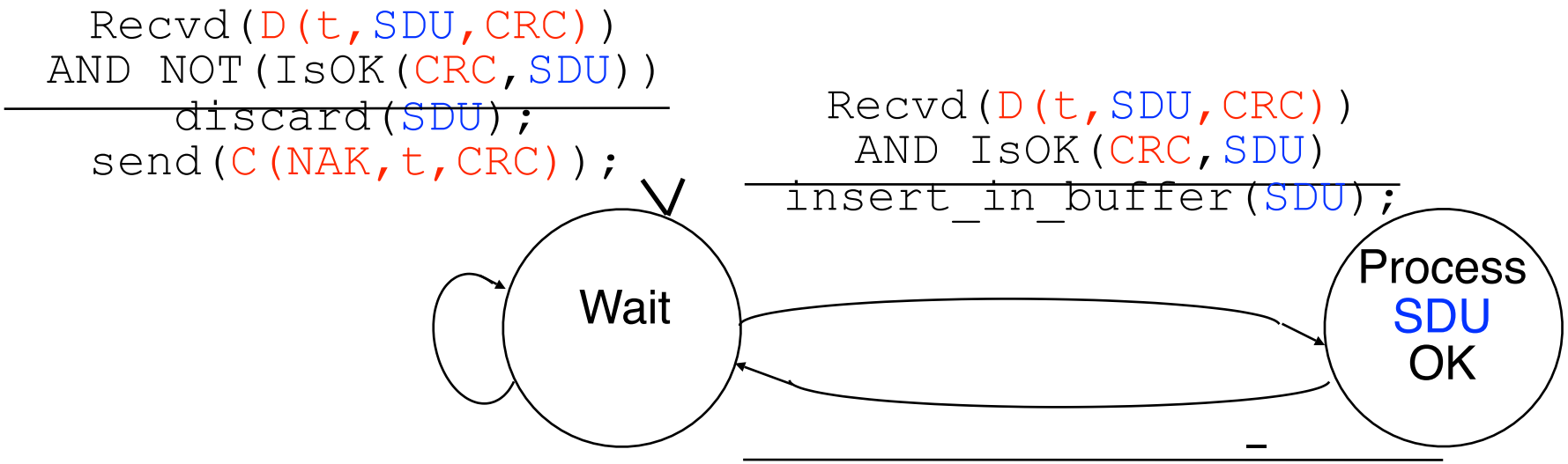
- may require one retransmission timer per segment

Selective-Repeat : Receiver

State variable

`next` : sequence number of expected data segment

`Last` : last received in-sequence segment



For all in sequence segments inside buffer
Data.ind(SDU);

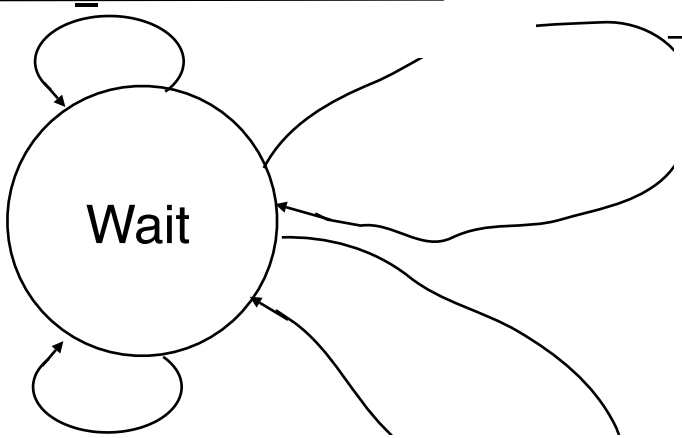
```
slide the sliding window;
update next and last
send(C(OK,(next-1)));
```

Selective Repeat : Sender

State variables

- `base` : sequence number of oldest unacknowledged segment
- `seq` : first free sequence number
- `W` : size of sending window

```
Recvd(C(?,?,CRC))
and NOT( CRCOK(C(?,?,CRC)))
```



Data.req(SDU)

```
AND ( window not full )
start_timer(seq) ;
insert_in_buffer(SDU);
send(D(seq,SDU,CRC));
seq=(seq+1) ;
```

```
[ Recvd(C(NAK,t,CRC))
and CRCOK(C(NAK,t,CRC))]
or timer (t) expires
send(D(t,SDU,CRC)); }
restart_timer(t);
```

```
Recvd(C(OK,t,CRC))
and CRCOK(C(OK,t,CRC))
For all segments i<=t
    cancel_timer(t);
slide sliding window to
the right;
```

Selective Repeat : Example

A

Sending window

0 1 2 3

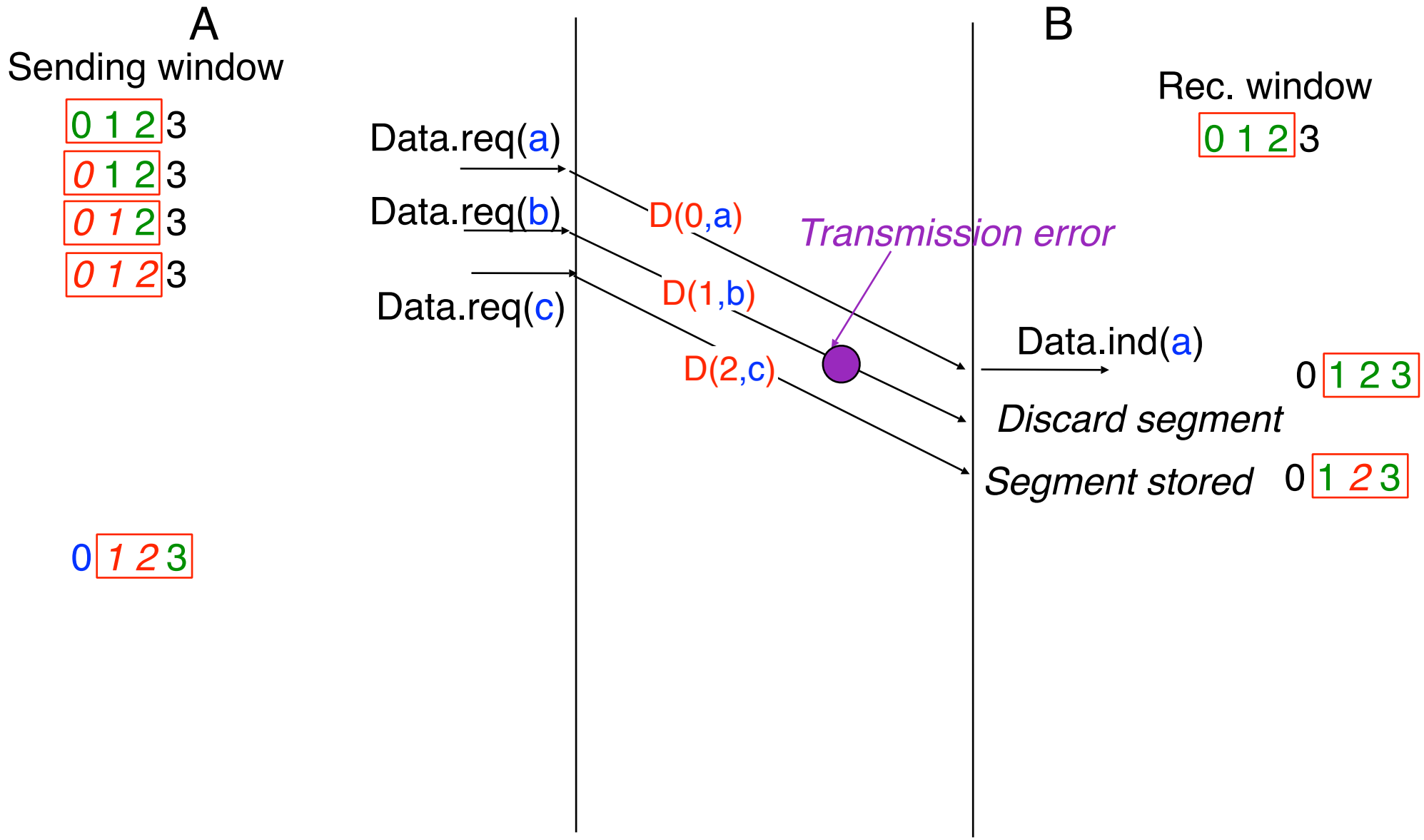
0 *1 2* 3

B

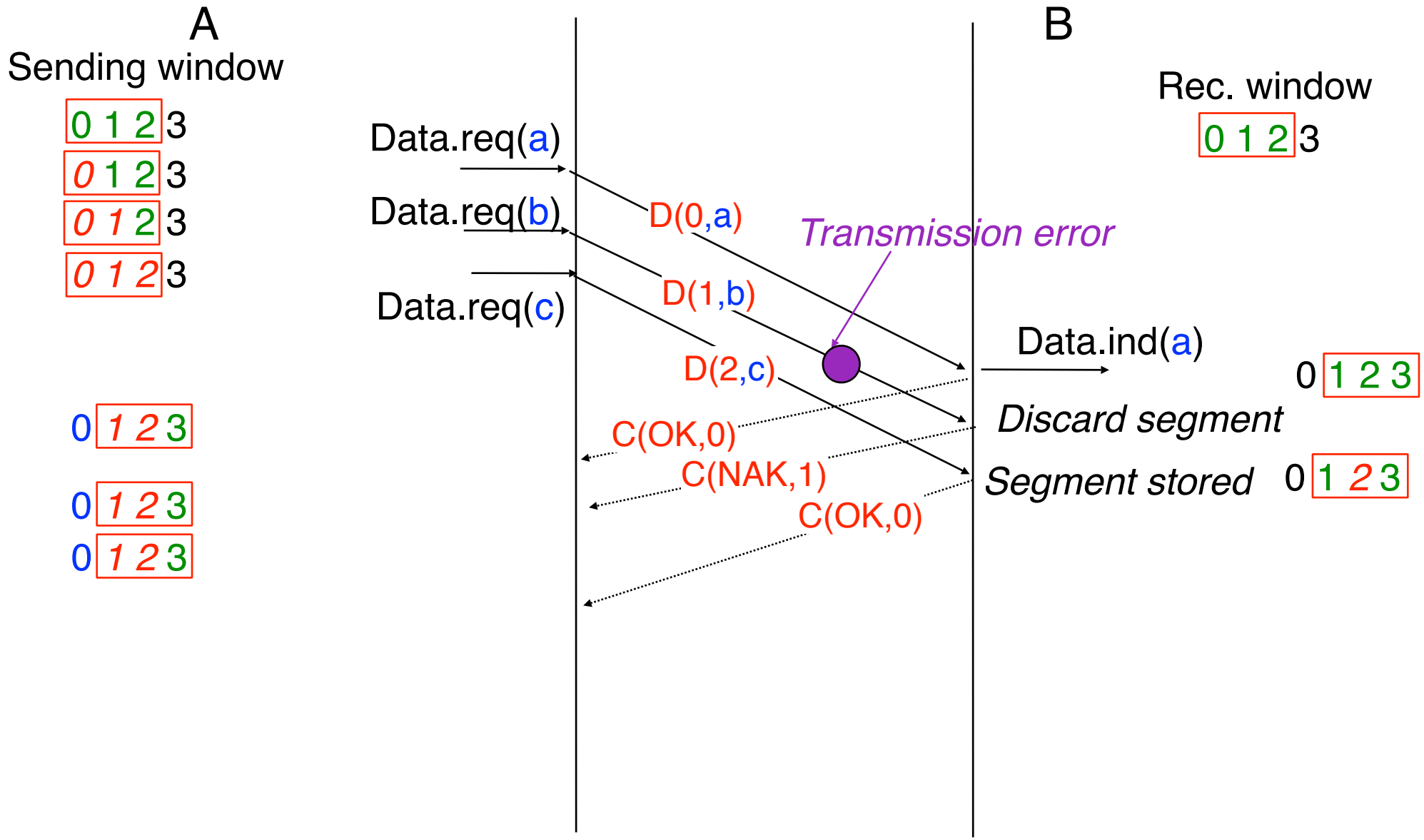
Rec. window

0 1 2 3

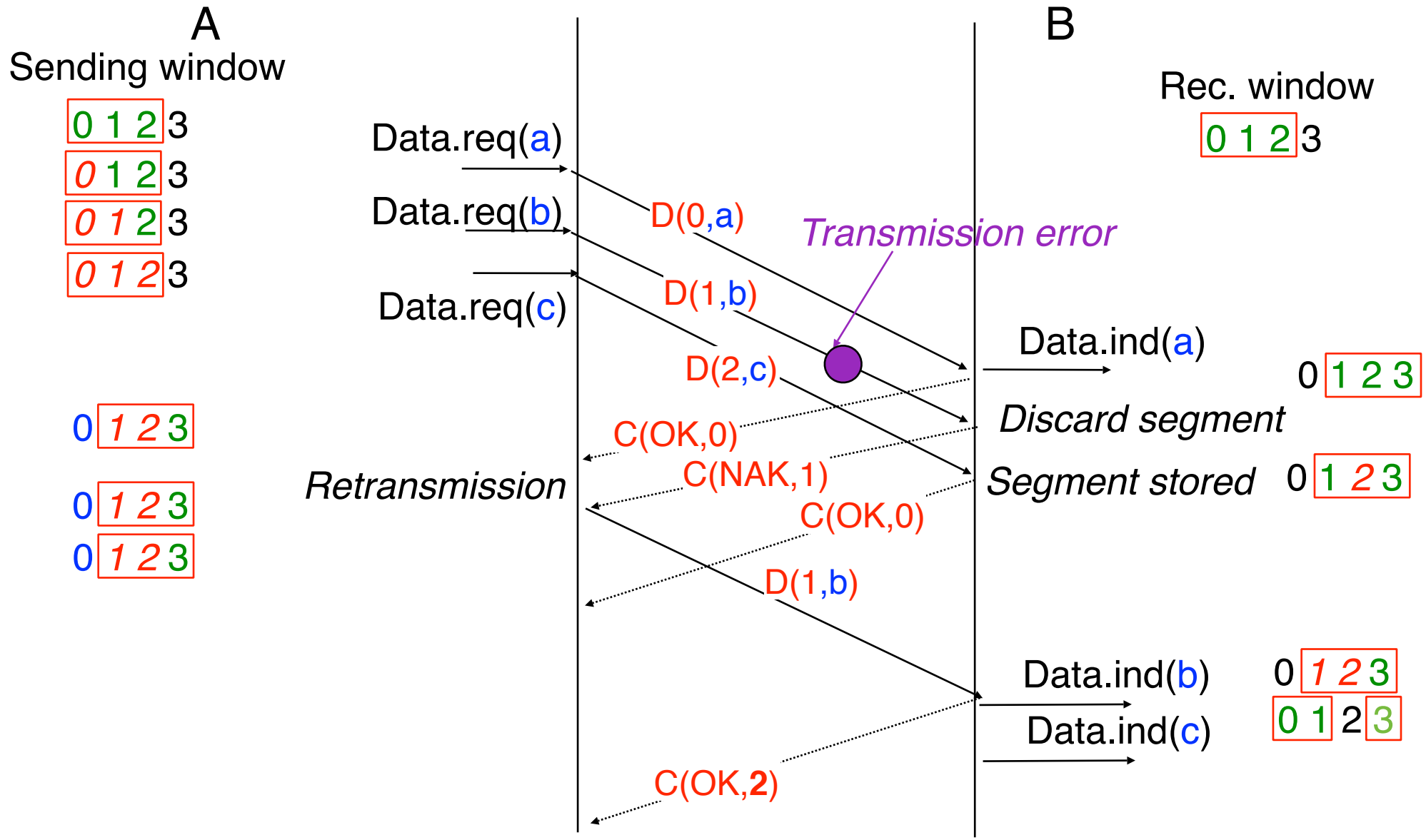
Selective Repeat : Example



Selective Repeat : Example



Selective Repeat : Example



Selective Repeat : Example (2)

A

Sending window

0 1 2 3

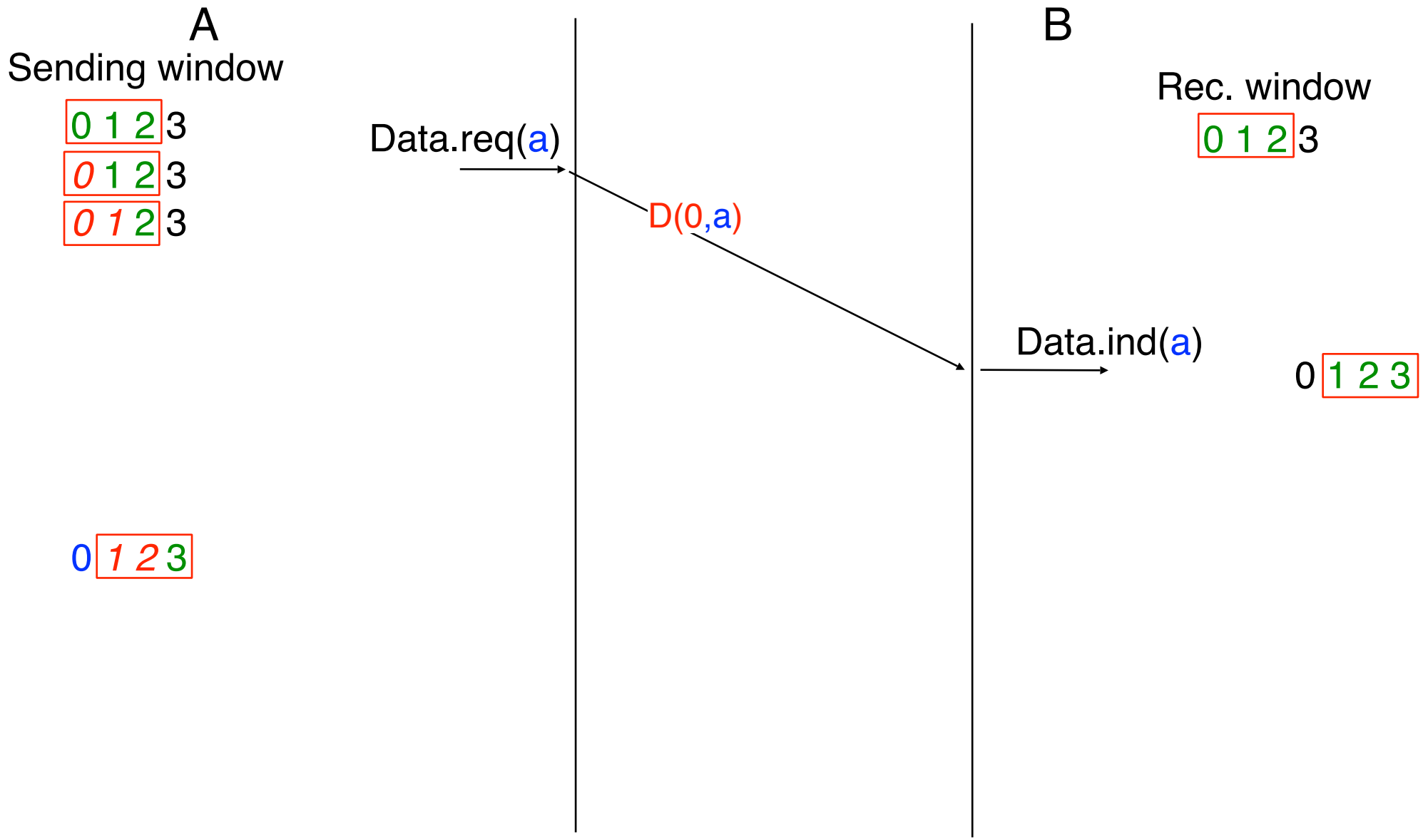
0 *1 2* 3

B

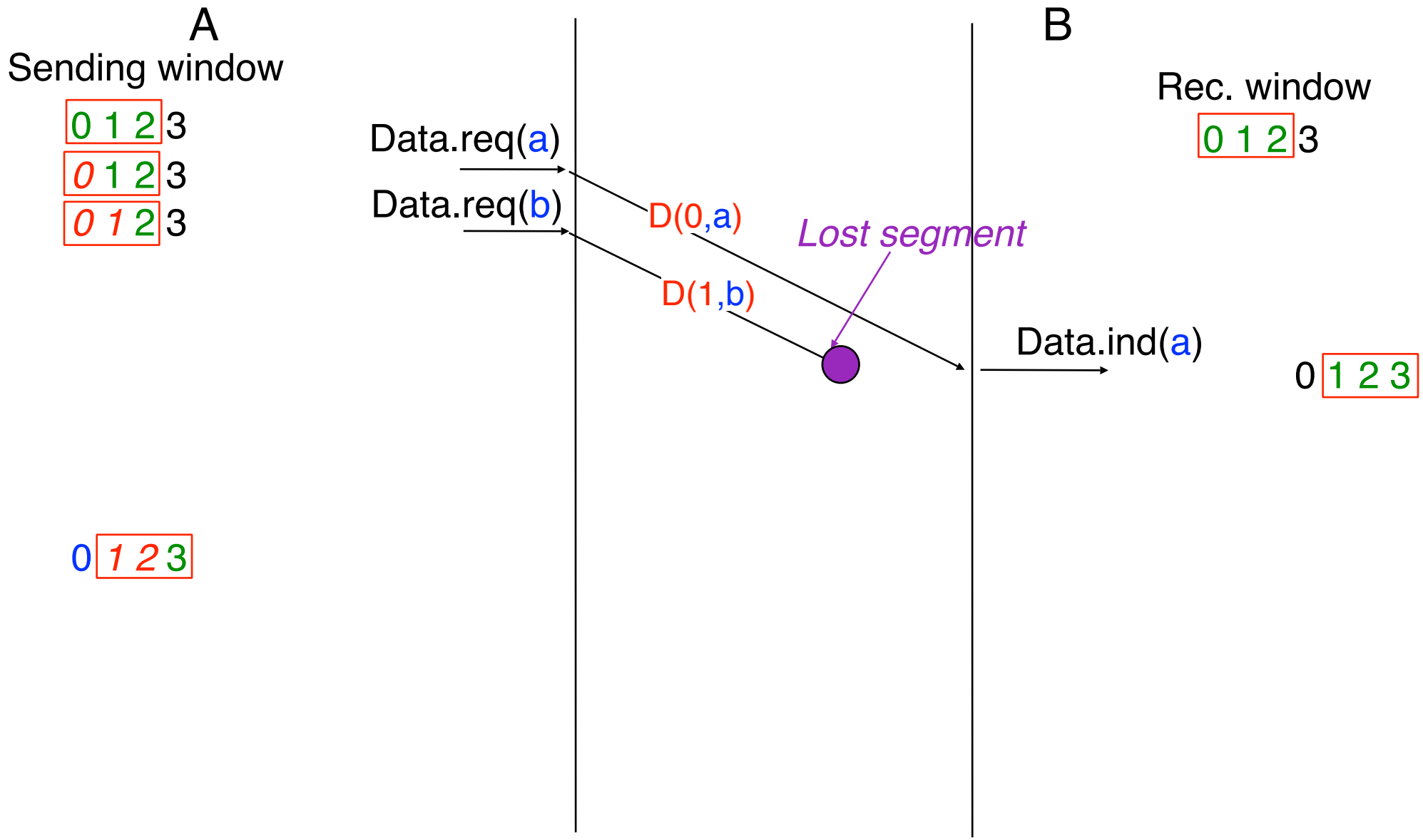
Rec. window

0 1 2 3

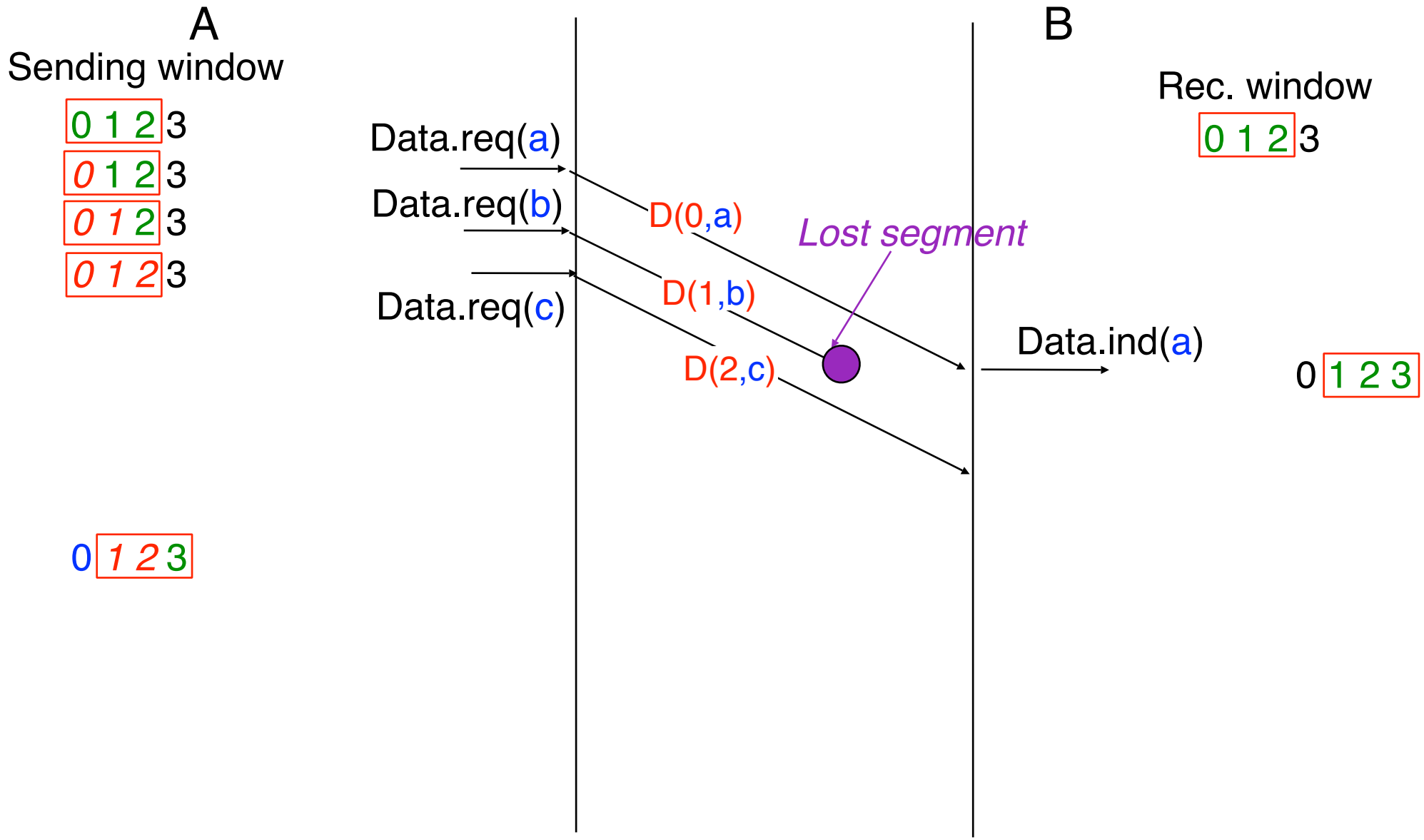
Selective Repeat : Example (2)



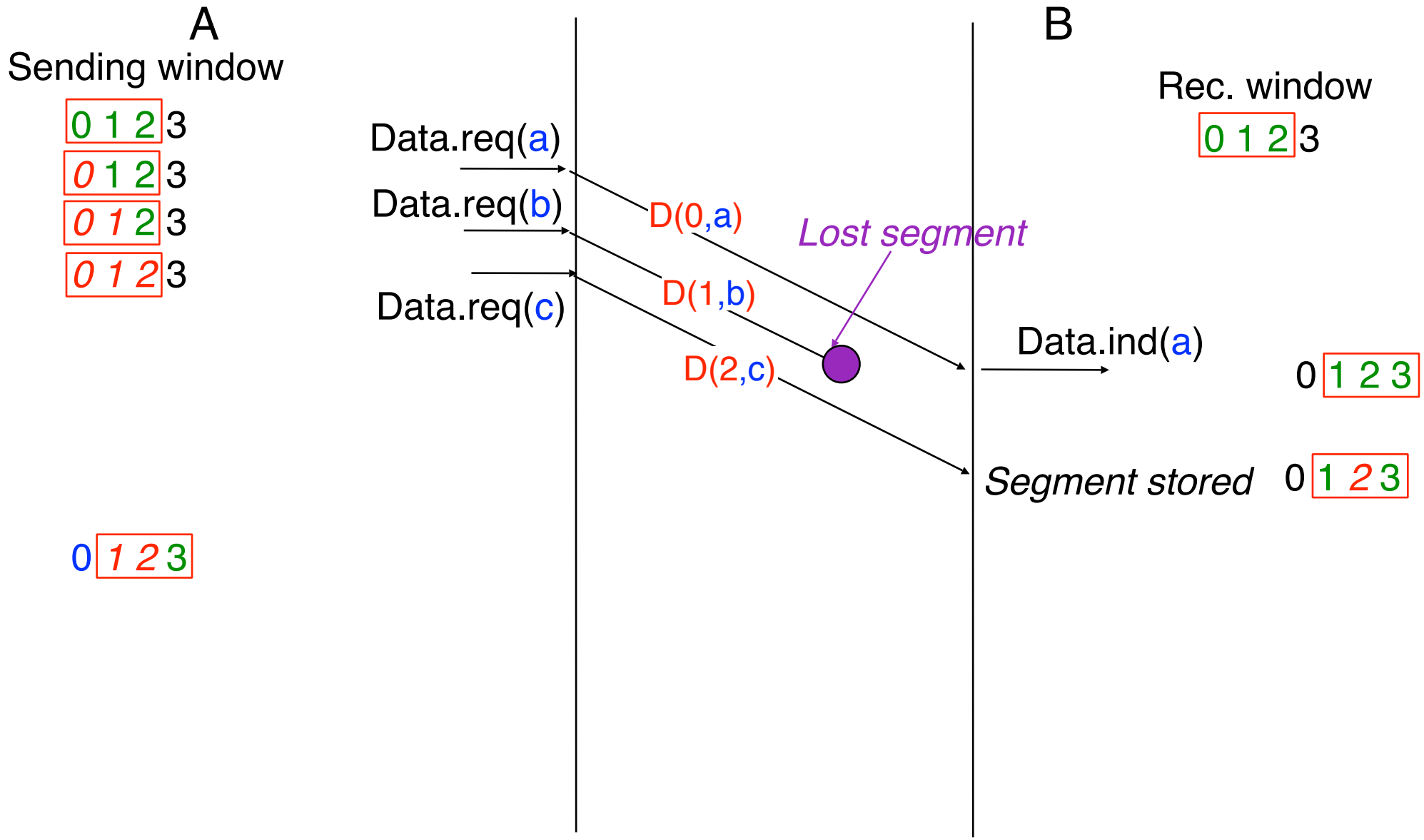
Selective Repeat : Example (2)



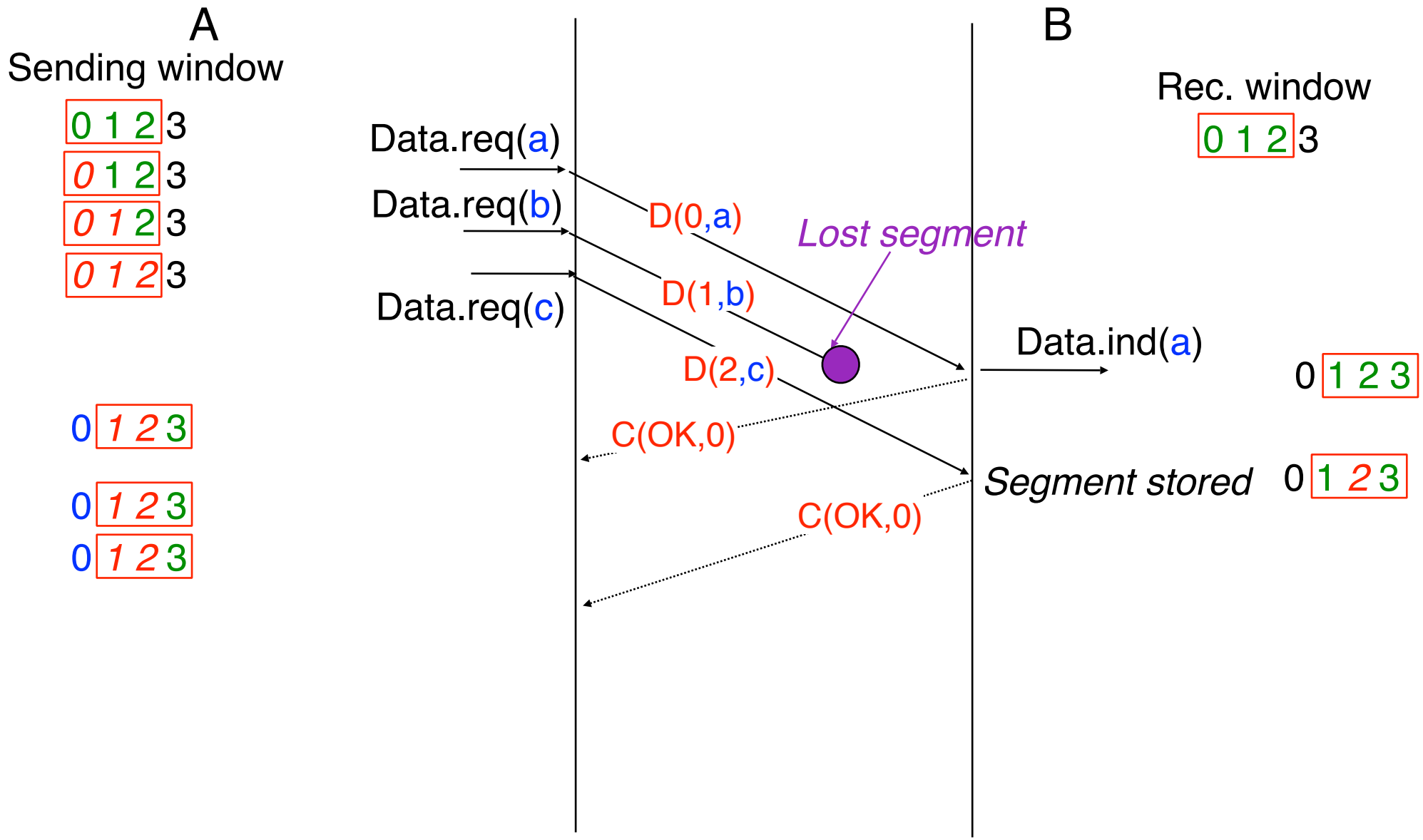
Selective Repeat : Example (2)



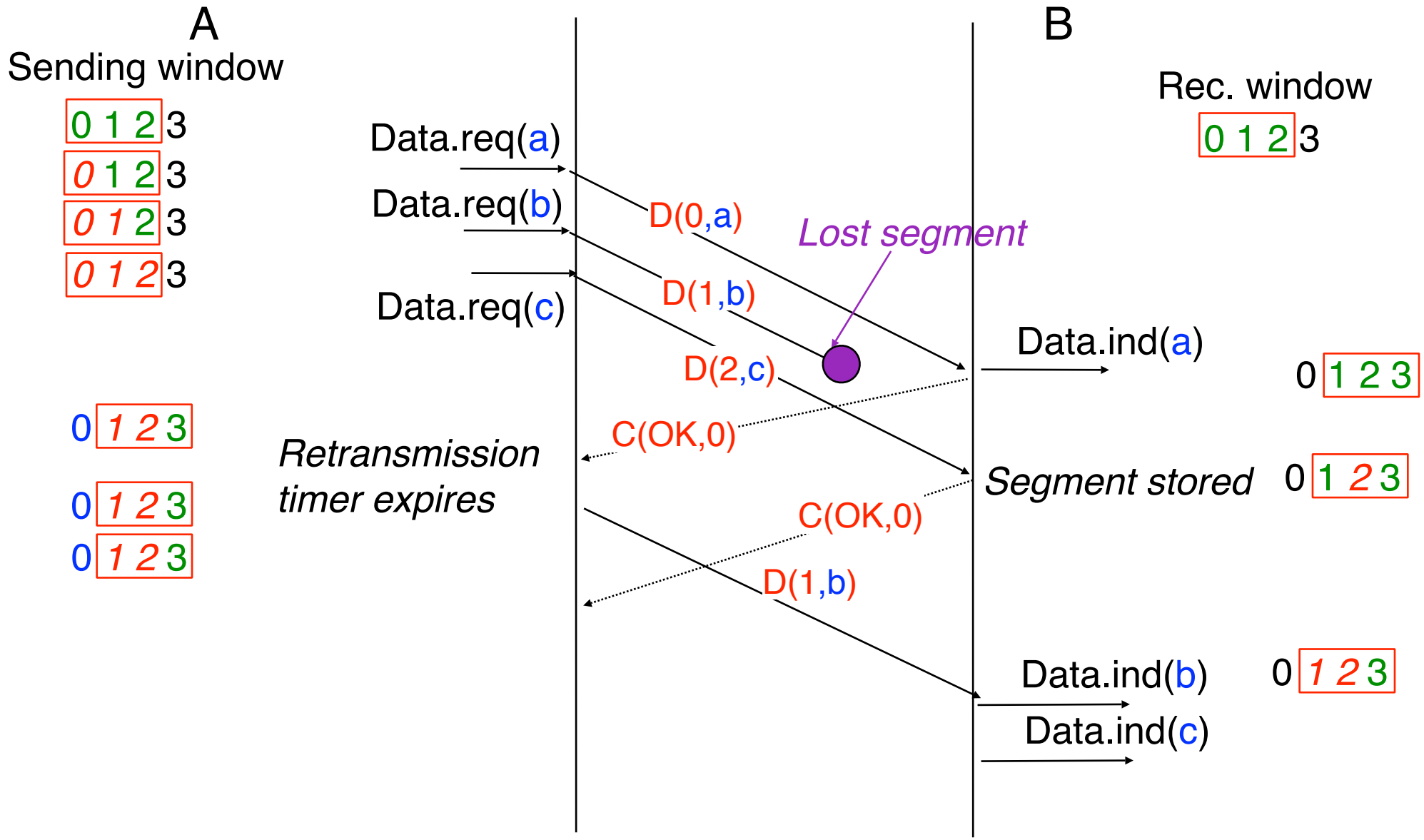
Selective Repeat : Example (2)



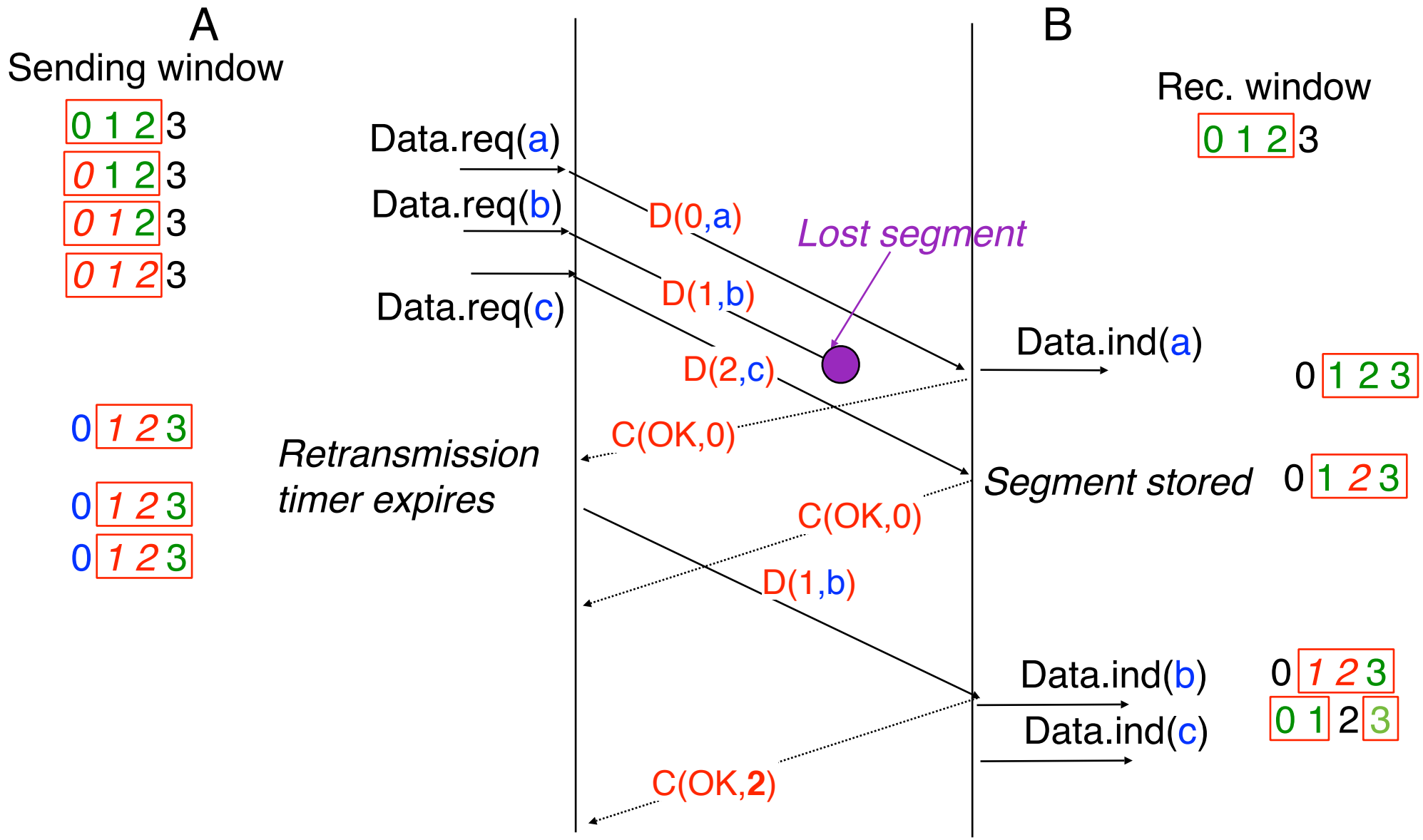
Selective Repeat : Example (2)



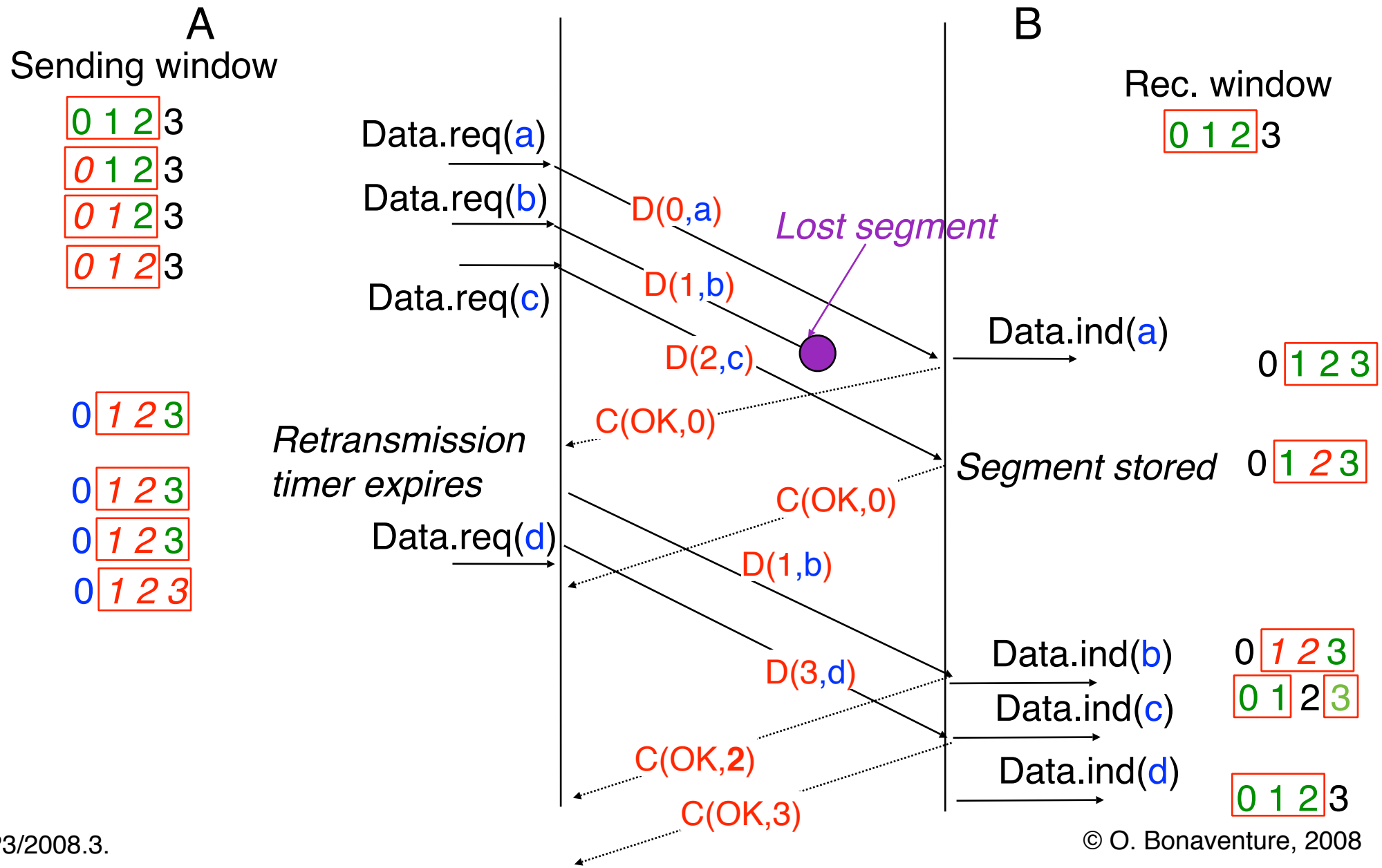
Selective Repeat : Example (2)



Selective Repeat : Example (2)

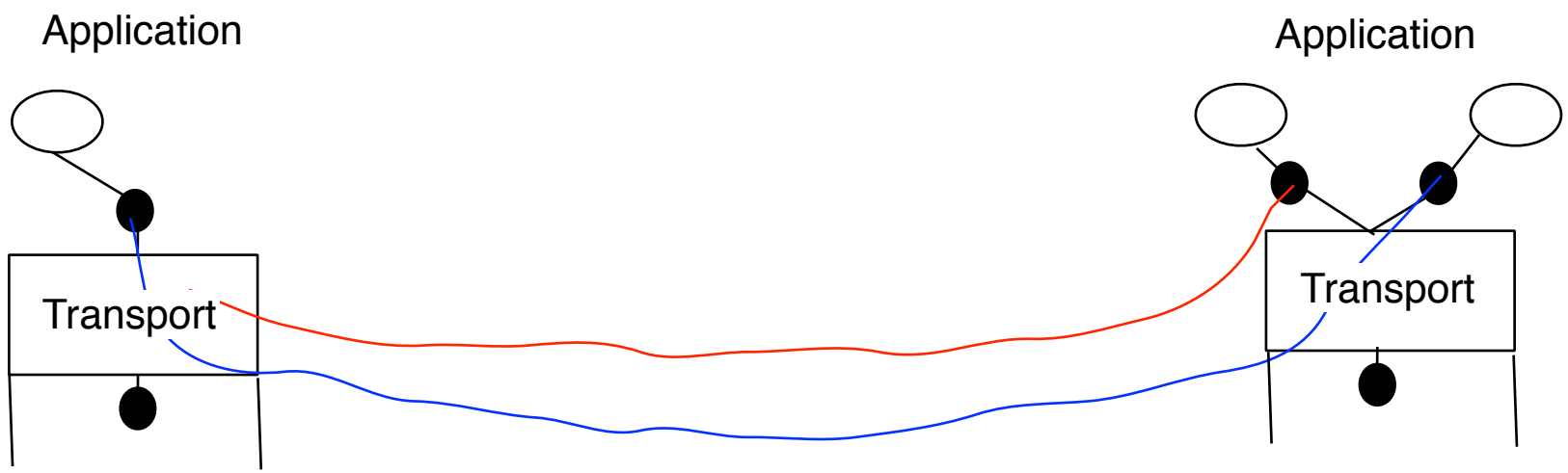


Selective Repeat : Example (2)



Buffer management

Problem



A transport entity may support many transport connections at the same time

- How can we share the available buffer among these connections ?
- The number of connections changes with time
- Some connections require large buffers while others can easily use smaller ones
  - `ftp` versus `telnet`

Buffer management (2)

Principle

Adjust the size of the receiving window according to the amount of buffering available on the receiver
Allow the receiver to advertise its current receiving window size to the sender

New information carried in control segments

`win` indicates the current receiving window's size

Changes to sender

Sending window : `swin` (function of available memory)
Keep in a state variable the receiving window advertised by the receiver : `rwin`
At any time, the sender is only allowed to send data segments whose sequence number fits inside min(`rwin`, `swin`)

Buffer management (3)

A

Swin=3, rwin=1

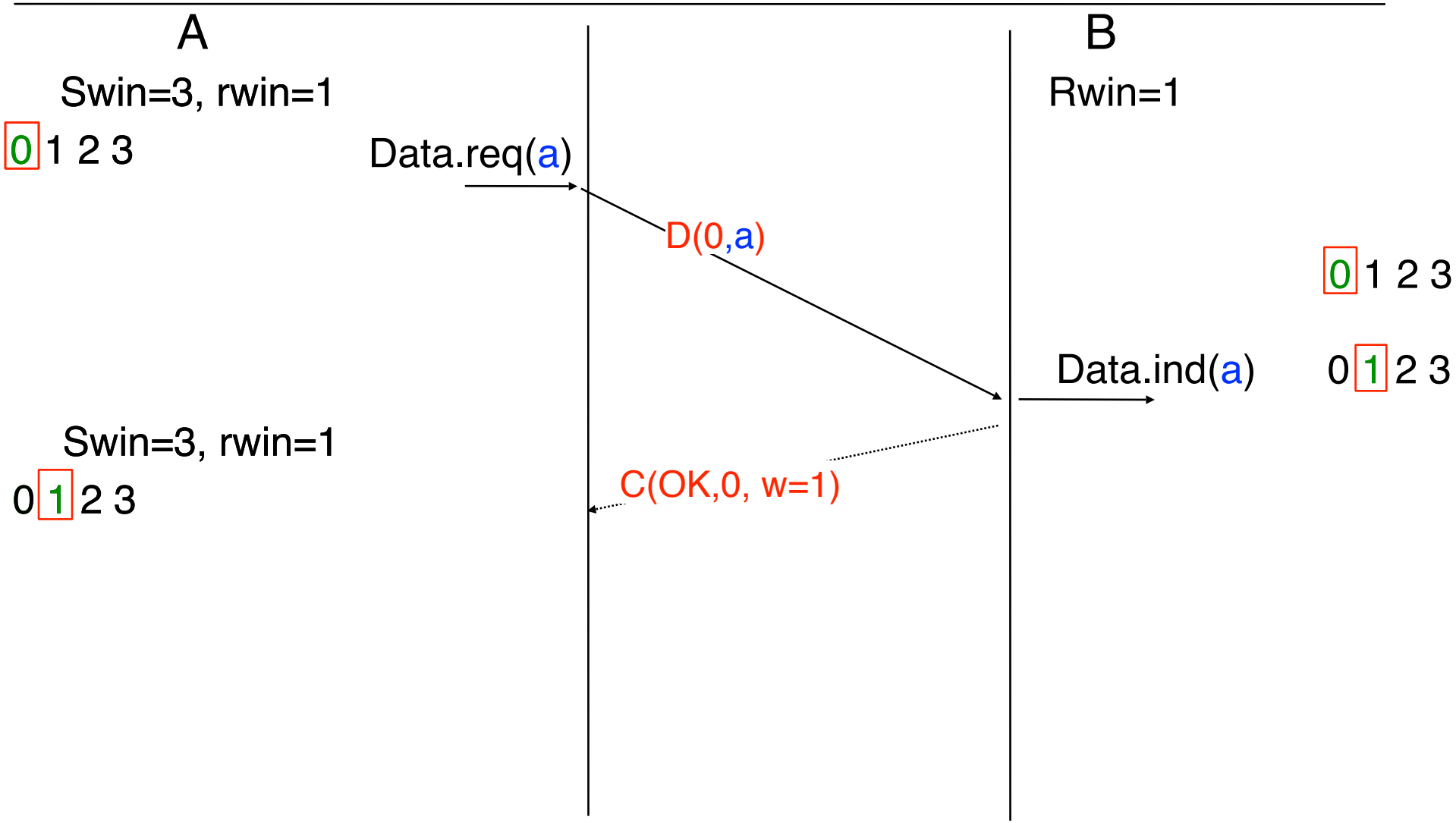
0 1 2 3

B

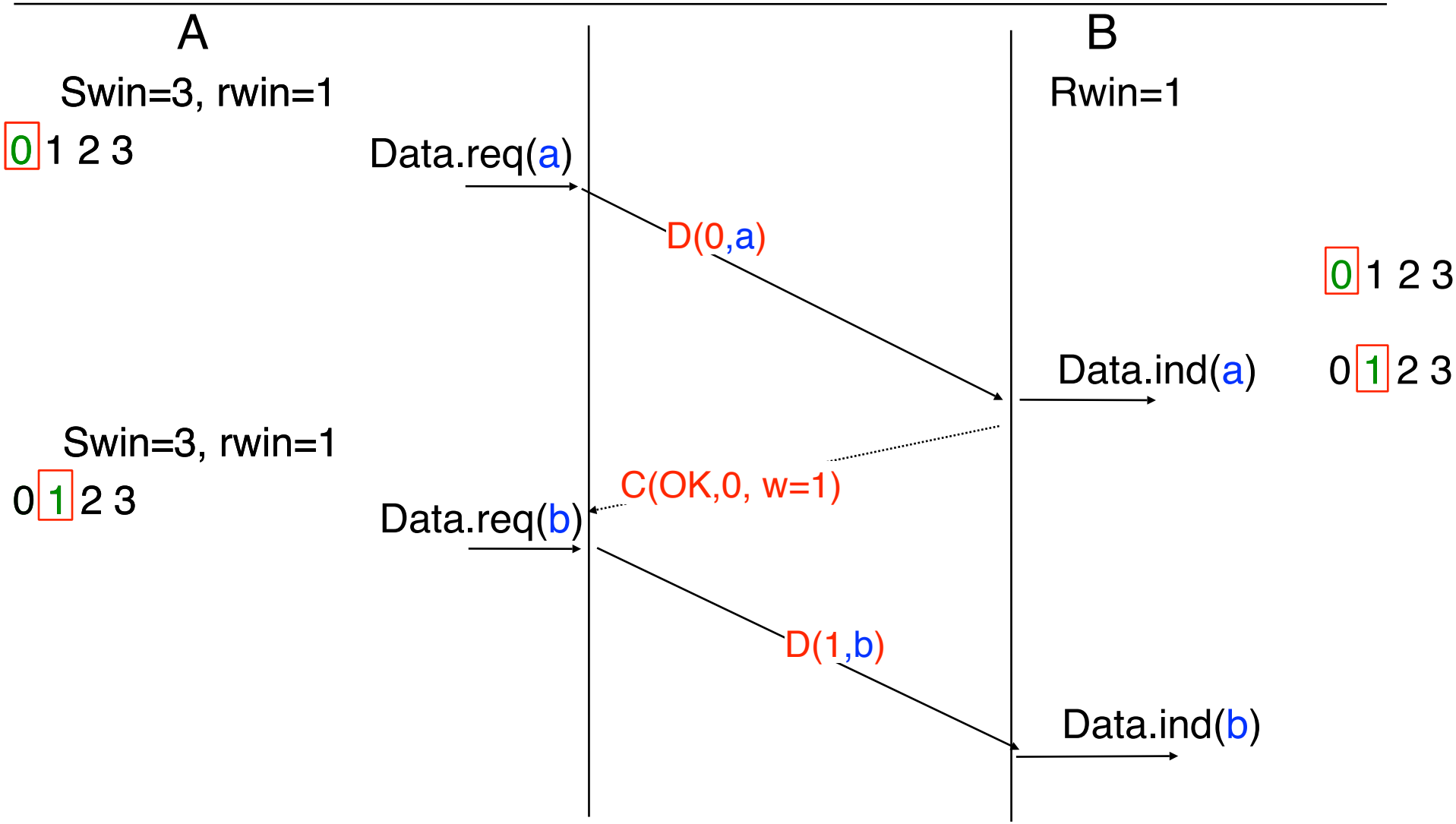
Rwin=1

0 1 2 3

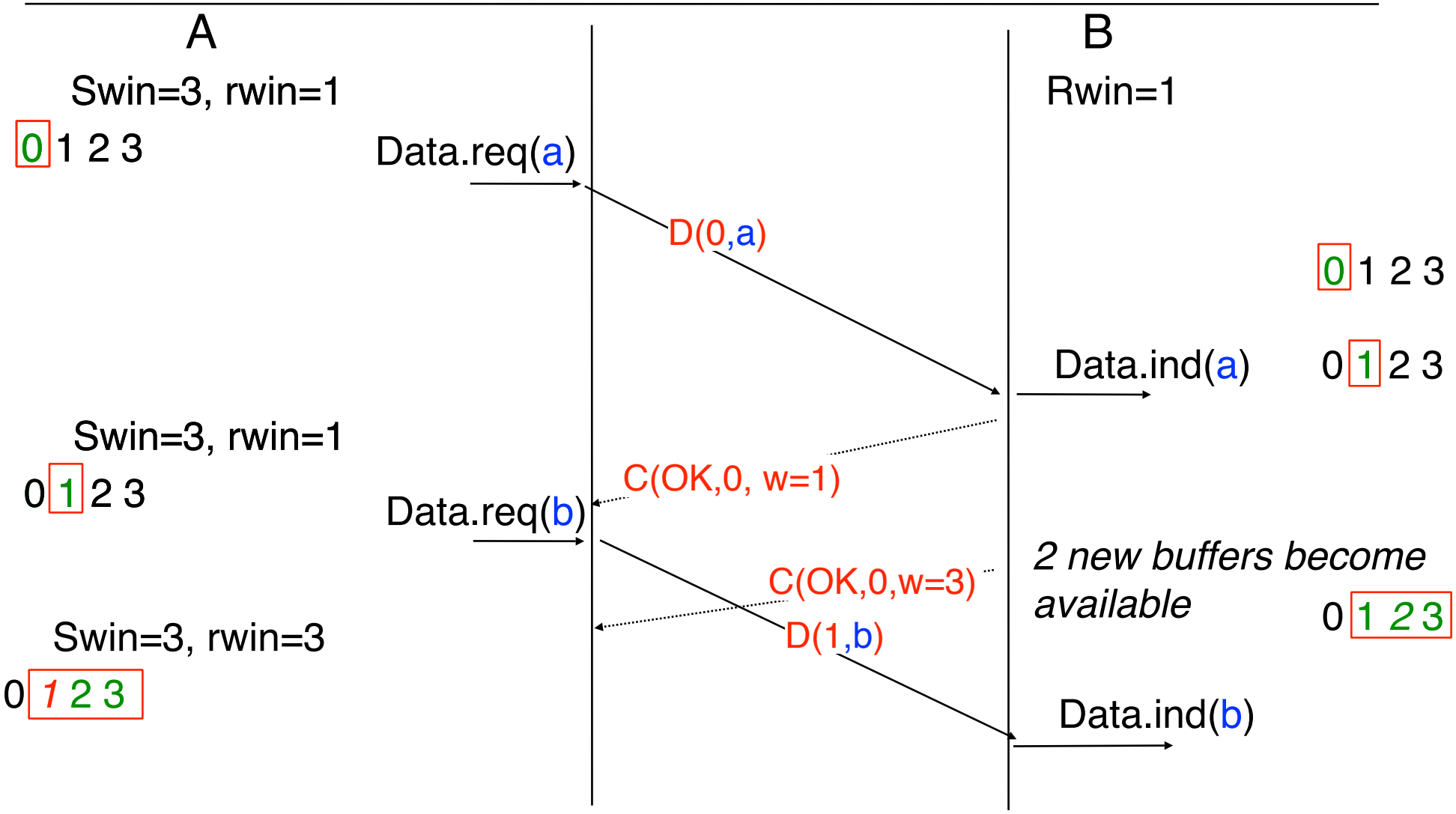
Buffer management (3)



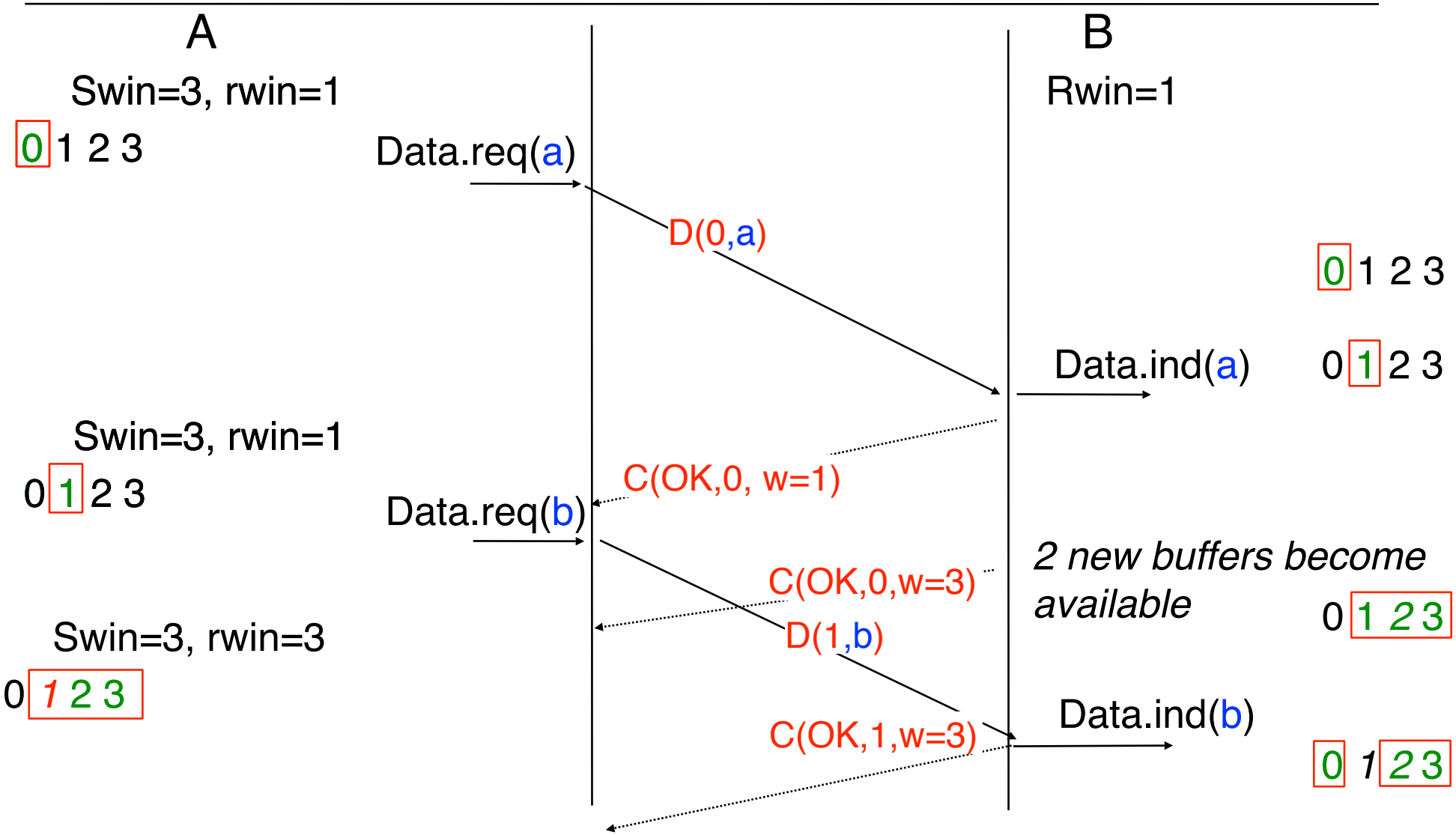
Buffer management (3)



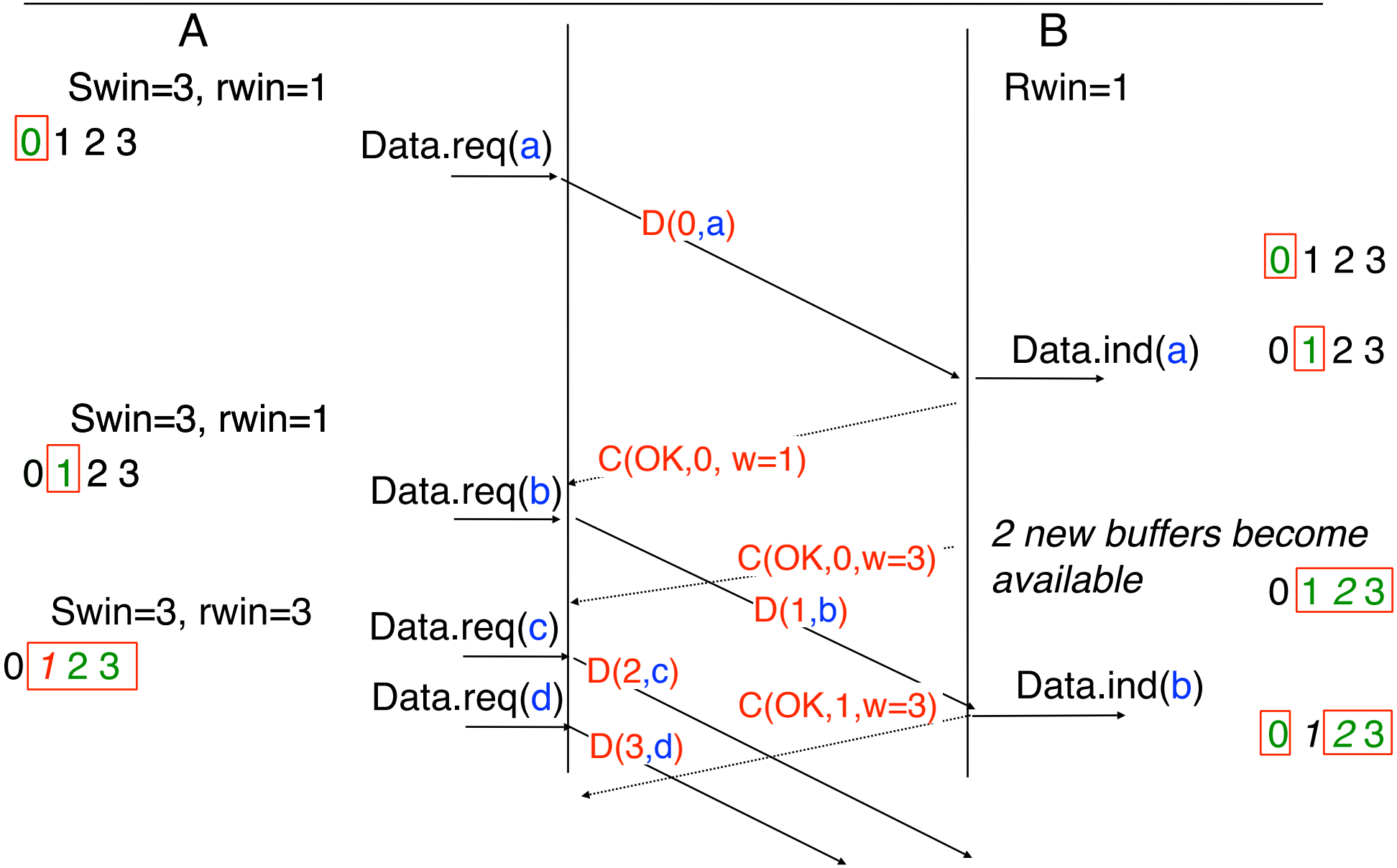
Buffer management (3)



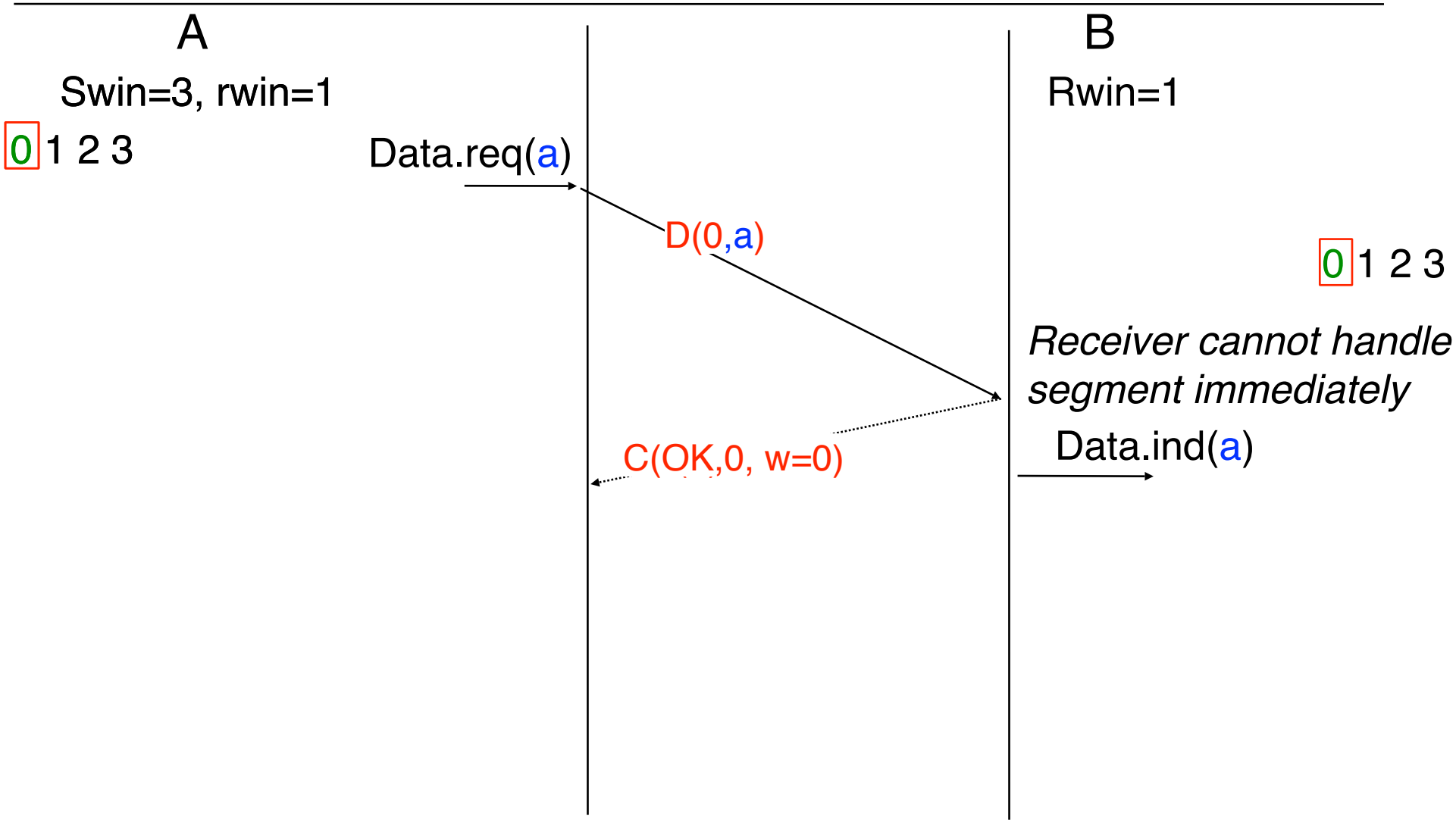
Buffer management (3)



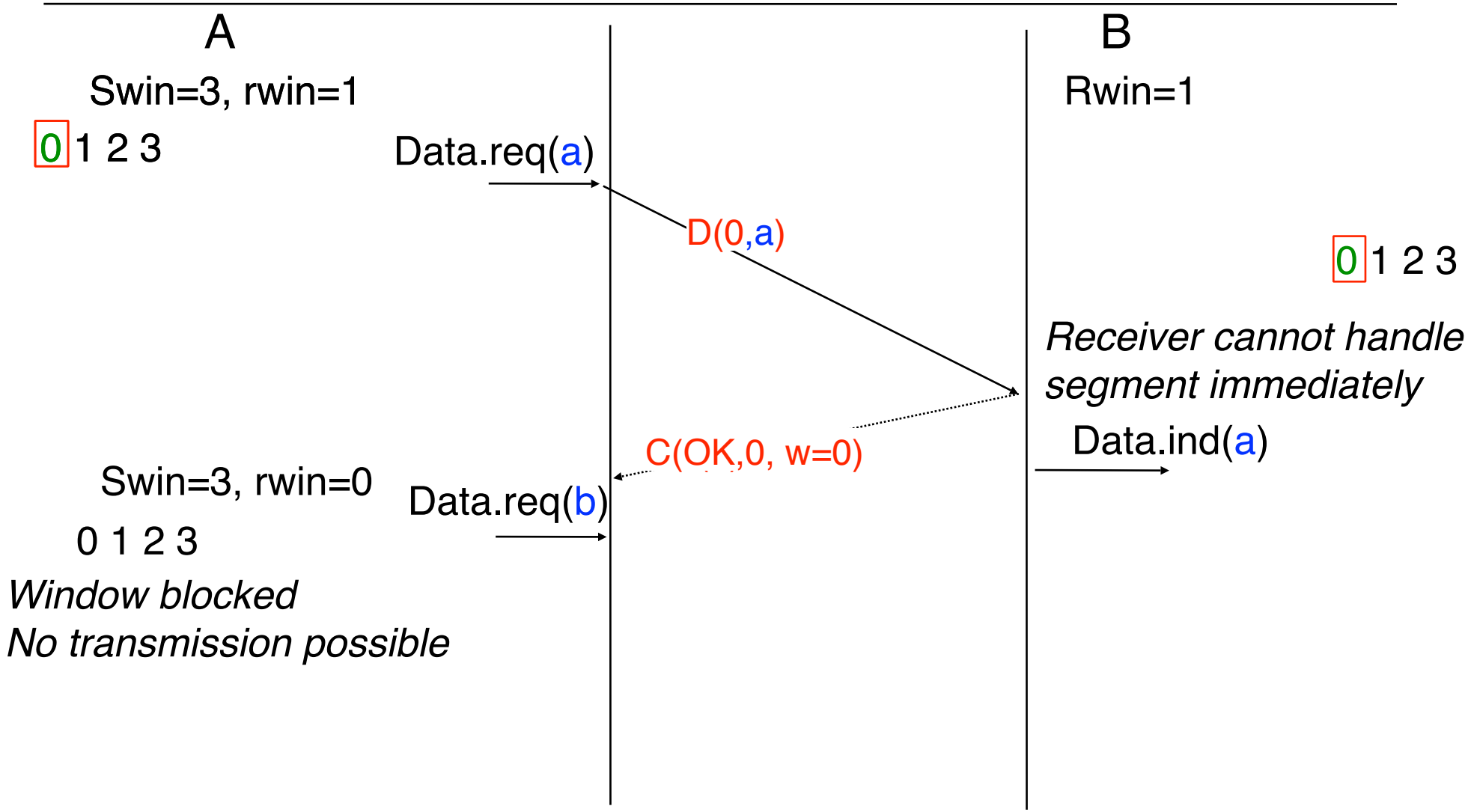
Buffer management (3)



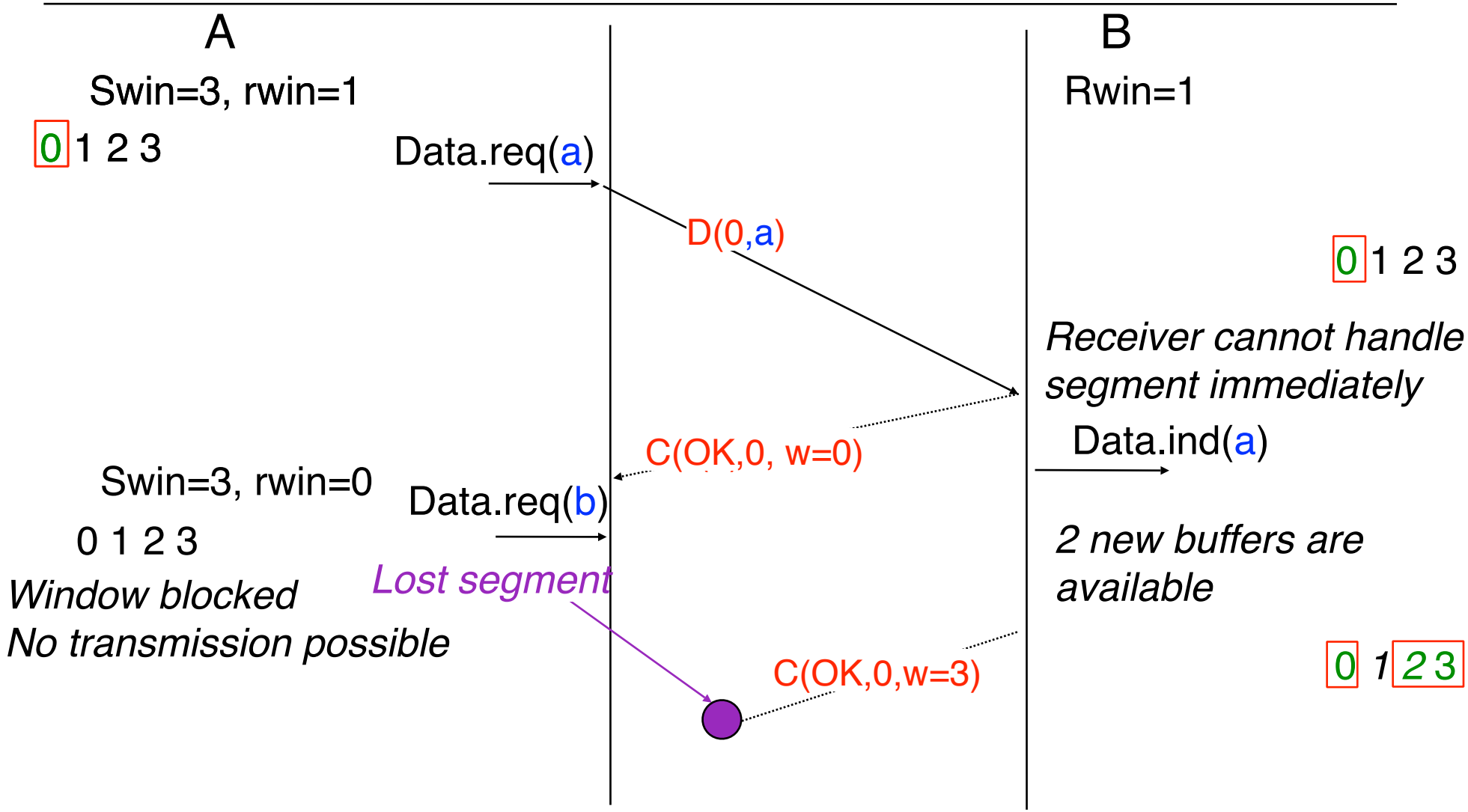
Buffer management (4)



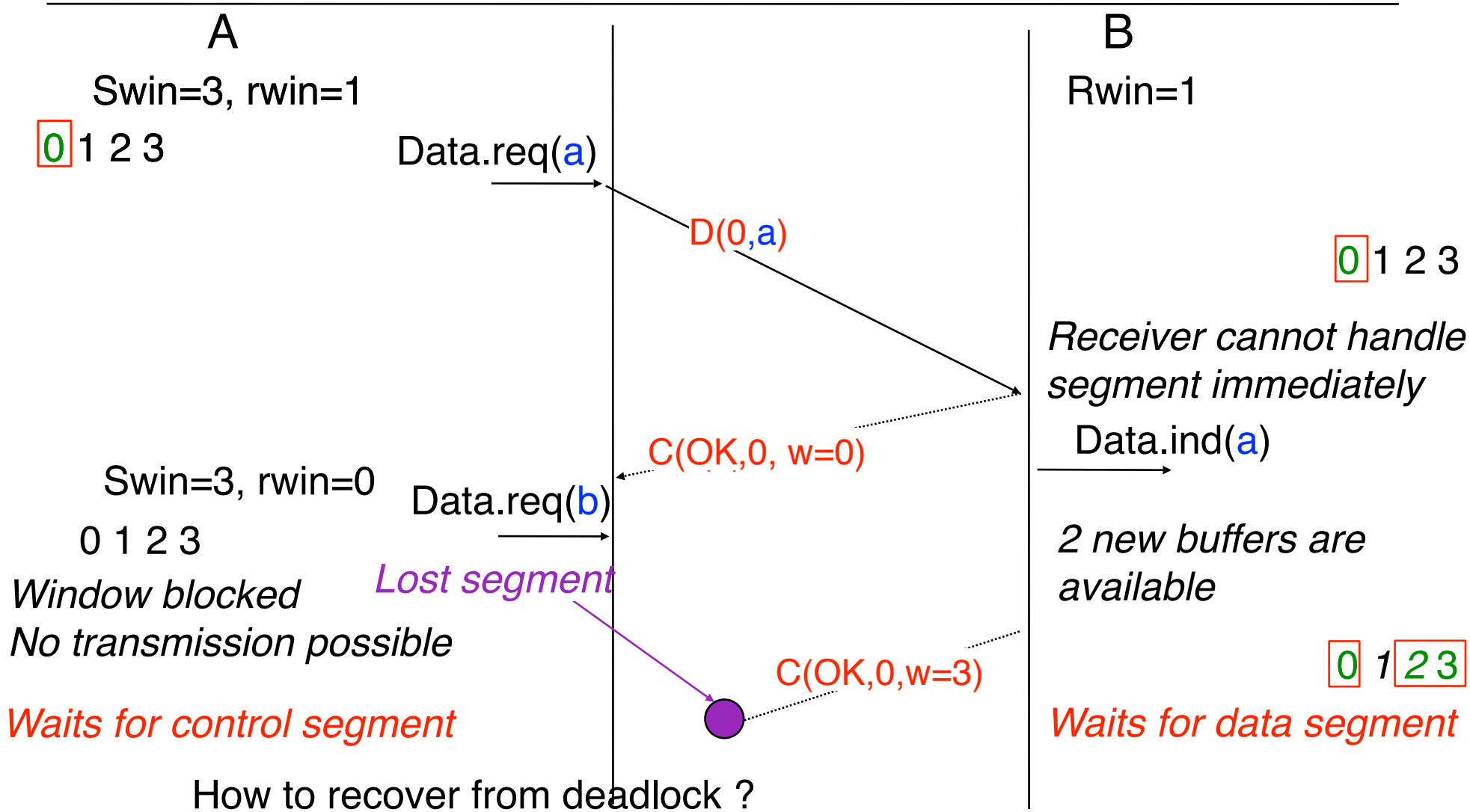
Buffer management (4)



Buffer management (4)



Buffer management (4)



How to recover from deadlock ?
Persitence timer on receiver, resend control segment after timer expiration

Duplication and reordering

How can we provide a reliable service in the transport layer ?

Hypotheses

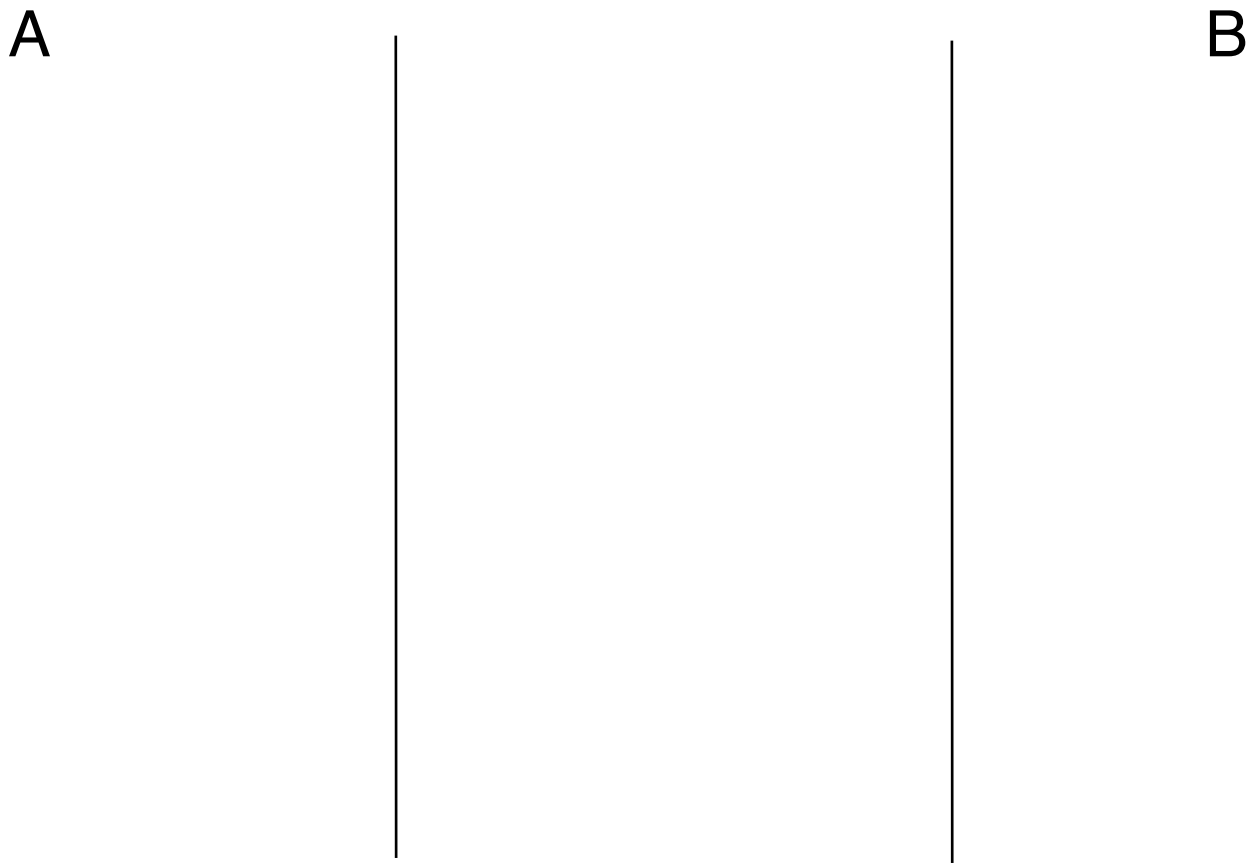
1. The application sends small SDUs
2. The network layer provides a perfect service
   1. Transmission errors are possible
   2. Packets can be lost
   3. Packet reordering is possible
   4. Packets can be duplicated
3. Data transmission is unidirectional

2. How to deal with these problems ?

Duplication and reordering (2)

Problem

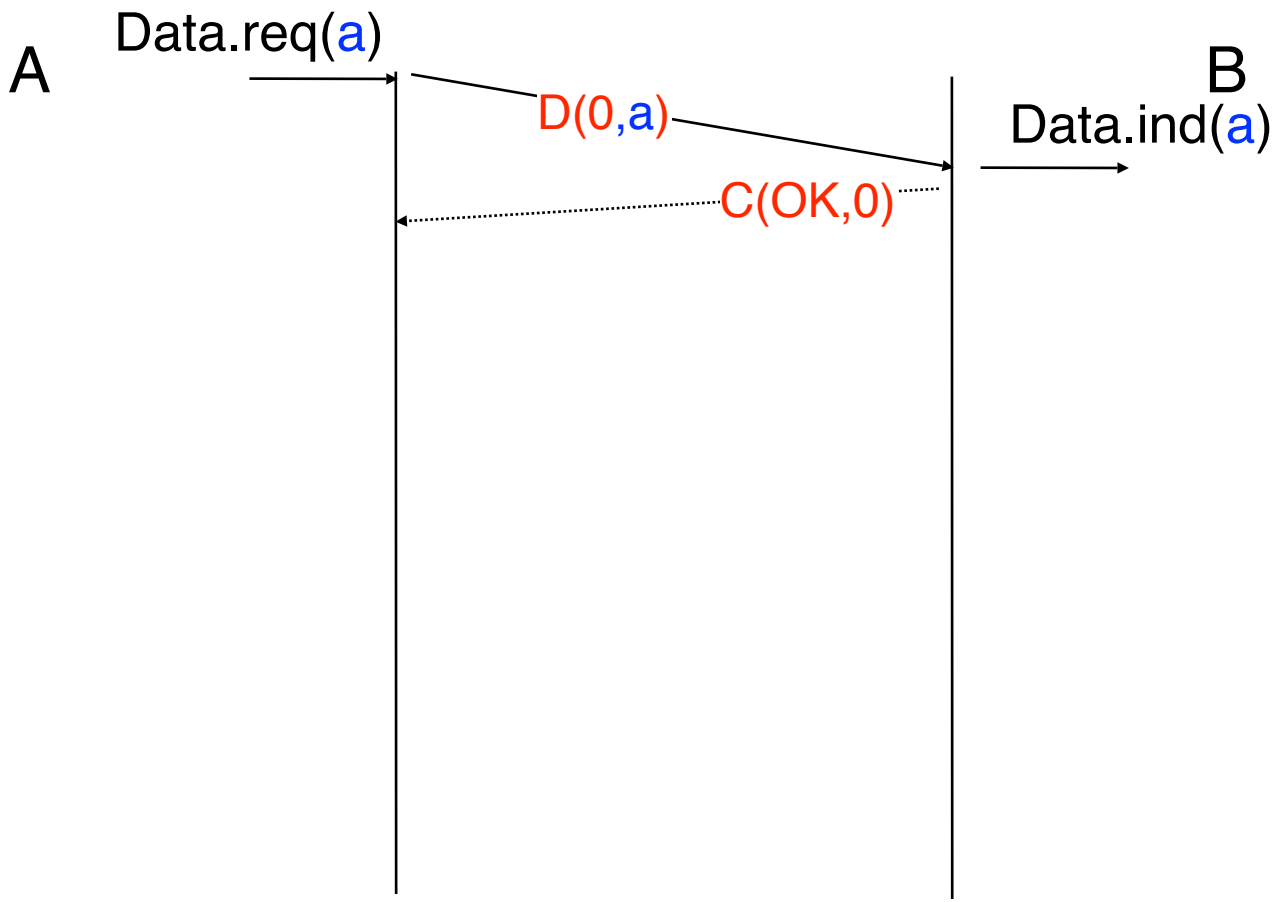
A late segment could be confused with a valid segment



Duplication and reordering (2)

Problem

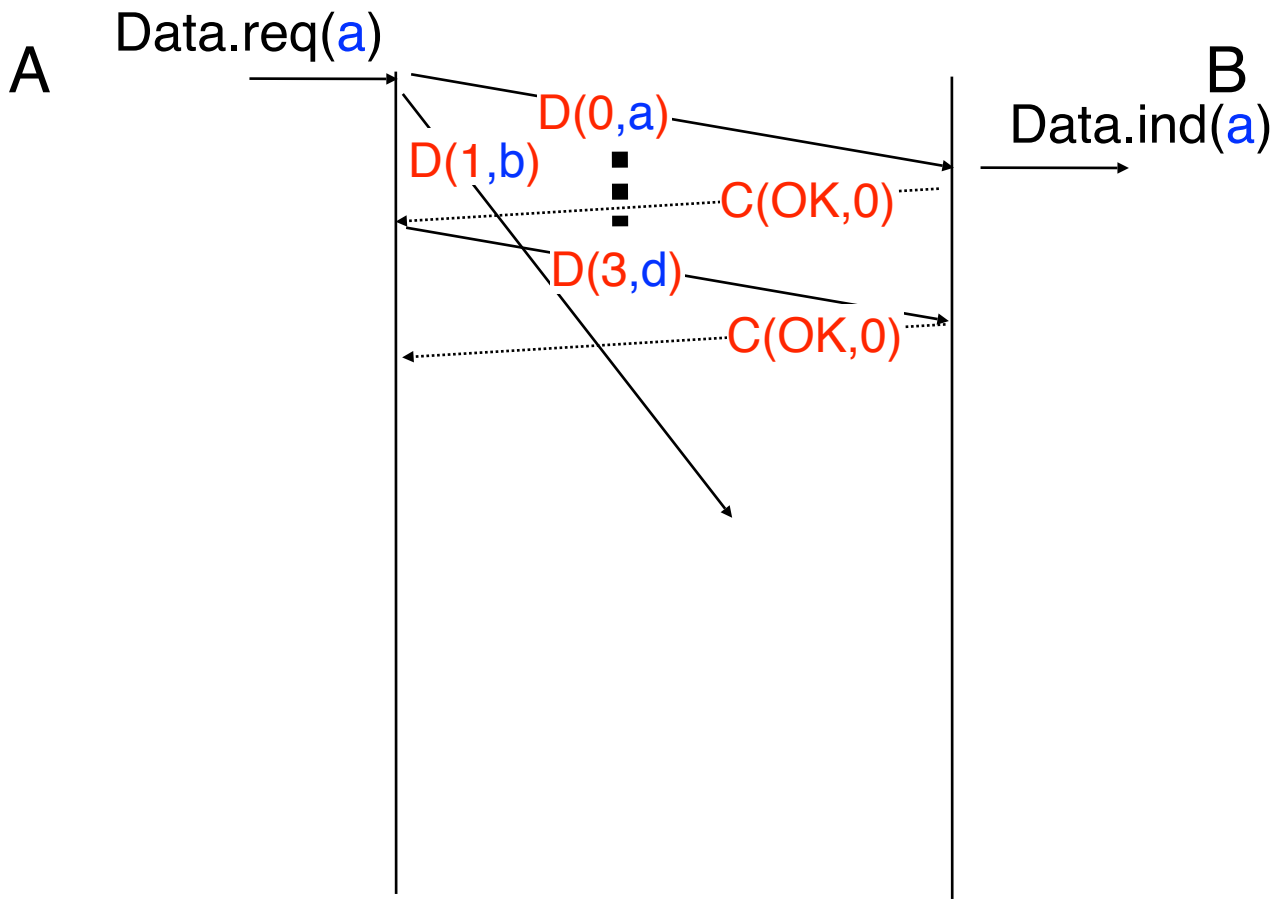
A late segment could be confused with a valid segment



Duplication and reordering (2)

Problem

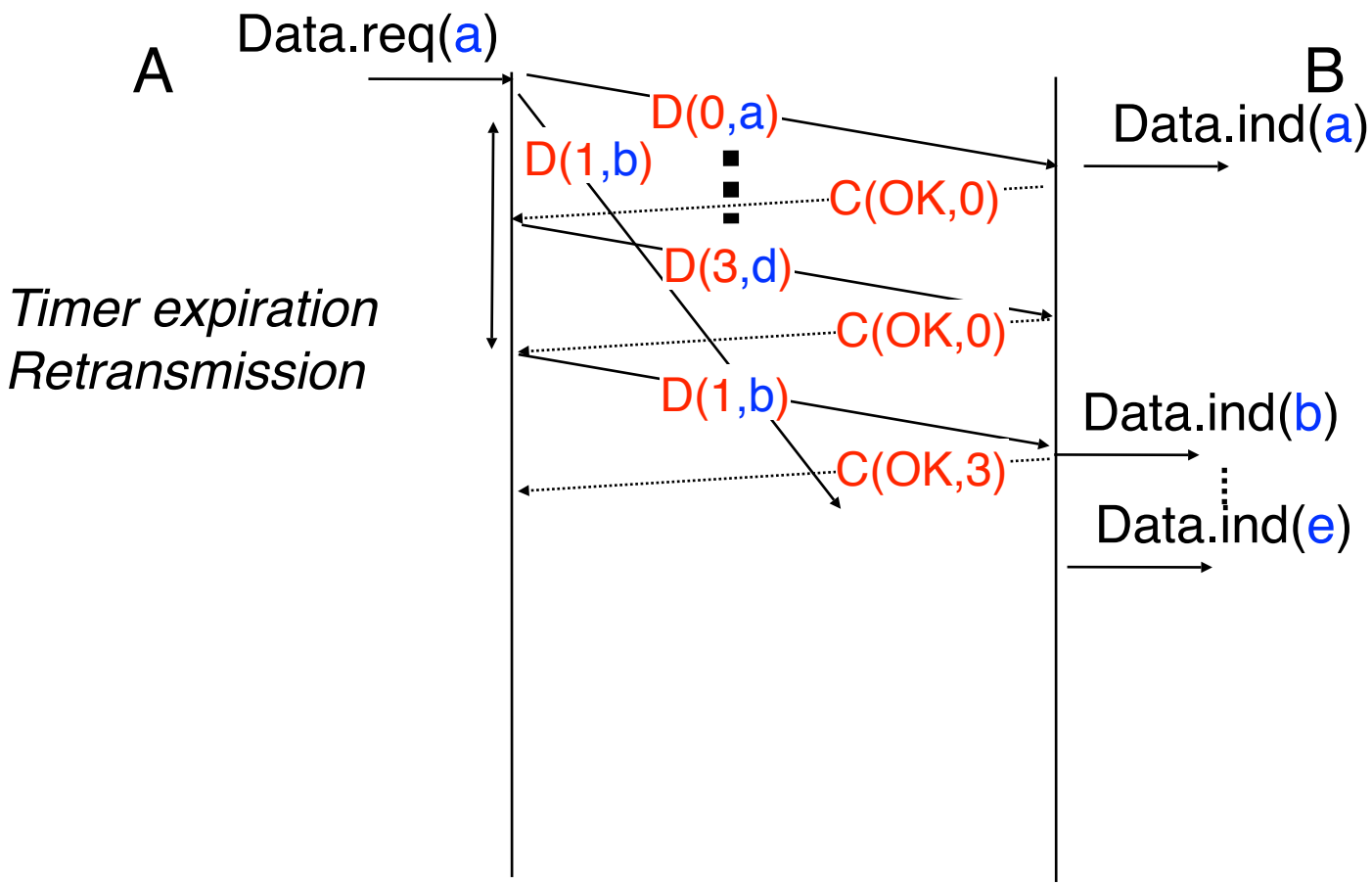
A late segment could be confused with a valid segment



Duplication and reordering (2)

Problem

A late segment could be confused with a valid segment



Duplication and reordering (2)

Problem

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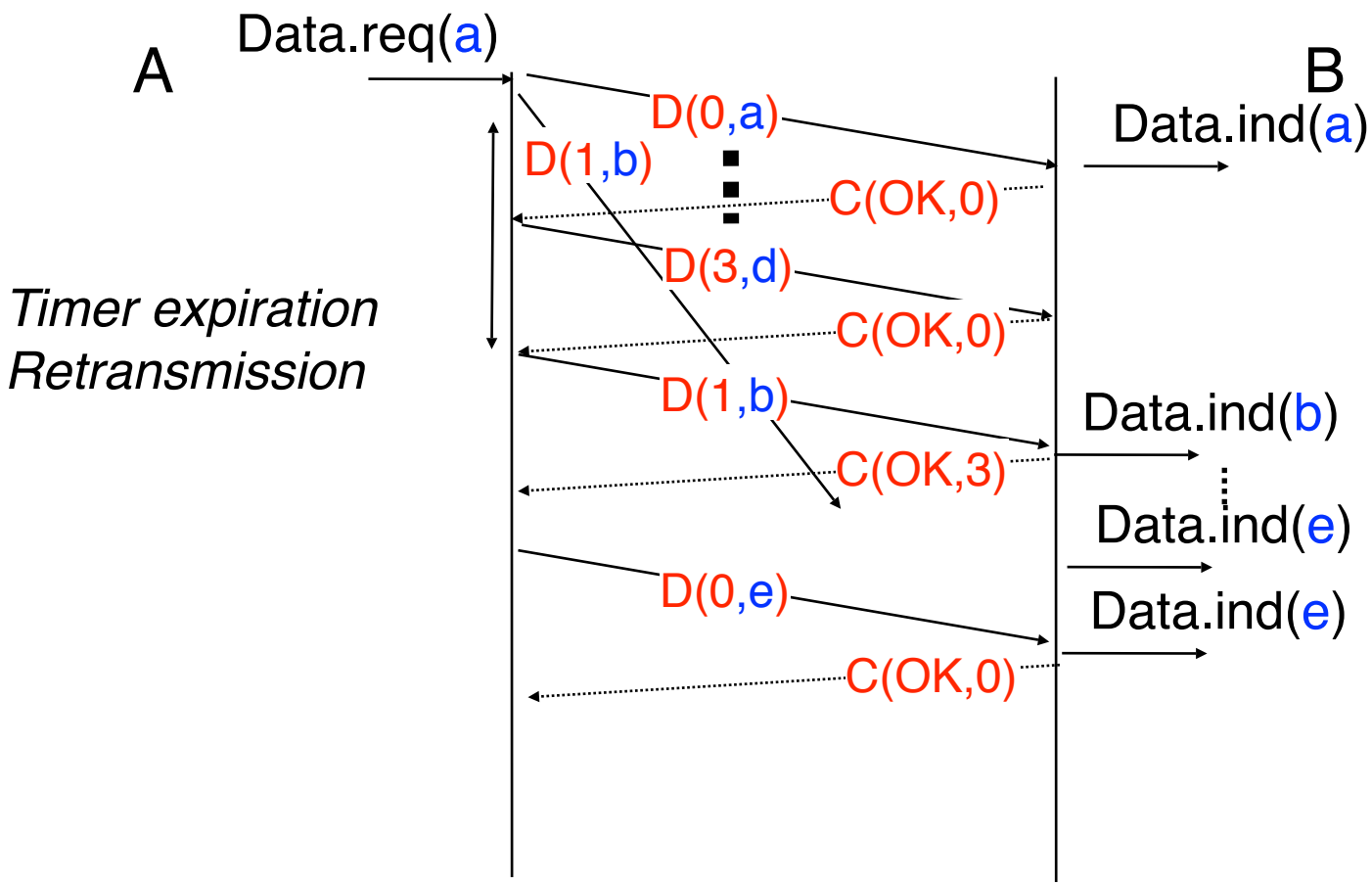

Duplication and reordering (2)

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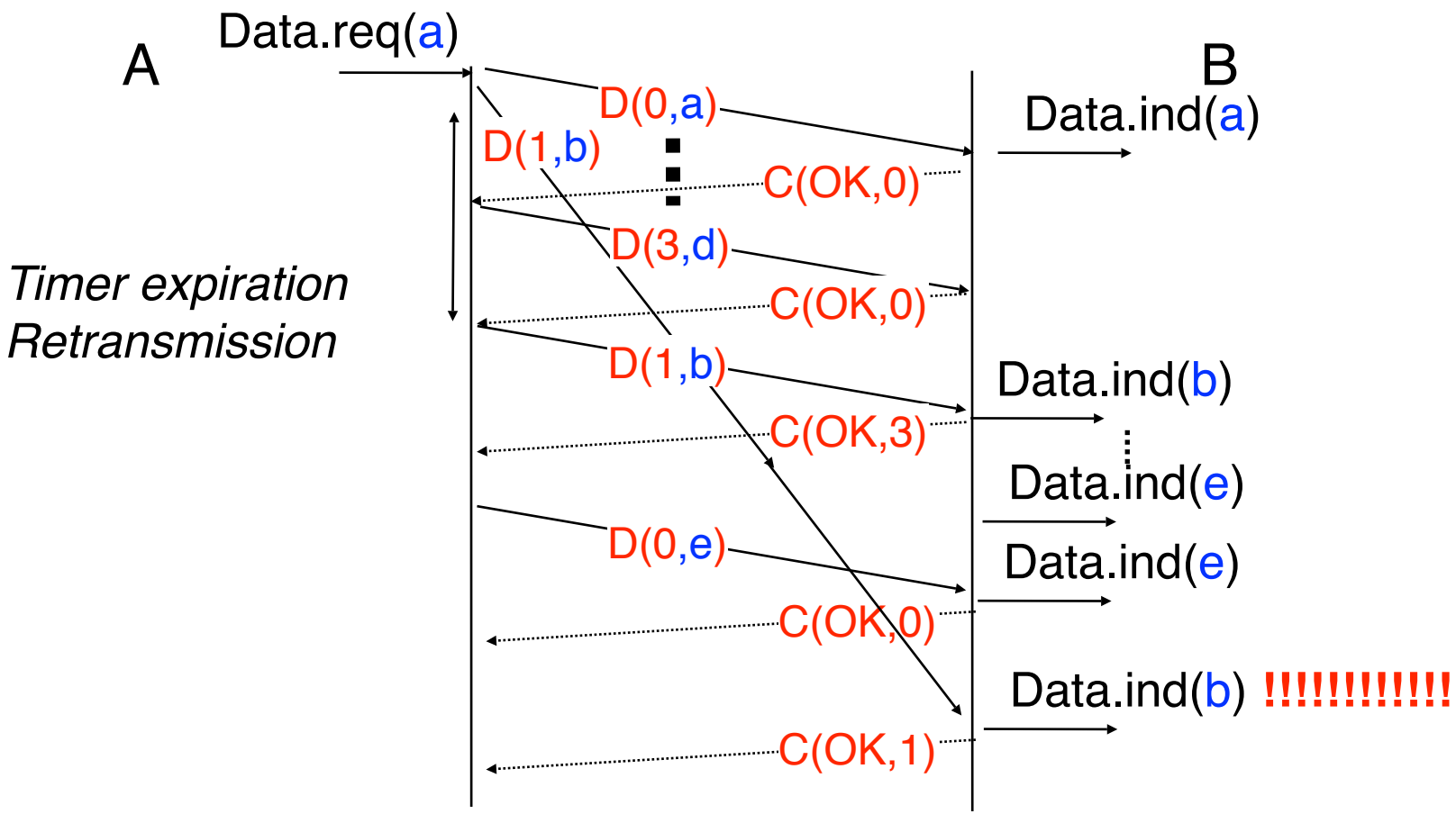


Duplication and reordering (3)

- How to deal with duplication and reordering ?
  - Possible provided that segments do not remain forever inside the network
  - Constraint on network layer
    - A packet cannot remain inside the network for more than MSL seconds
- Principle of the solution
  - Only one segment carrying sequence number x can be transmitted during MSL seconds
    - upper bound on maximum throughput

Bidirectional flow

How can we allow both hosts to transmit data ?

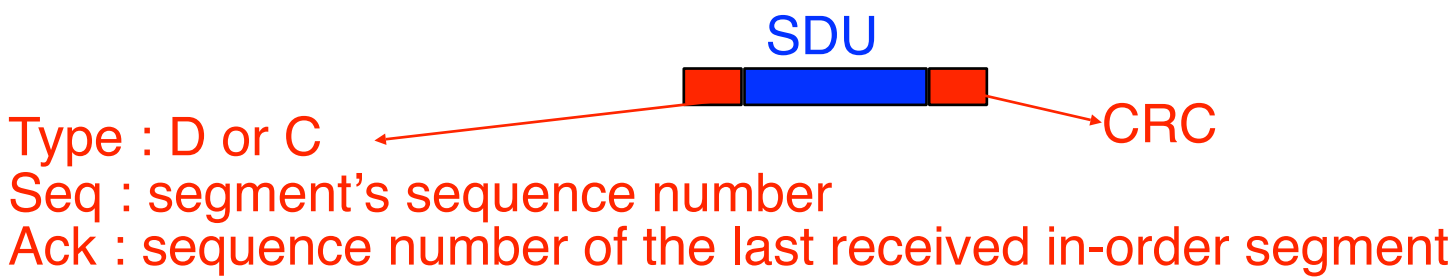
Principle

Each host sends both control and data segments

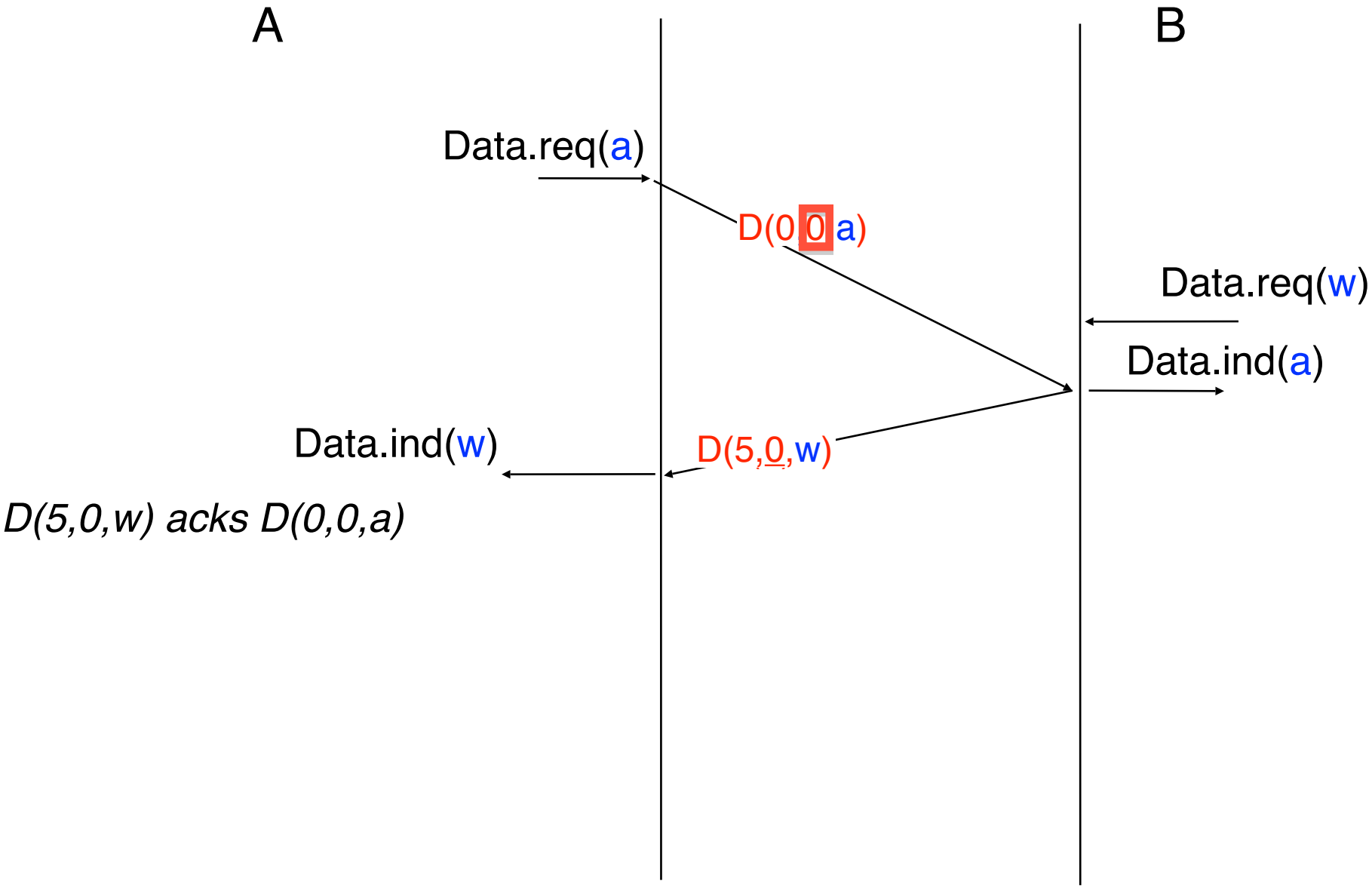
Piggybacking

Place control fields inside the data segments as well (e.g. window, ack number) so that data segments also carry control information

Reduces the transmission overhead

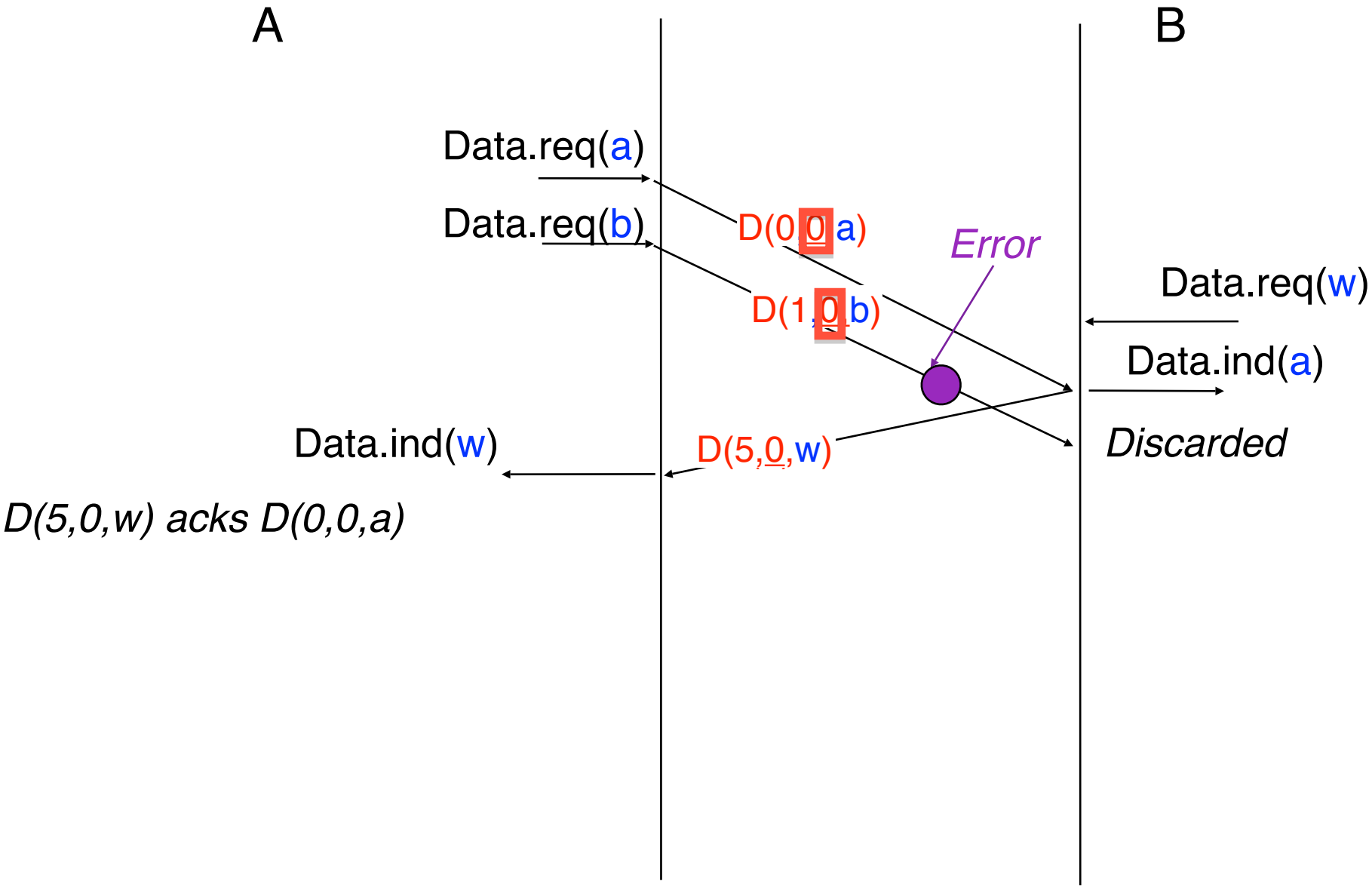


Bidirectional flow Example

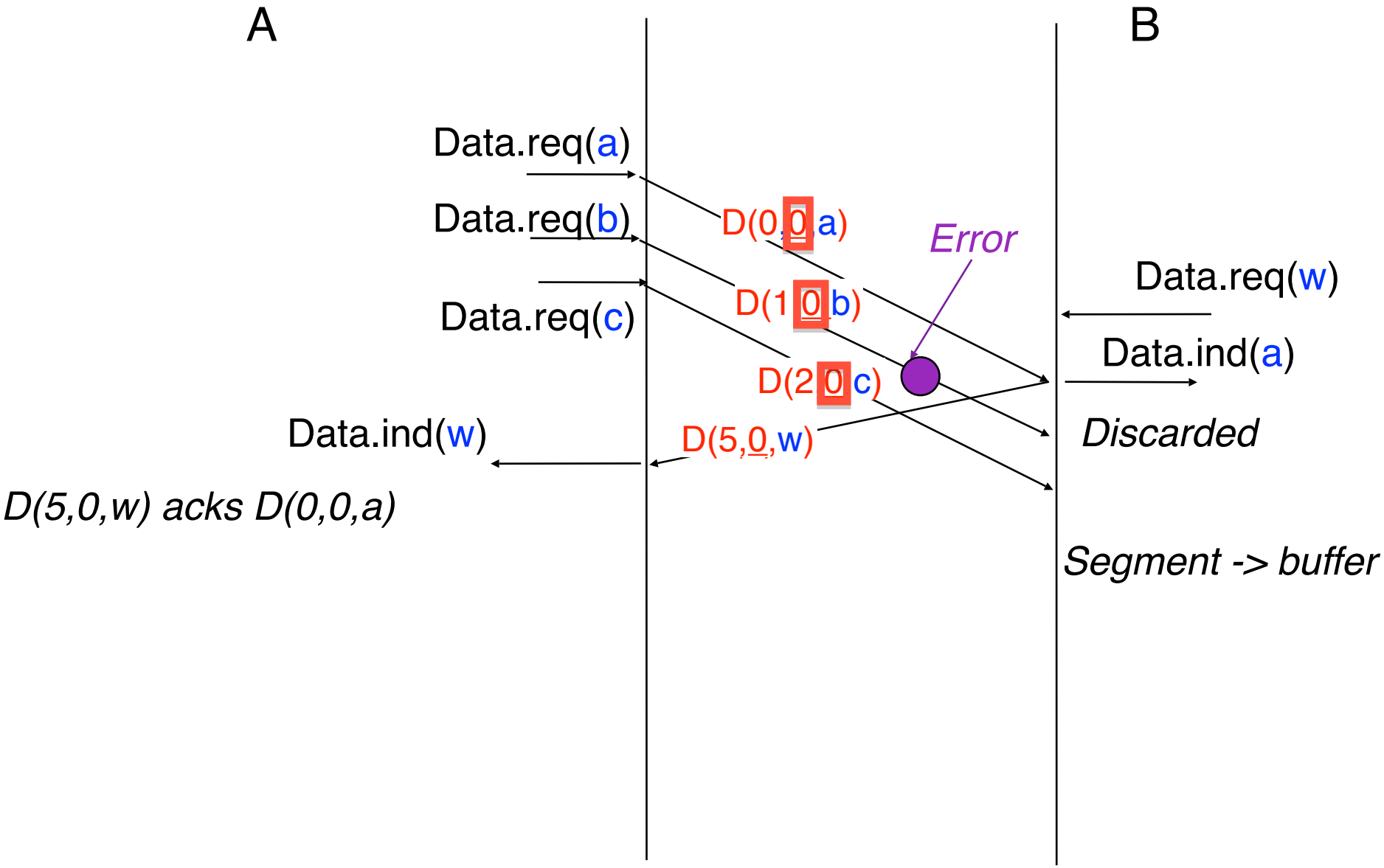


D(5,0,w) acks D(0,0,a)

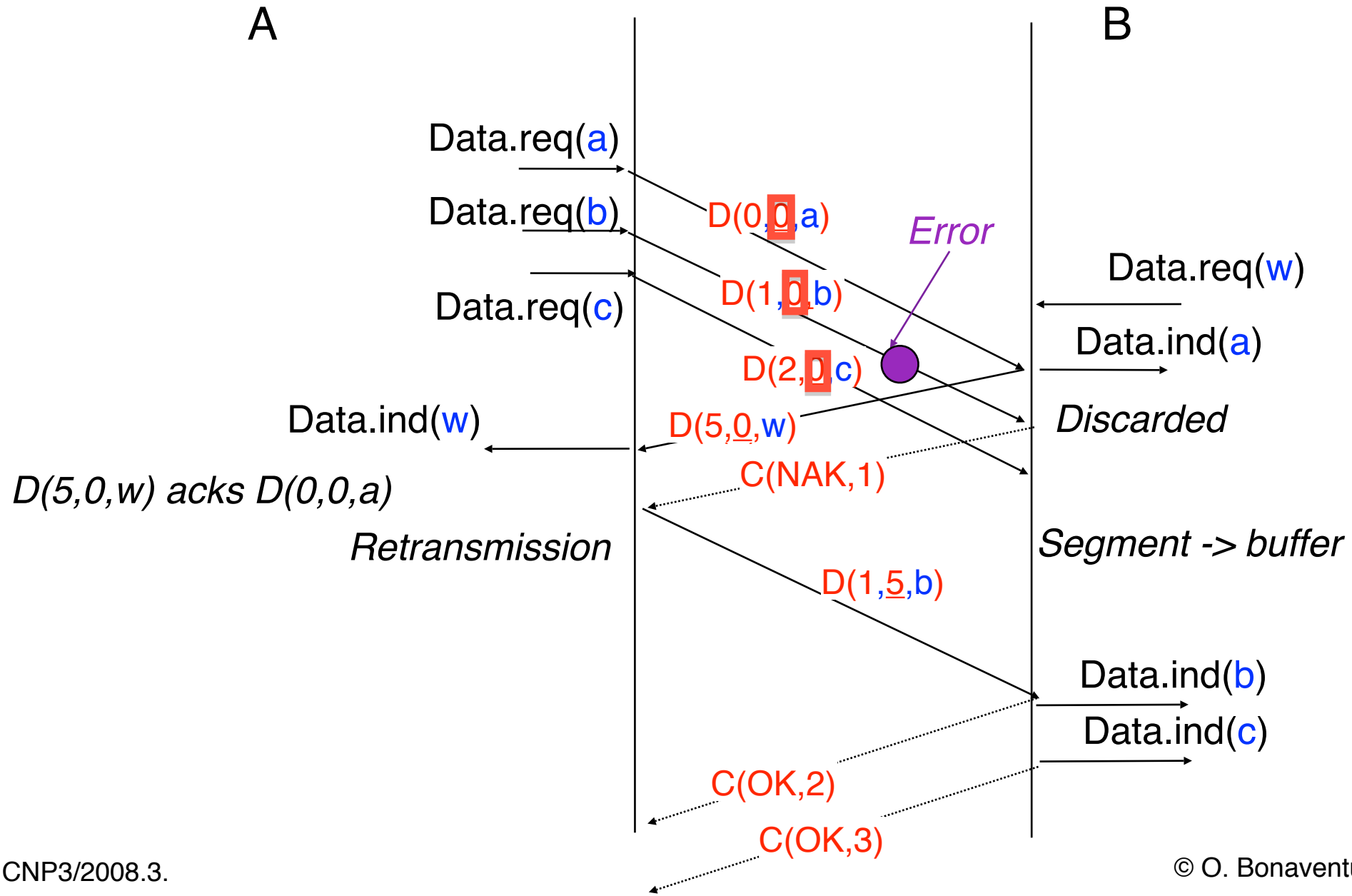
Bidirectional flow Example



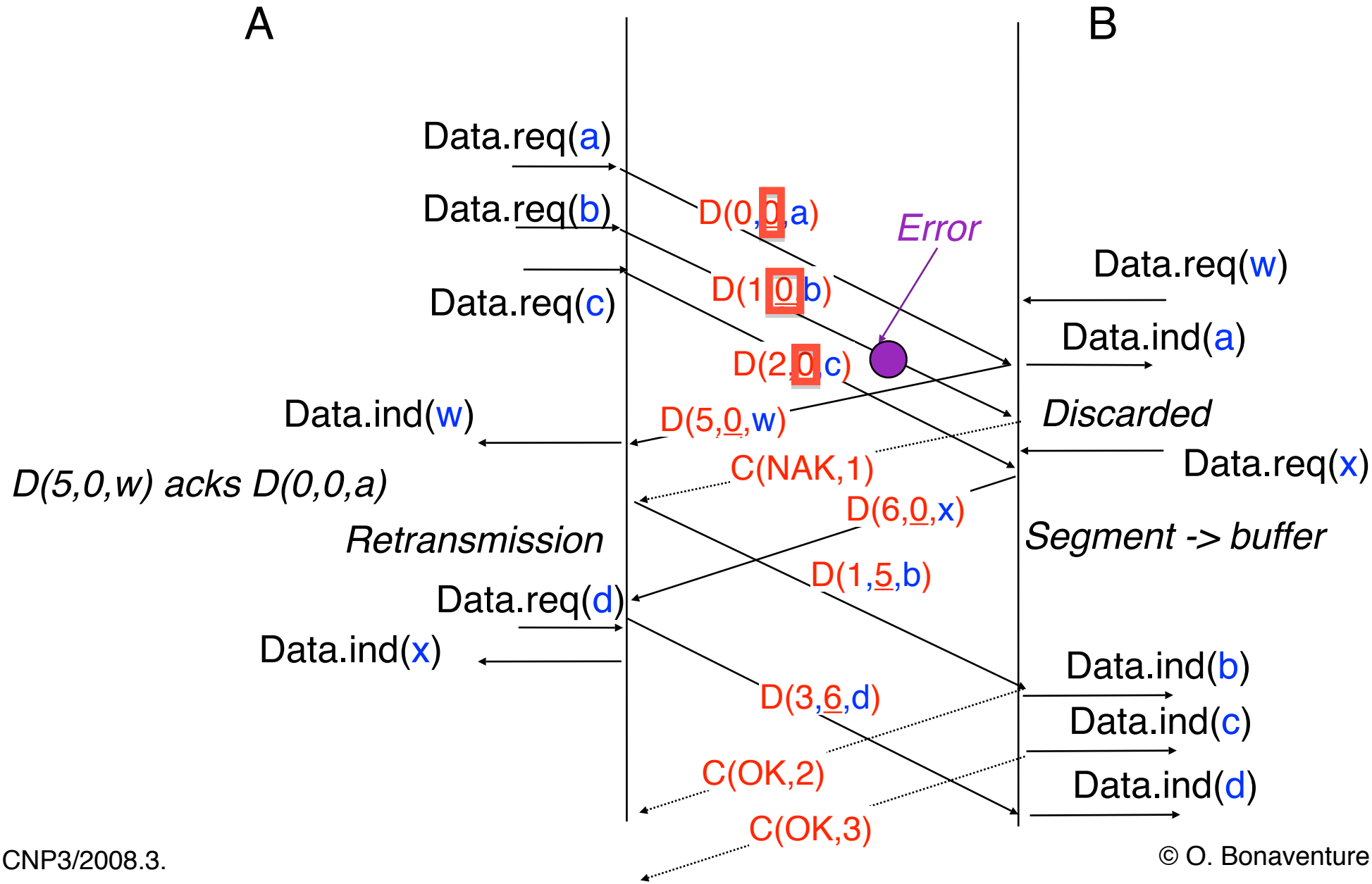
Bidirectional flow Example



Bidirectional flow Example

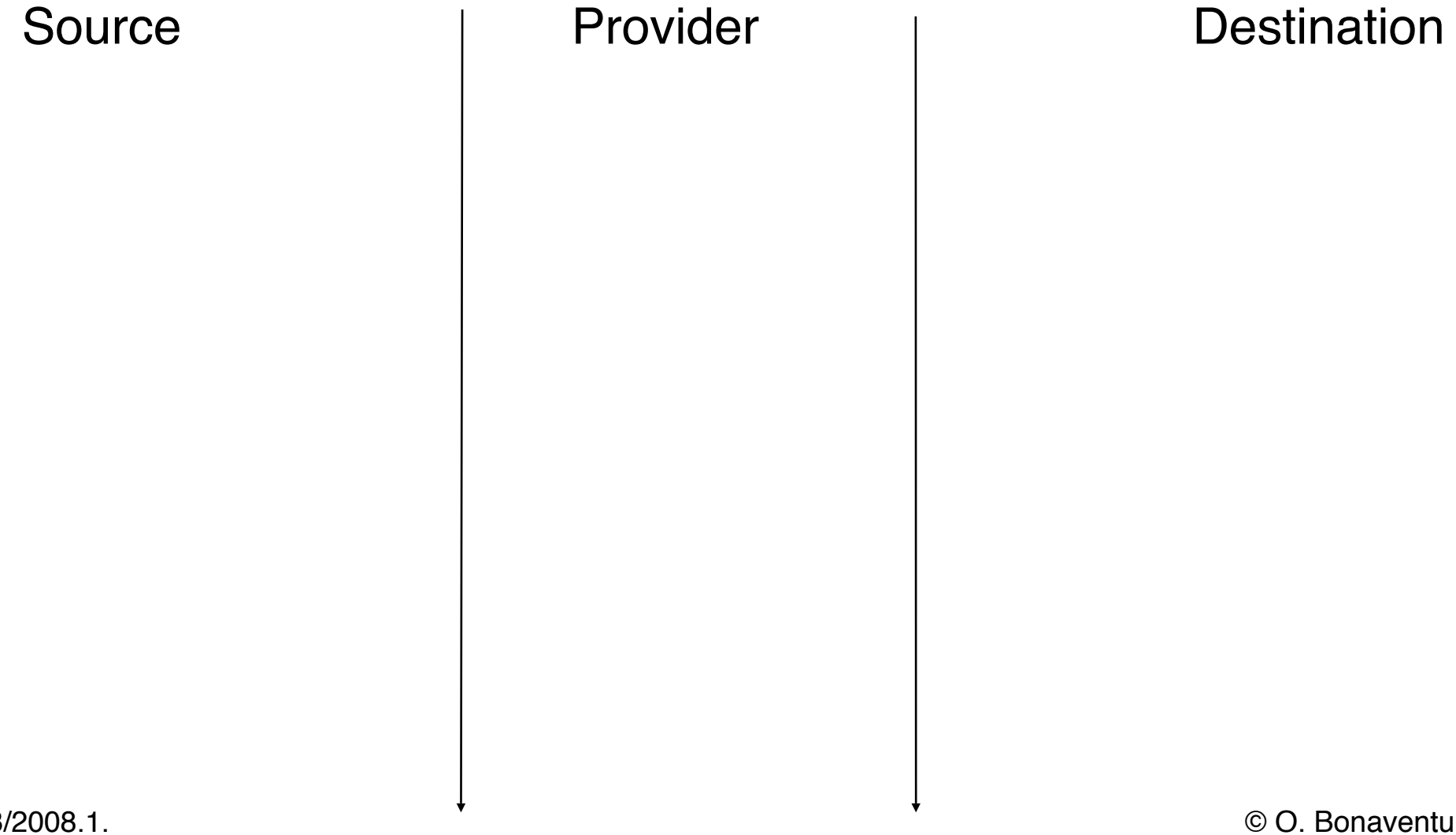


Bidirectional flow Example



Data transfer : stream mode

The providers delivers a stream of characters from source to destination



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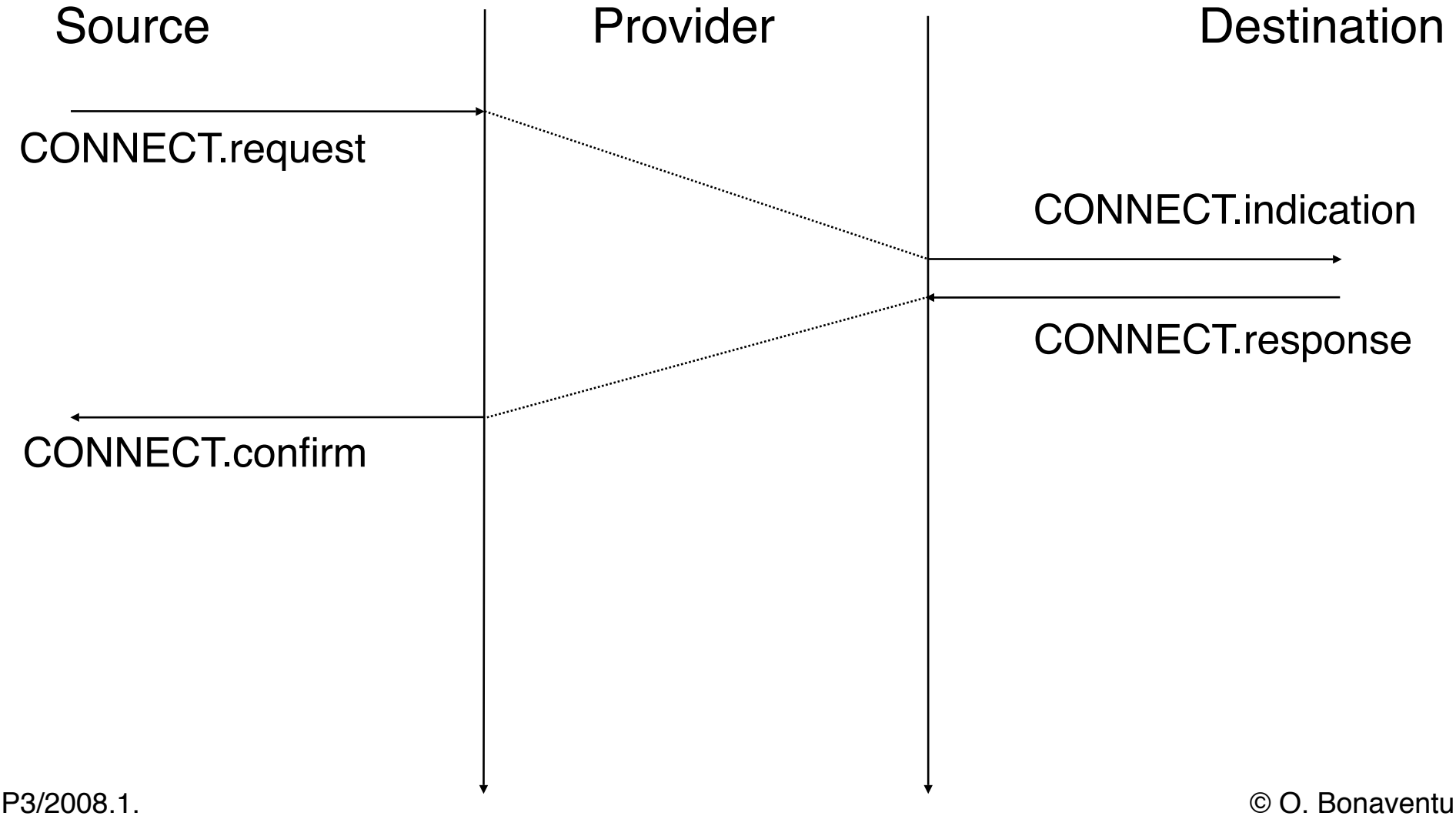

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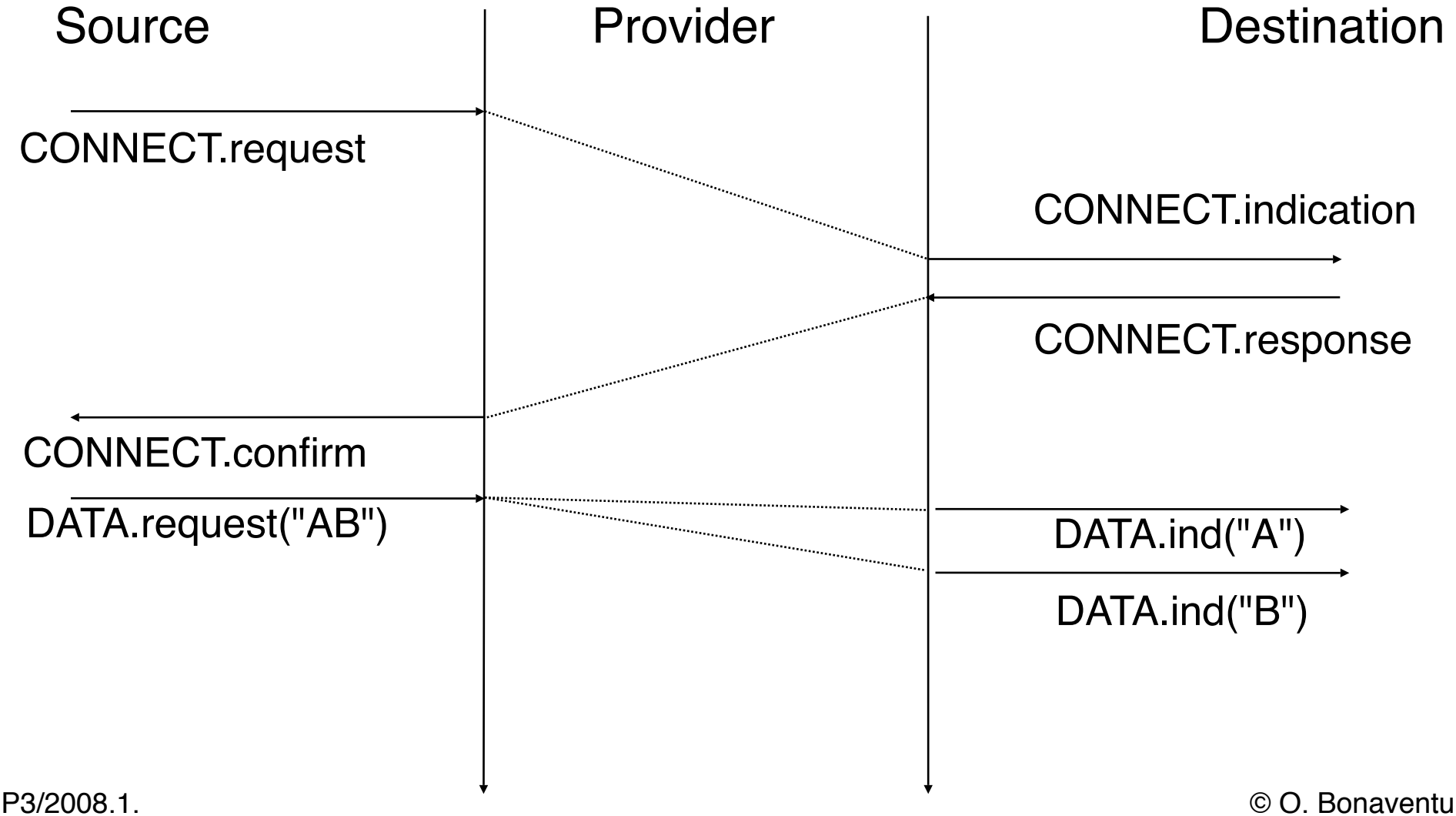

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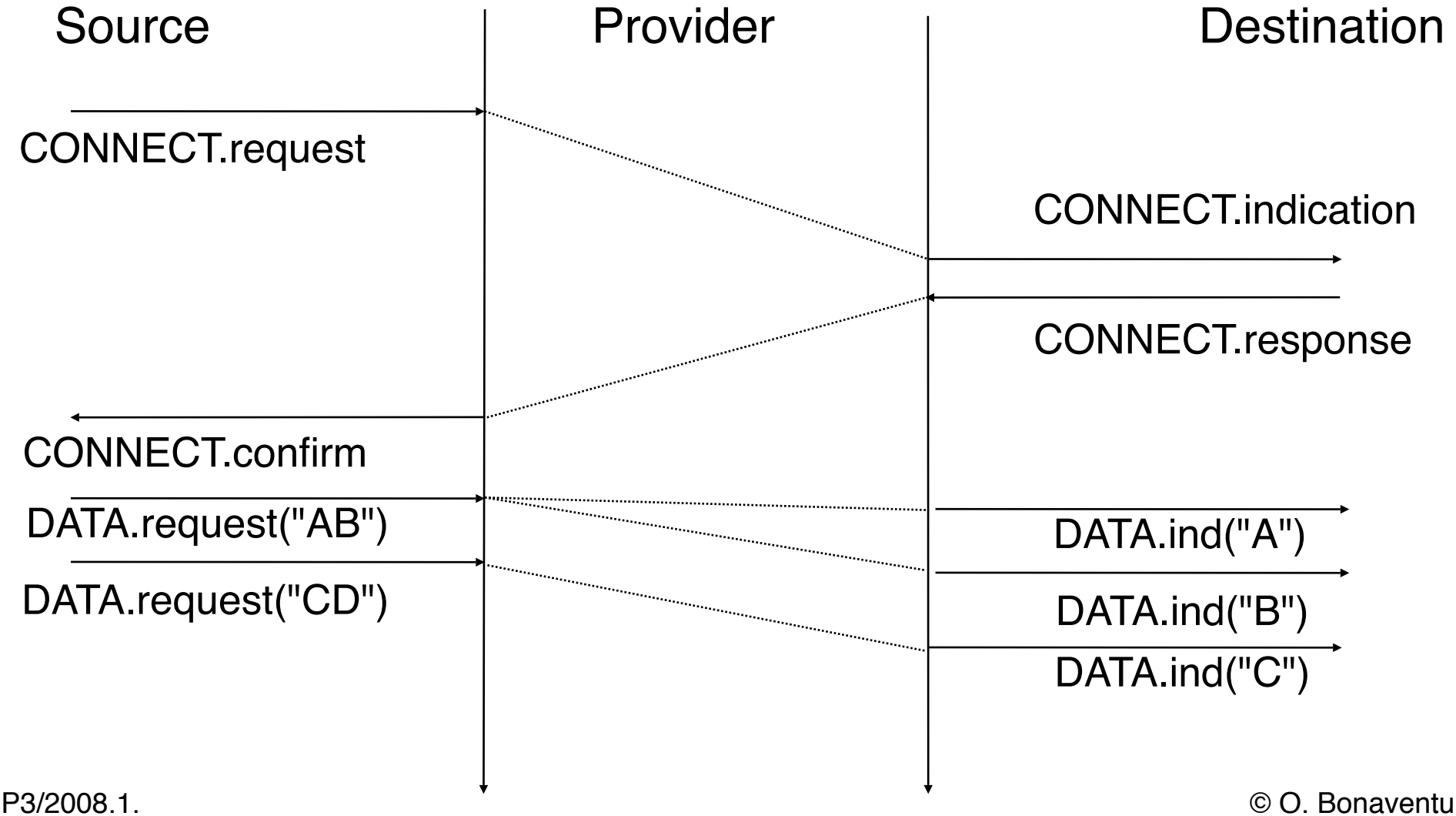

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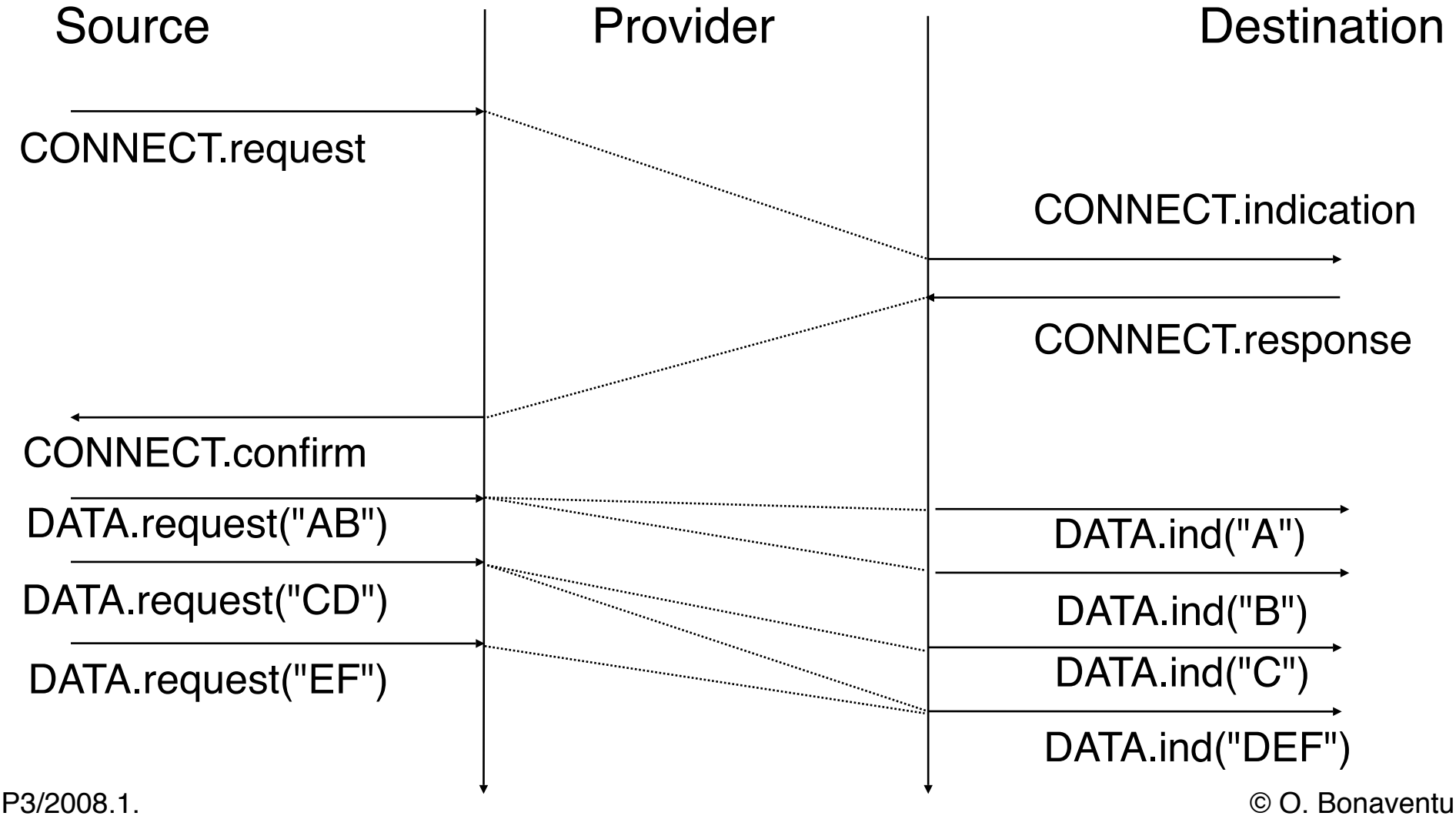
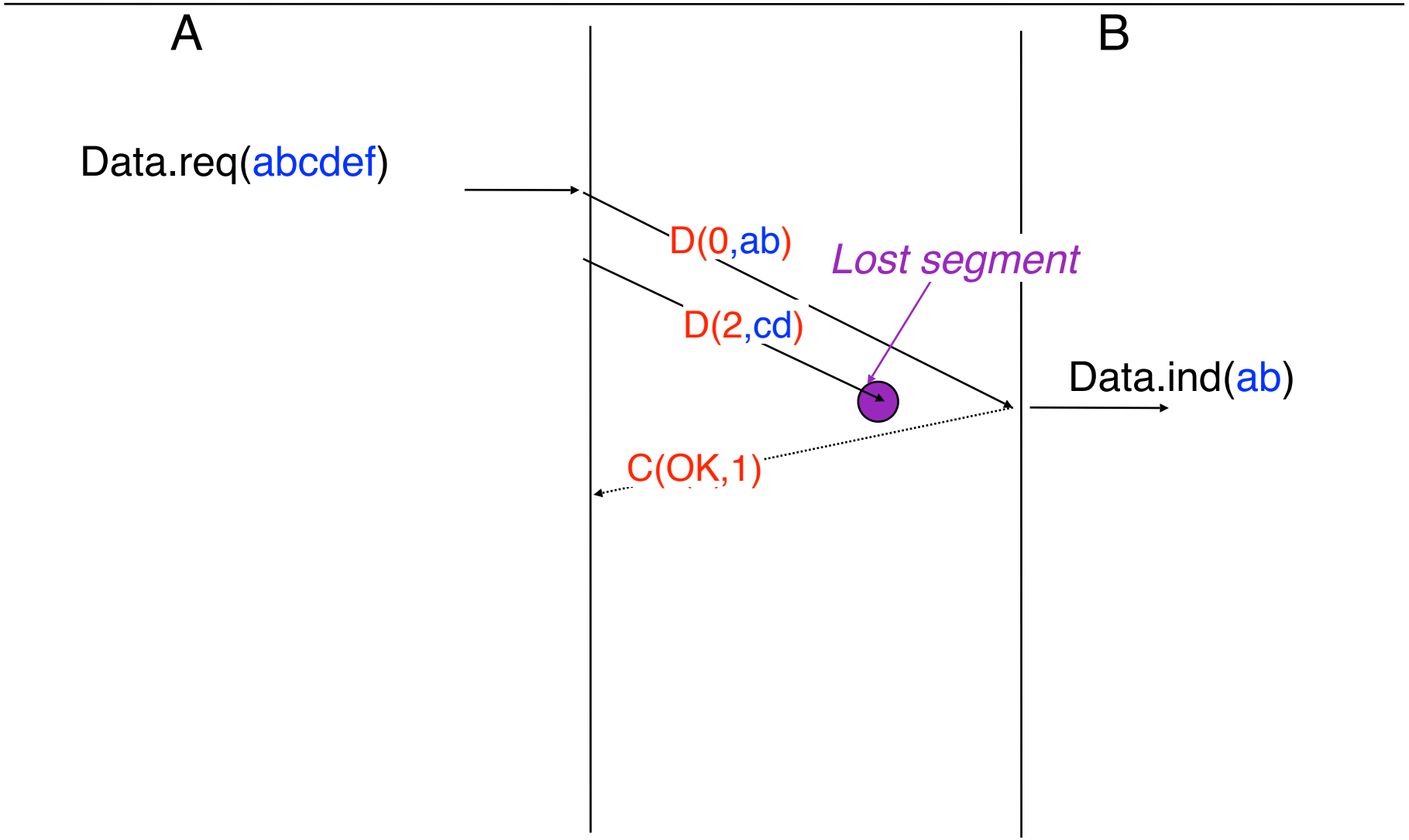


Byte stream service

How to provide a byte stream service ?

- Principle
  - Sender splits the byte stream in segments
  - Receiver delivers the payload of the received in-sequence segments to its user
  - Usually each octet of the byte stream has its own sequence number and the segment header contains the sequence number of the first byte of the payload
    - In this case, window sizes are often also expressed in bytes

Byte stream service (2)



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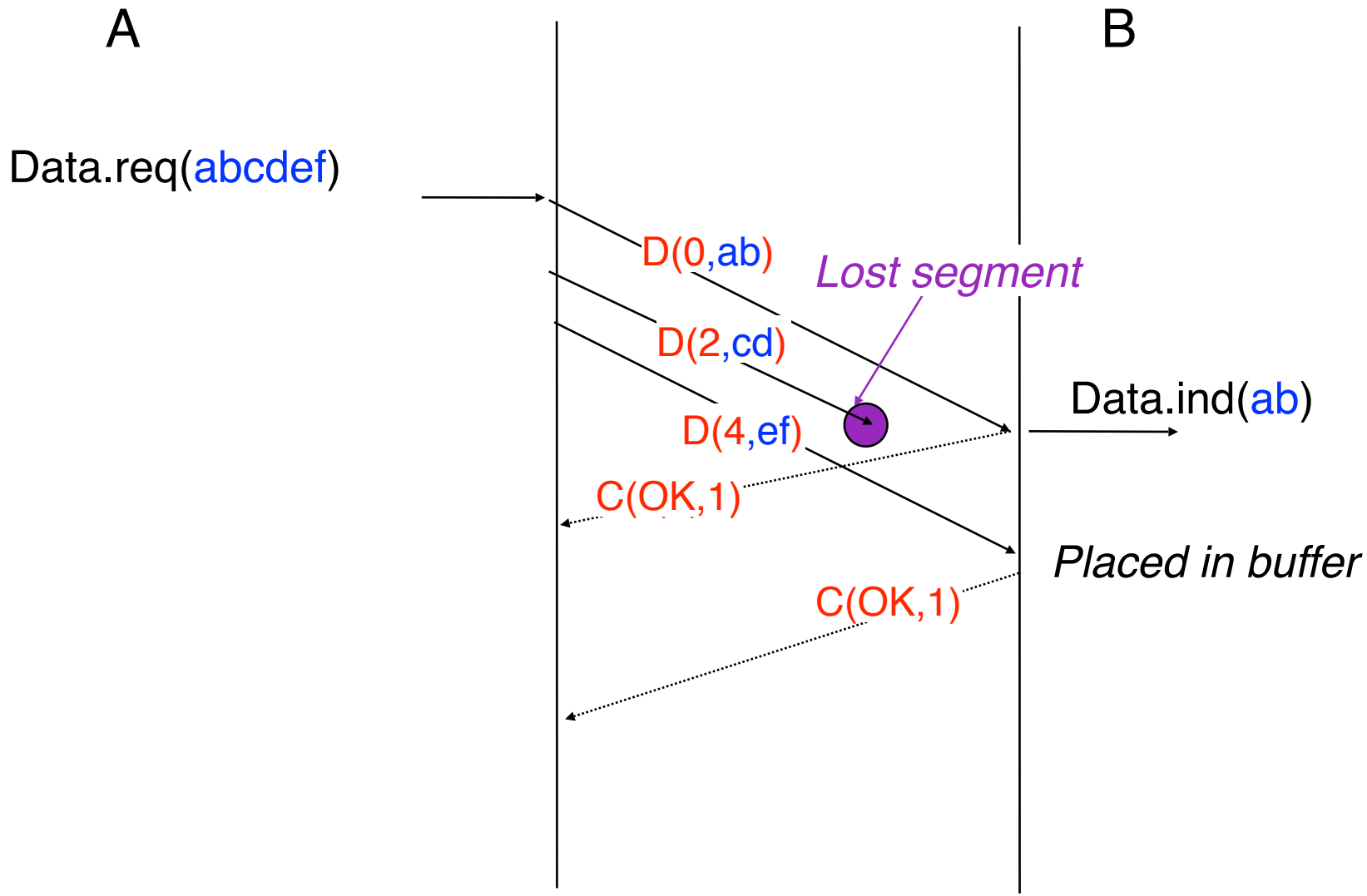

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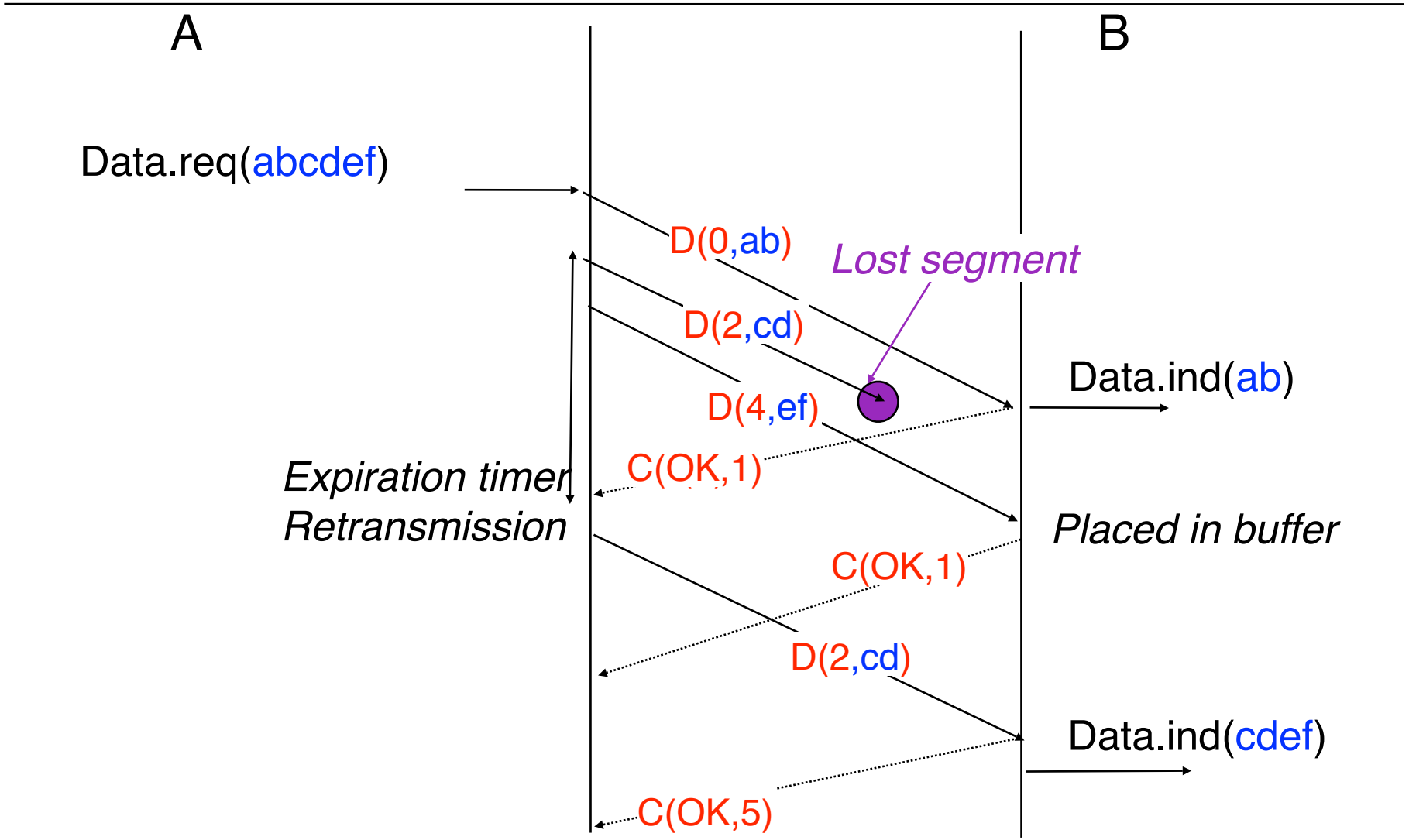

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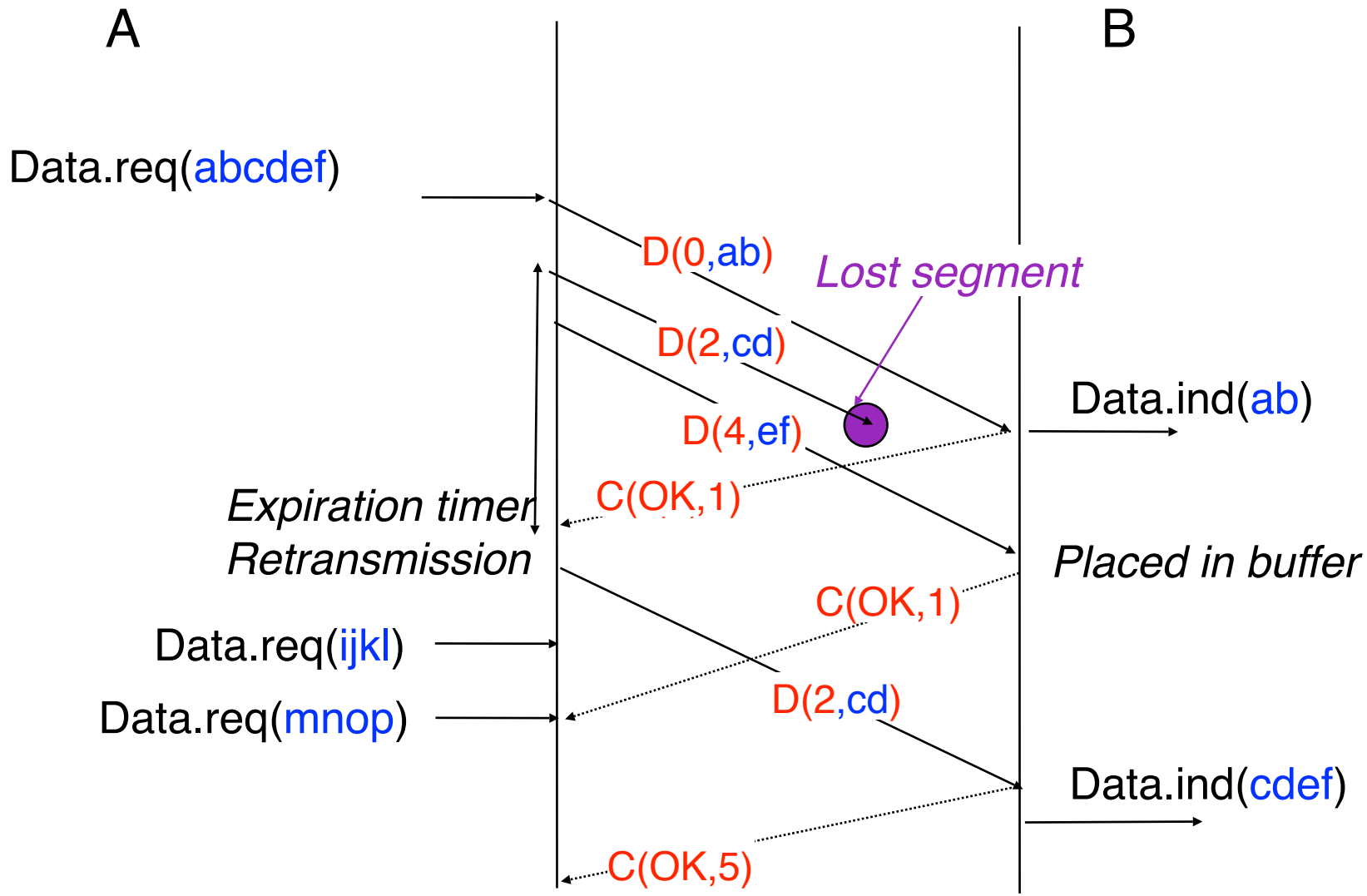

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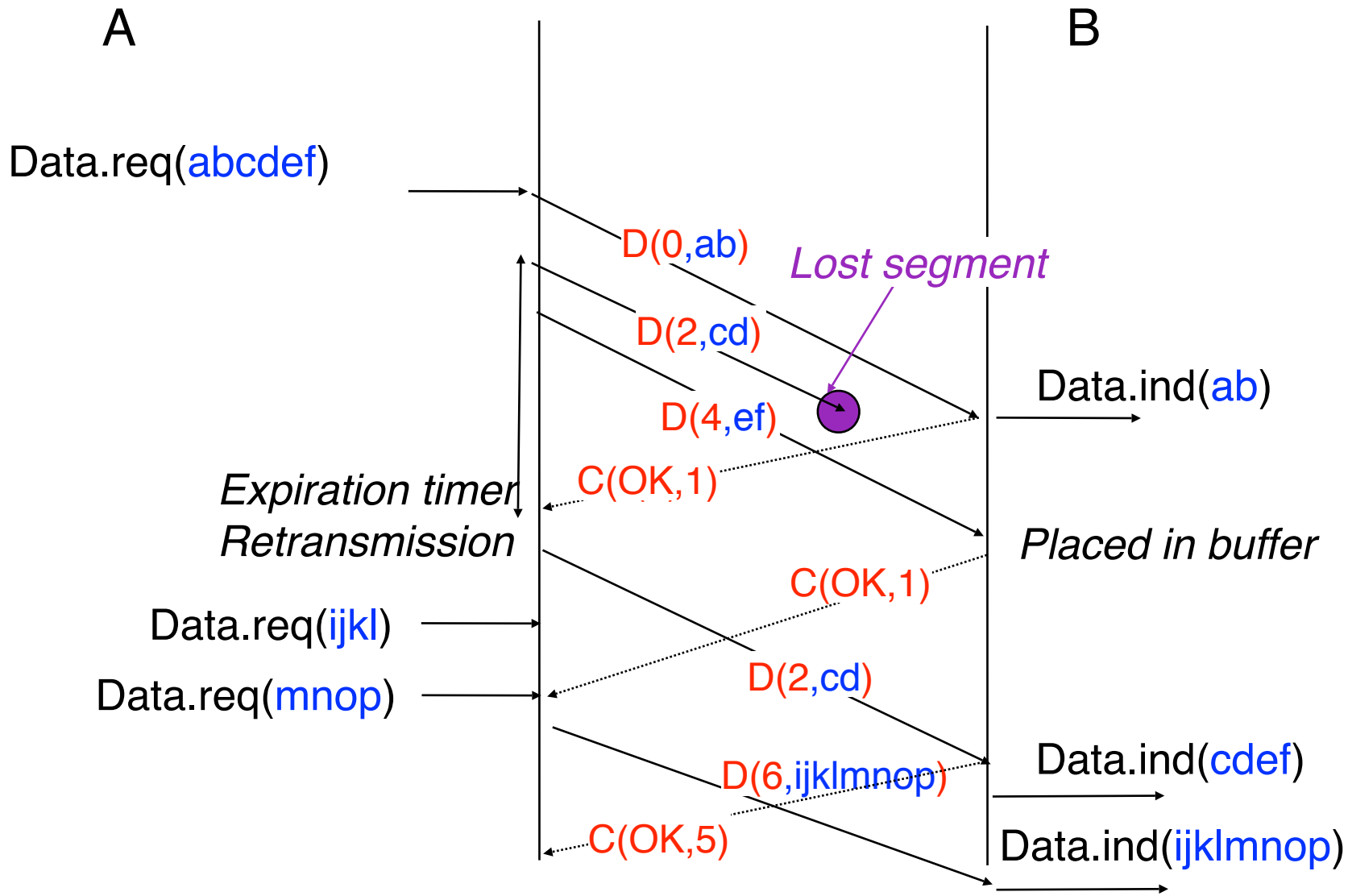

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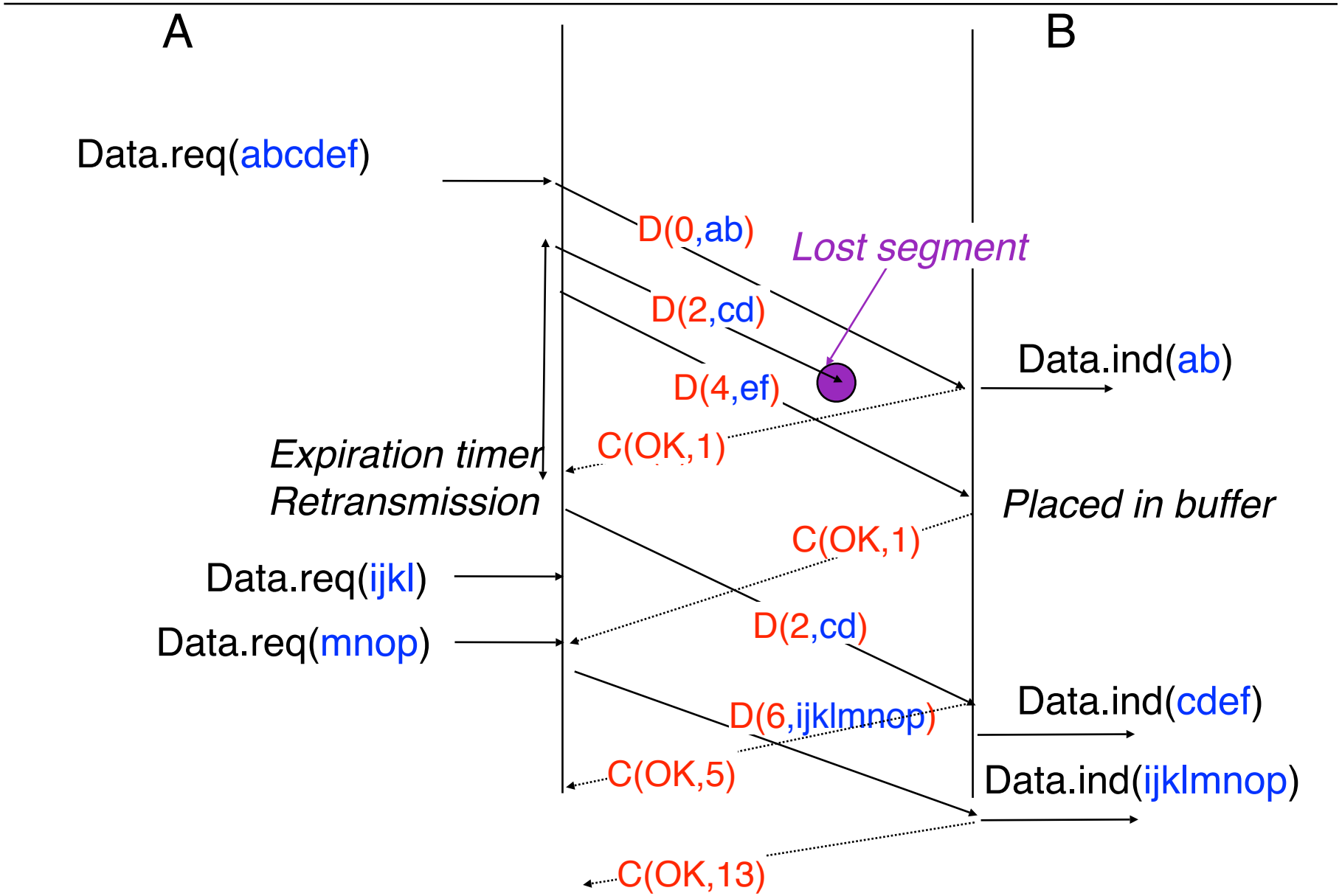


Module 3 : Transport Layer

Basics

Building a reliable transport layer
- Reliable data transmission
- → Connection establishment
- Connection release

UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

Transport connection establishment

How to open a transport connection between two transport entities ?

- The transport layer uses the imperfect network layer service
  - Transmission errors are possible
  - Segments can get lost
  - Segments can get reordered
  - Segments can be duplicated

- Hypothesis
  - We will first assume that a single transport connection needs to be established between the two transport entities

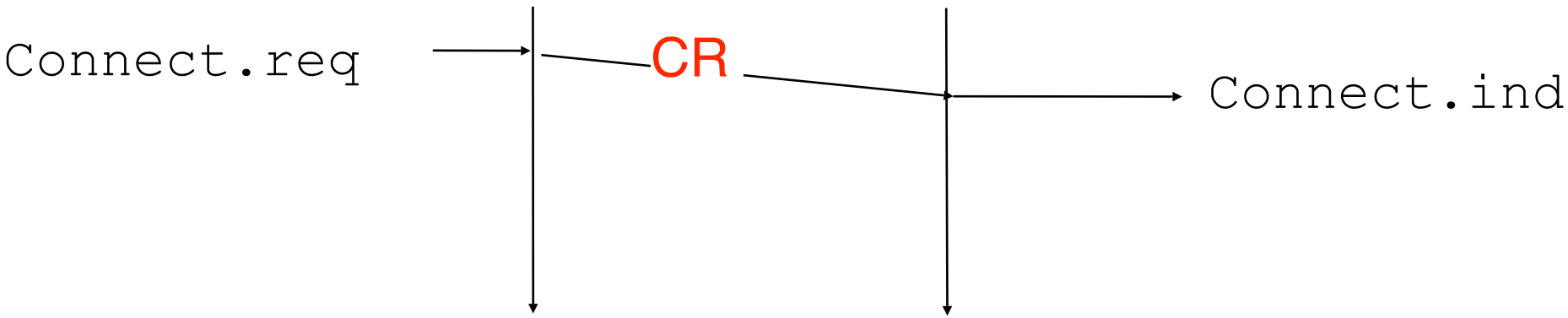
Simple solution

Principle

- 2 control segments
  - CR is used to request a connection establishment
  - CA is used to acknowledge a connection establishment

Is this sufficient with an imperfect network layer service ?

Simple solution



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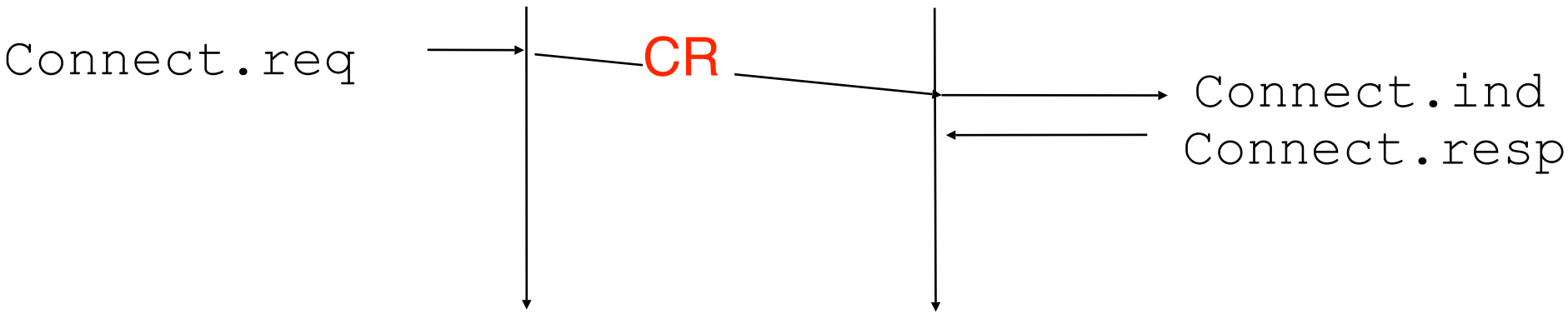

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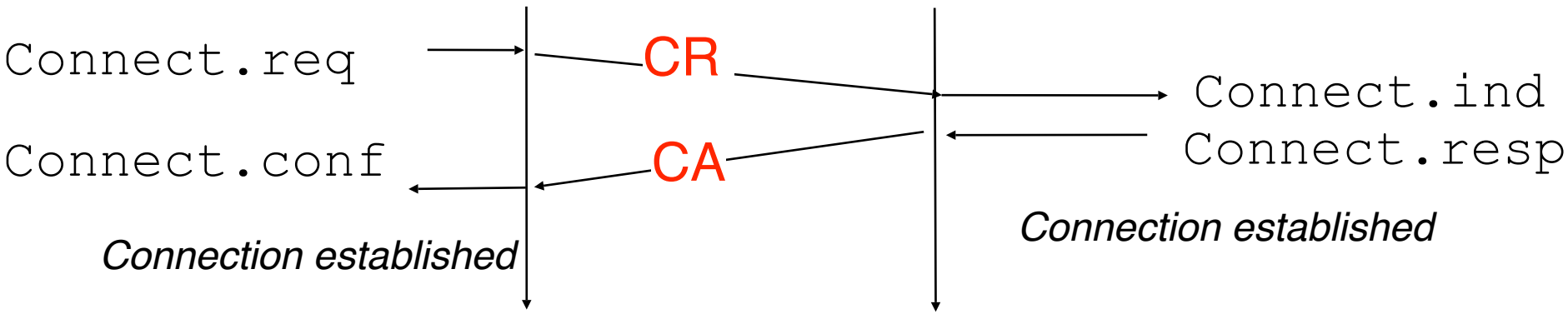


Principle

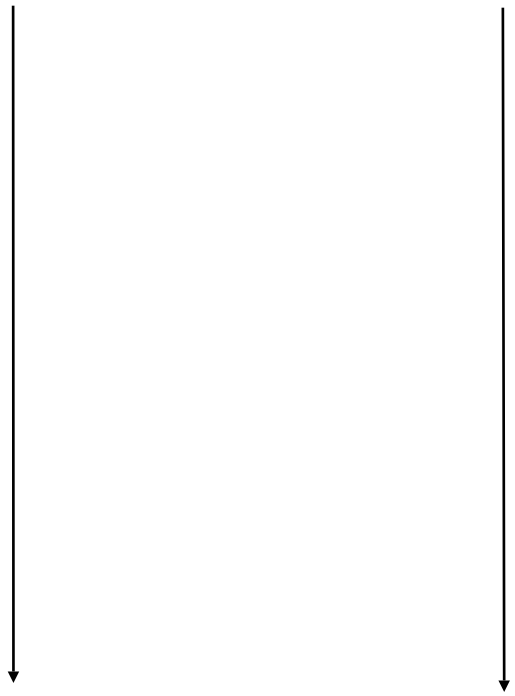
- 2 control segments
  - CR is used to request a connection establishment
  - CA is used to acknowledge a connection establishment

Is this sufficient with an imperfect network layer service ?

Simple solution (2)

How to deal with losses and transmission errors ?

- Control segments must be protected by CRC or checksum
- Retransmission timer is used to protect against segment losses segments



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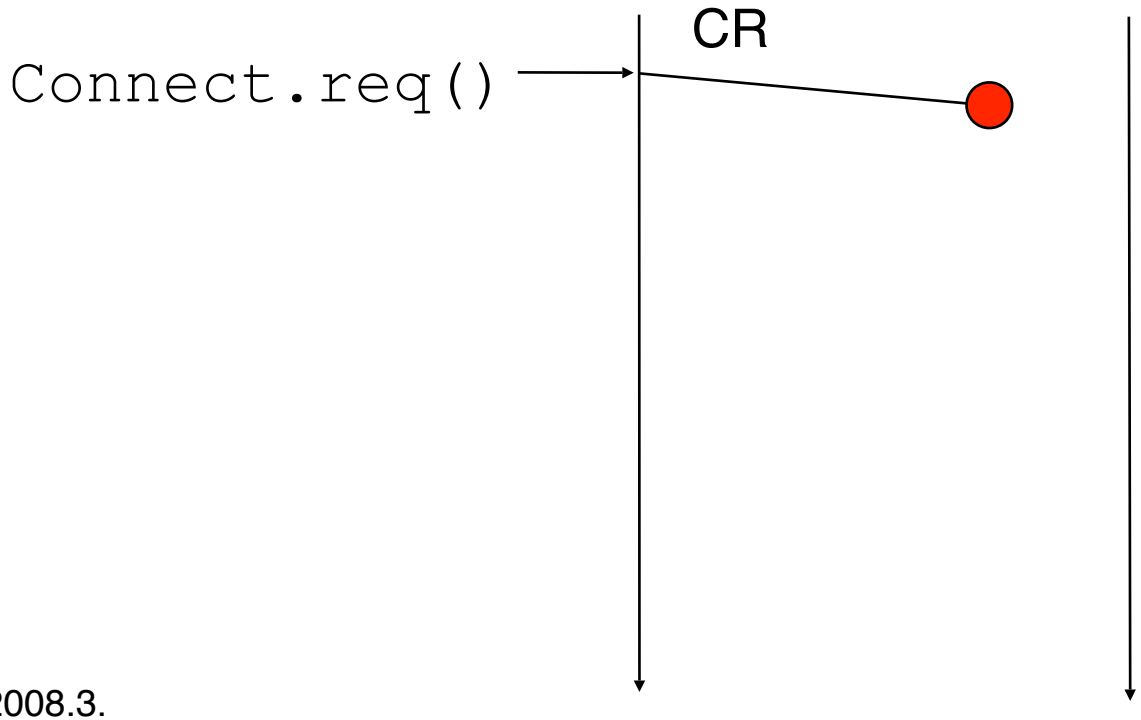

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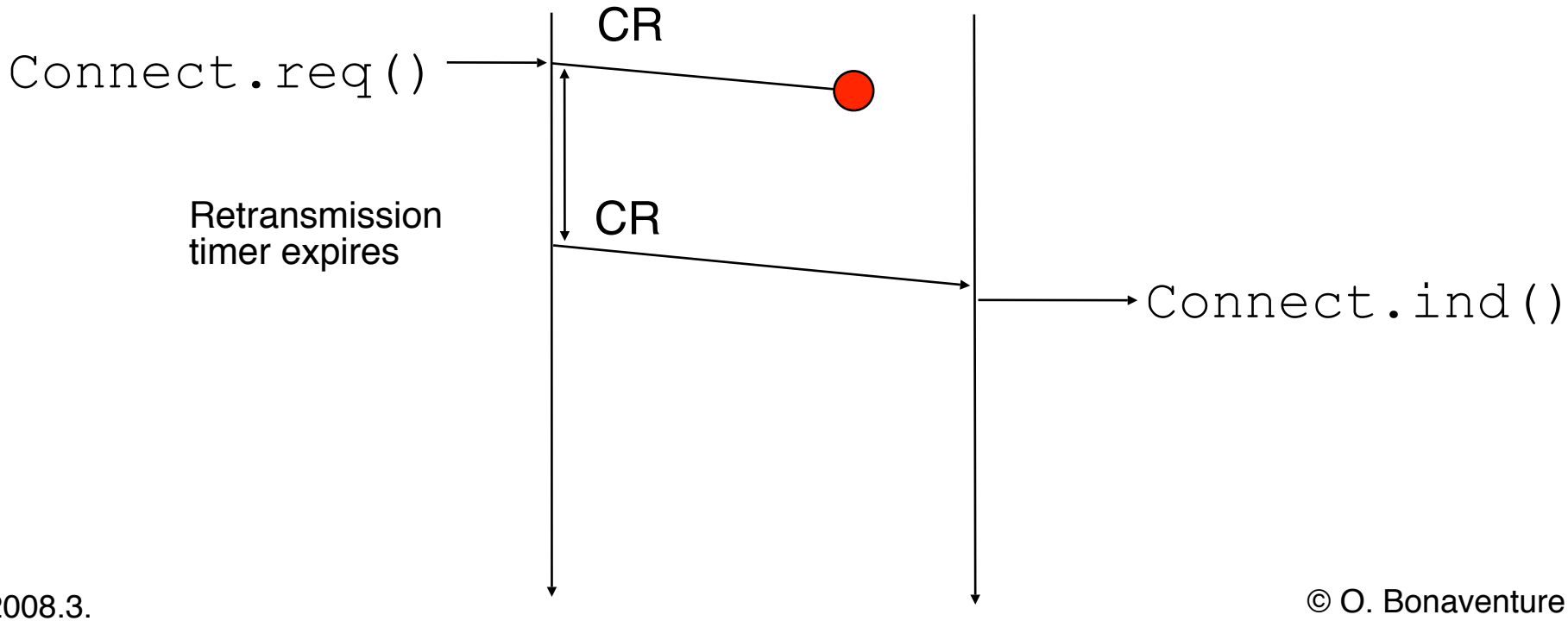

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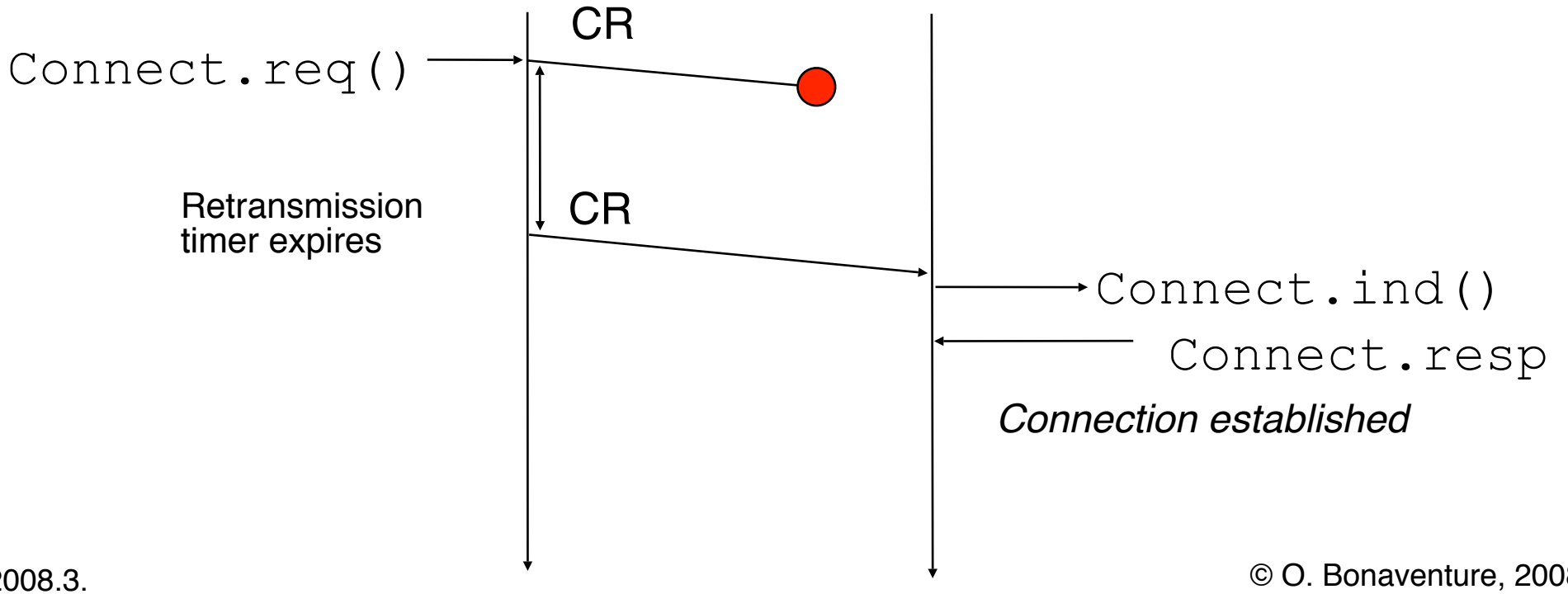

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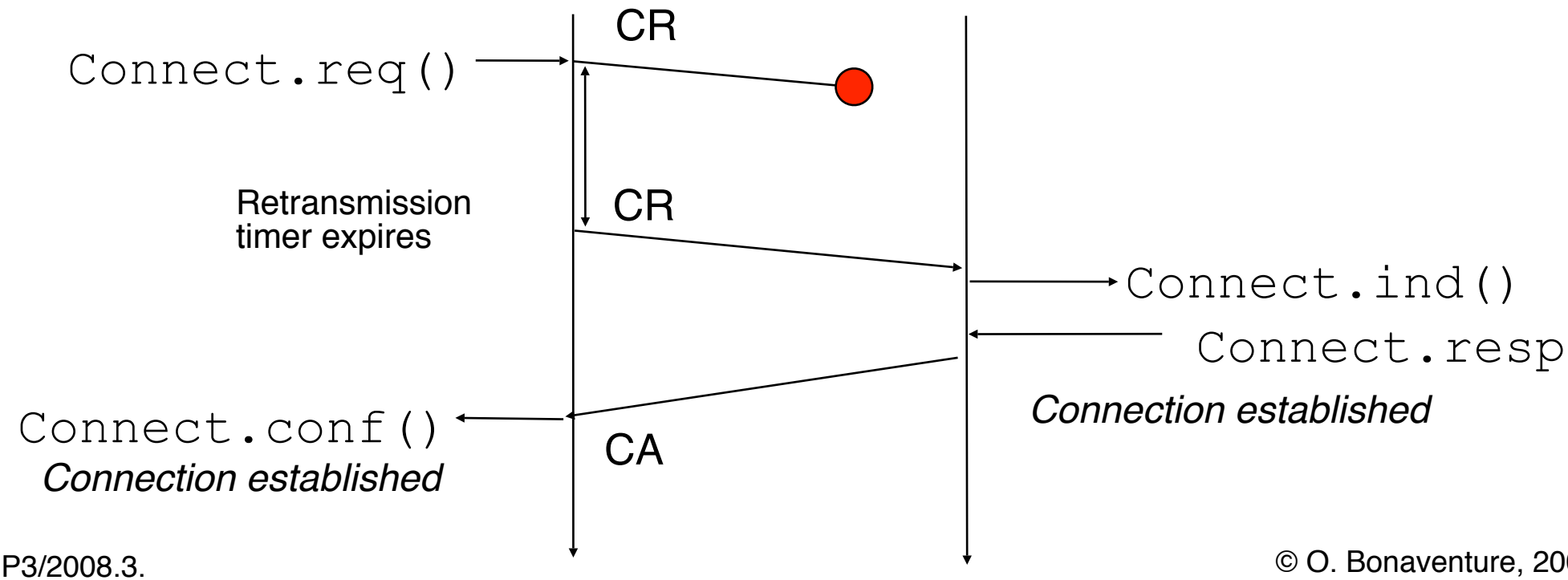
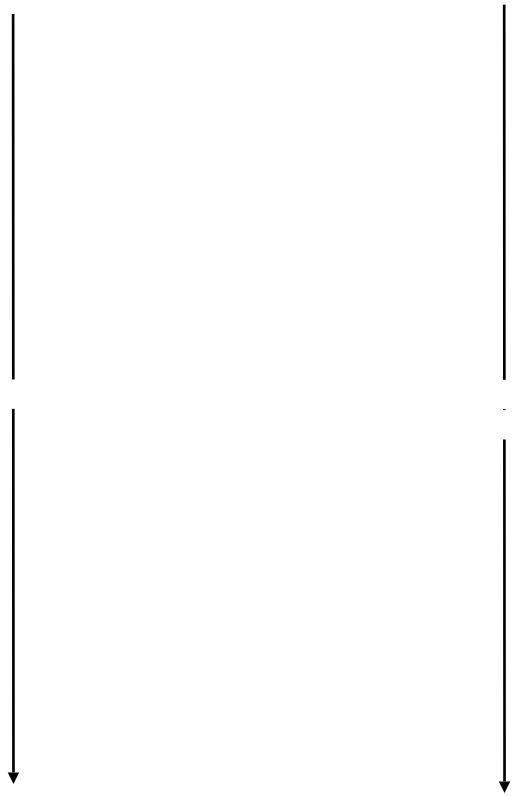


Connection establishment

How to deal with duplicated or delayed packets ?

- A duplicated CR should not lead to the establishment of two transport connections instead of a single one



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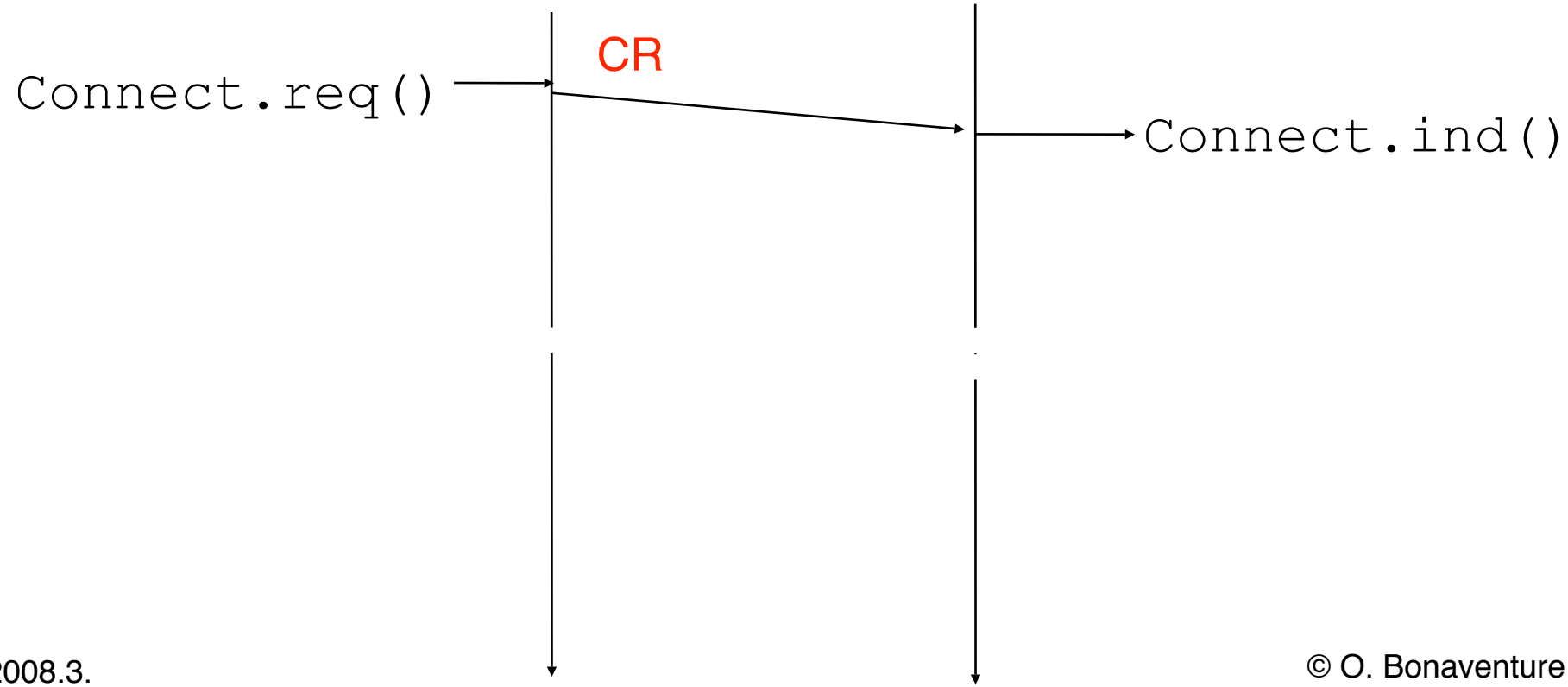

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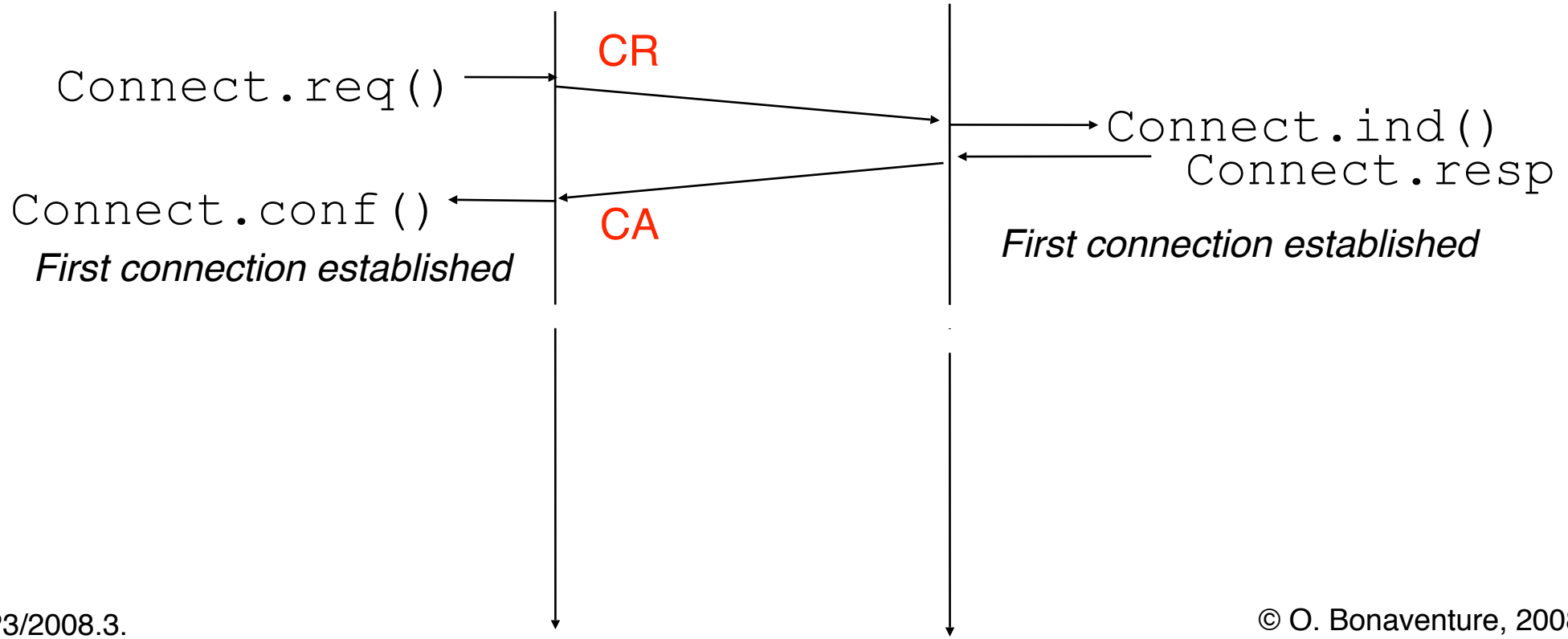

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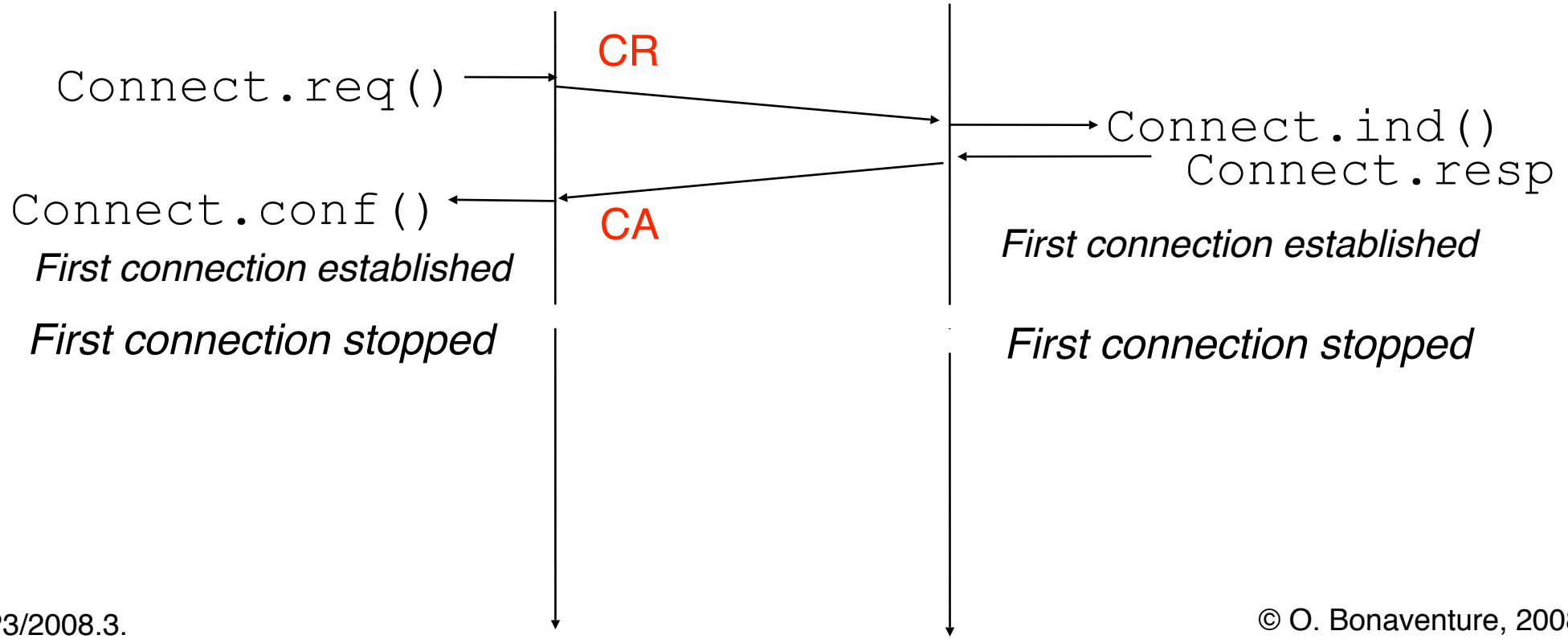

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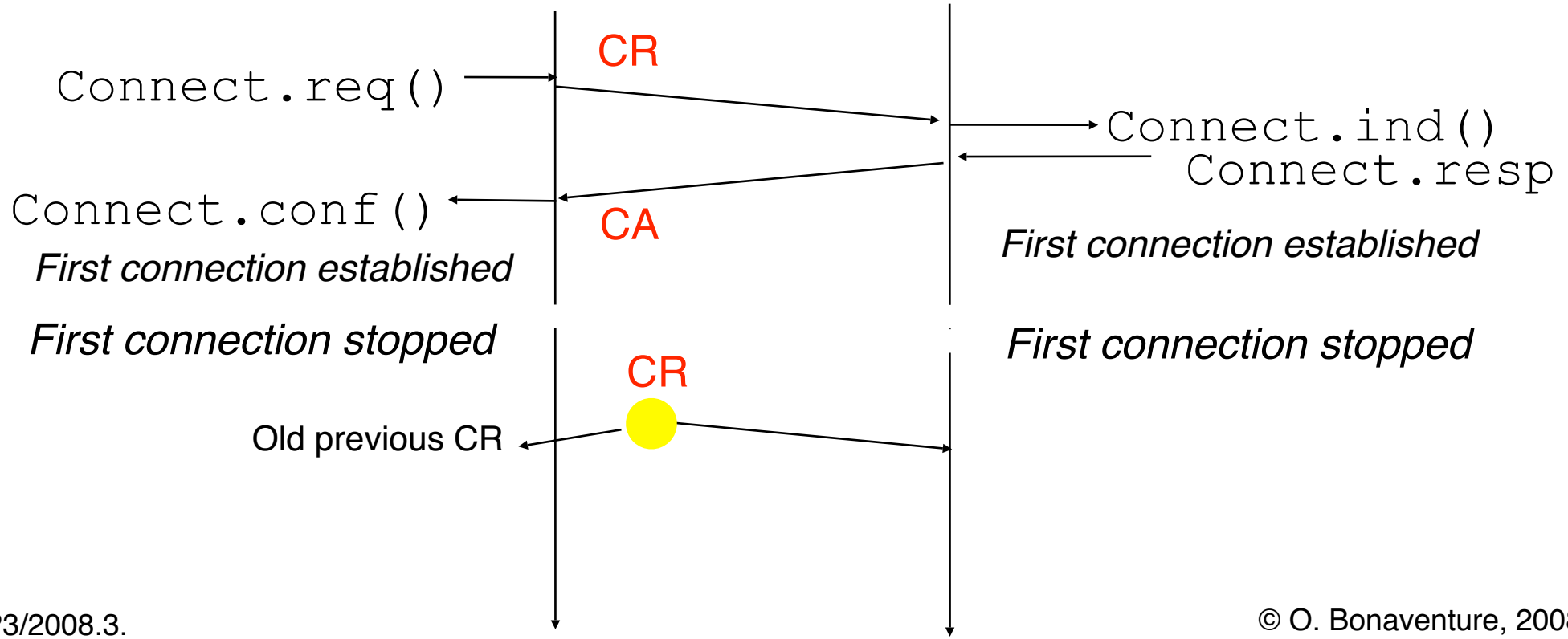

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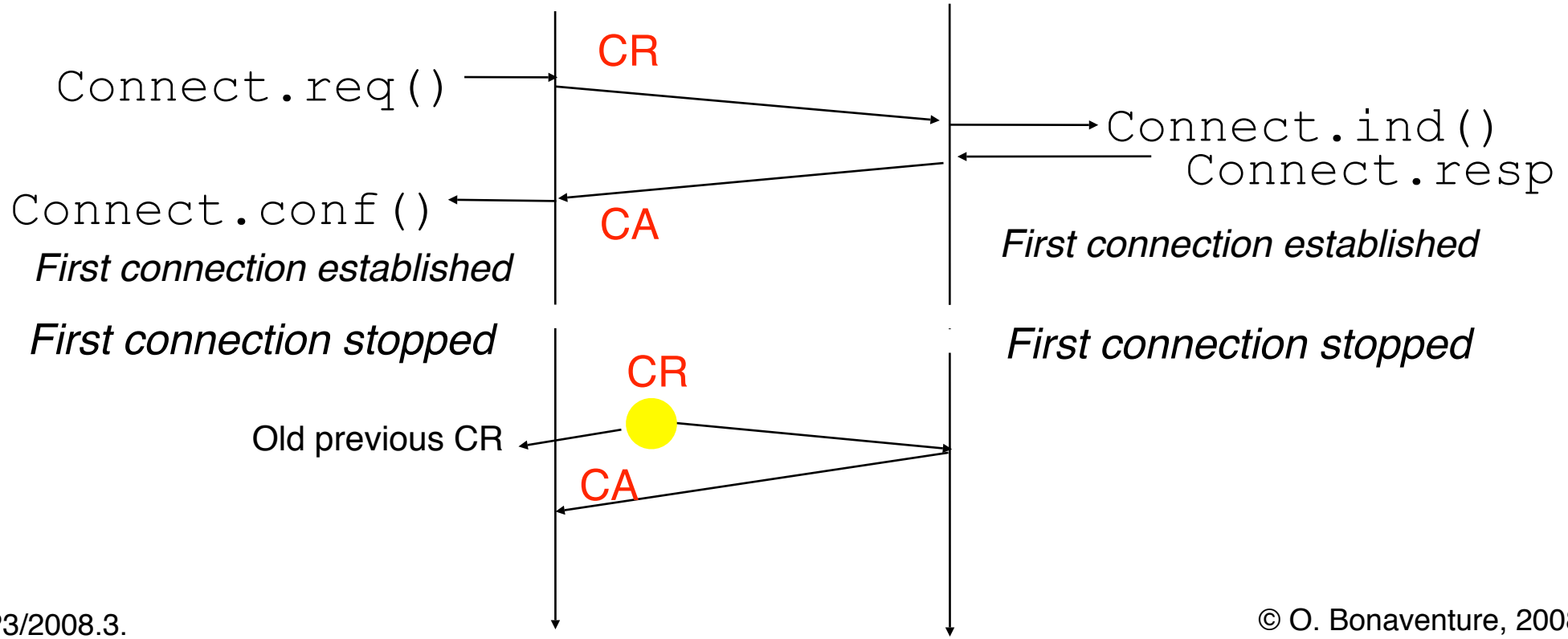

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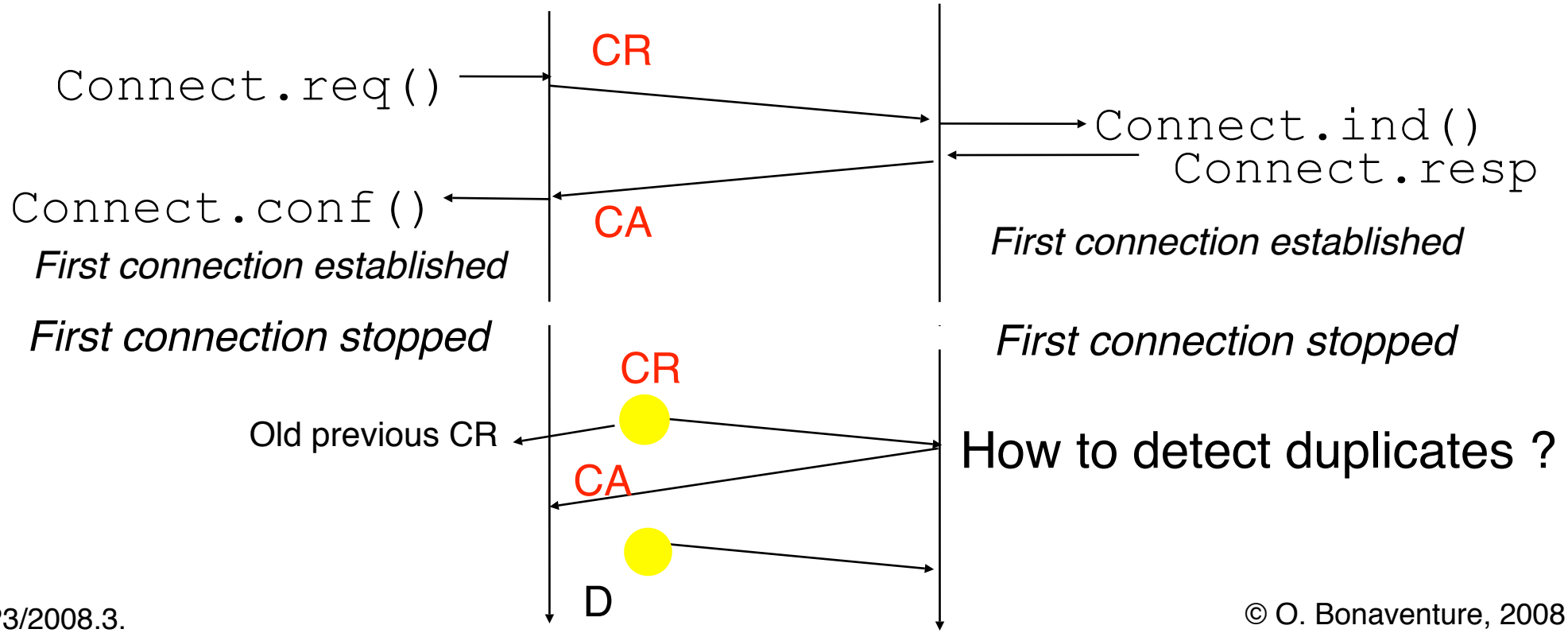


Connection establishment (2)

How to detect duplicates ?

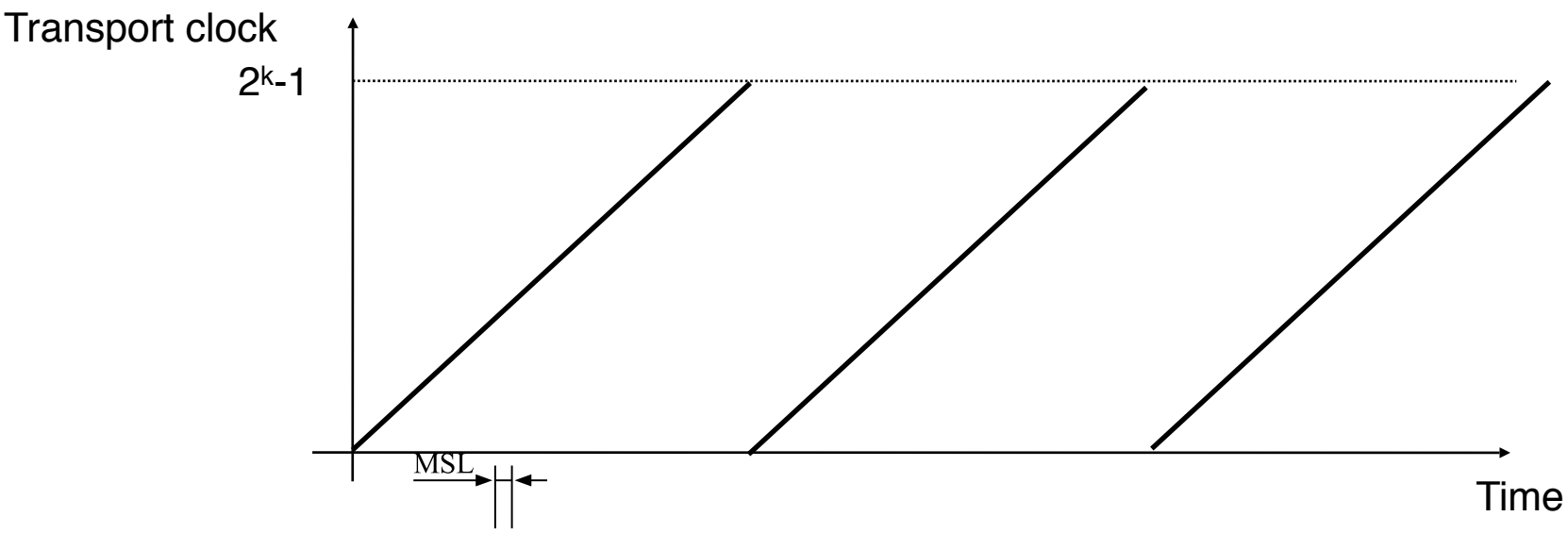
Principles

- The network layer guarantees by its protocols and internal organisation that a packet and its duplicates will not live forever inside the network
  - No packet will survive more than MSL seconds inside the network
- Transport entities rely on a local clock to detect duplicated connection establishment requests

Connection establishment (3)

Transport clock

- Maintained by each transport entity
  - usually implemented as a k-bits counter
    - 2^k * clock cycle >> MSL
  - Must continue to count even if the transport entity stops or reboots
  - Transport clocks are not synchronised
    - neither with other transport clocks nor with realtime



Three way handshake

Host A

Host B

Three way handshake

Host A

Host B

Sequence number x read
from local transport clock

Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Three way handshake

Host A

Host B

Sequence number x read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Sequence number y read from
local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

CA (seq=y, ack=x)

Three way handshake

Host A

Host B

Sequence number x read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Sequence number y read from
local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

CA (seq=y, ack=x)

Received CA acknowledges CR
Send CA to ack received CA
Local state :
Connection to B :
- established
- current_seq = x

CA (seq=x, ack=y)

Connection established

Three way handshake

Host A

Host B

Sequence number x read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Sequence number y read from
local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

CA (seq=y, ack=x)

Received CA acknowledges CR
Send CA to ack received CA
Local state :
Connection to B :
- established
- current_seq = x

Connection established

CA (seq=x, ack=y)

Local state :
Connection to A :
- established
- current_seq=y

Connection established

Three way handshake

Host A

Host B

Sequence number x read from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Sequence number y read from local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

CA (seq=y, ack=x)

Received CA acknowledges CR
Send CA to ack received CA
Local state :
Connection to B :
- established
- current_seq = x

Connection established

CA (seq=x, ack=y)

Local state :
Connection to A :
- established
- current_seq=y

Connection established

D(x)

The sequence numbers used for the data segments will start from x

Three way handshake

Host A

Host B

Sequence number x read from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (x)
- Start retransmission timer

CR (seq=x)

Sequence number y read from local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

CA (seq=y, ack=x)

Received CA acknowledges CR
Send CA to ack received CA
Local state :
Connection to B :
- established
- current_seq = x

Connection established

CA (seq=x, ack=y)

Local state :
Connection to A :
- established
- current_seq=y

Connection established

D(x)

The sequence numbers used for the data segments will start from x

D(y)

The sequence numbers used for the data segments will start from y

Three way handshake (2)

What happens with duplicates

Duplicate CR

Host A

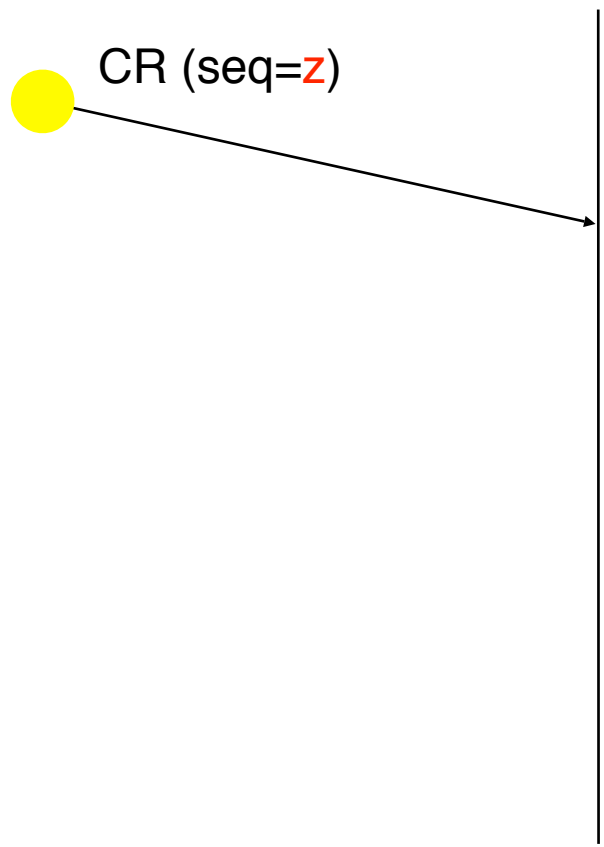
Host B

Three way handshake (2)

What happens with duplicates

Duplicate CR

Host A



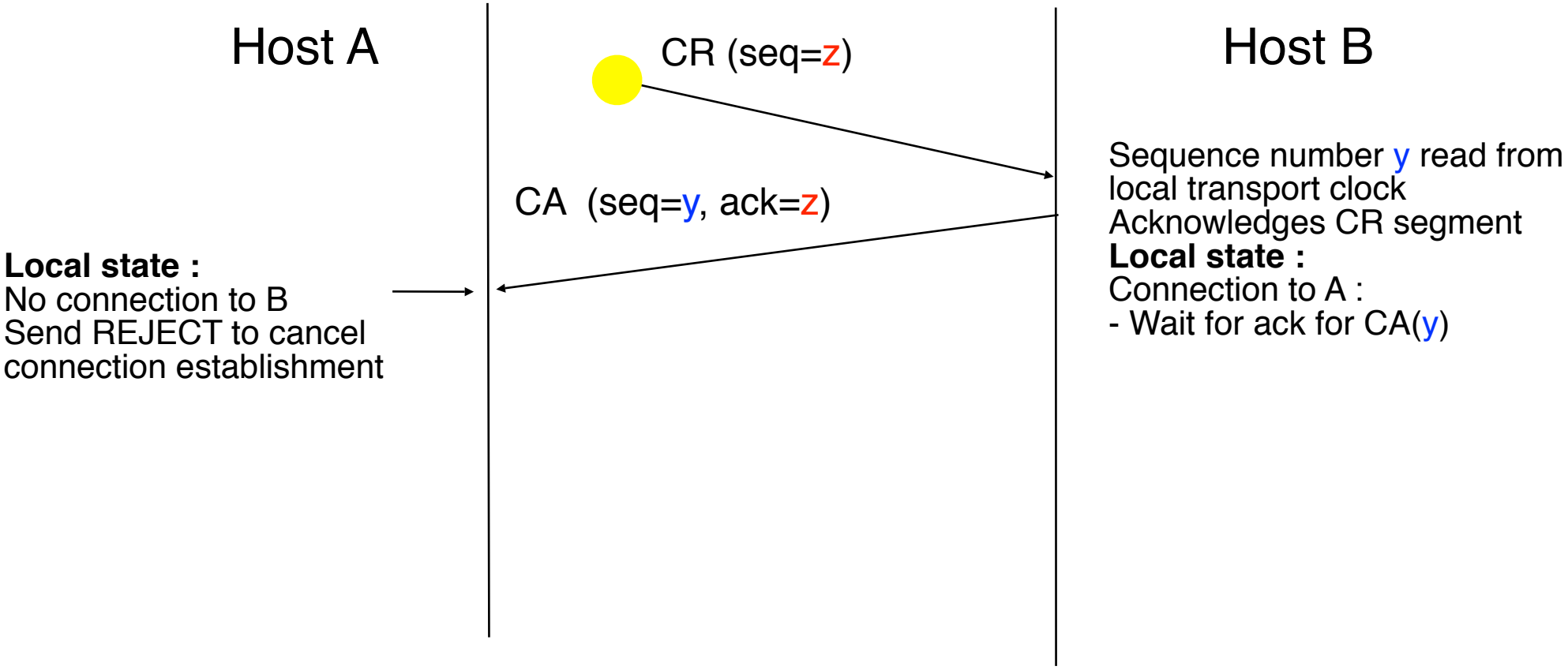
Host B

Sequence number y read from local transport clock
Acknowledges CR segment
Local state :
Connection to A :
- Wait for ack for CA(y)

Three way handshake (2)

What happens with duplicates

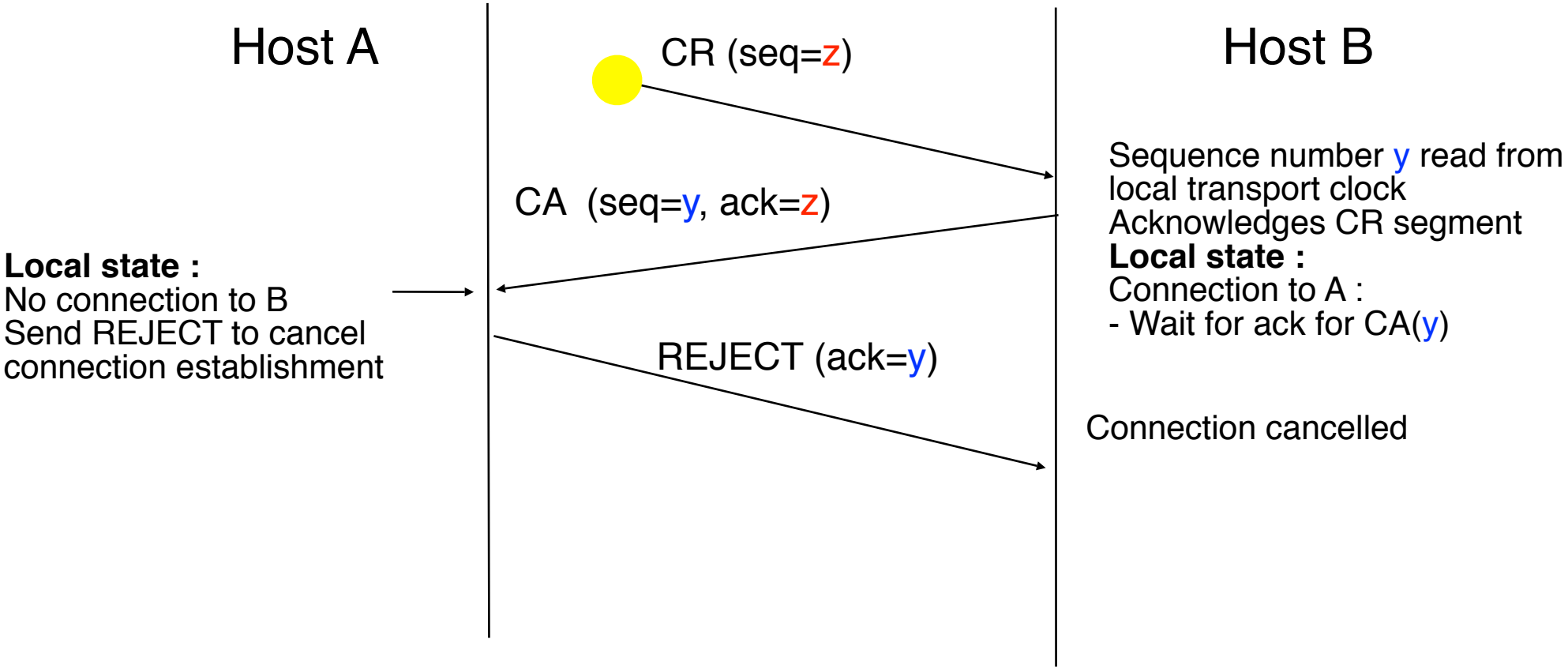
Duplicate CR



Three way handshake (2)

What happens with duplicates

Duplicate CR



No connection is established

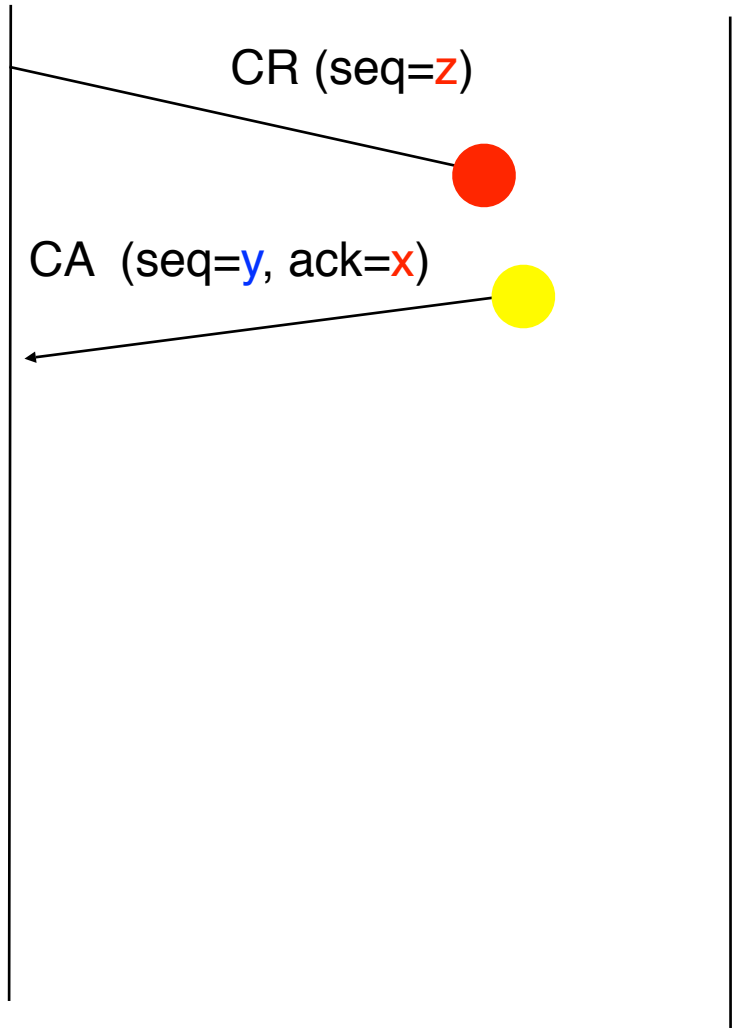
Three way handshake (3)

Host A

Host B

Sequence number z read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (z)
- Start retransmission timer

Current state does not contain
a CR with seq=x



Three way handshake (3)

Host A

Host B

Sequence number z read
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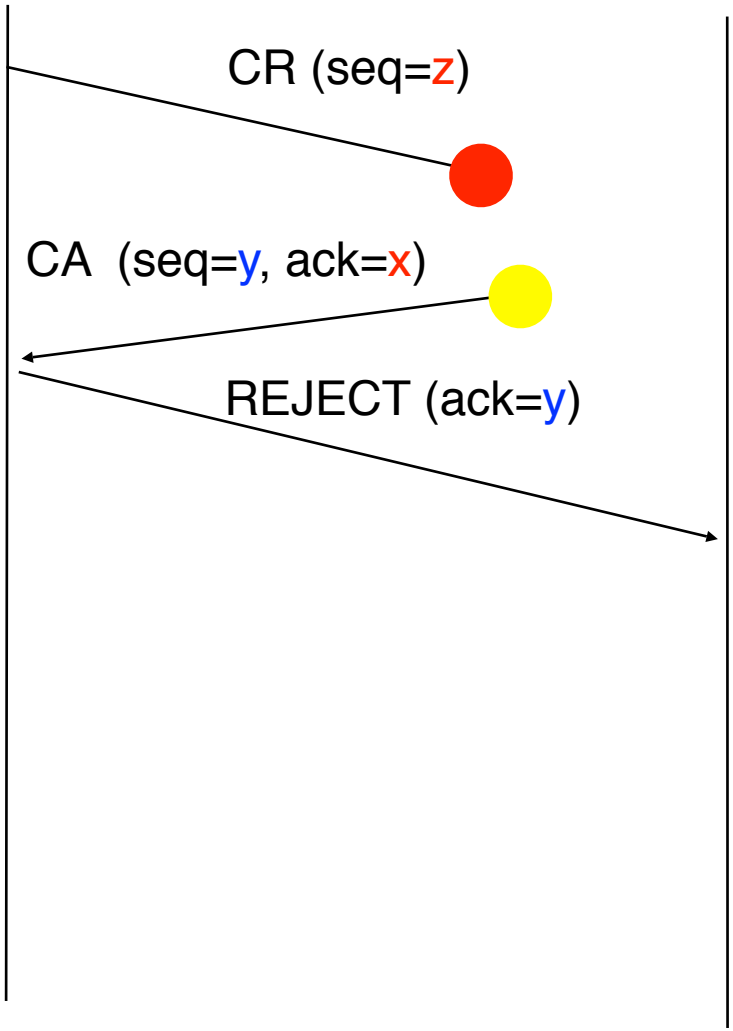
Local state :
Connection to B :
- Wait for ack for CR (z)
- Start retransmission timer

Current state does not contain
a CR with seq=x



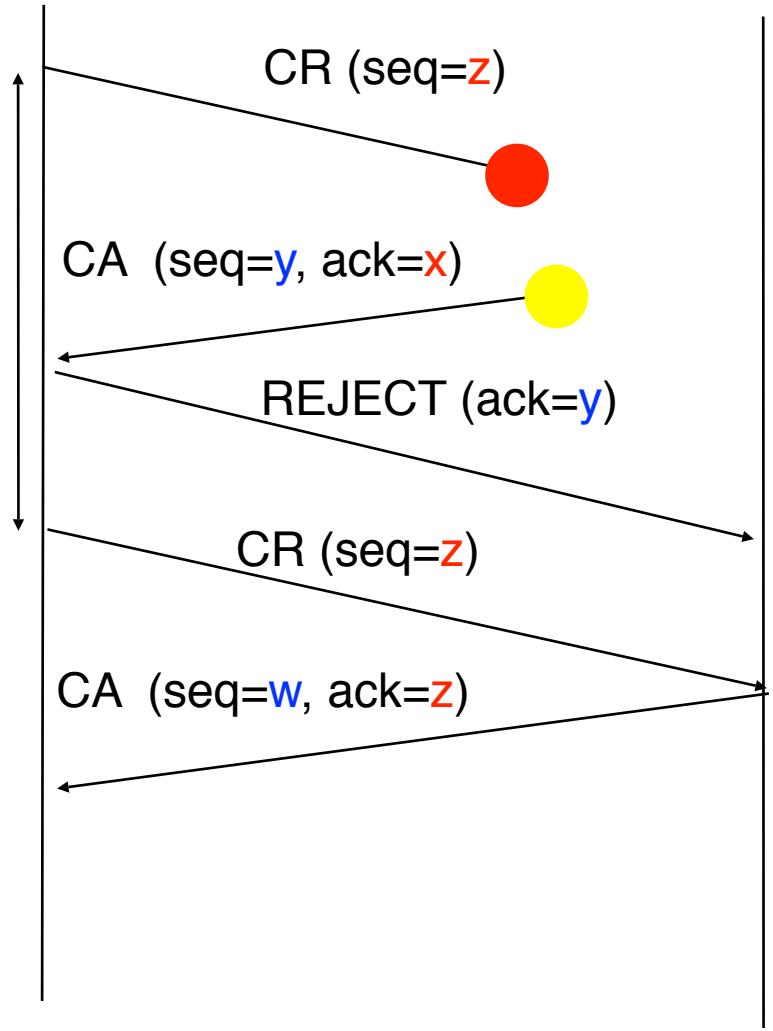
Current state does not contain
a segment with seq=y
REJECT ignored

Three way handshake (3)

Host A | Host B

Sequence number z read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (z)
- Start retransmission timer

Current state does not contain
a CR with seq=x



Retransmission timer
expires

Current state does not contain
a segment with seq=y
REJECT ignored

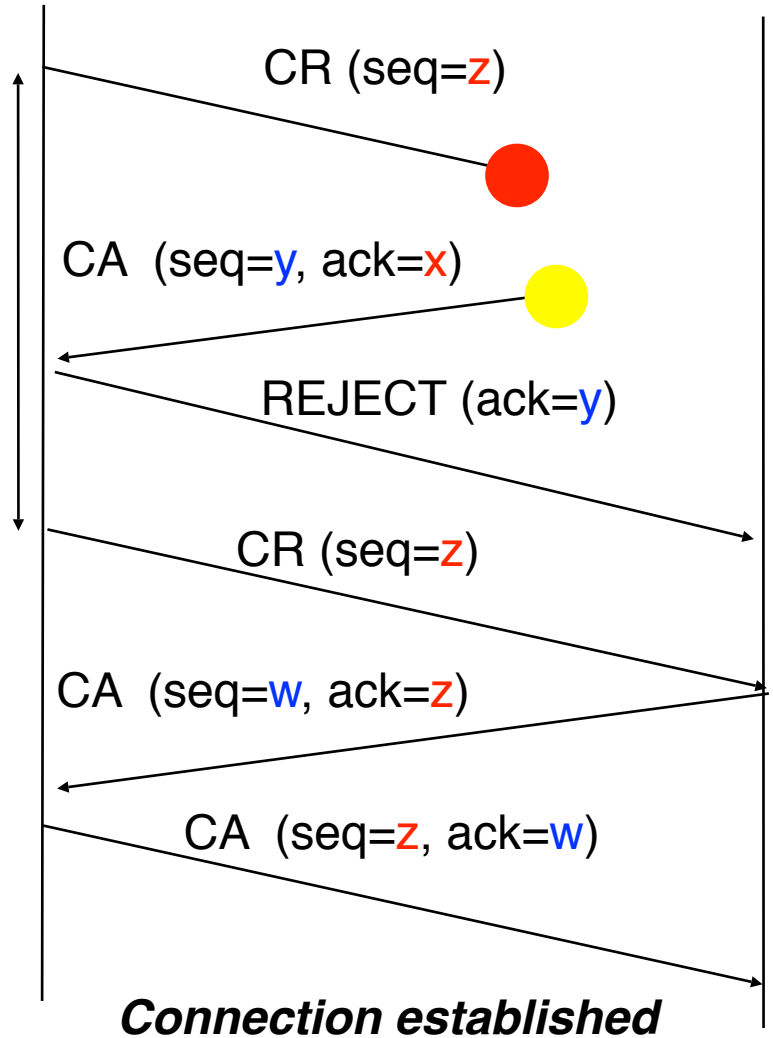
Sequence number w read from
local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(w)

Three way handshake (3)

Host A | Host B

Sequence number z read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (z)
- Start retransmission timer

Current state does not contain
a CR with seq=x



Retransmission timer
expires

Current state does not contain
a segment with seq=y
REJECT ignored

Received CA acknowledges CR
Send CA to ack received CA
Local state :
Connection to B :
- established
- current_seq = z

Sequence number w read from
local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(w)

Connection established

Three way handshake (4)

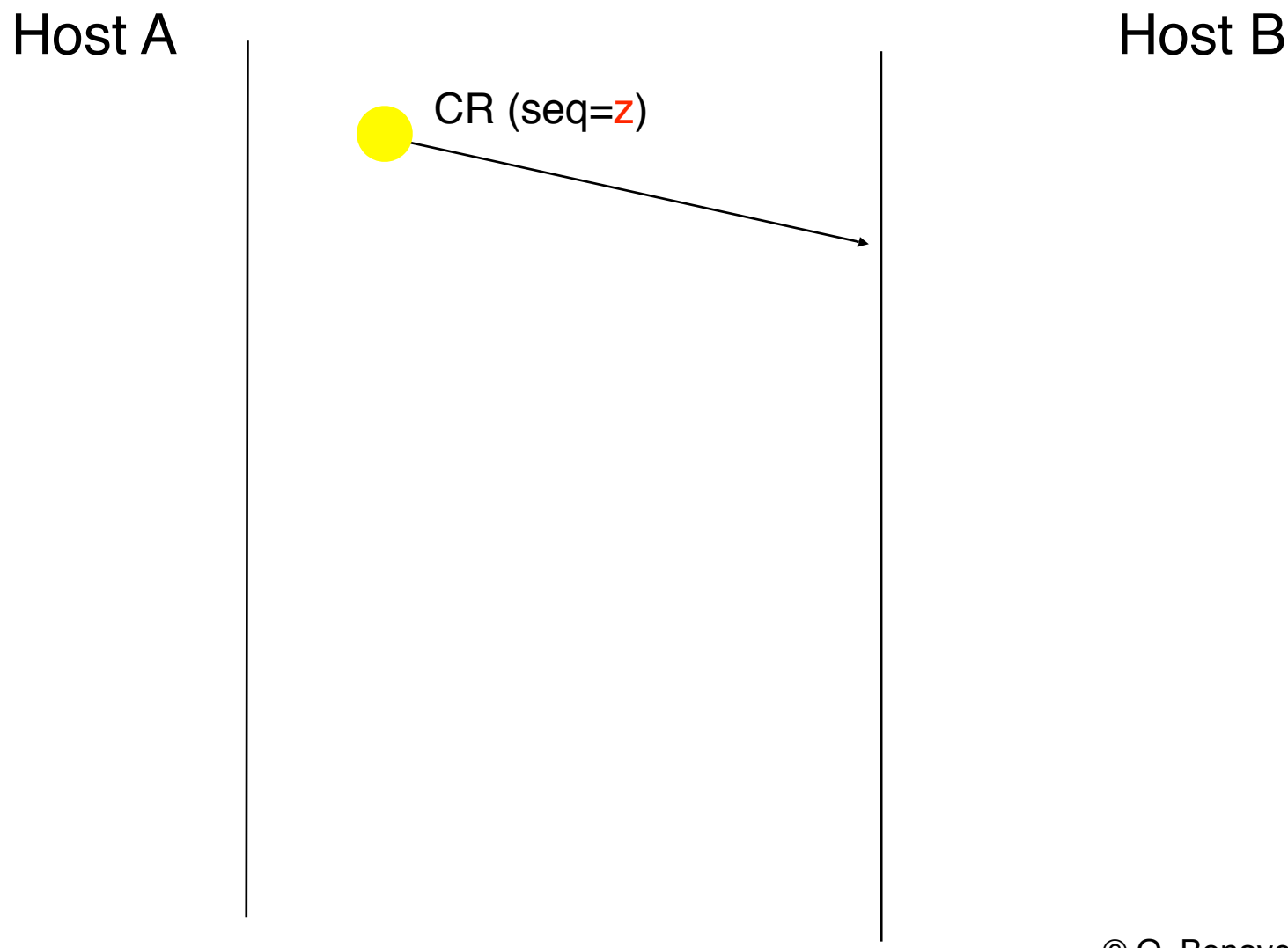
Another scenario

Host A

Host B

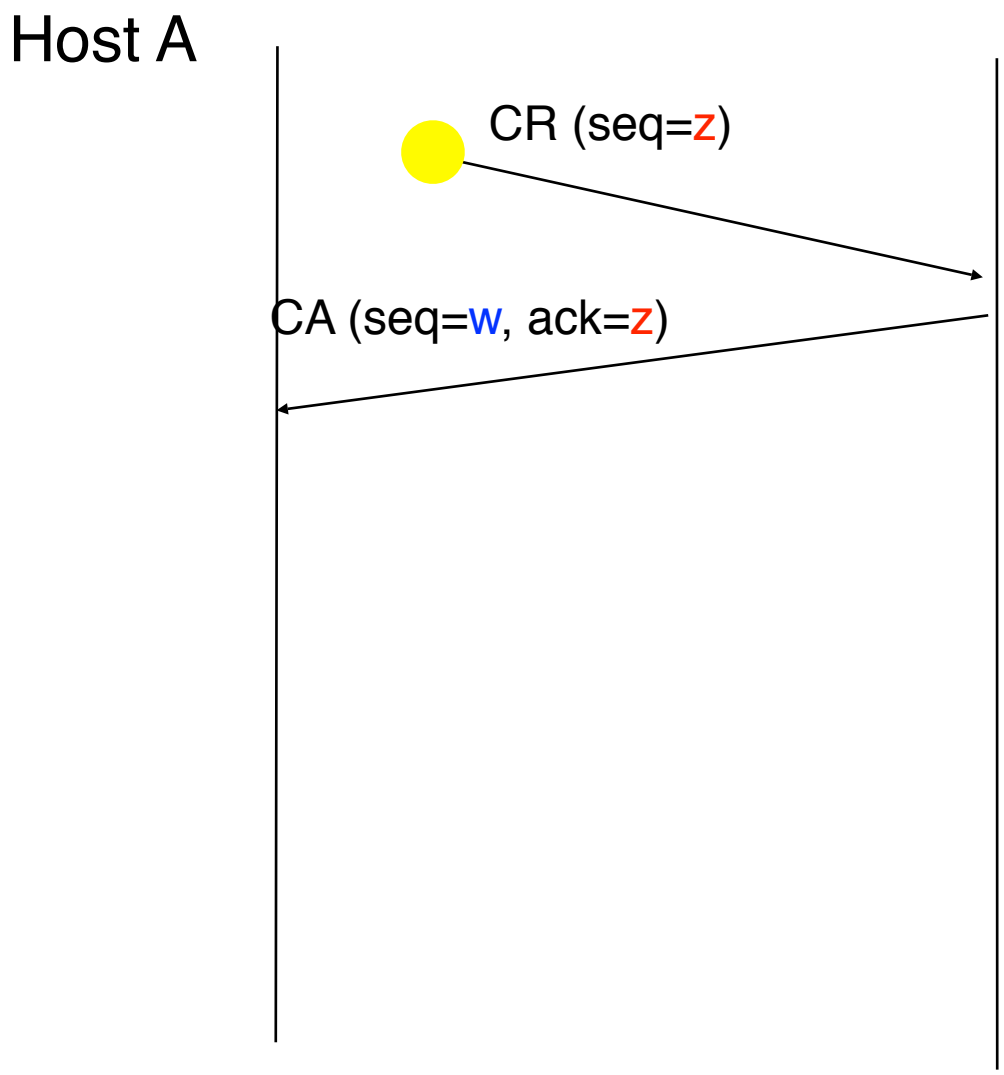
Three way handshake (4)

Another scenario



Three way handshake (4)

Another scenario



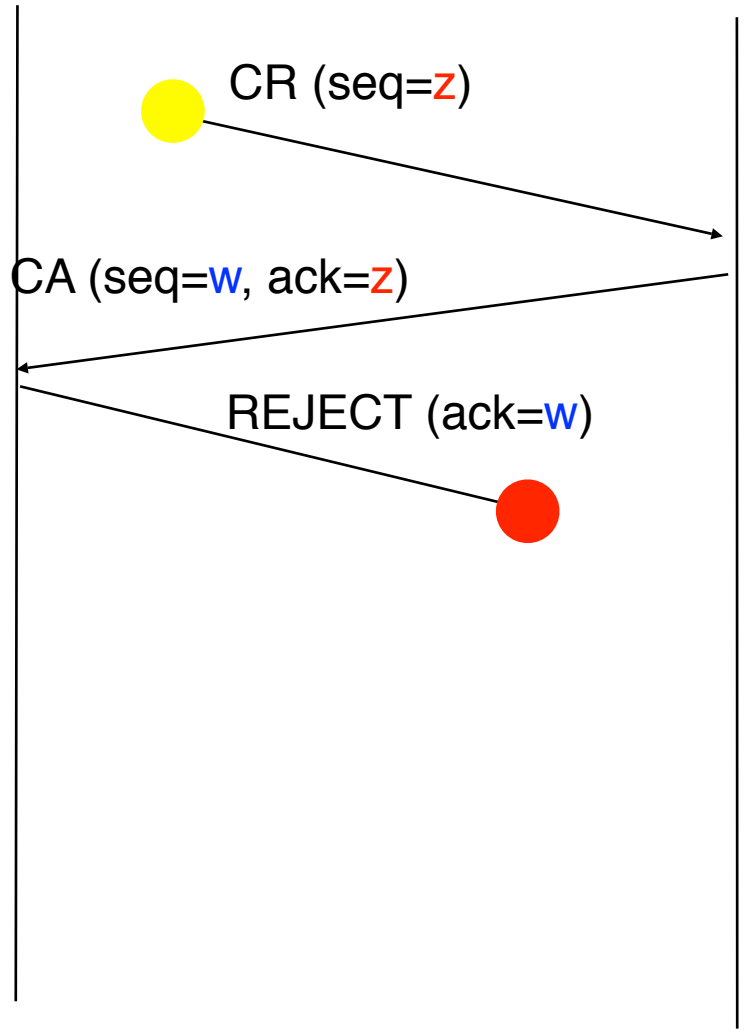
Sequence number w read from local transport clock
Acknowledges CR segment
Local state :
Connection to A :
- Wait for ack for CA(w)

Three way handshake (4)

Another scenario

Host A

Host B



Current state does not contain a CR with seq=z

Sequence number w read from local transport clock
Acknowledges CR segment
Local state :
Connection to A :
- Wait for ack for CA(w)

Three way handshake (4)

Another scenario

Host A

Host B

CR (seq=z)

Sequence number w read from local transport clock
Acknowledges CR segment
Local state :
Connection to A :
- Wait for ack for CA(w)

Current state does not contain a CR with seq=z

CA (seq=w, ack=z)

REJECT (ack=w)

CA (seq=z, ack=y)

Invalid CA received from A
Send REJECT

REJECT (ack=z)

No connection is established

Module 3 : Transport Layer

Basics

Building a reliable transport layer
- Reliable data transmission
- Connection establishment
- → Connection release

UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

Connection release

A transport connection can be used in both directions

Types of connection release

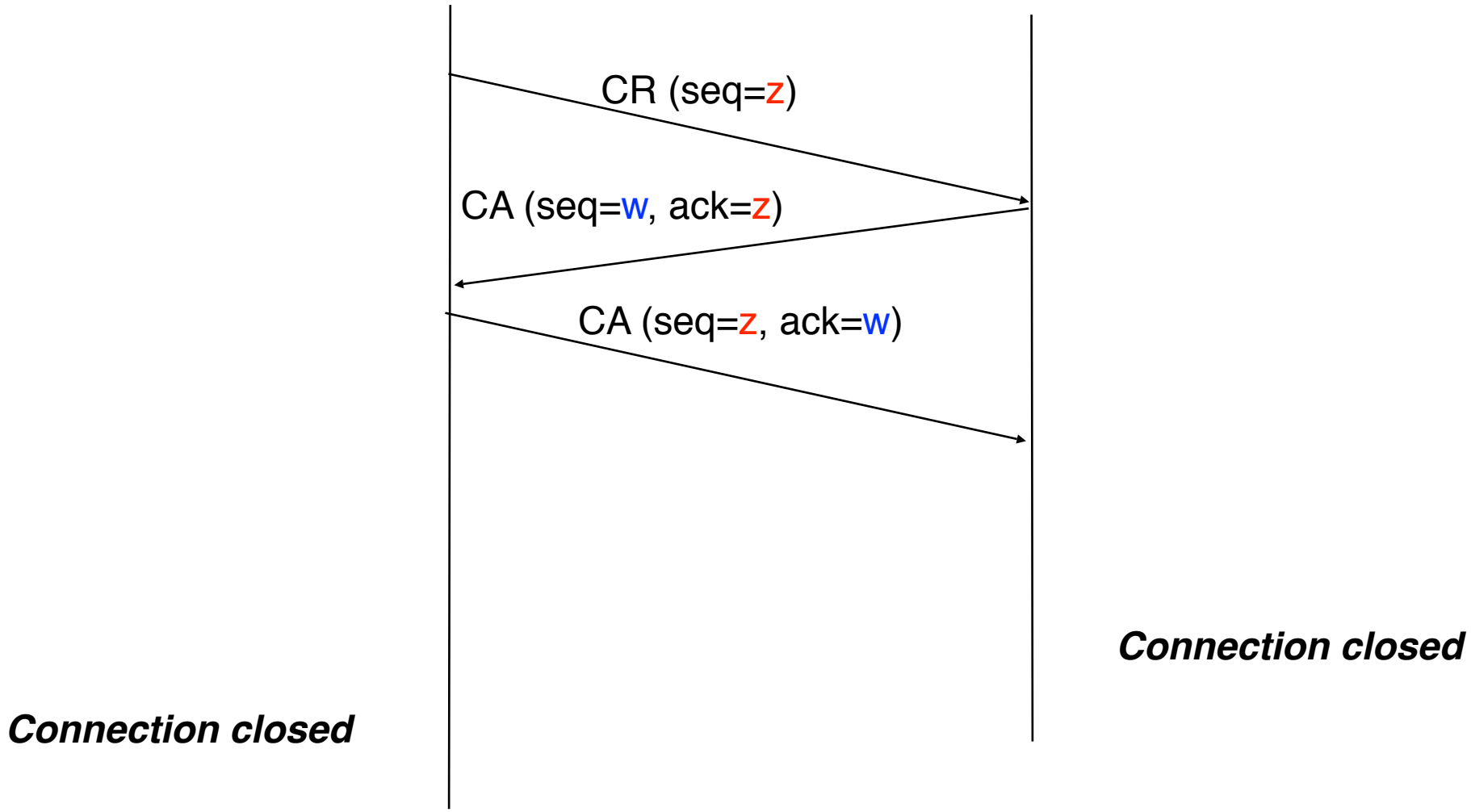
- Abrupt connection release
  - One of the transport entities closes both directions of data transfer
  - can lead to losses of data
- Graceful release
  - Each transport entity closes its own direction of data transfer
  - connection will be closed once all data has been correctly delivered

Abrupt release

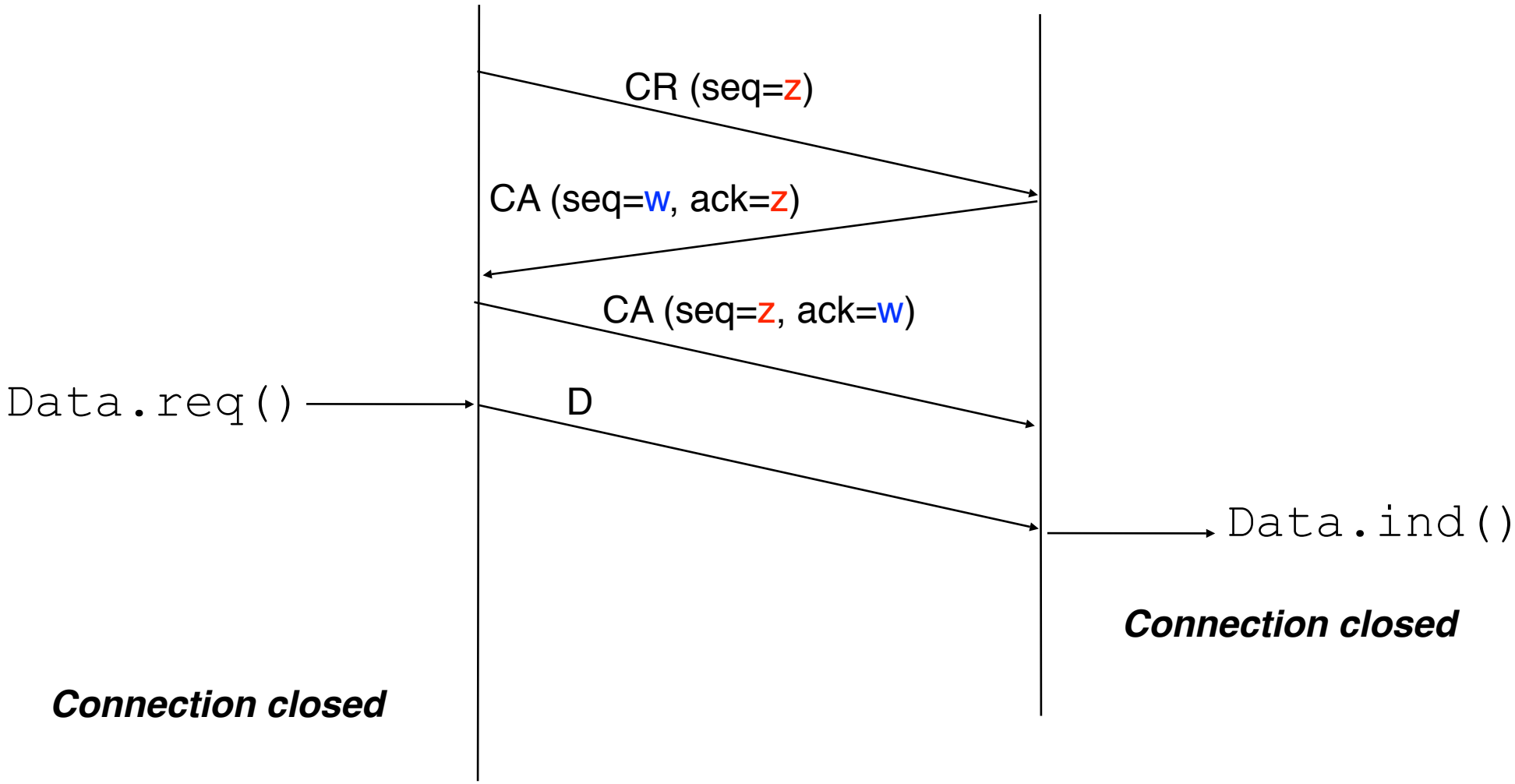
Connection closed

Connection closed

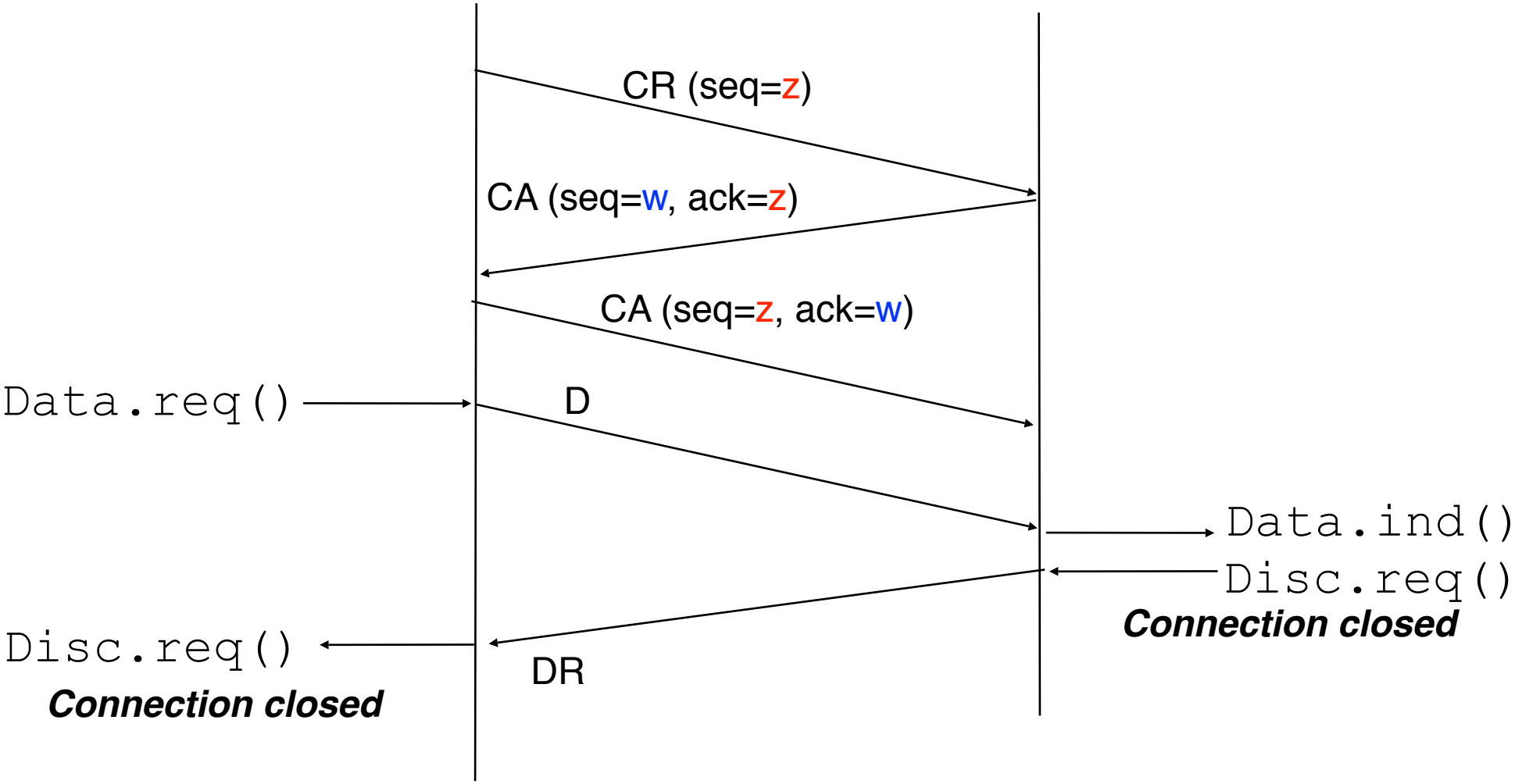
Abrupt release



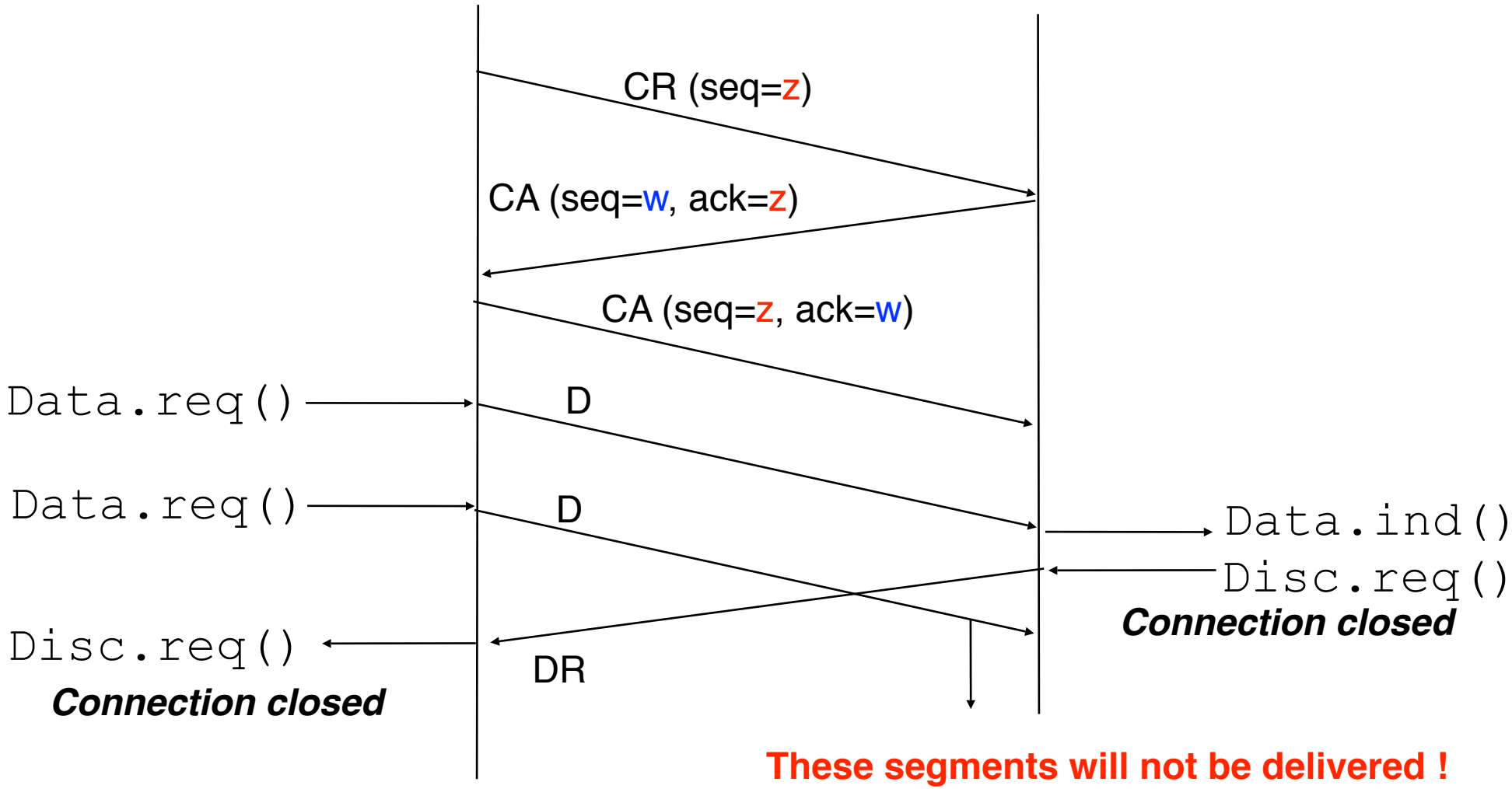
Abrupt release



Abrupt release



Abrupt release



Abrupt release (2)

A transport layer entity may itself be forced to release a transport connection

- the same data segment has been transmitted multiple times without receiving an acknowledgement
- the network layer reports that the destination host is not reachable anymore
- the transport layer entity does not have enough resources available to support this connection (e.g. not enough memory)

In this case, the transport layer entity will perform an abrupt disconnection

Graceful shutdown

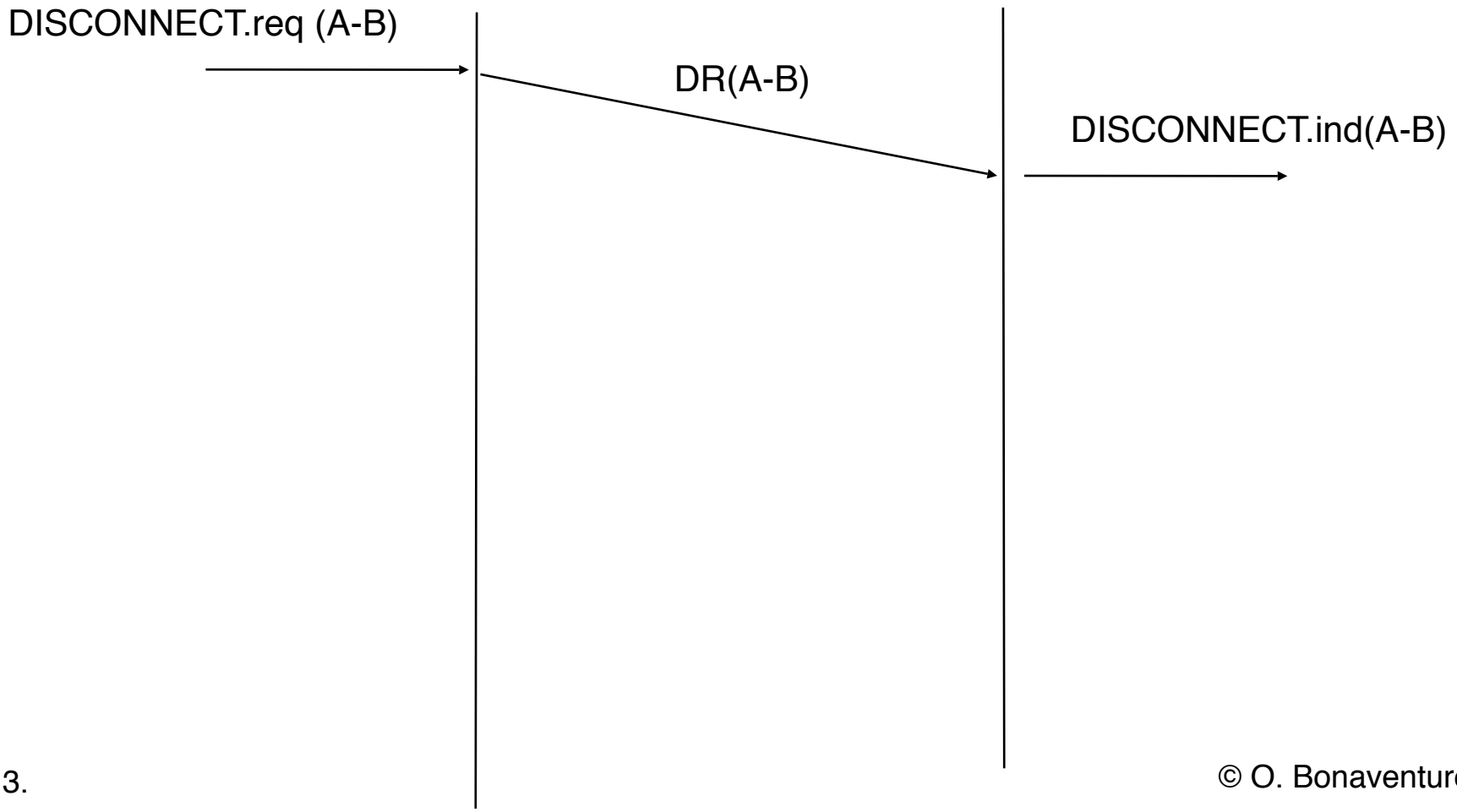
Principle

Each entity closes its own direction of data transfer once all its data have been sent

Graceful shutdown

Principle

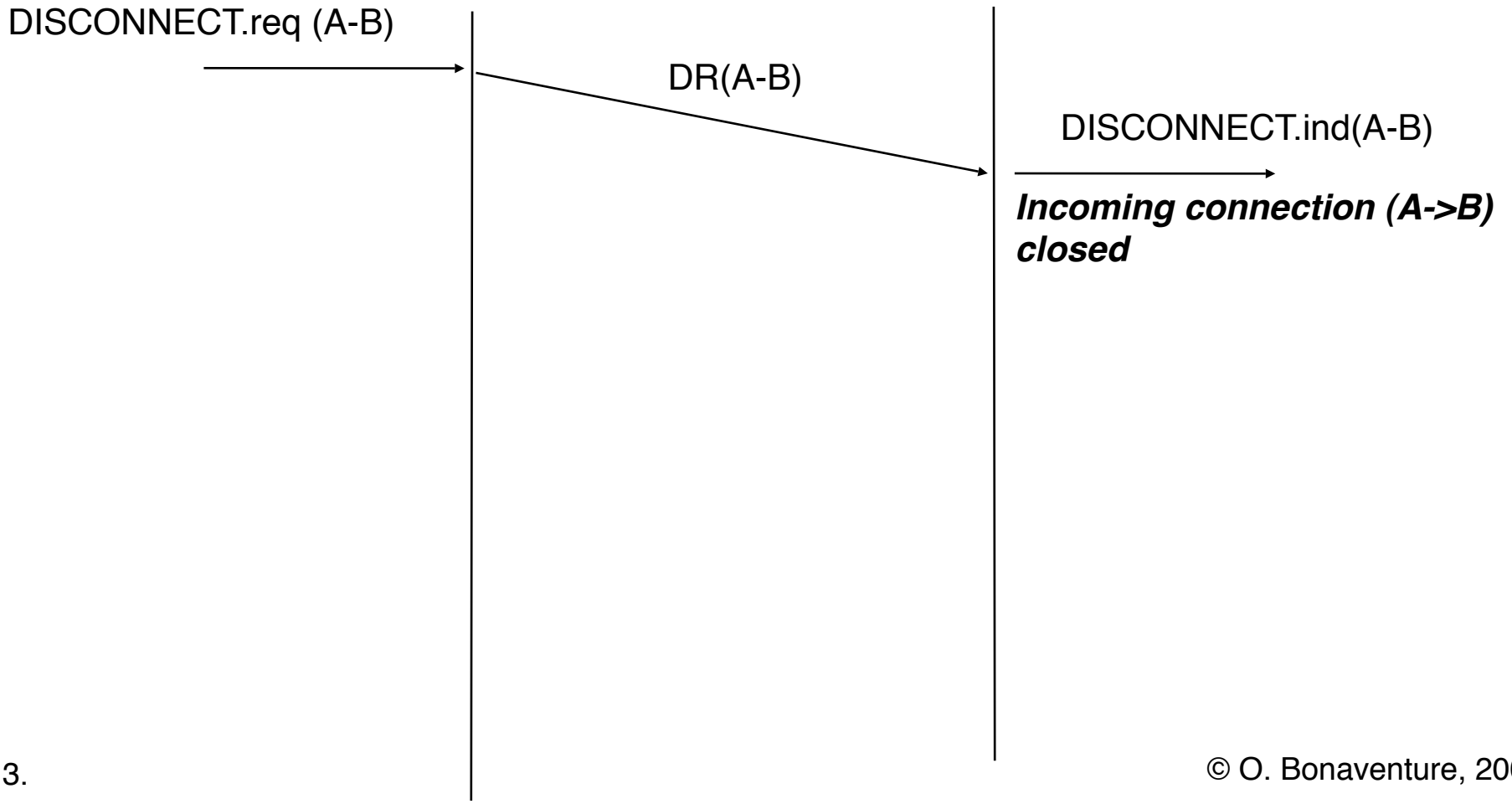
Each entity closes its own direction of data transfer once all its data have been sent



Graceful shutdown

Principle

Each entity closes its own direction of data transfer once all its data have been sent



Graceful shutdown

Principle

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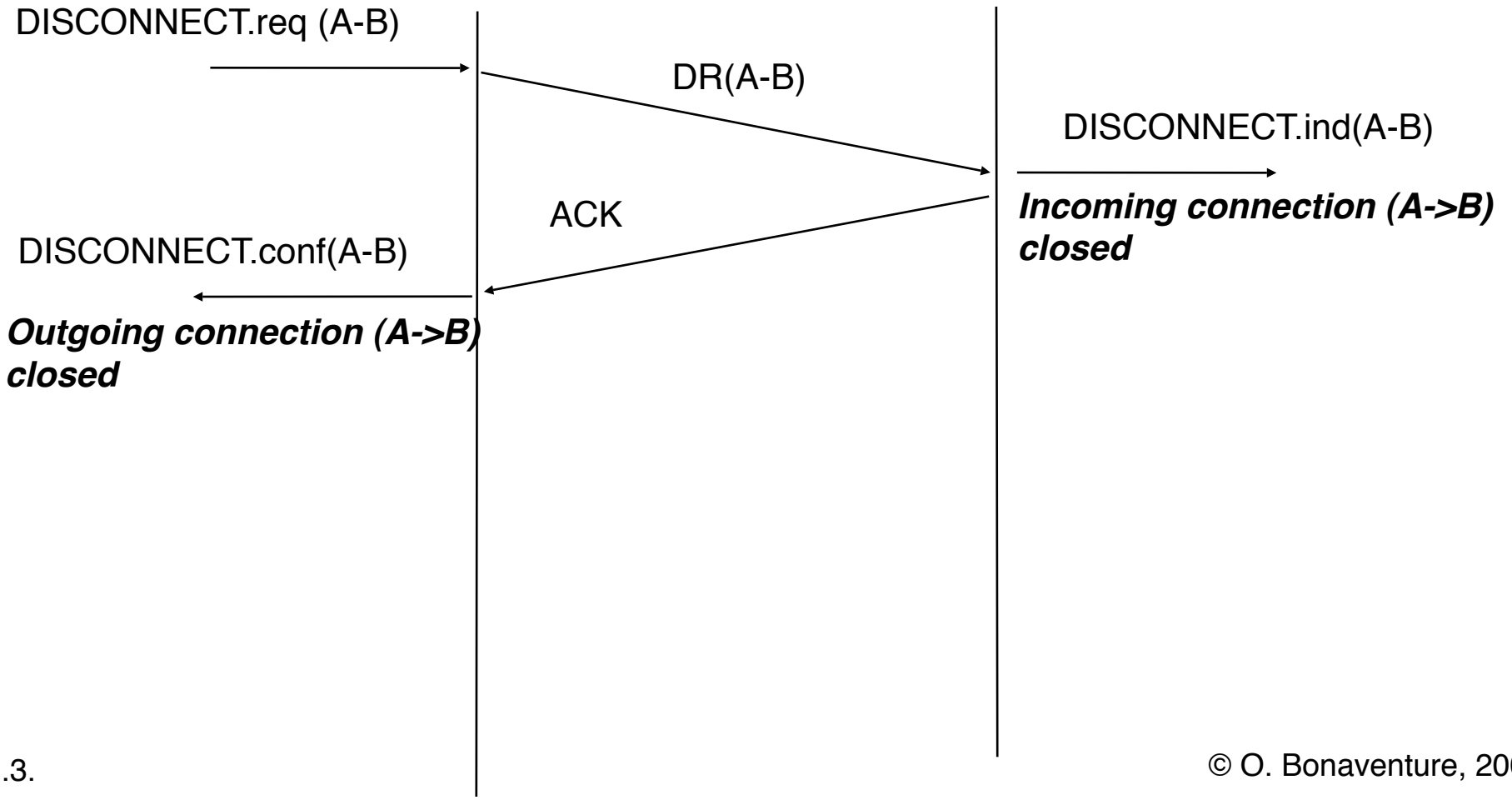

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Principle

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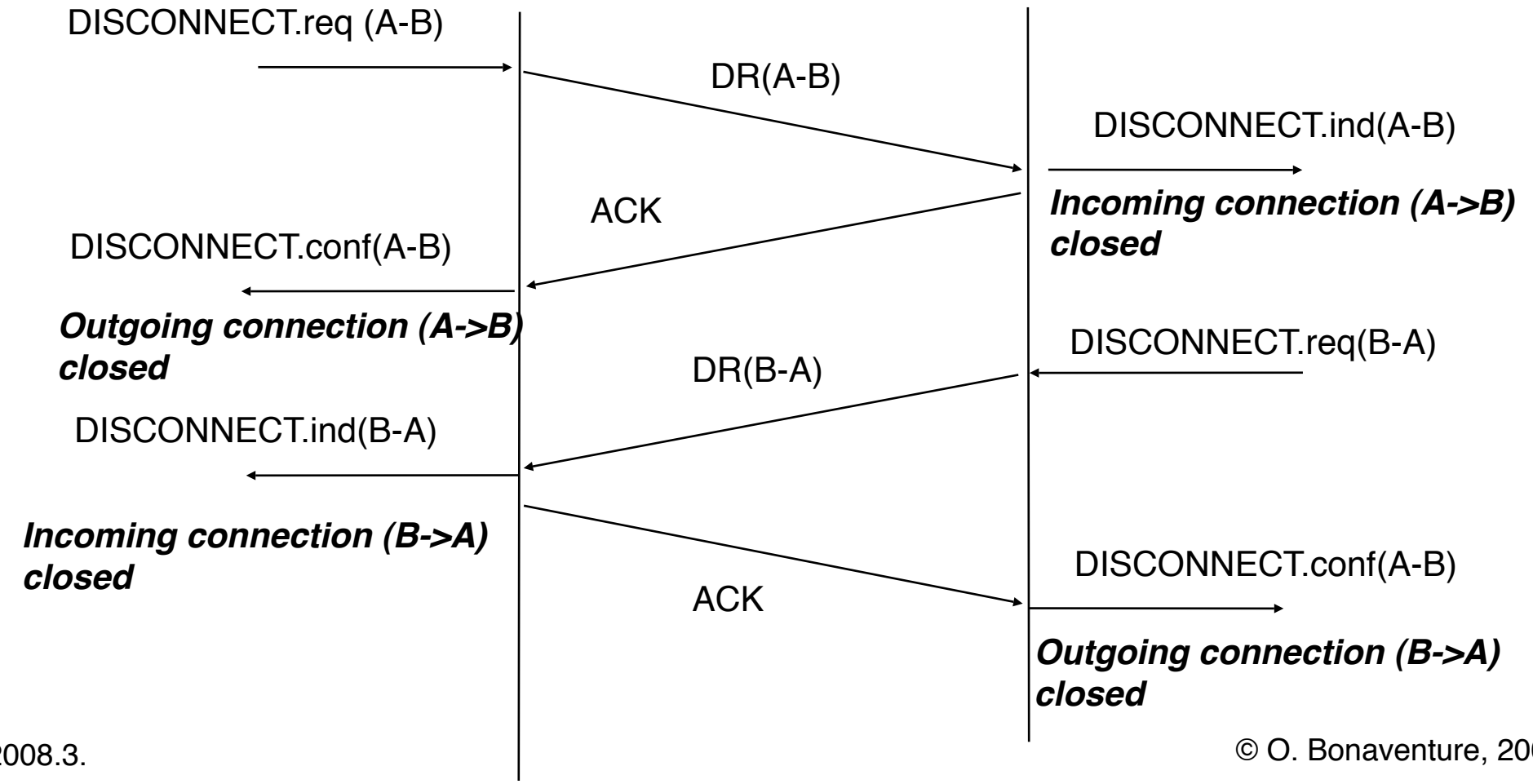


Reliability of the transport layer

- Limitations
  - Transport layer provides a reliable data transfer during the lifetime of the transport connection
    - If a connection is gracefully shutdown, then all the data sent of this connection have been received correctly
    - data transfer may be unreliable (e.g. loss of segments) if the connection is abruptly released
- Transport layer does not recover itself from abrupt connection releases
  - Possible solutions
    - Application reopens the connection and restarts the data transfer
    - Session Layer
    - Transaction processing

Module 3 : Transport layer

Basics

Building a reliable transport layer

→ UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

A simple transport protocol

User Datagram Protocol (UDP)

The simplest transport protocol

Goal

Allow applications to exchange small SDUs by relying on the IP service

- on most operating systems, sending raw IP packets requires special privileges while any application can use directly the transport service

Constraint

The implementation of the UDP transport entity should remain as simple as possible

UDP : design choices

Which mechanisms inside UDP ?

Application identification

Several applications running on the same host must be able to use the UDP service

Solution

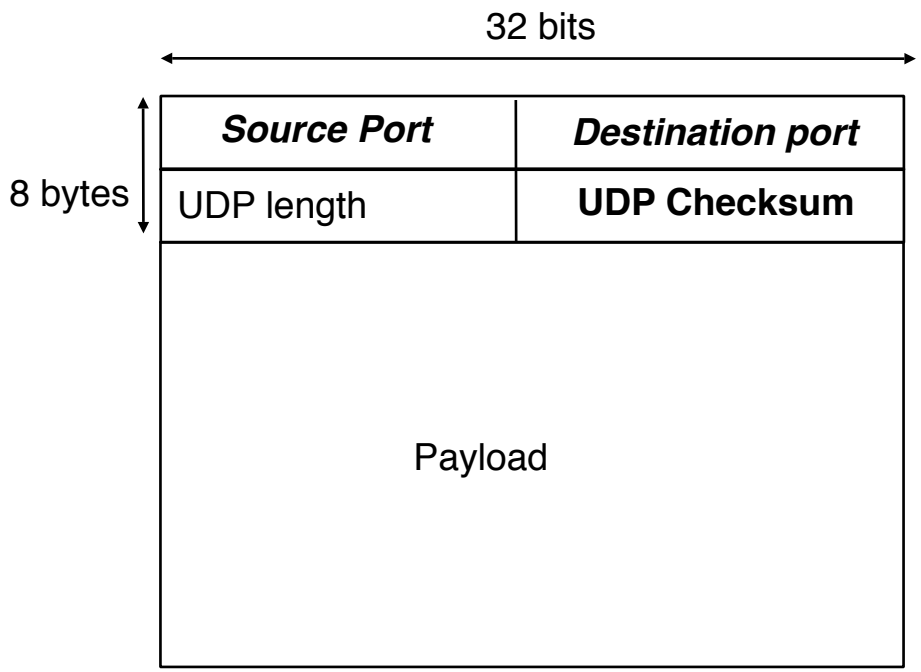
Source port to identify sending application
Destination port to identify receiving application
Each UDP segment contains both the source and the destination ports

Detection of transmission errors

UDP protocol

2 UDP entities exchange UDP segments

UDP segment format

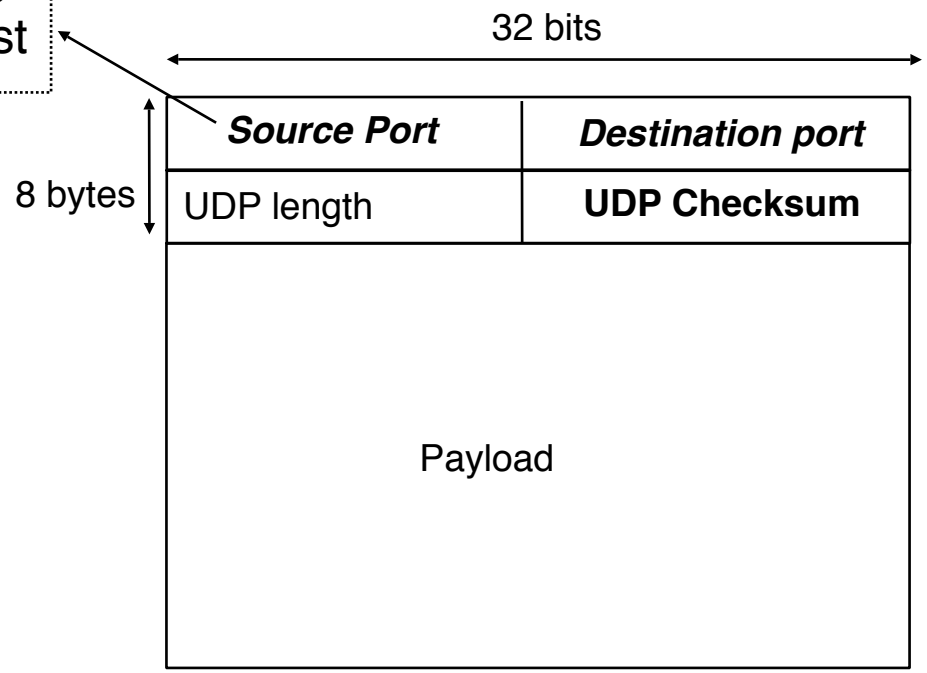


UDP protocol

2 UDP entities exchange UDP segments

UDP segment format

Used to identify the application that sent this segment on sending host



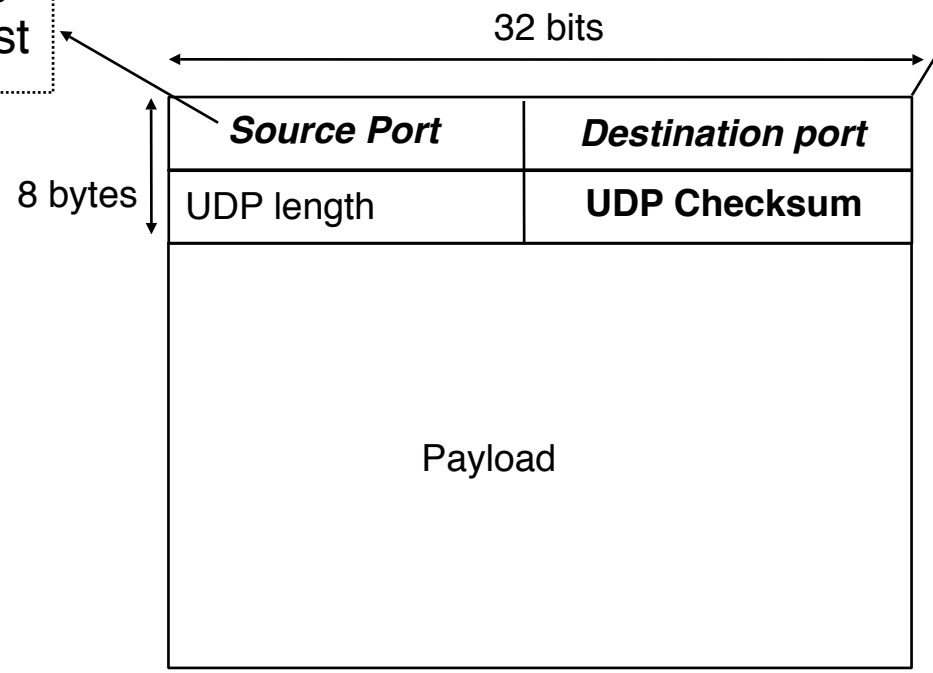
UDP protocol

2 UDP entities exchange UDP segments

UDP segment format

Used to identify the application that sent this segment on sending host

Used to identify the application that will receive this segment on destination host



UDP protocol

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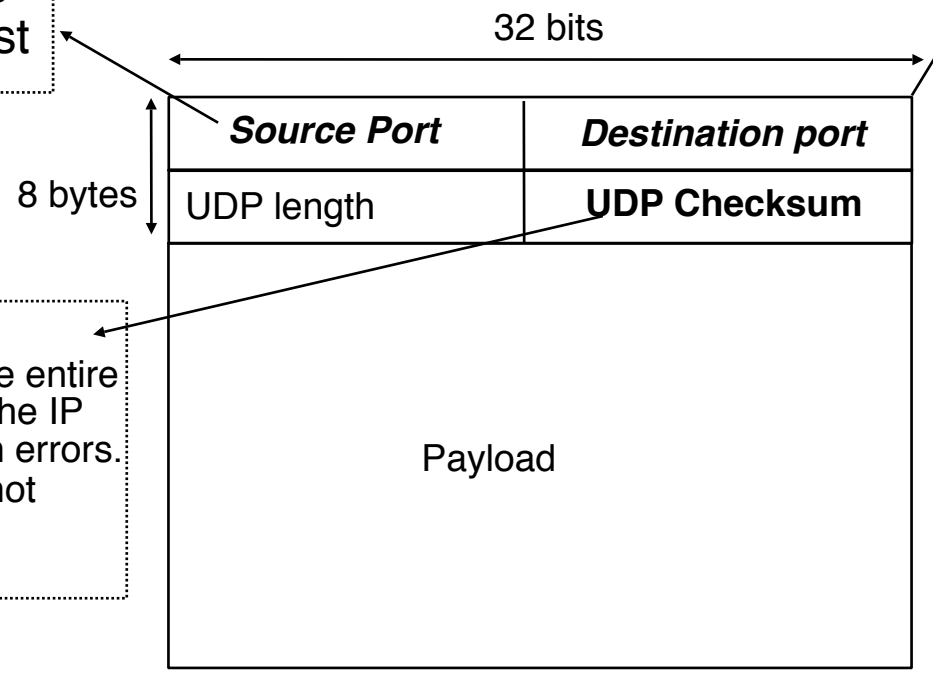

Checksum computed over the entire UDP segment and part of the IP header to detect transmission errors. 0 means that the sender did not compute a checksum.

UDP protocol

2 UDP entities exchange UDP segments

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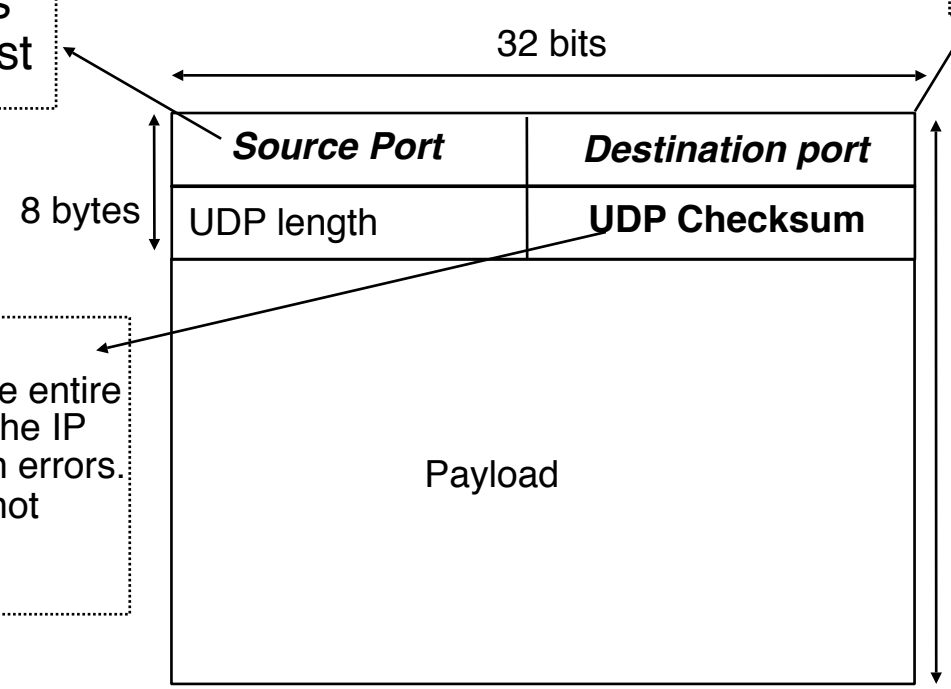
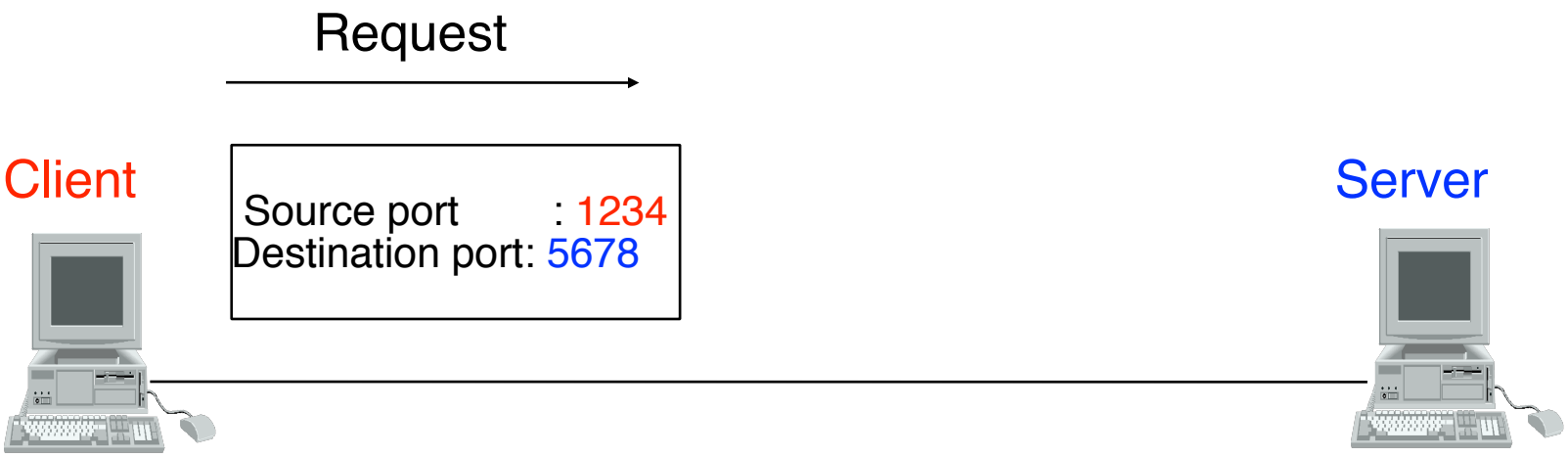


Checksum computed over the entire UDP segment and part of the IP header to detect transmission errors. 0 means that the sender did not compute a checksum.

Constraint
Each UDP segment must fit inside a single IP packet

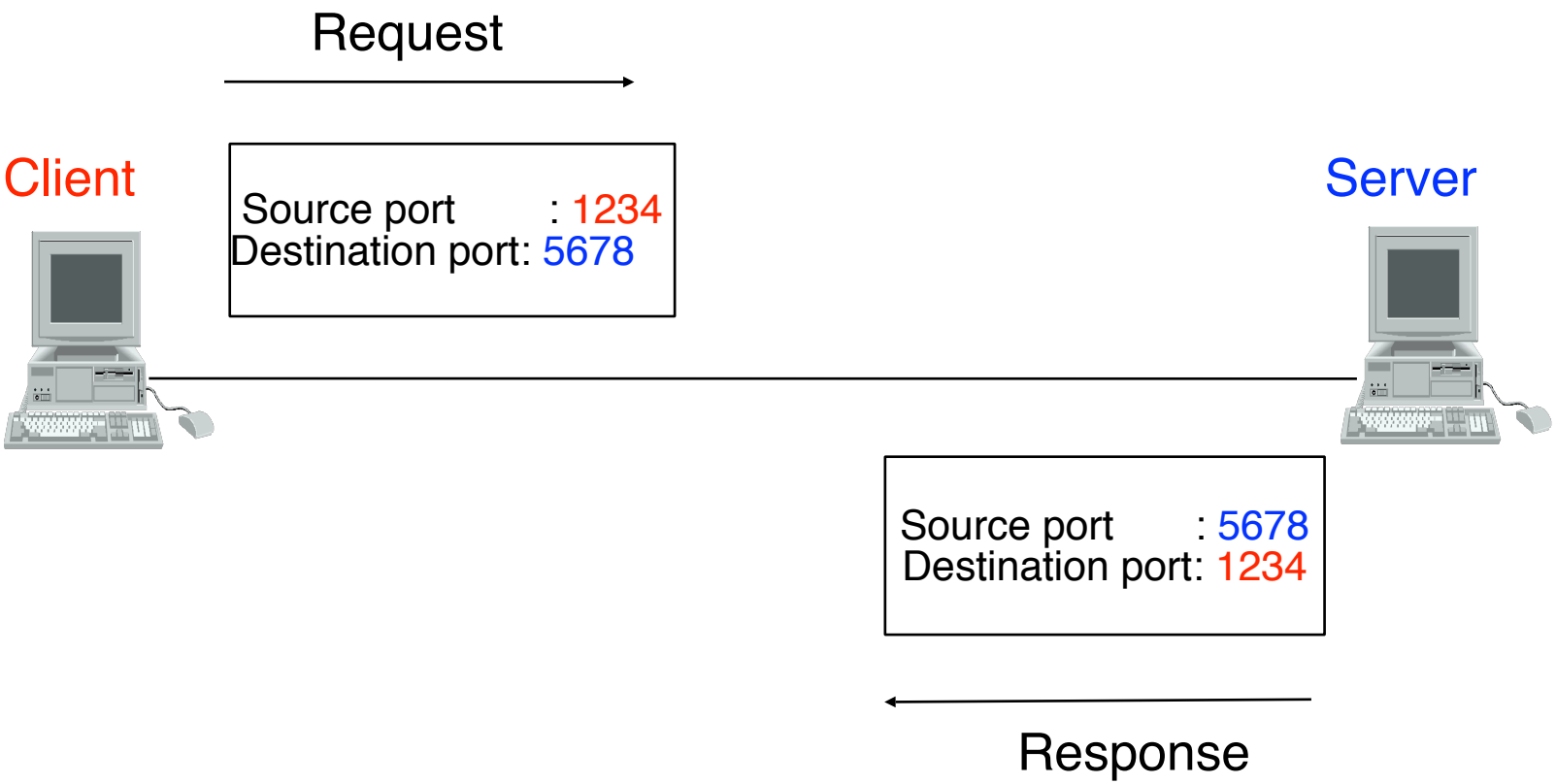
UDP Protocol (2)

Utilisation of the UDP ports



UDP Protocol (2)

Utilisation of the UDP ports



Limitations of the UDP service

Limitations

- Maximum length of UDP SDUs depends on maximum size of IP packets

- Unreliable connectionless service
  - SDUs can get lost but transmission errors will be detected

  - UDP does not preserve ordering

  - UDP does not detect nor prevent duplication

Usage of UDP

Request-response applications where requests and responses are short and short delay is required or used in LAN environments

- DNS
- Remote Procedure Call
- NFS
- Games

Multimedia transfer were reliable delivery is not necessary and retransmissions would cause too long delays

- Voice over IP
- Video over IP

Module 3 : Transport Layer

Basics

Building a reliable transport layer

UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

- TCP connection establishment
- TCP connection release
- Reliable data transfer
- Congestion control

TCP

Transmission Control Protocol

Provides a reliable byte stream service

Characteristics of the TCP service

- TCP connections
- Data transfer is reliable
  - no loss
  - no errors
  - no duplications
- Data transfer is bidirectional
- TCP relies on the IP service
- TCP only supports unicast

TCP connection

How to identify a TCP connection

- Address of the source application
  - IP Address of the source host
  - TCP port number of the application on source host
- Address of the destination application
  - IP Address of the destination host
  - TCP port number of the application on destination host

Each TCP segment contains the identification of the connection it belongs to

TCP connection (2)

Usage of TCP port numbers

Request

Client : C

Source Port : 1234
Destination Port: 5678

Server : S

Source Port : 5678
Destination Port: 1234

Response

Established TCP connections on client

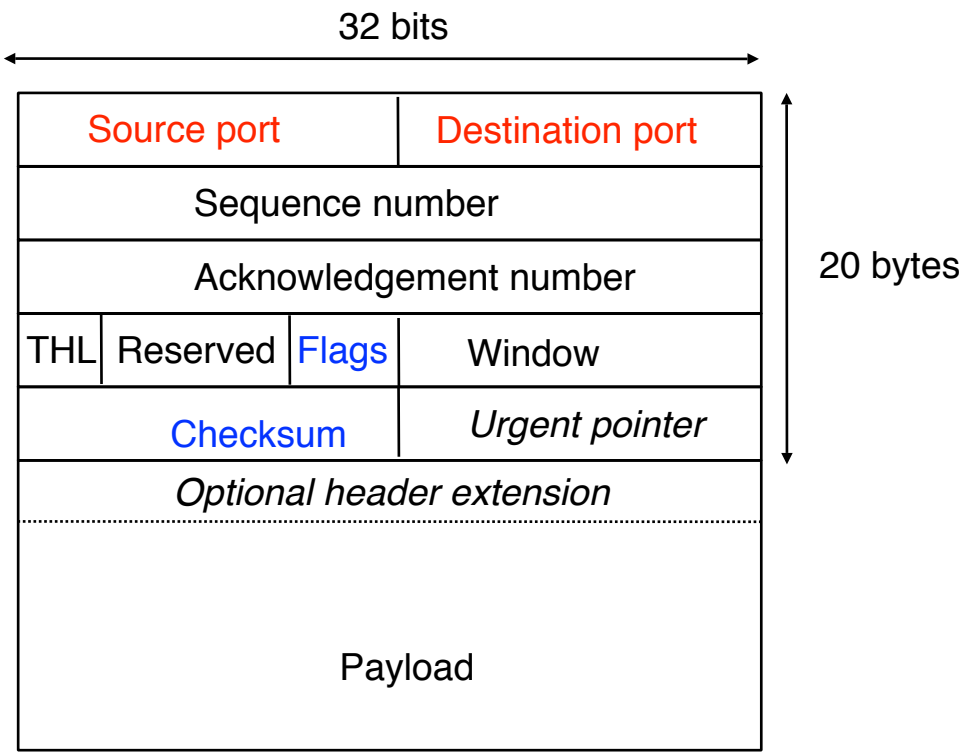
Local IP	Remote IP	Local Port	Remote Port
C	S	1234	5678

Established TCP connections on server

Local IP	Remote IP	Local Port	Remote Port
S	C	5678	1234

TCP protocol

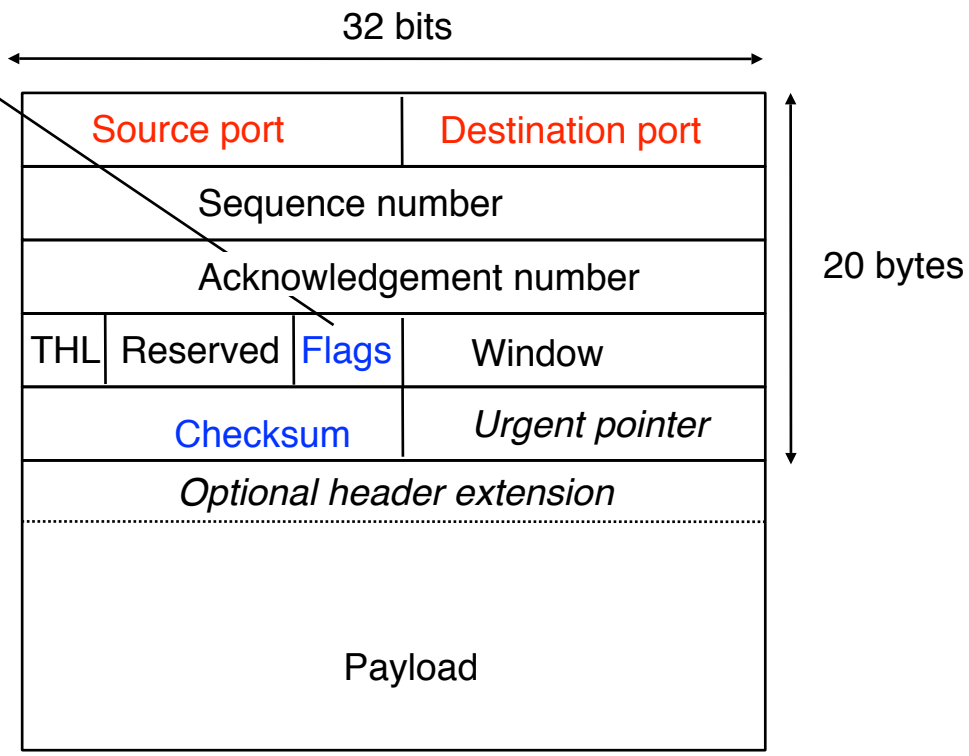
Single segment format



TCP protocol

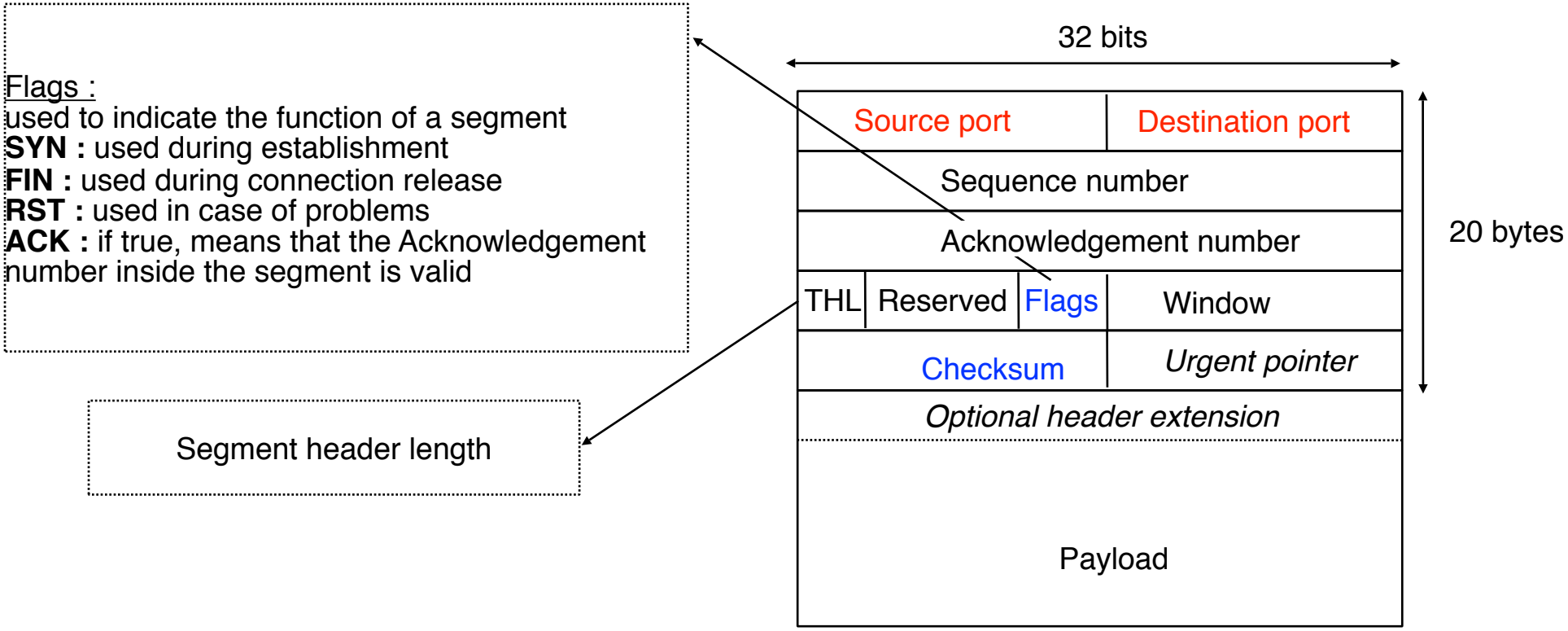
Single segment format

Flags :
used to indicate the function of a segment
SYN : used during establishment
FIN : used during connection release
RST : used in case of problems
ACK : if true, means that the Acknowledgement number inside the segment is valid



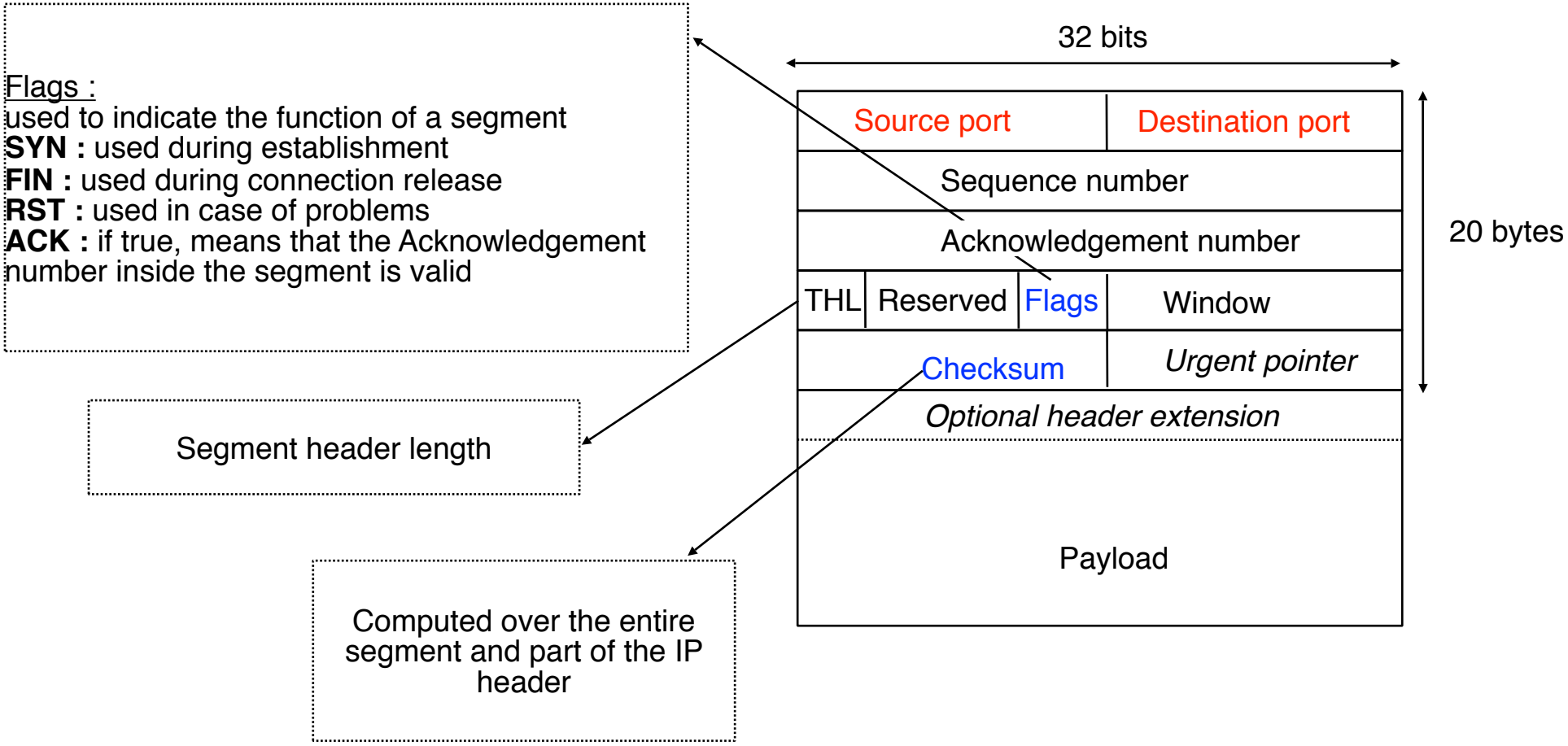
TCP protocol

Single segment format



TCP protocol

Single segment format

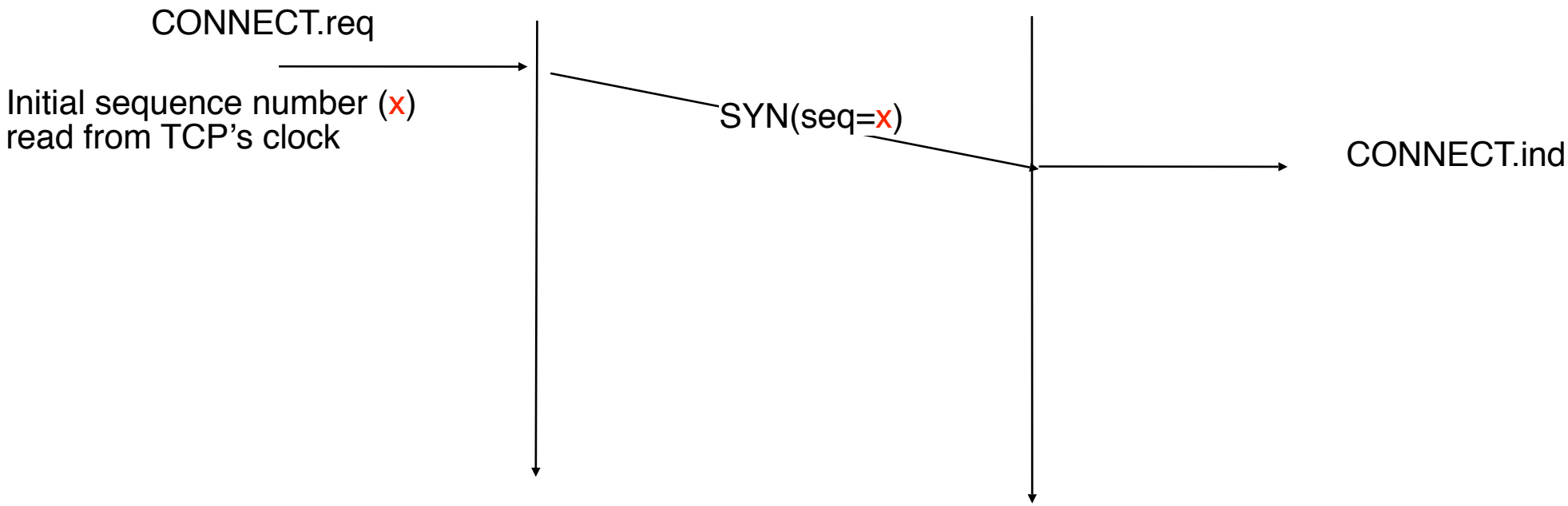


TCP connection establishment

Three-way handshake

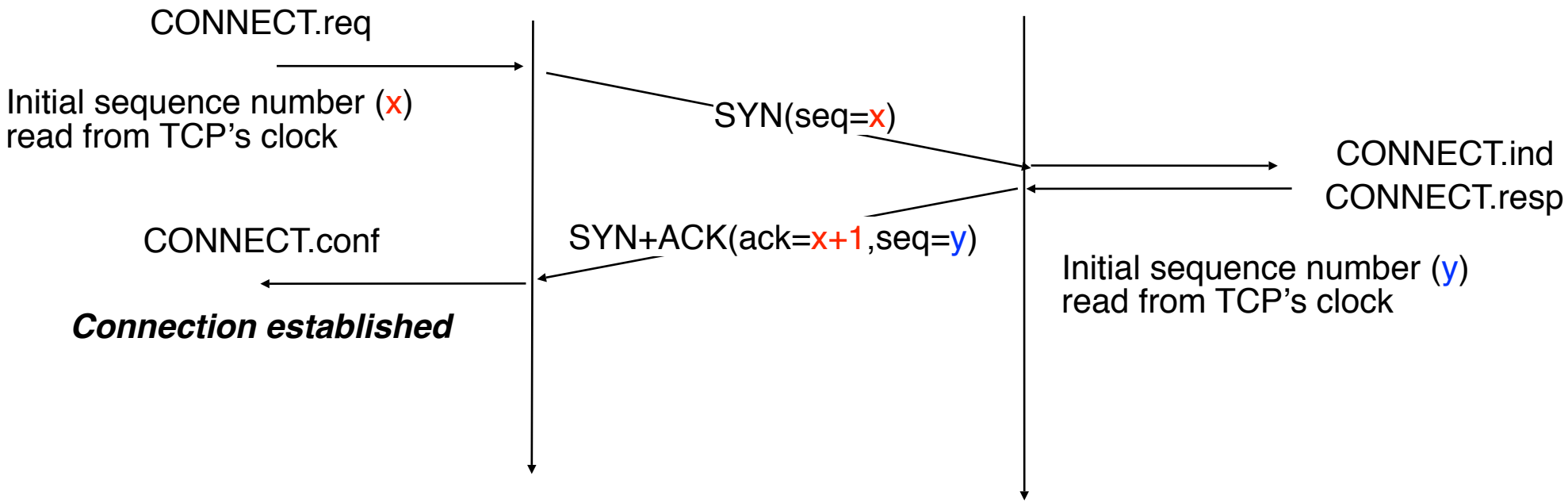
TCP connection establishment

Three-way handshake



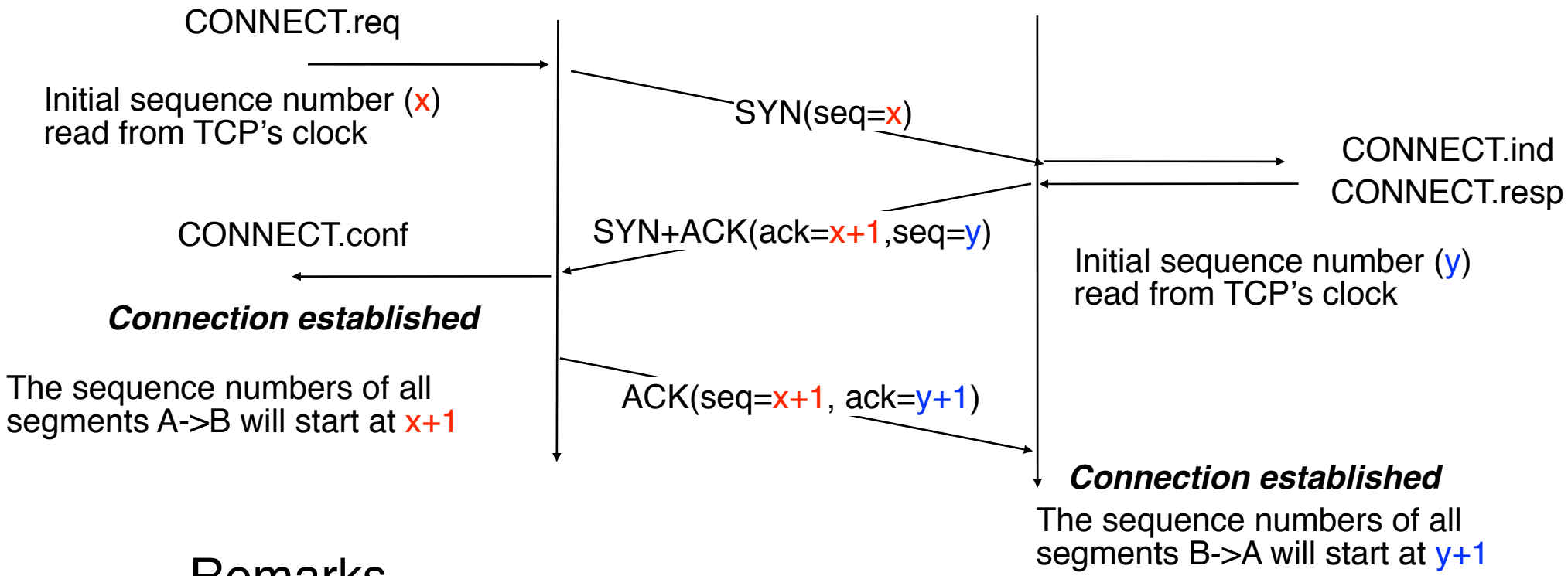
TCP connection establishment

Three-way handshake



TCP connection establishment

Three-way handshake



Remarks

- Setting the SYN flag in a segment consumes one sequence number
- The ACK flag is set only when the acknowledgement field contains a valid value
- The default recommendation for the TCP clock is to be incremented by 1 at least after 4 microseconds and after each TCP connection establishment

TCP connection establishment (2)

Option negotiation

- During the opening of a connection, it is possible to negotiate the utilisation of TCP extensions
  - Option encoded inside the optional part of TCP header
    - Maximum segment size (MSS)
    - RFC1323 timestamp extensions
    - Selective Acknowledgments

MSS : 1460 bytes

MSS : 536 bytes (default)

TCP connection establishment (2)

Option negotiation

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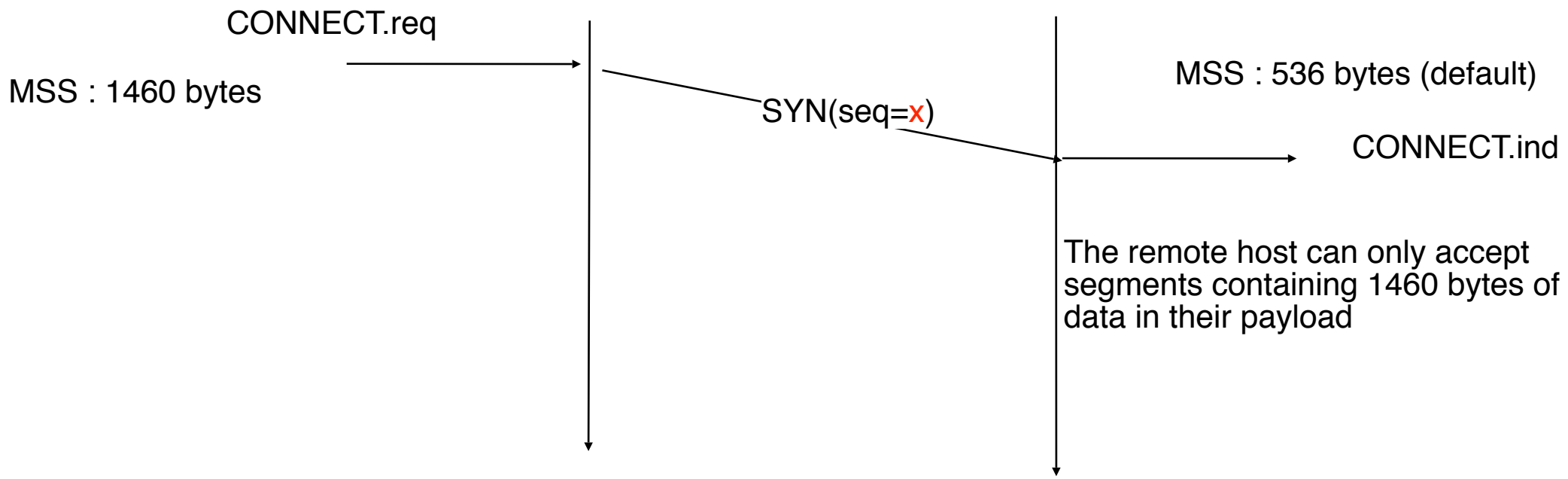

TCP connection establishment (2)

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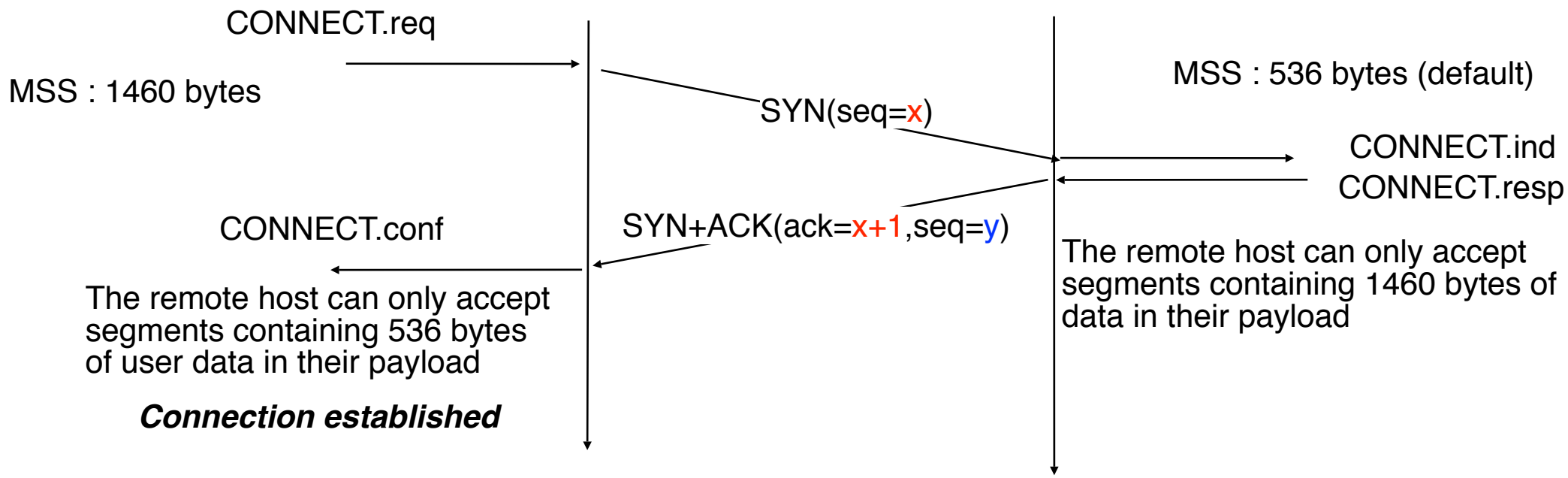

TCP connection establishment (2)

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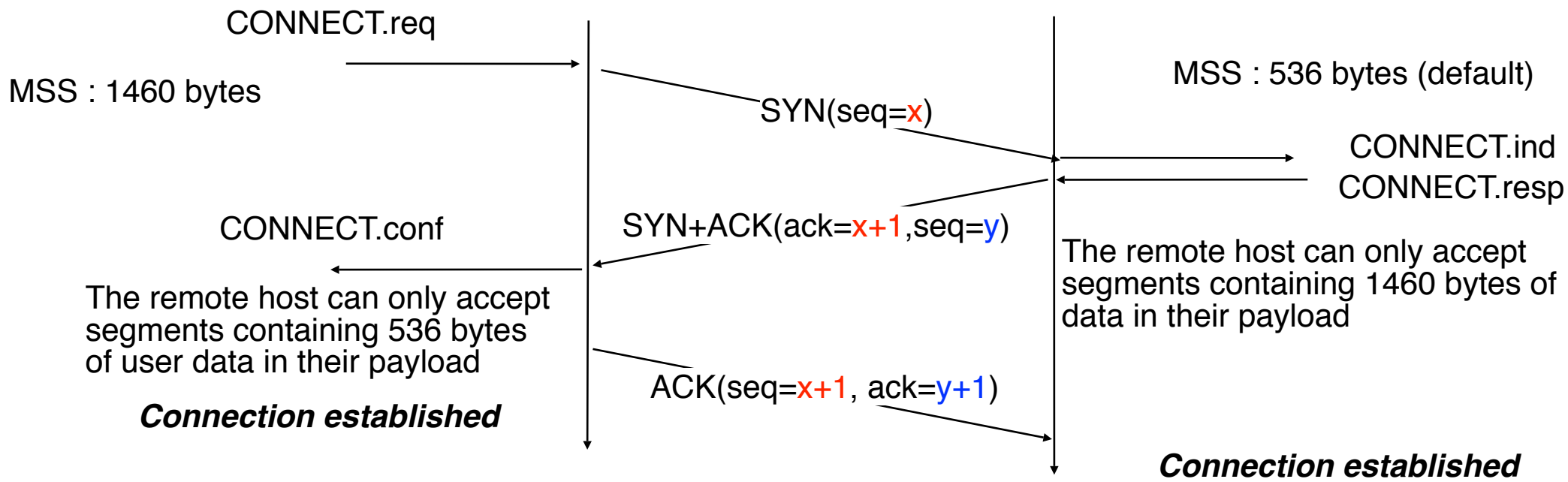
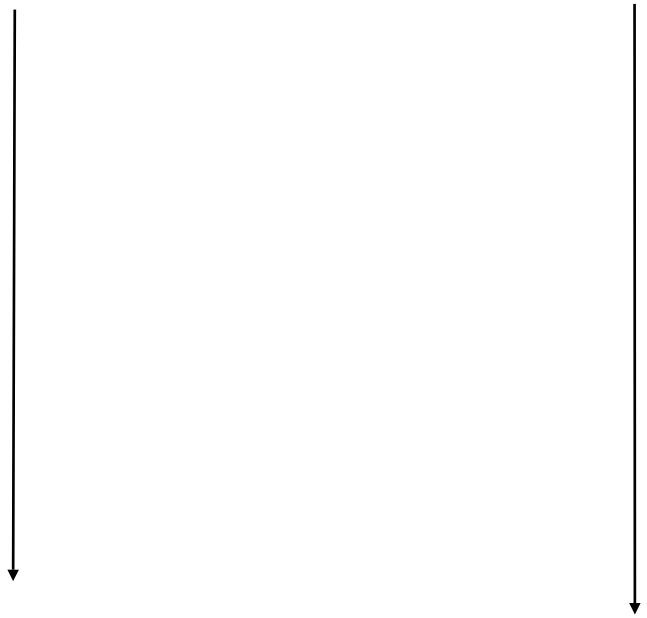


TCP connection establishment (3)

Rejection of connection establishment



TCP connection establishment (3)

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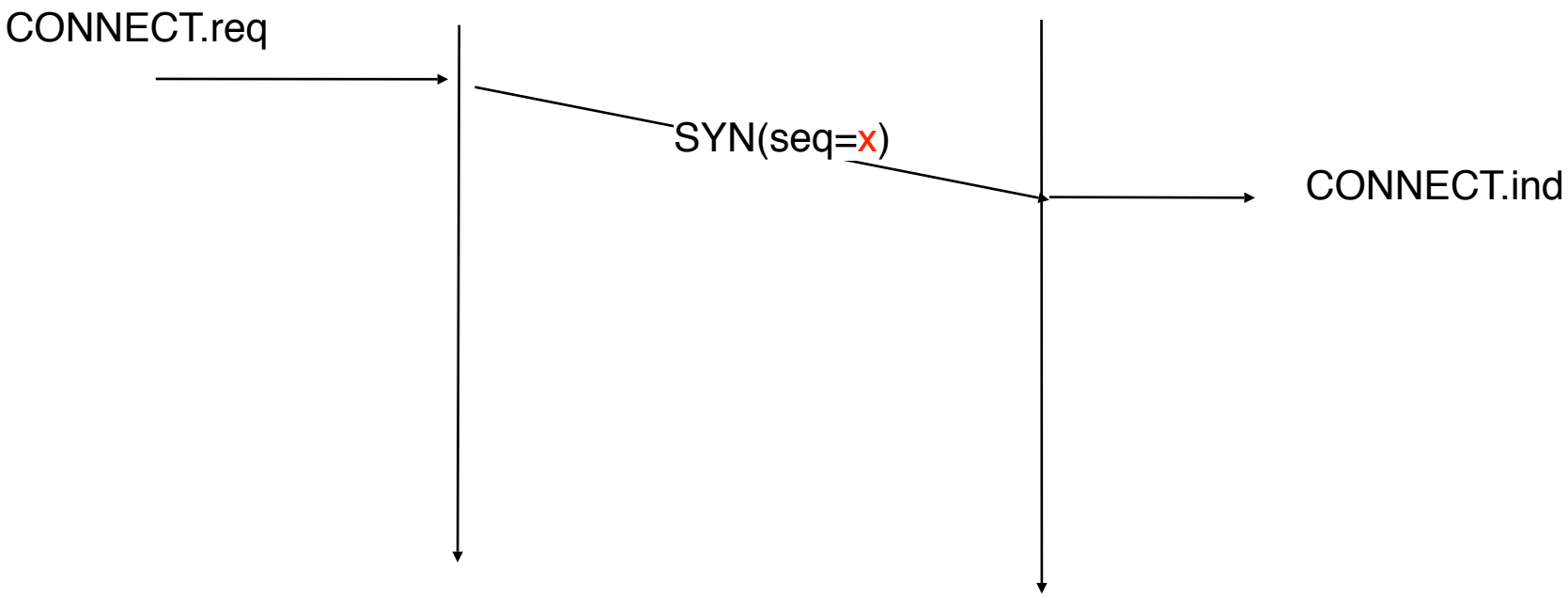

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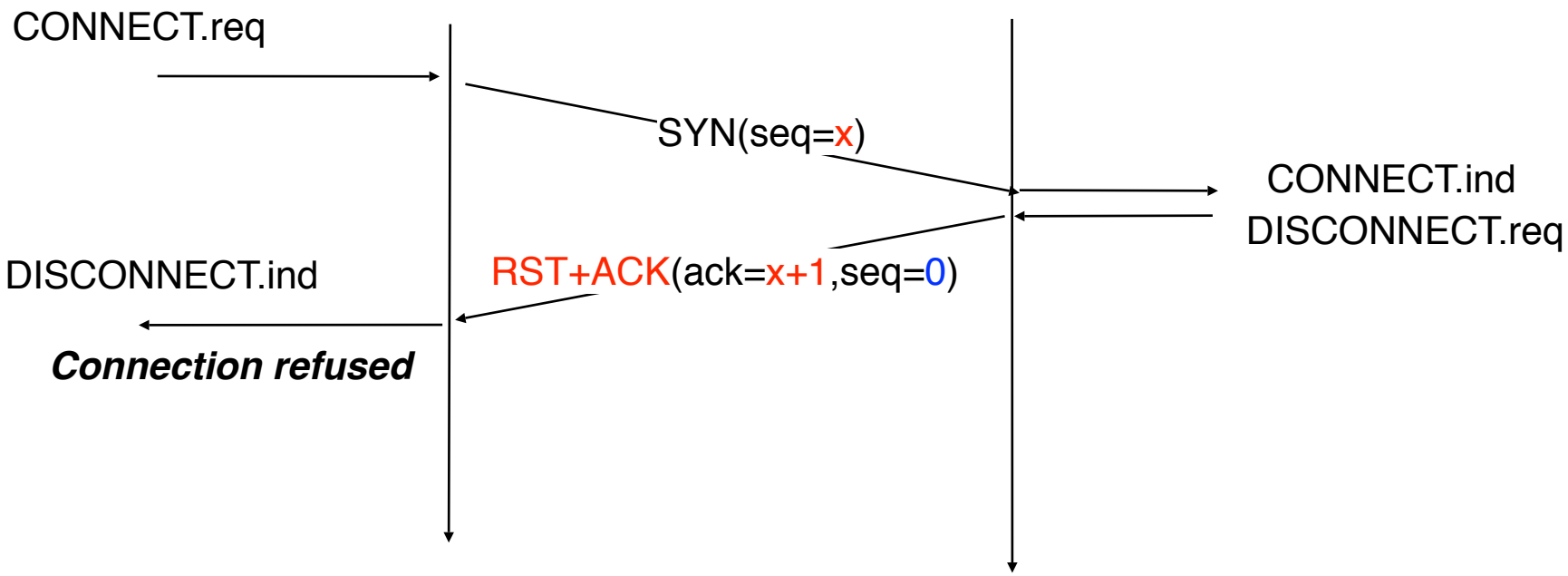
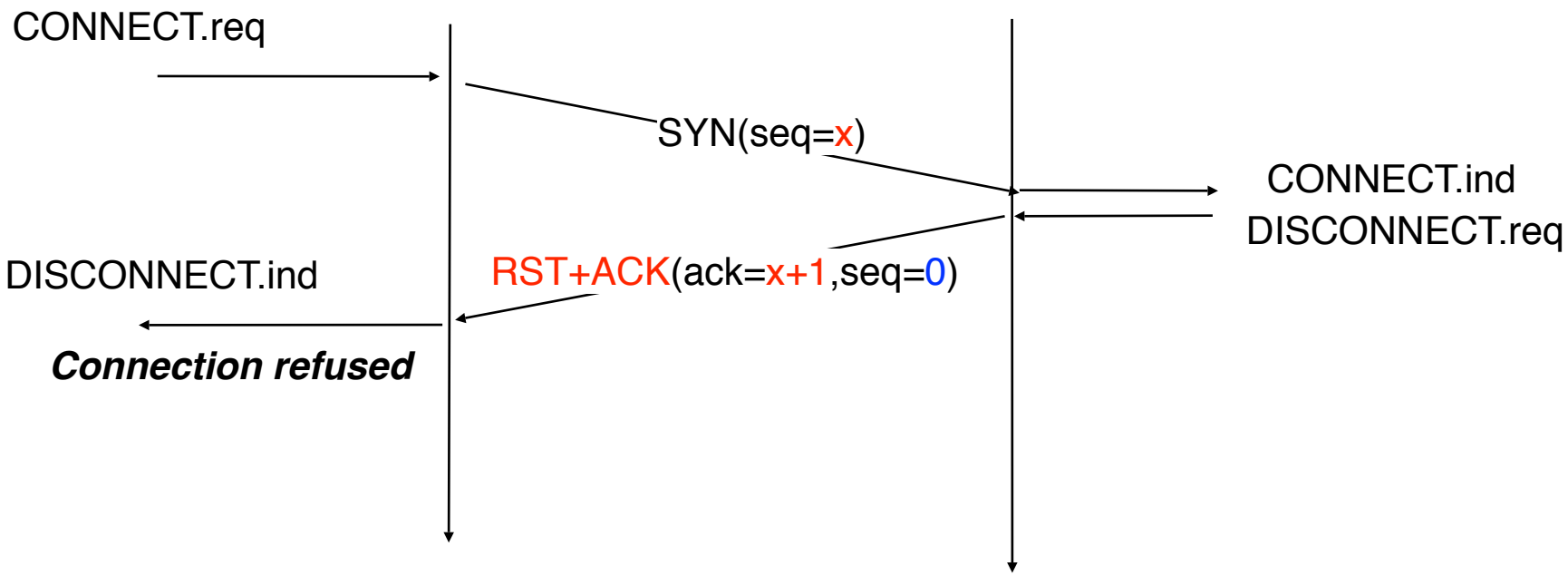


TCP connection establishment (3)

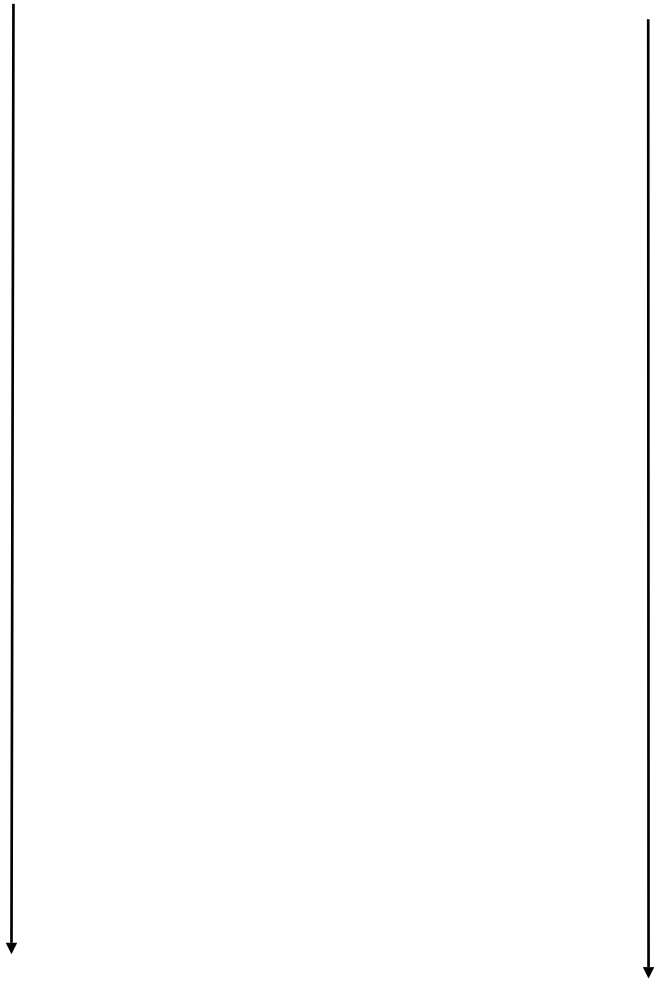
Rejection of connection establishment



A TCP entity should never send a RST segment upon reception of another RST segment

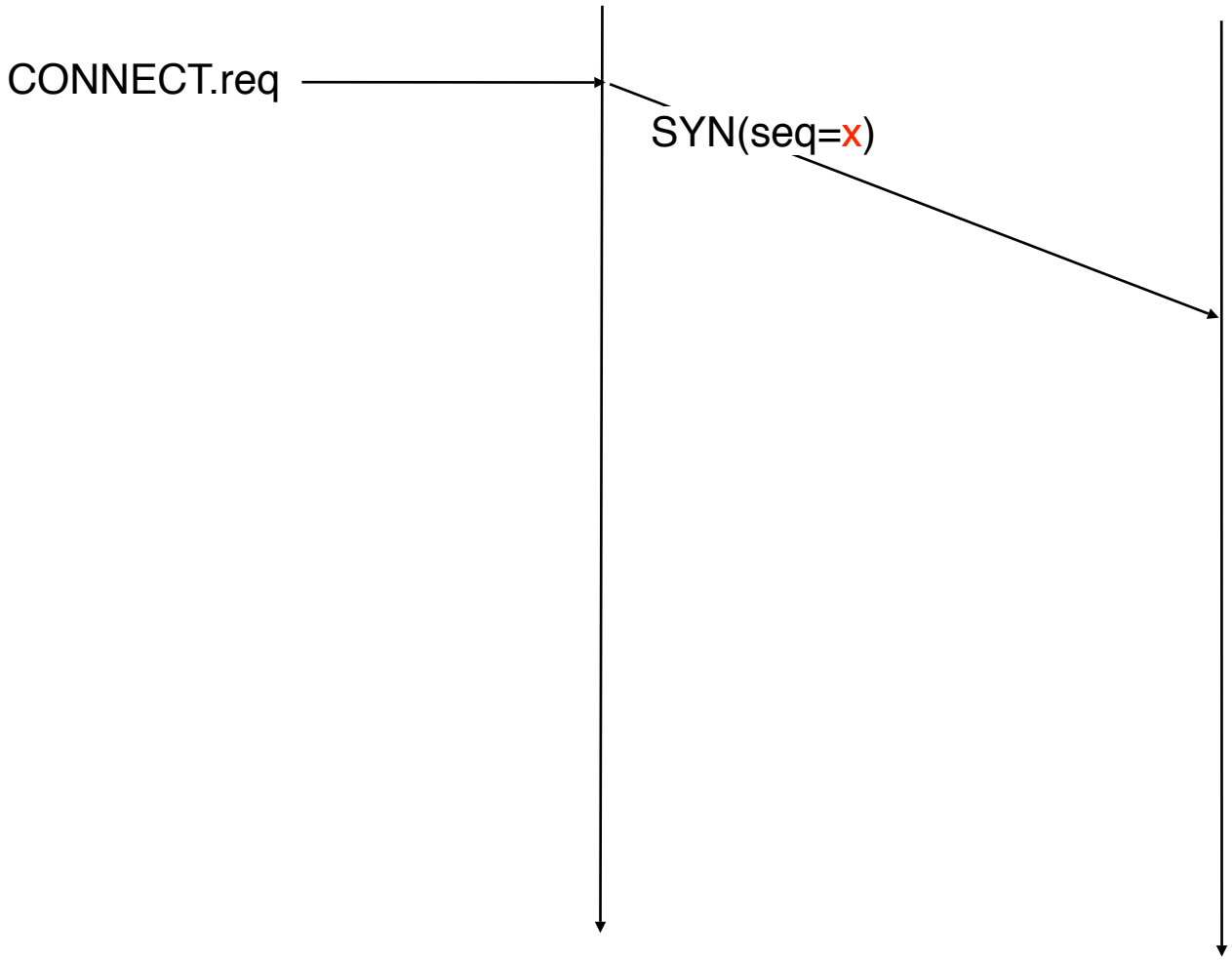
TCP connection establishment (4)

Simultaneous establishment



TCP connection establishment (4)

Simultaneous establishment



TCP connection establishment (4)

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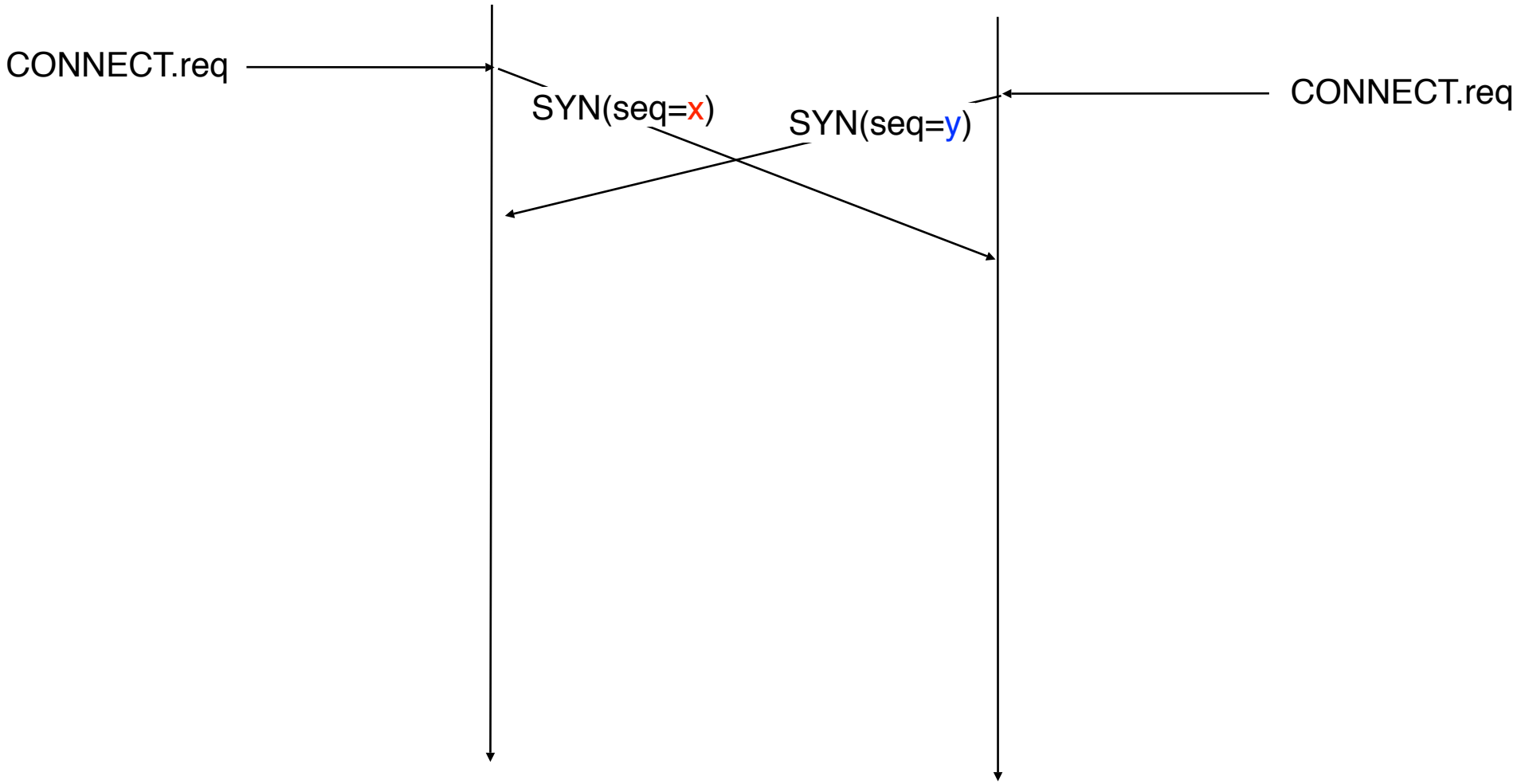
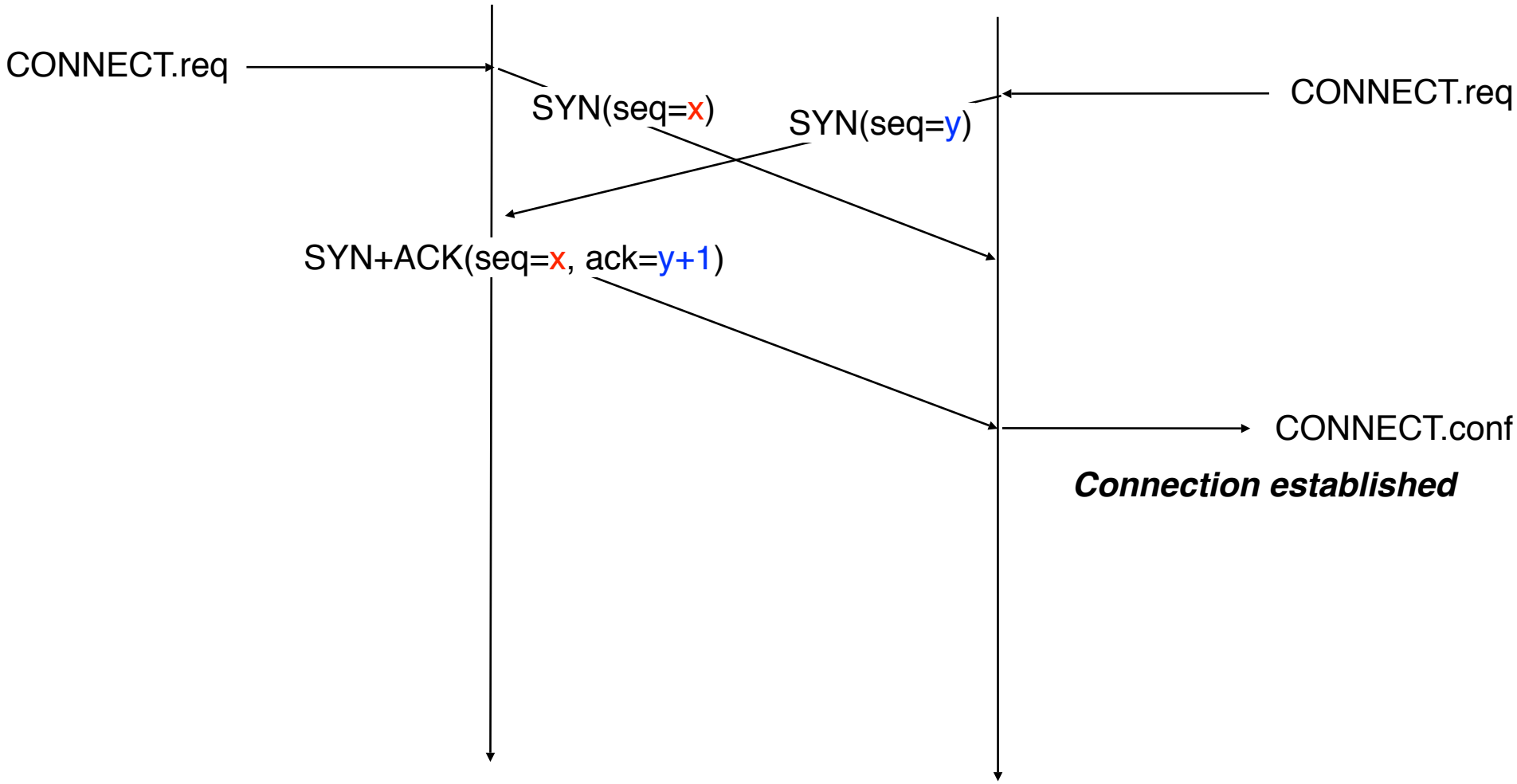


TCP connection establishment (4)

Simultaneous establishment



TCP connection establishment (4)

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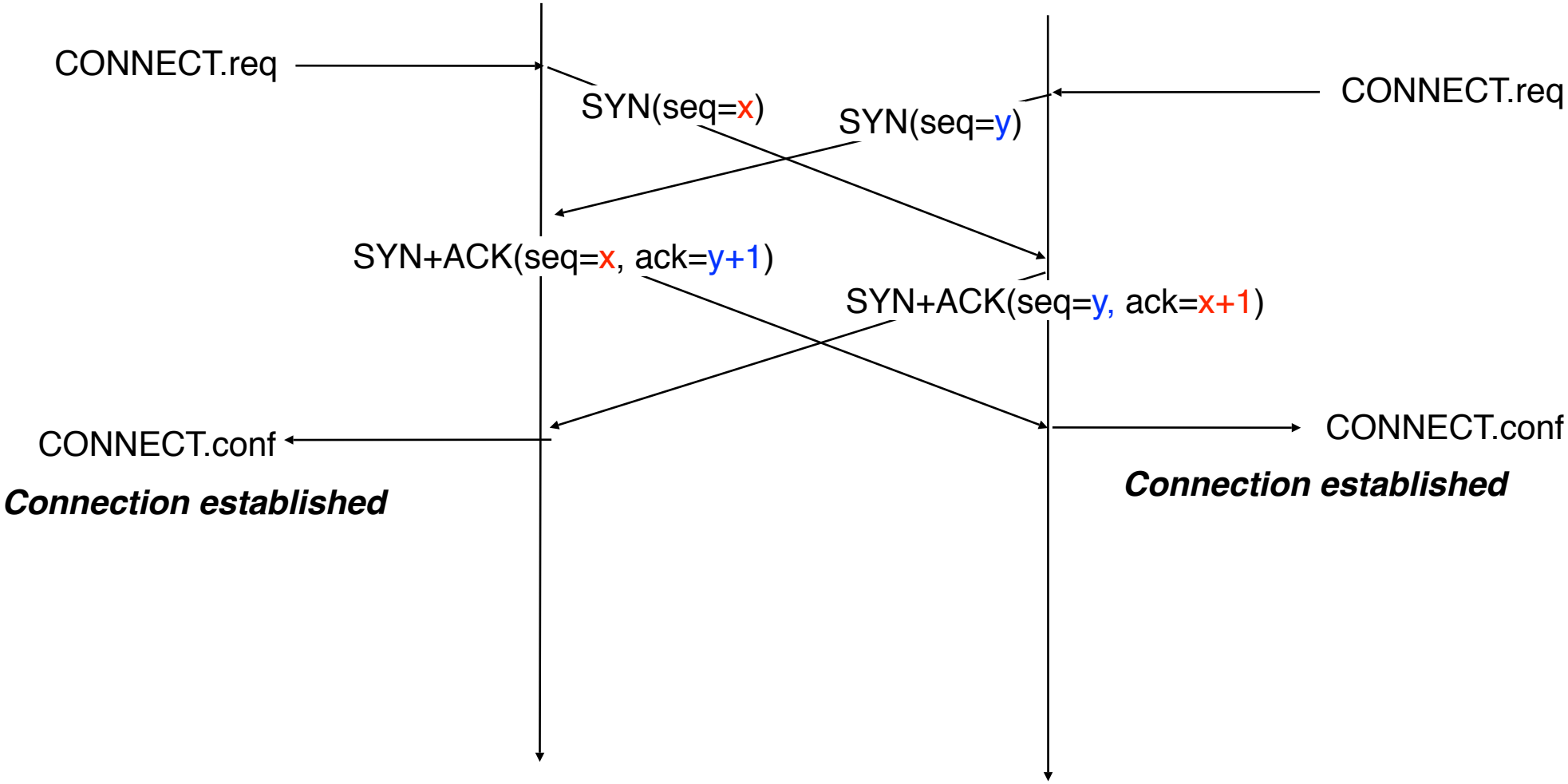
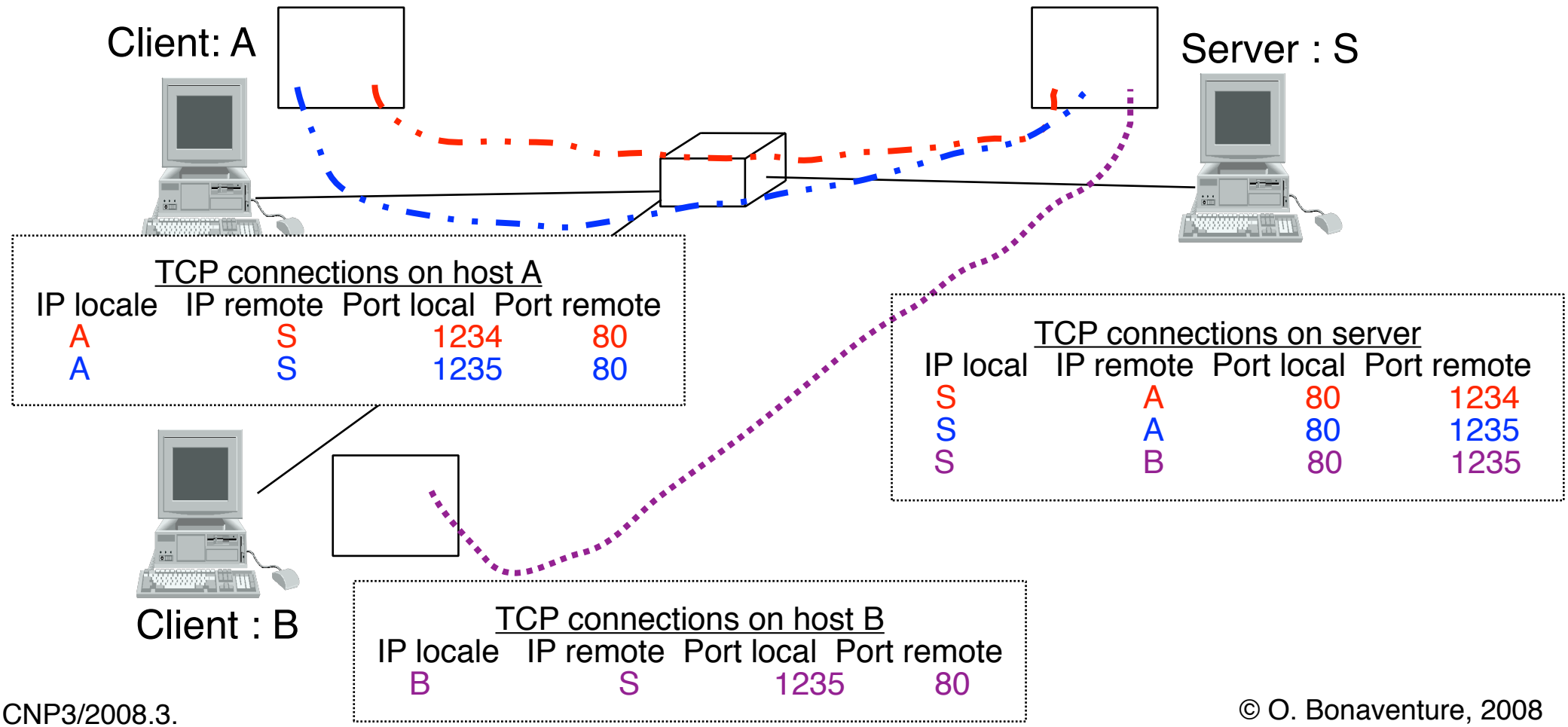


TCP connection establishment (6)

How to open several TCP connections at the same time ?



Module 3 : Transport Layer

Basics

Building a reliable transport layer

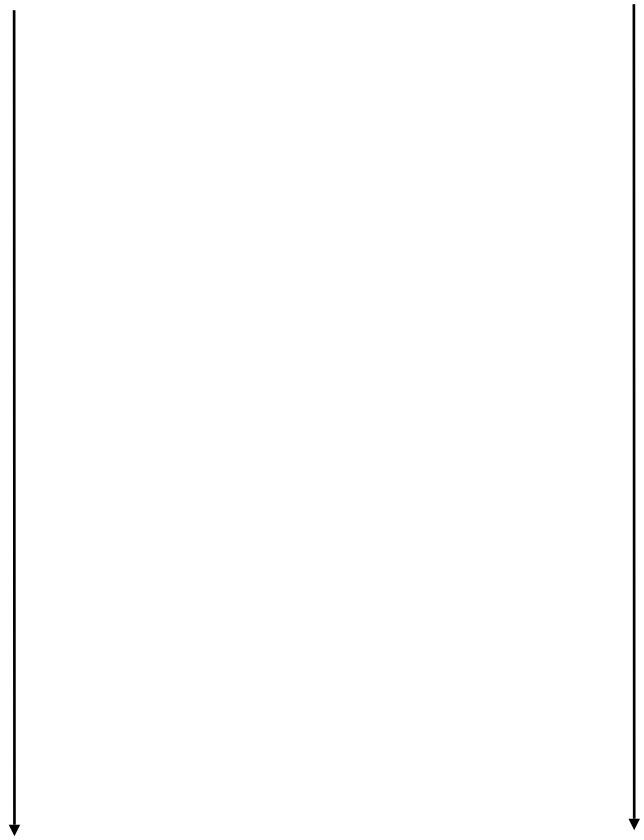
UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

- TCP connection establishment
- → TCP connection release
- Reliable data transfer
- Congestion control

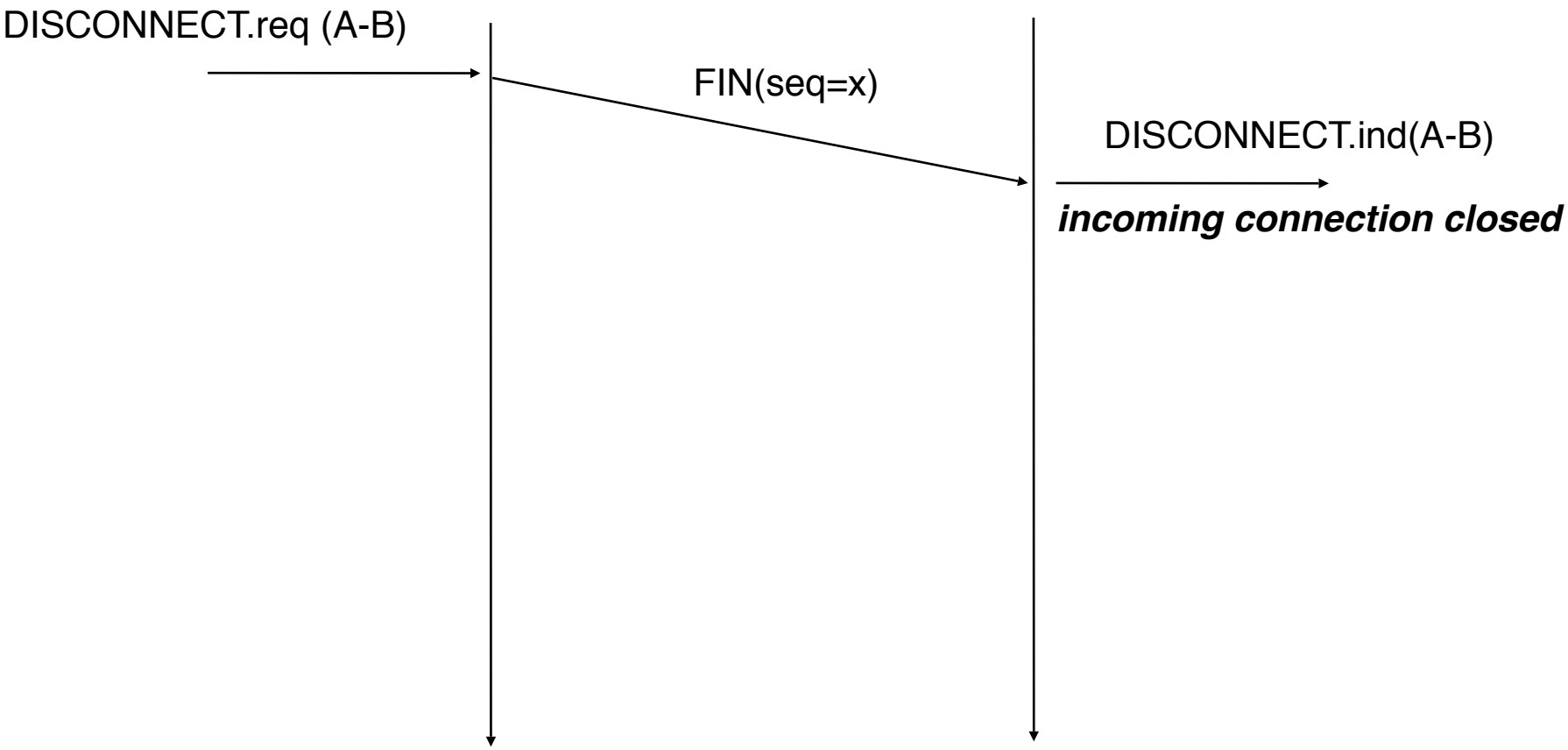
TCP connection release

Graceful shutdown of a TCP connection



TCP connection release

Graceful shutdown of a TCP connection



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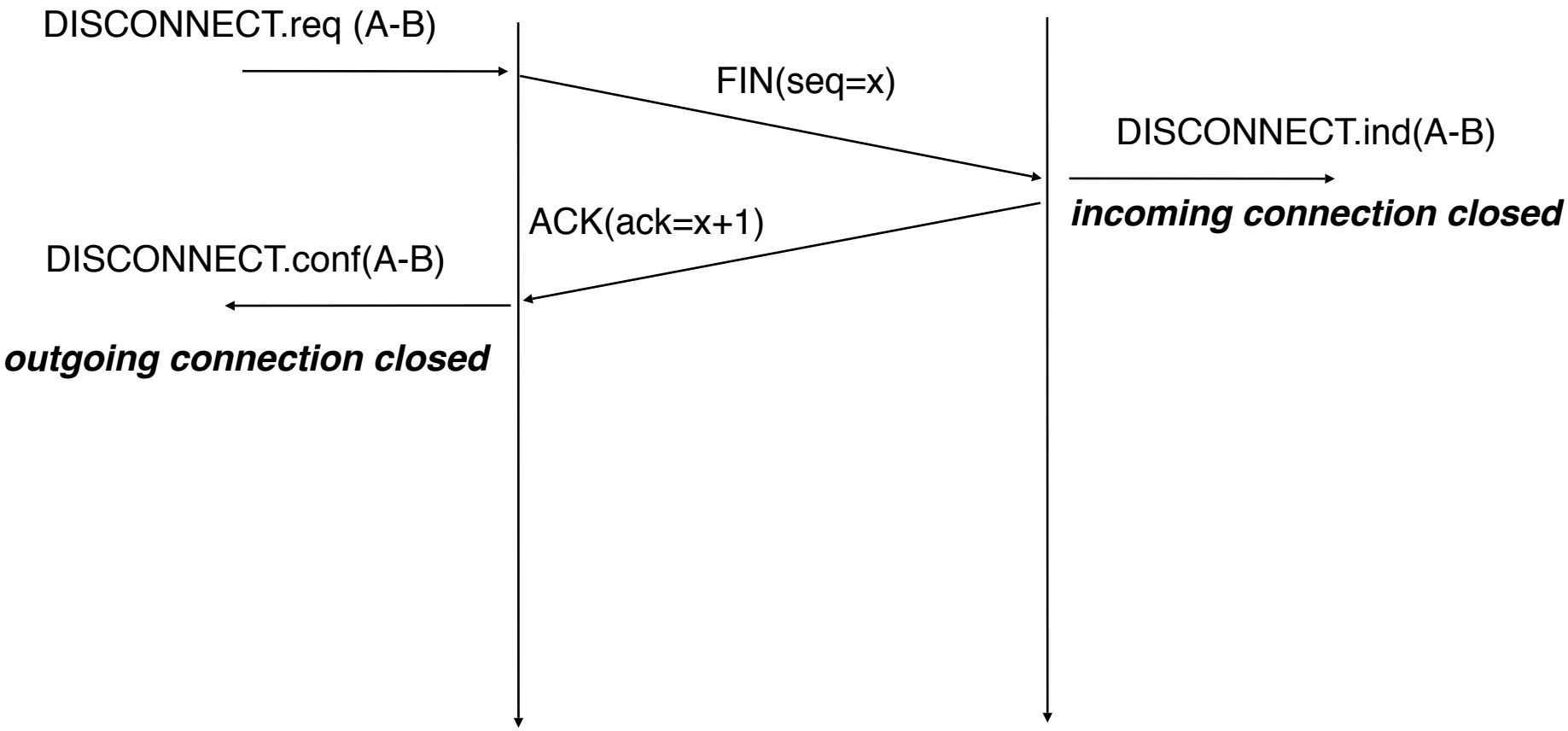

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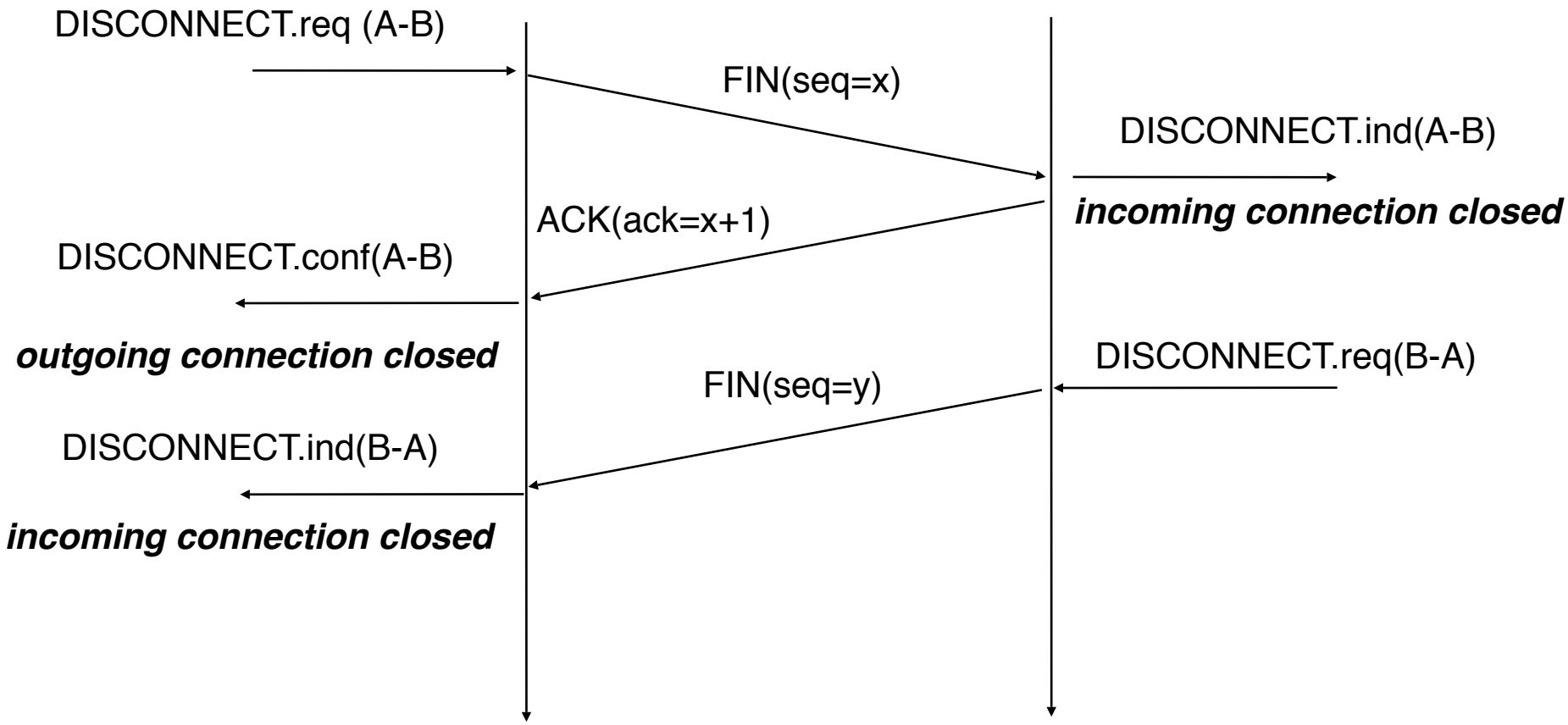

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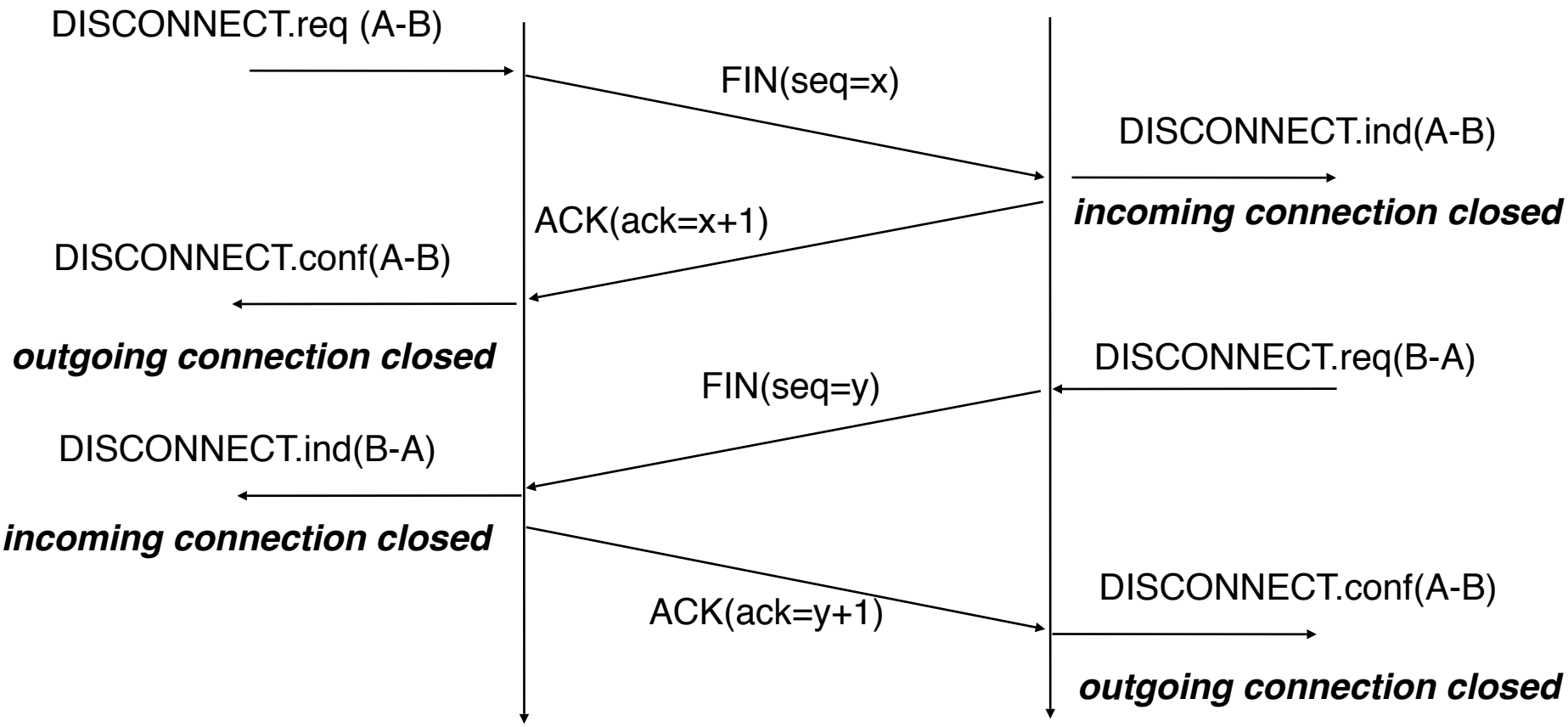

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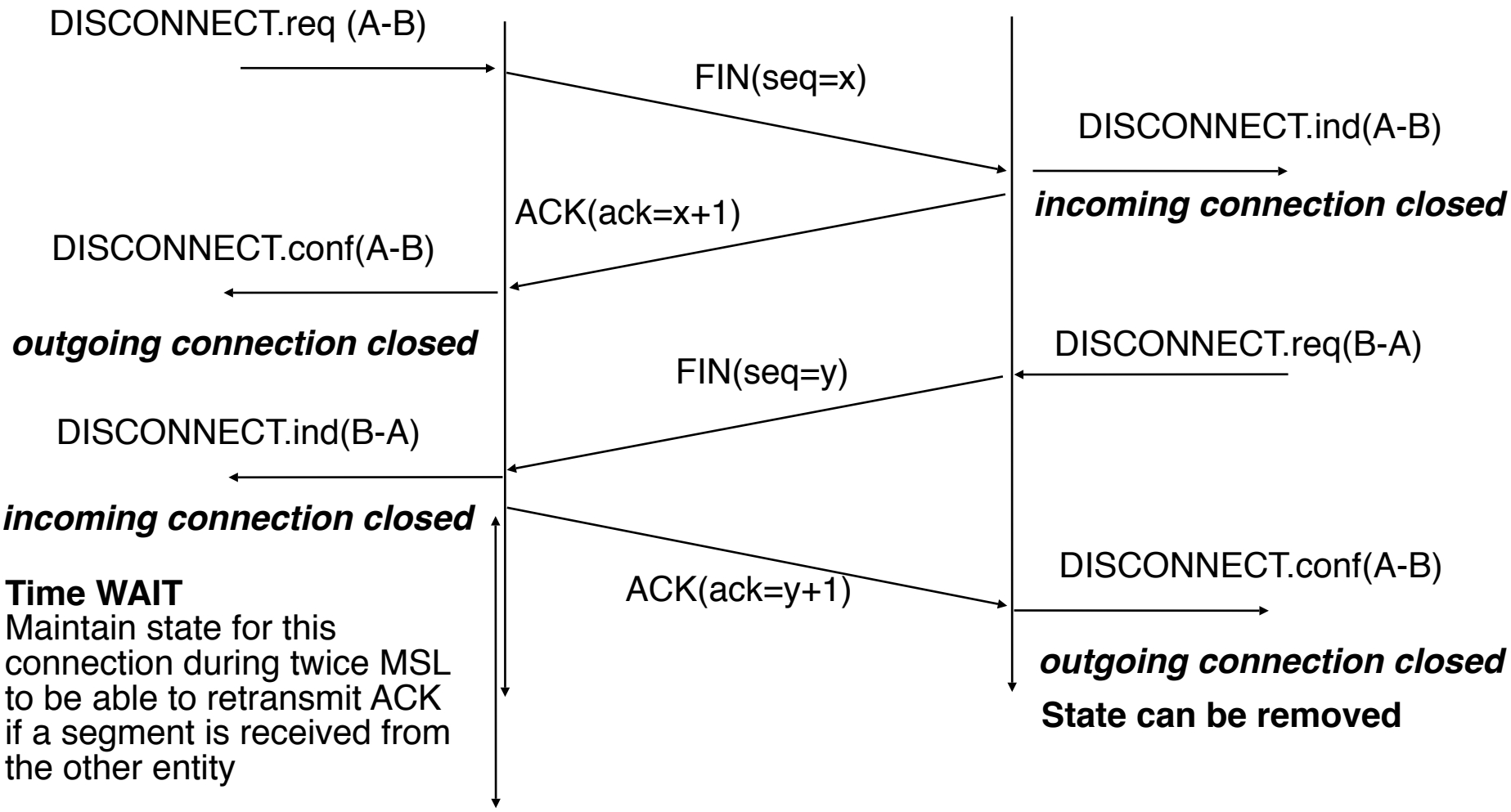

Abrupt TCP connection release

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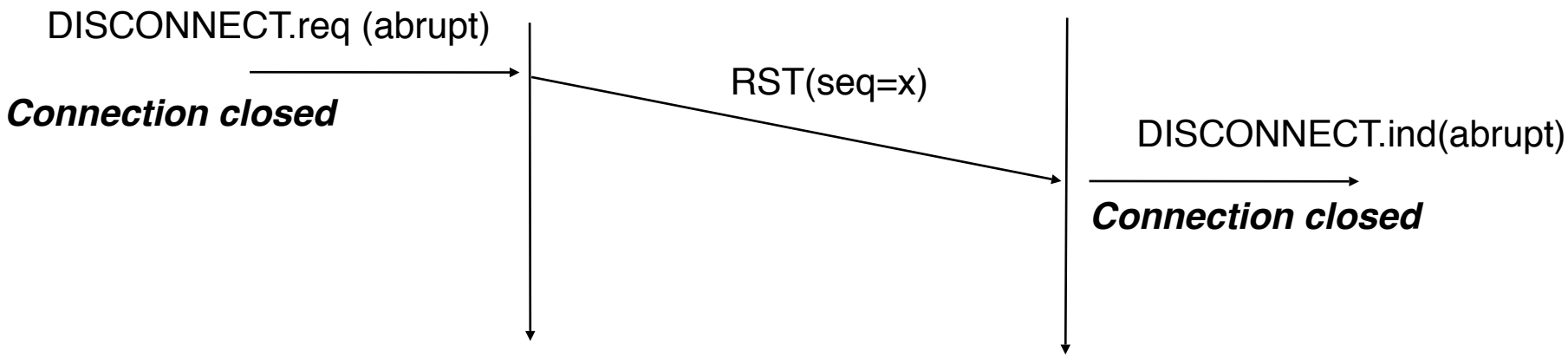

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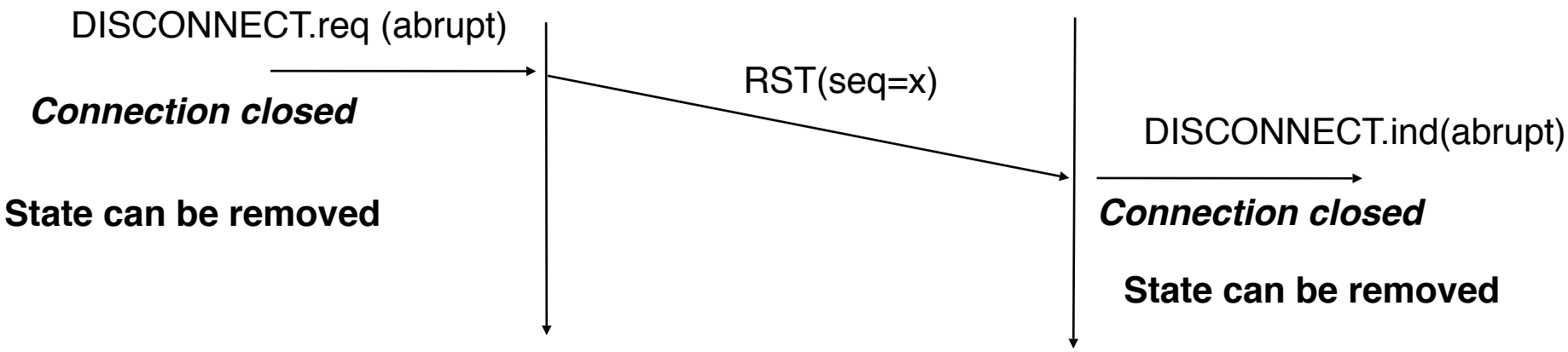

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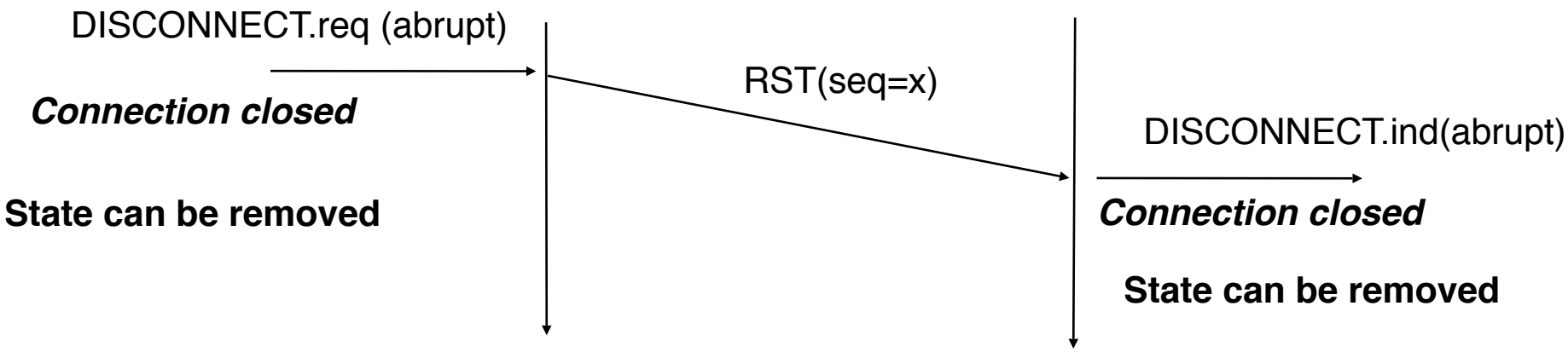

Data segments can be lost during such an abrupt release

No entity needs to wait in TIME_WAIT state after such a release

- anyway, any segment received when there is no state causes the transmission of a RST segment

Module 3 : Transport Layer

Basics

Building a reliable transport layer

UDP : a simple connectionless transport protocol

TCP : a reliable connection oriented transport protocol

- TCP connection establishment
- TCP connection release
- → Reliable data transfer
- Congestion control

Reliable data transfer

Each TCP segment contains

- 16 bits checksum
  - used to detect transmission errors affecting paylaod
- 32 bits sequence number (one byte=one seq. number)
  - used by sender to delimitate sent segments
  - used by receiver to reorder received segments
- 32 bits acknowledgement number
  - used (when ACK flag is 1) by receiver to advertise the sequence number of the next expected byte (last byte received in sequence+1)

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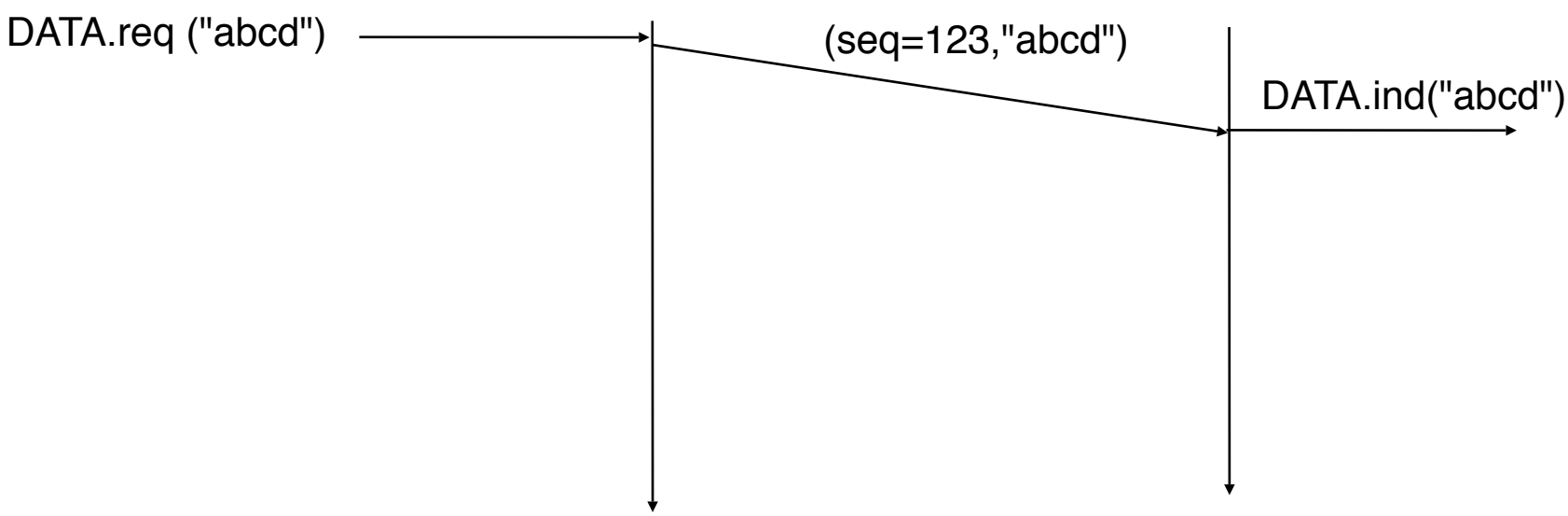

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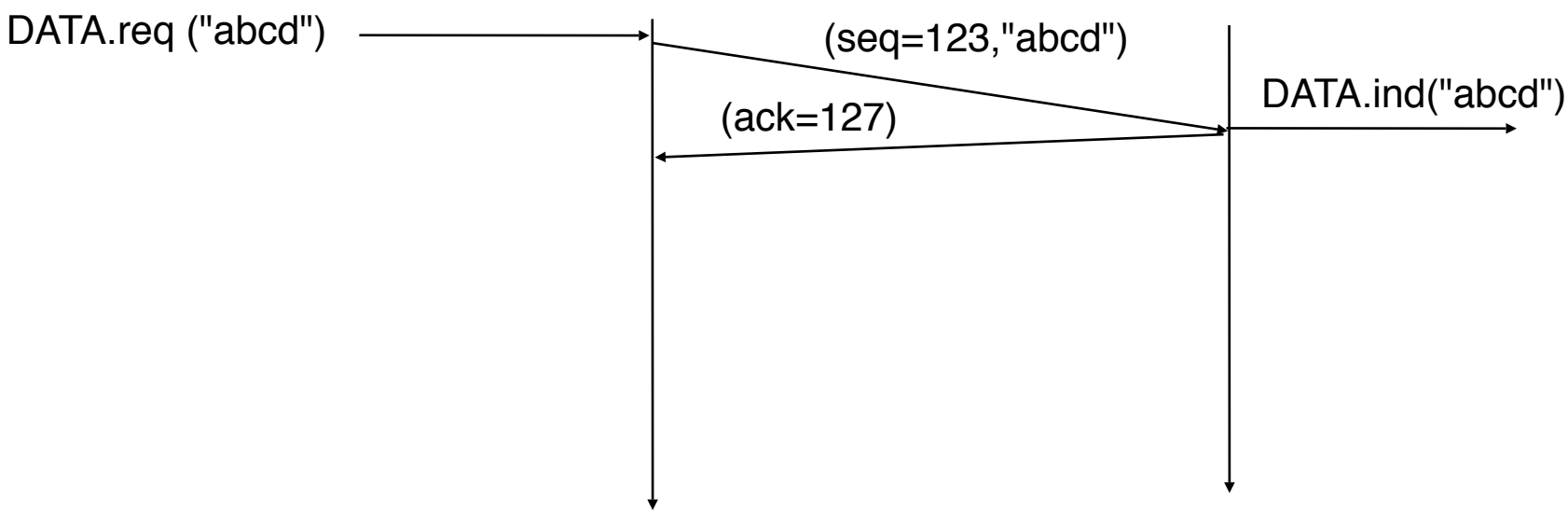

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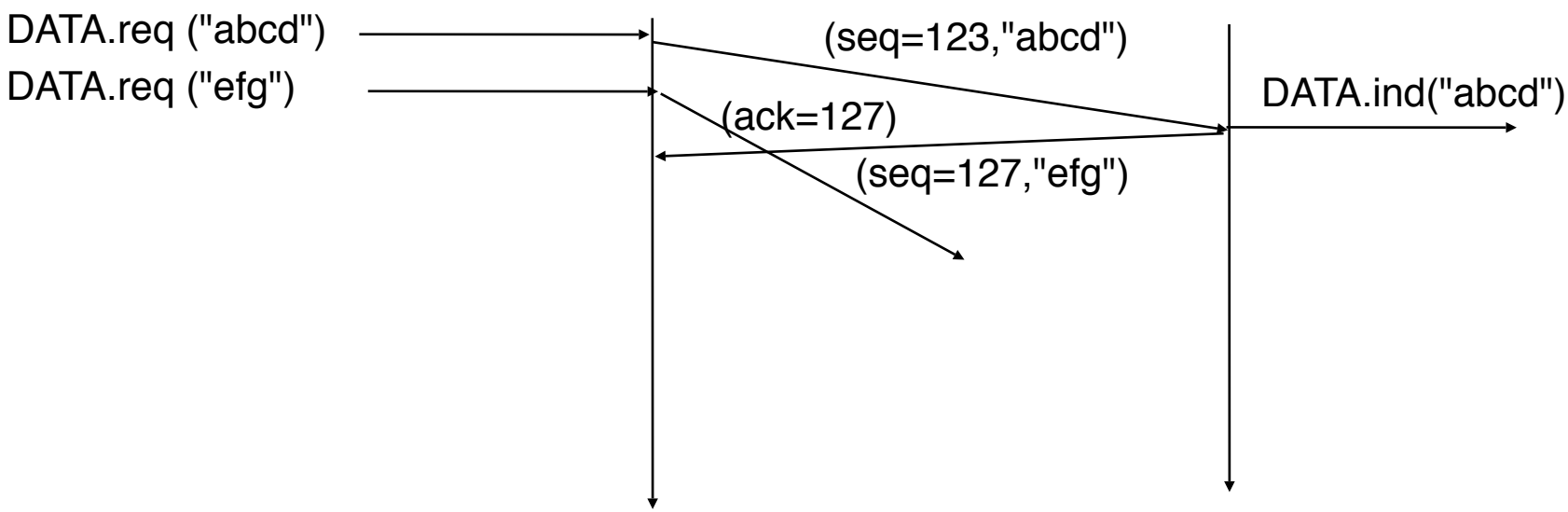

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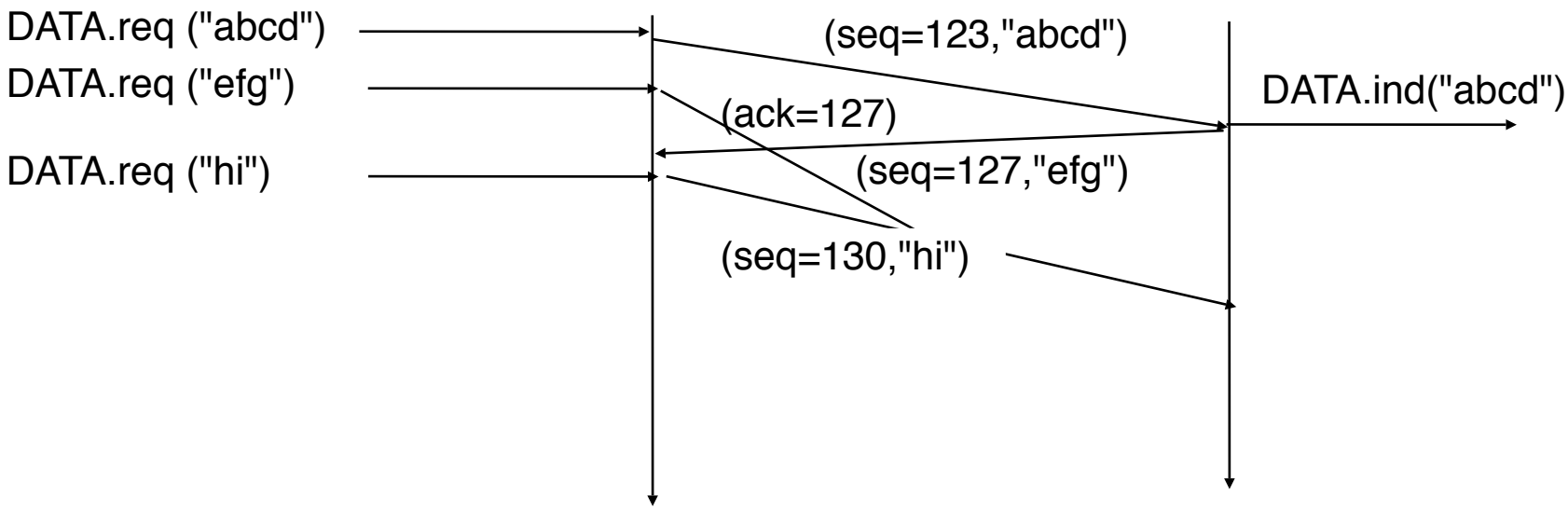

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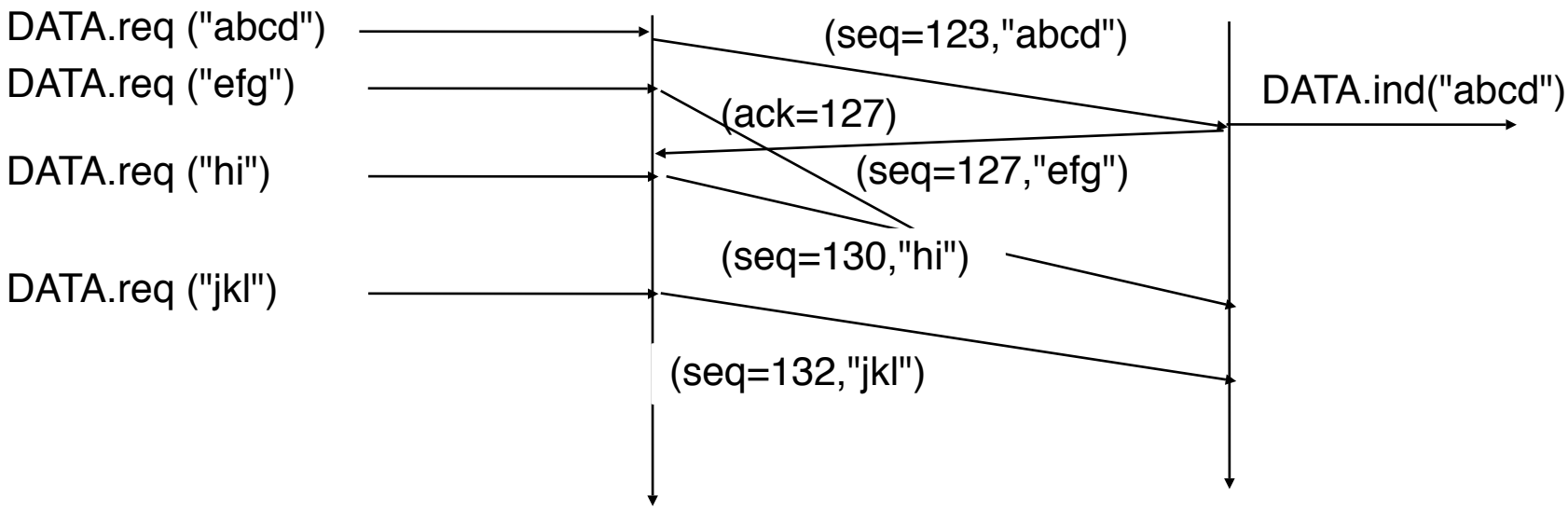

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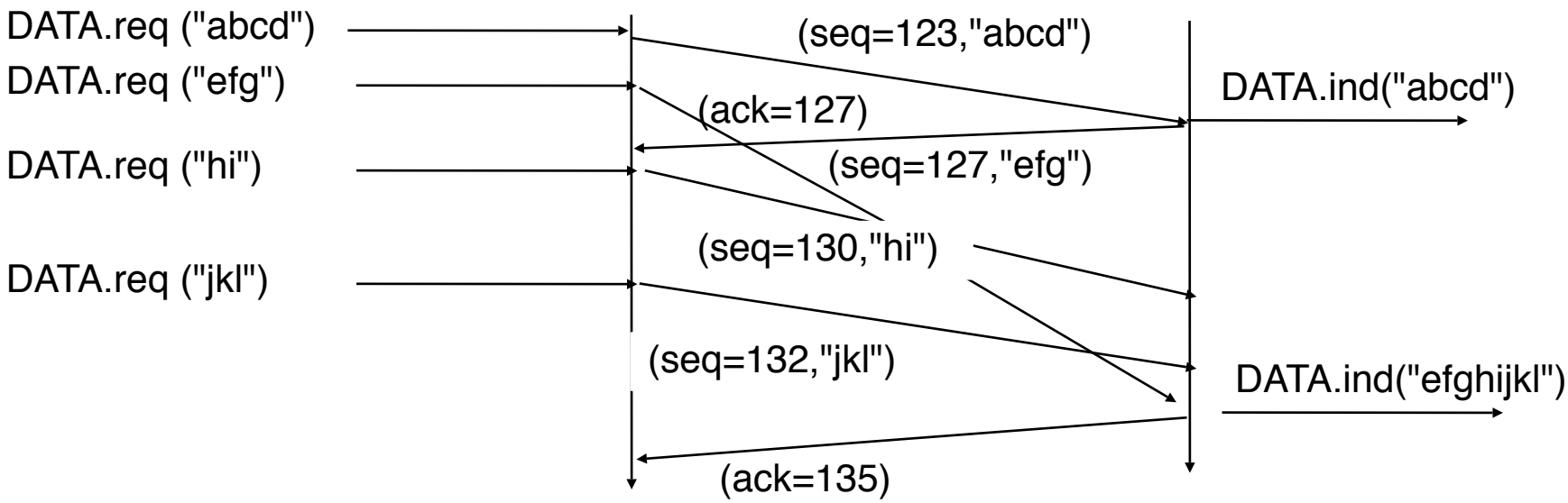

Reliable data transfer

- How to deal with segment losses ?
  - TCP uses a retransmission timer
    - If the retransmission timer expires, TCP performs go-back-n and retransmits all the unacknowledged segments
    - usually a single retransmission timer is running at a given time

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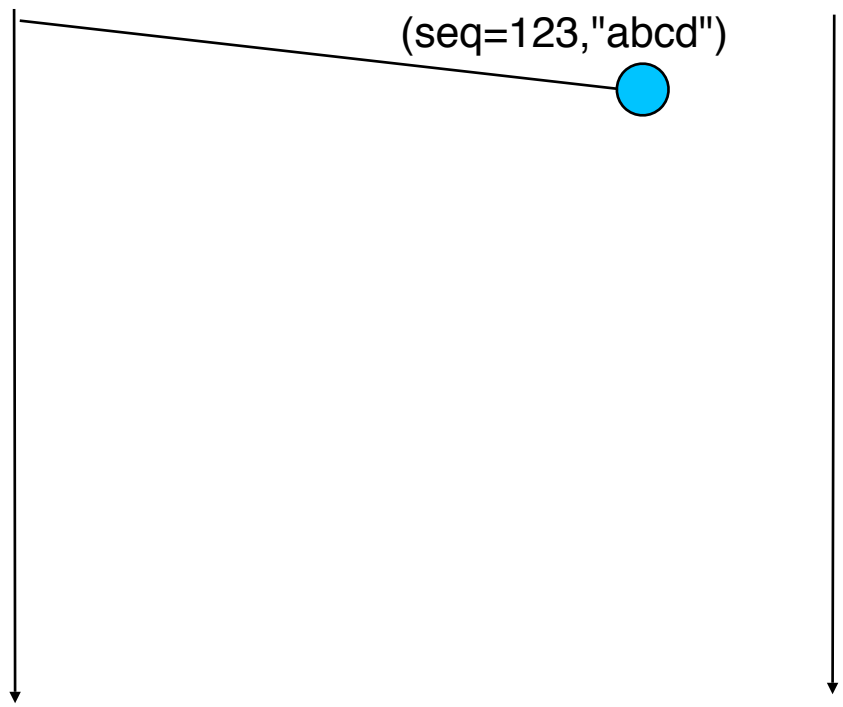

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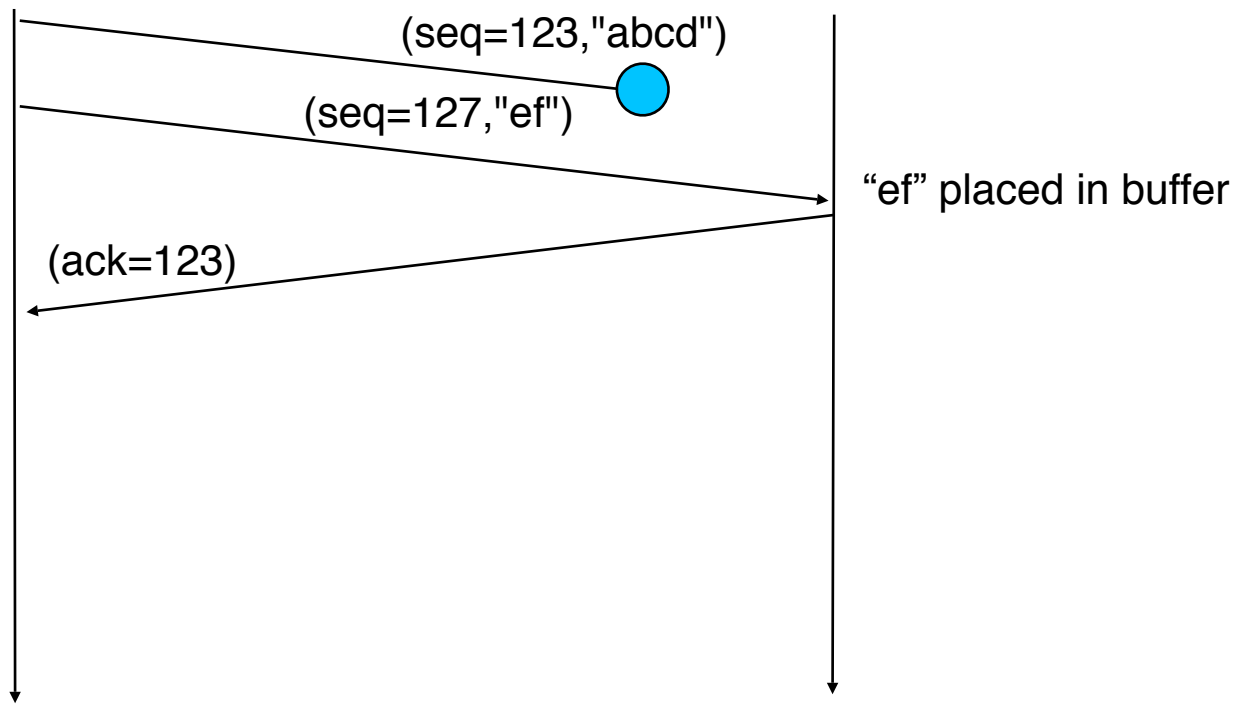

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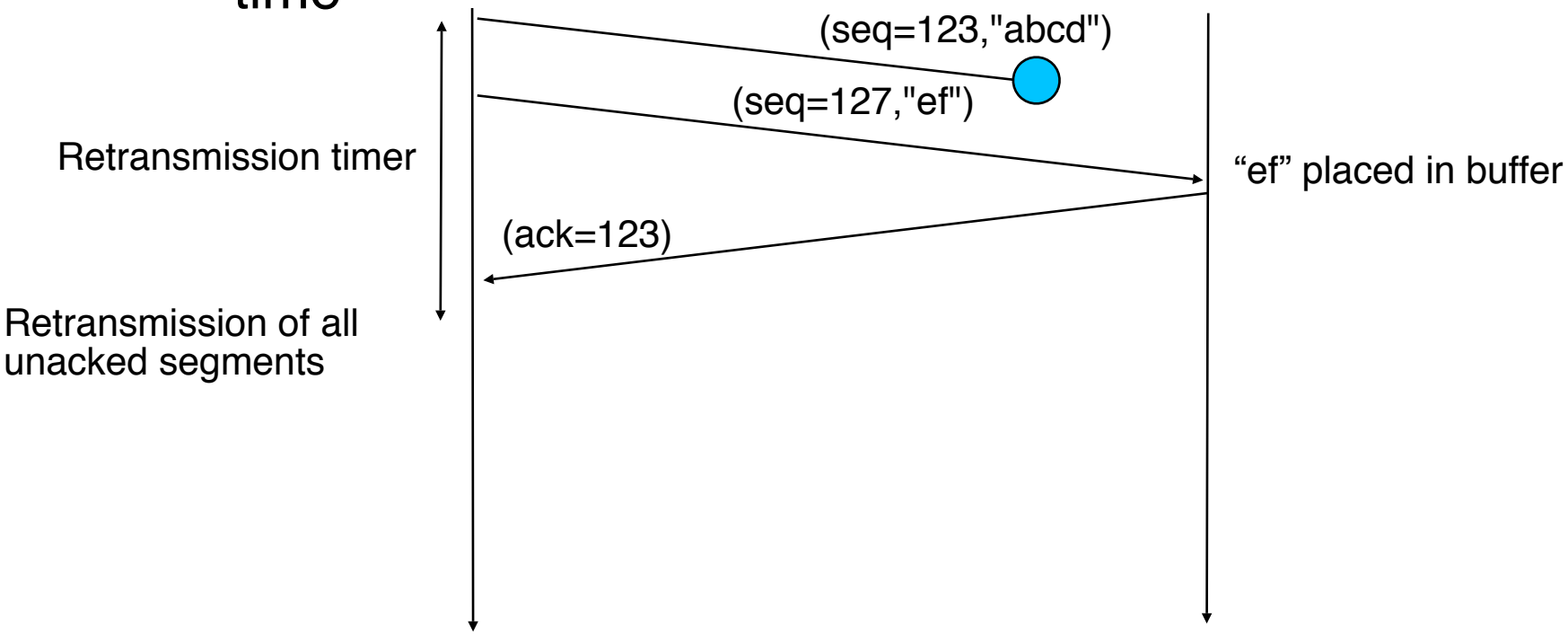

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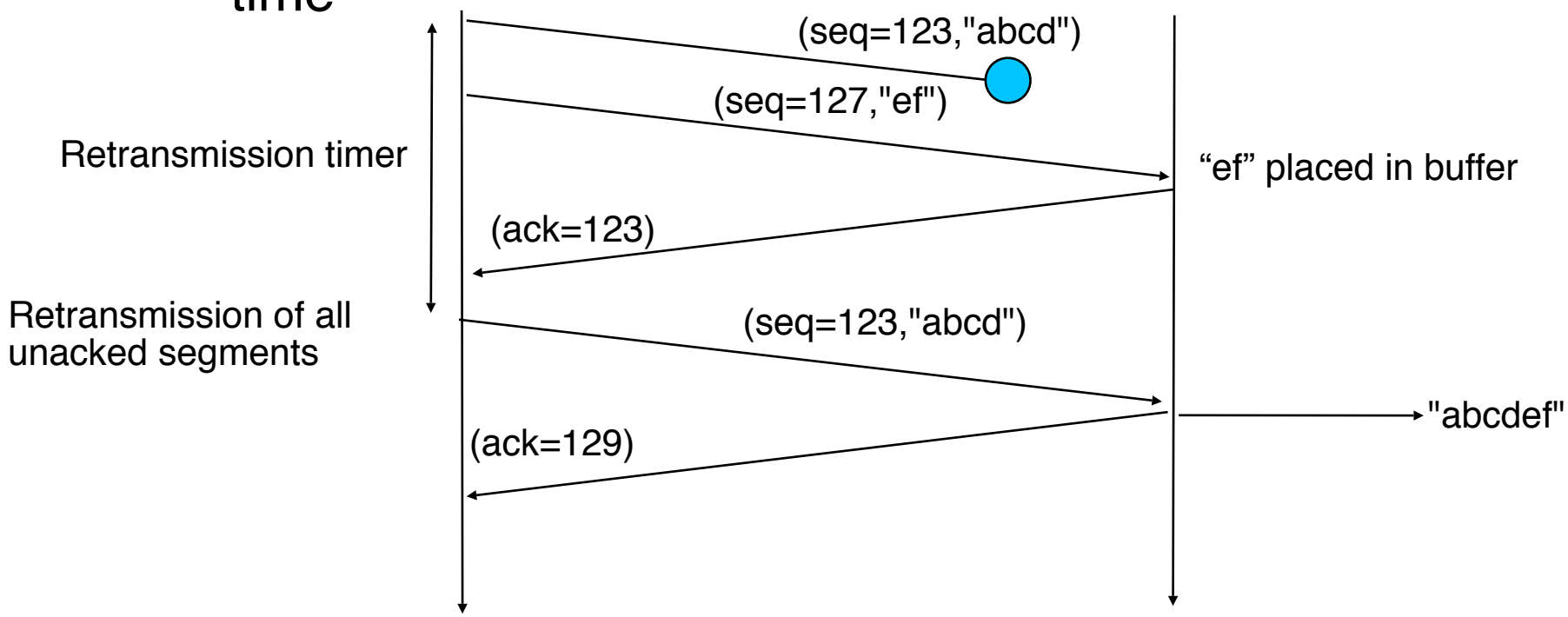

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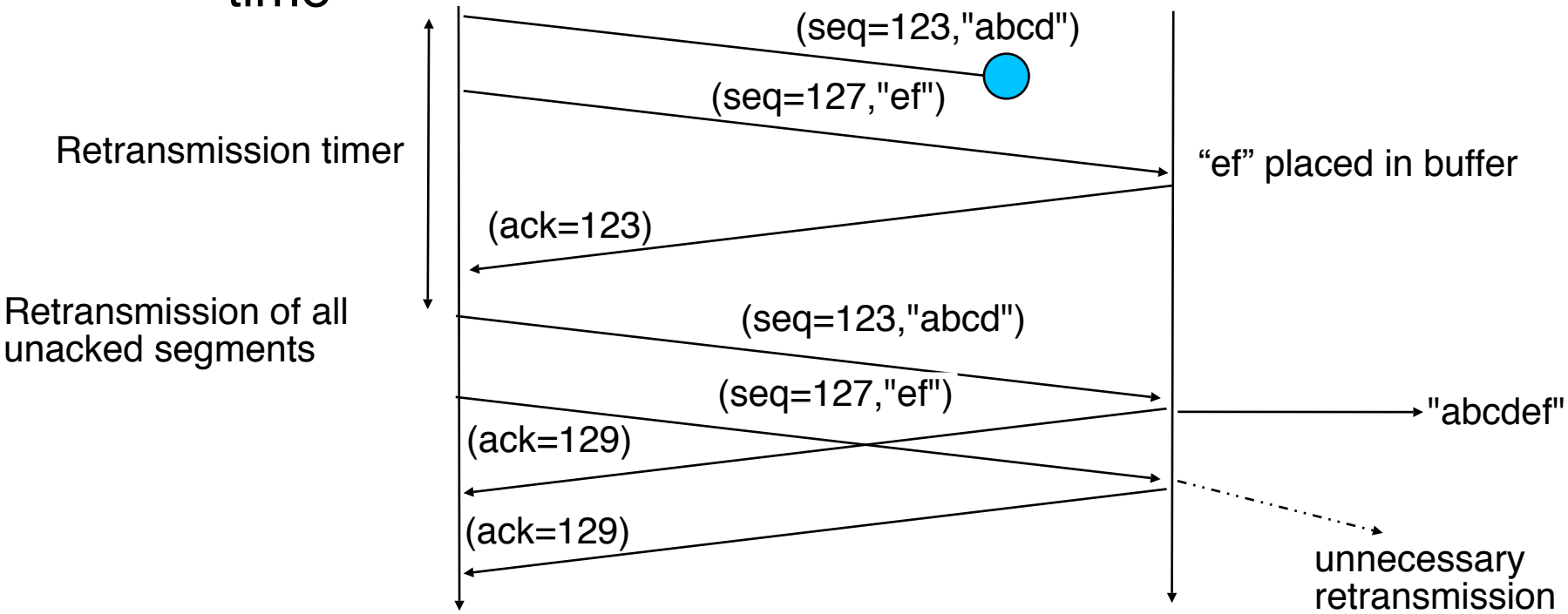
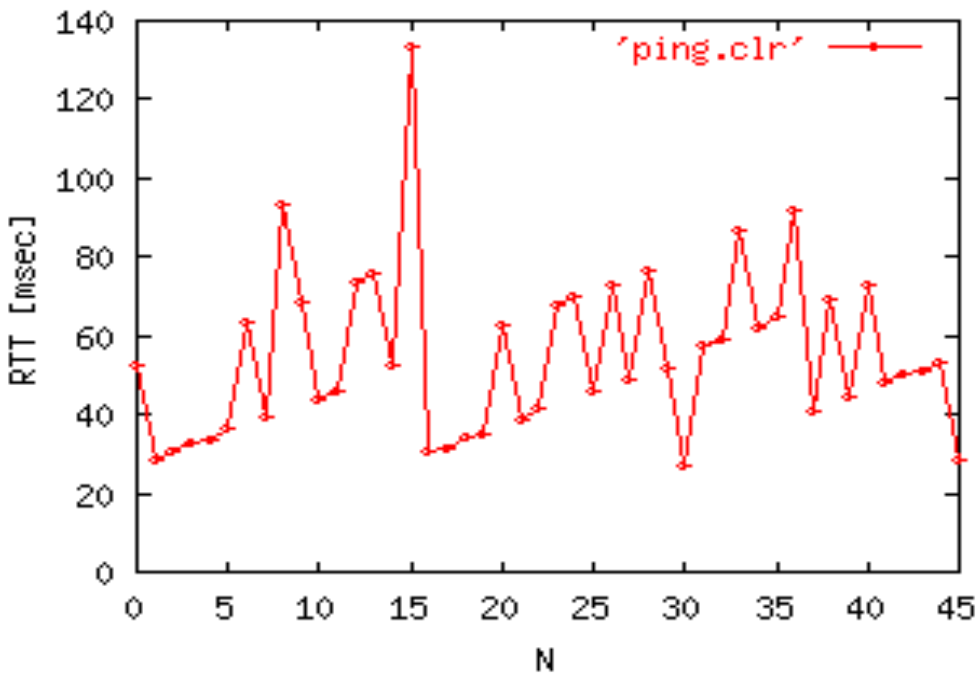


Retransmission timer

How to compute it ?

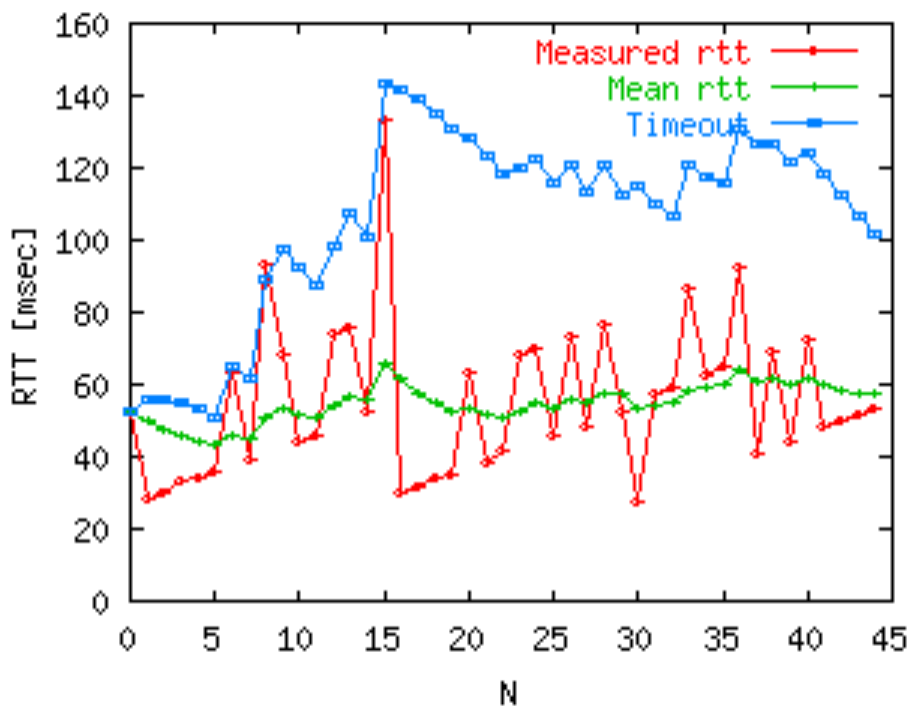
- Issue
  - round-trip-time may change frequently during the lifetime of a TCP connection



Retransmission timer

TCP's retransmission timer

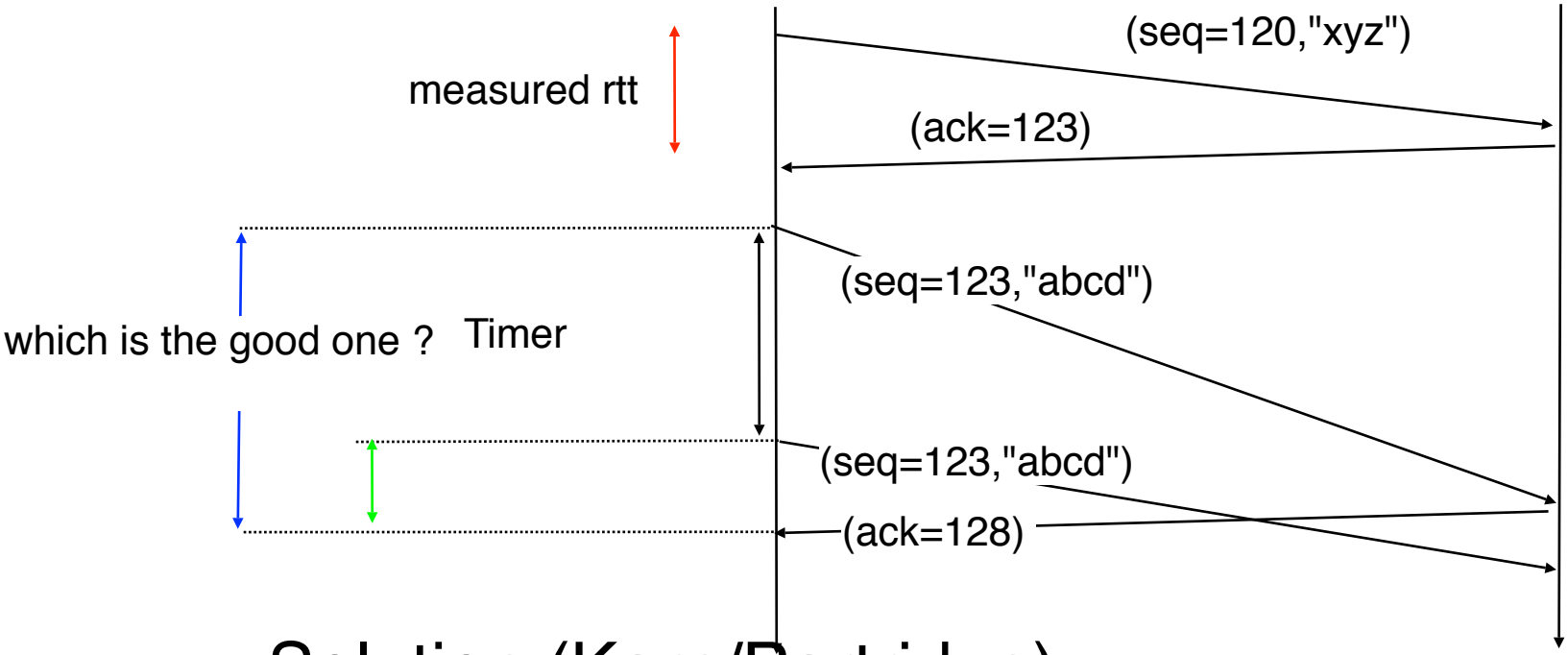
- One timer per connection
  - timer = mean(rtt) + 4*std_dev(rtt)
  - Estimation of the mean
    - est_mean(rtt) = (1-α)*est_mean(rtt) +α*rtt_measured
  - Estimation of the standard deviation of the rtt
    - est_std_dev=(1-β)*est_std_dev+β*|rtt_measured - est_mean(rtt)|



Round-trip-time estimation

Problem

How to measure rtt after retransmissions ?



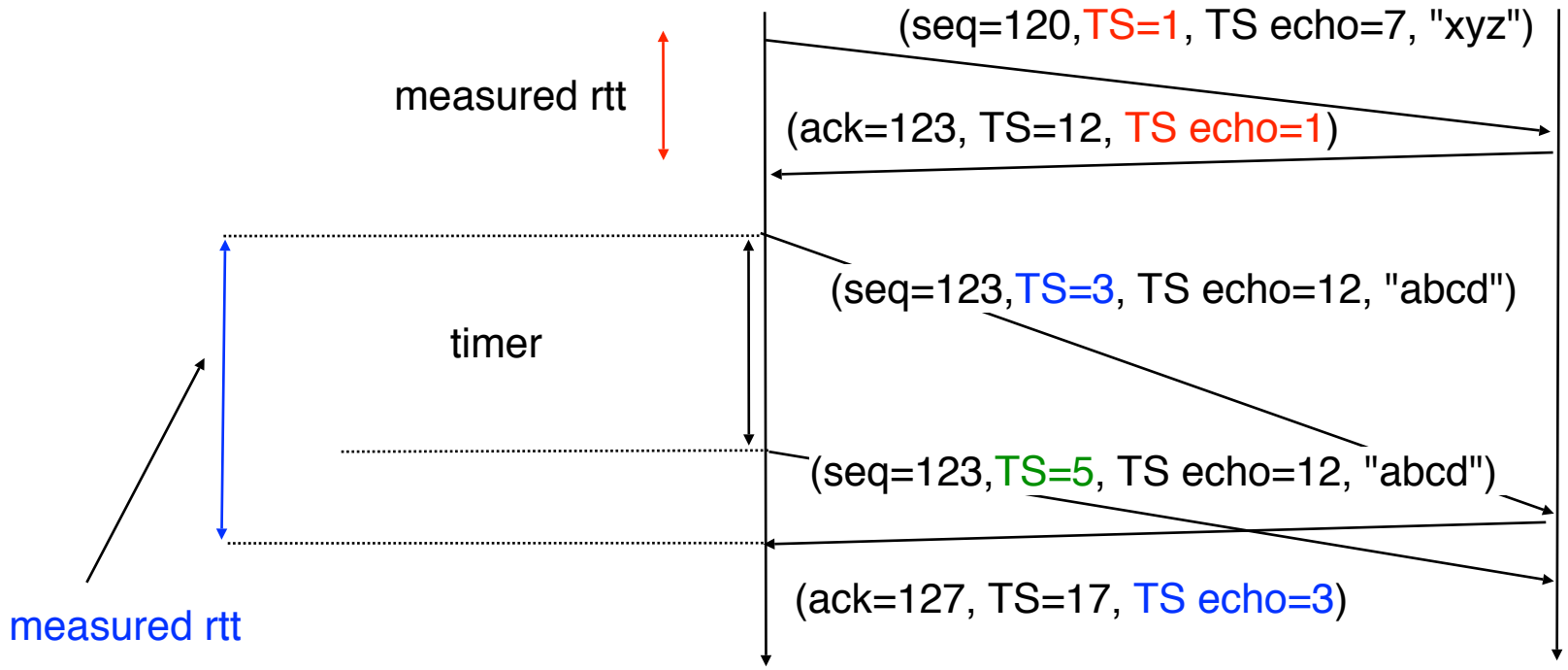
Solution (Karn/Partridge)

1. Do not measure rtt of retransmitted segments

Round-trip-time estimation (2)

Improvement to Karn/Partridge

- Add a timestamp in each segment sent
  - TS and TSEcho (RFC1323)



Improving the reliable data transfer

- How to improve the reaction to segment losses ?
  - TCP receiver should send an ack everytime an out-of-sequence segment is received
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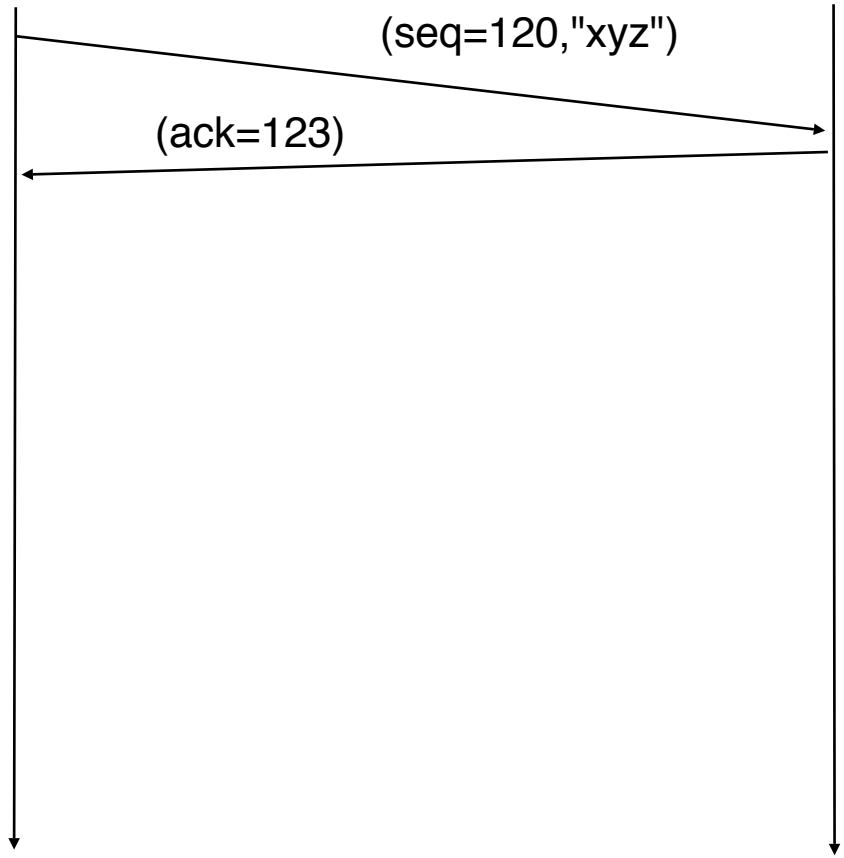

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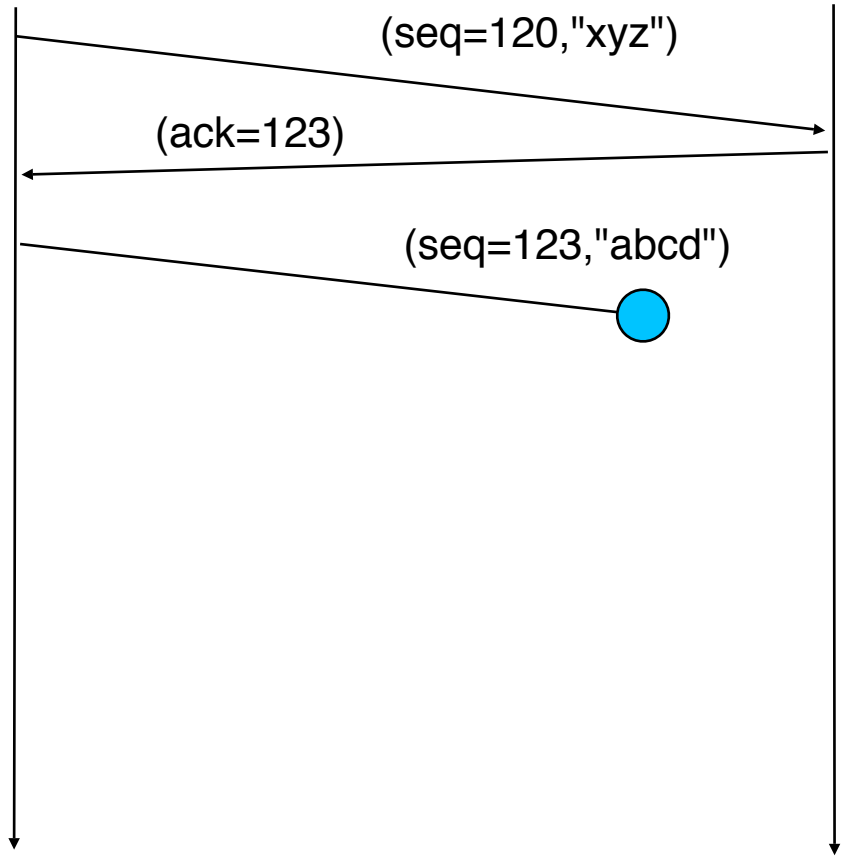

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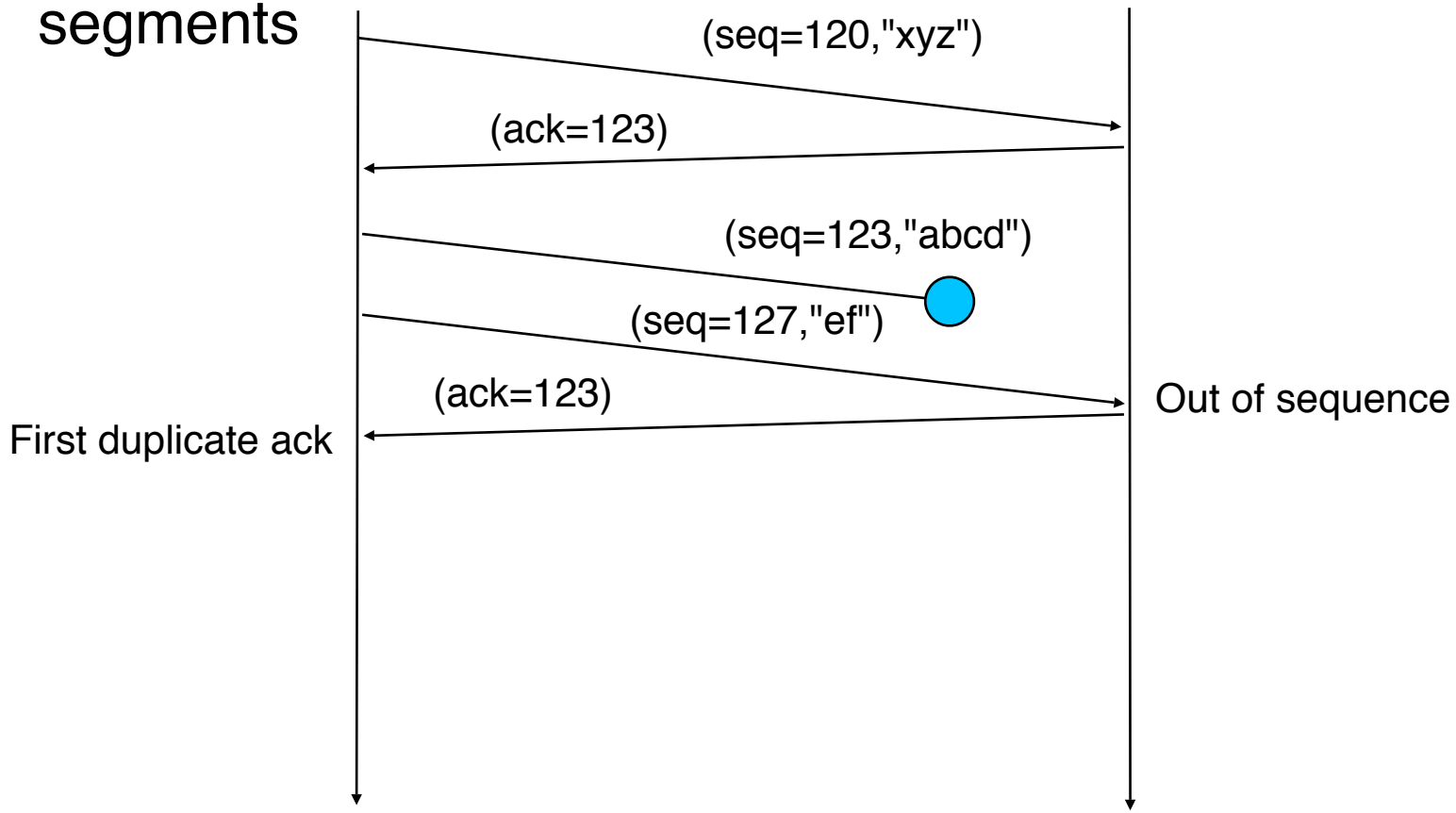

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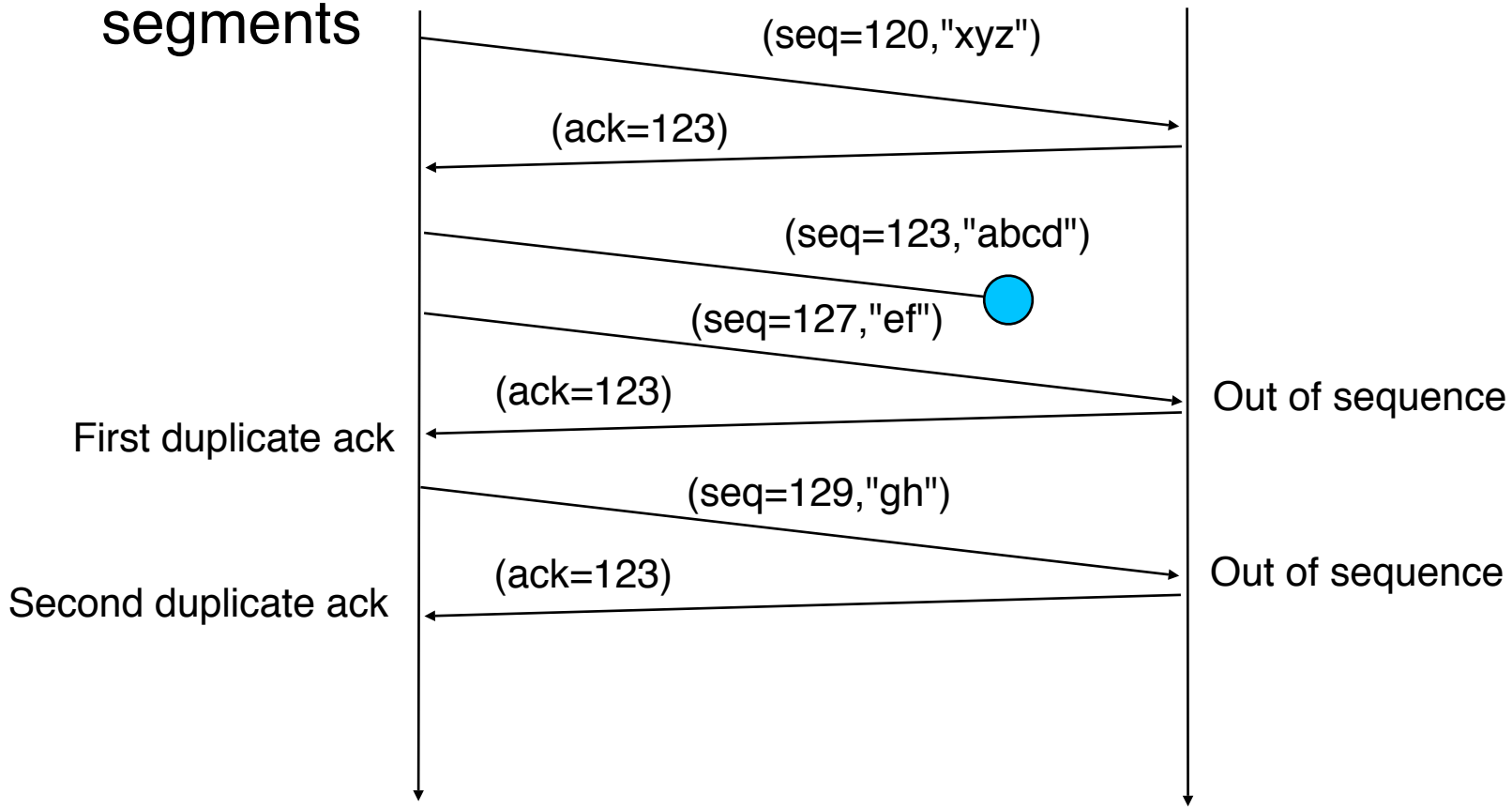

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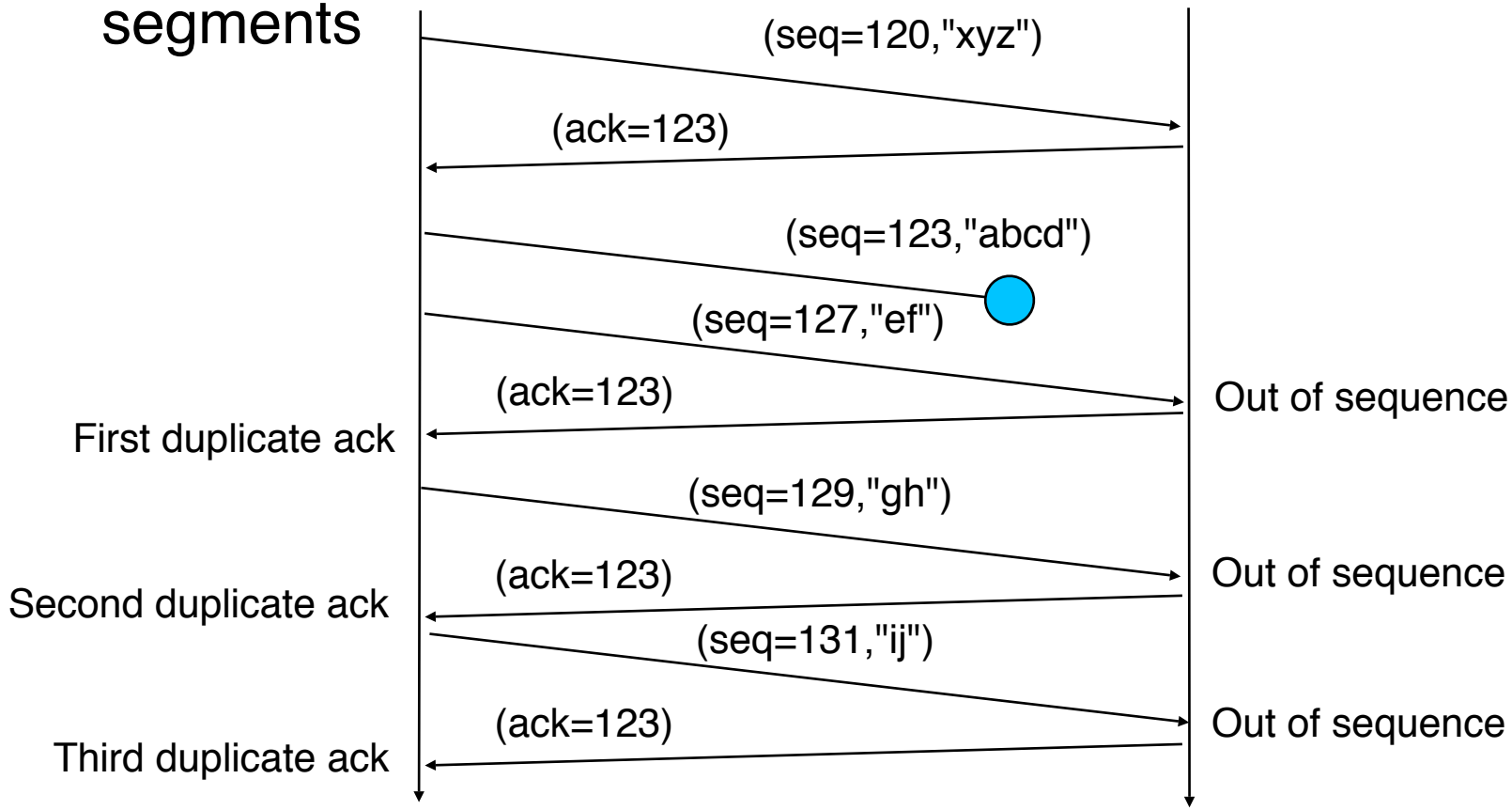

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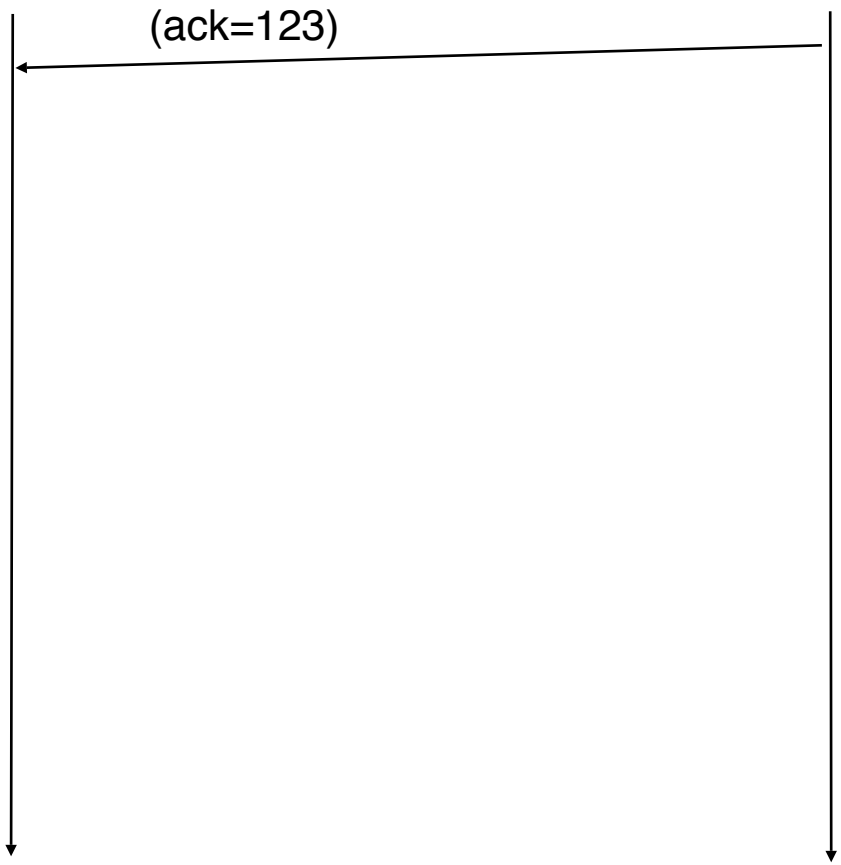

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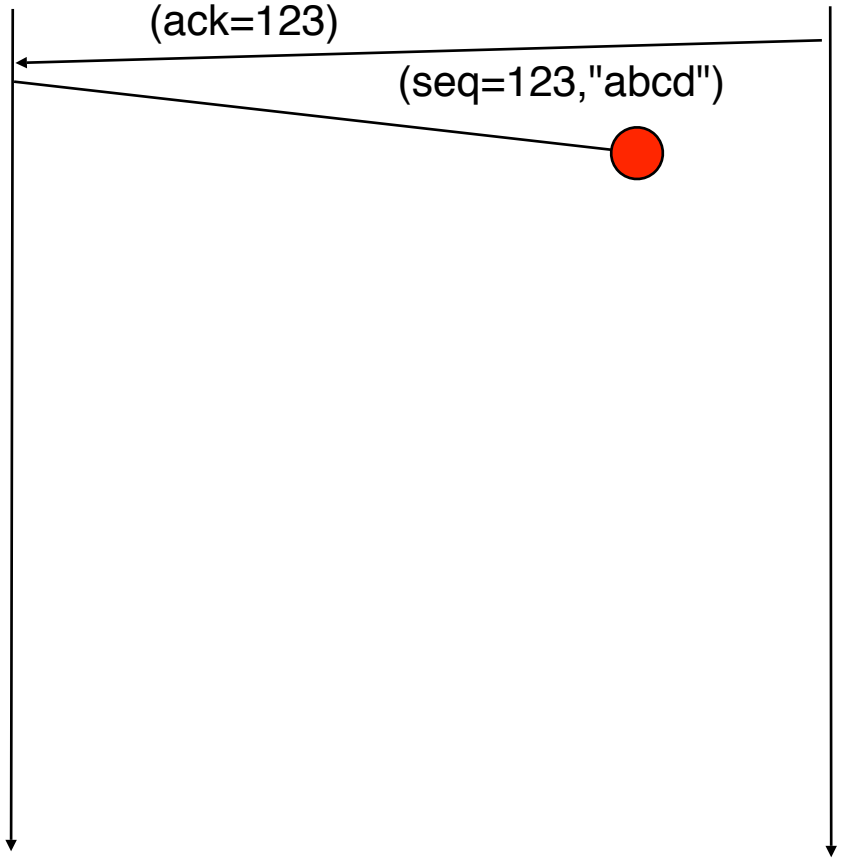

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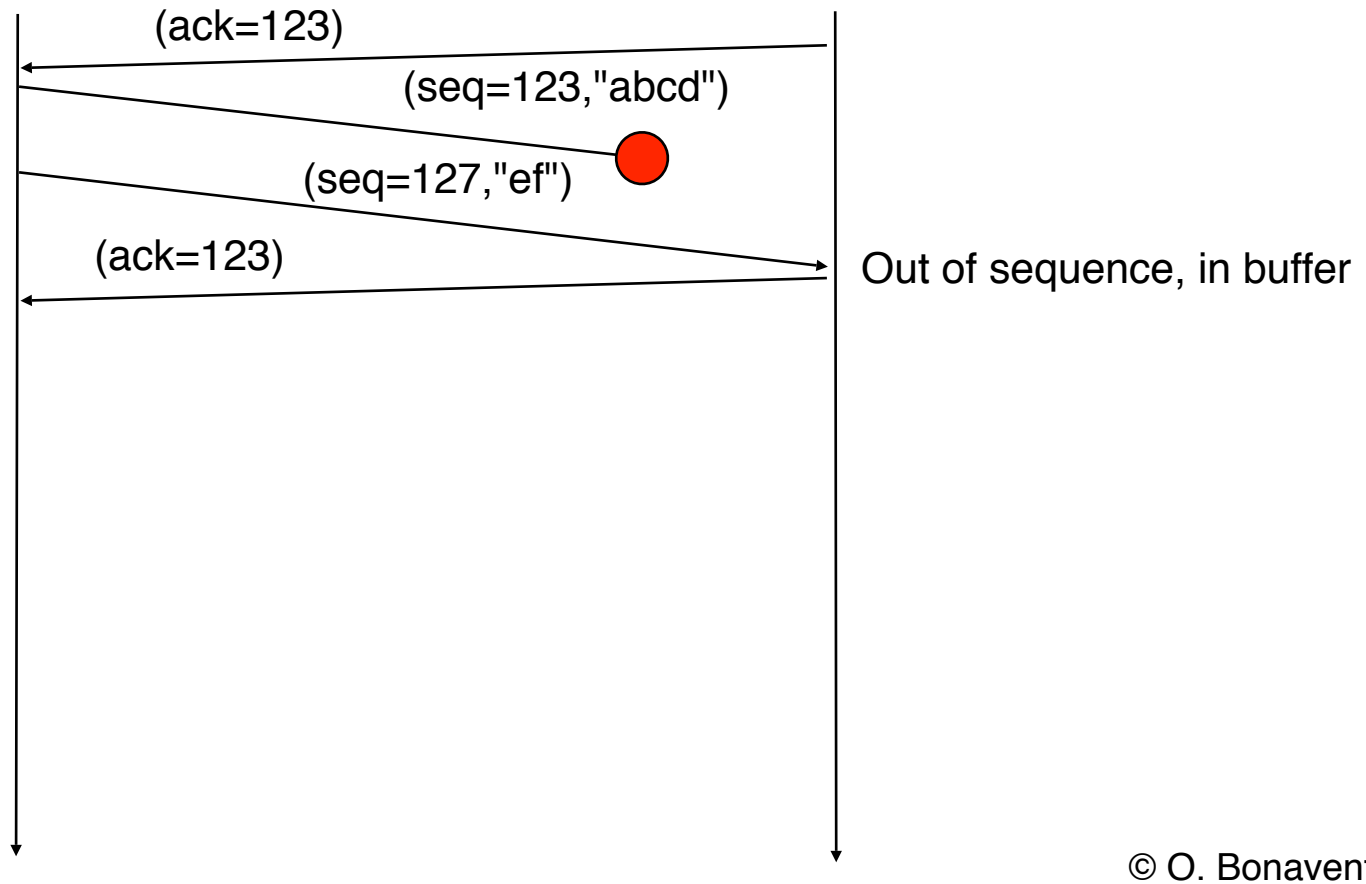

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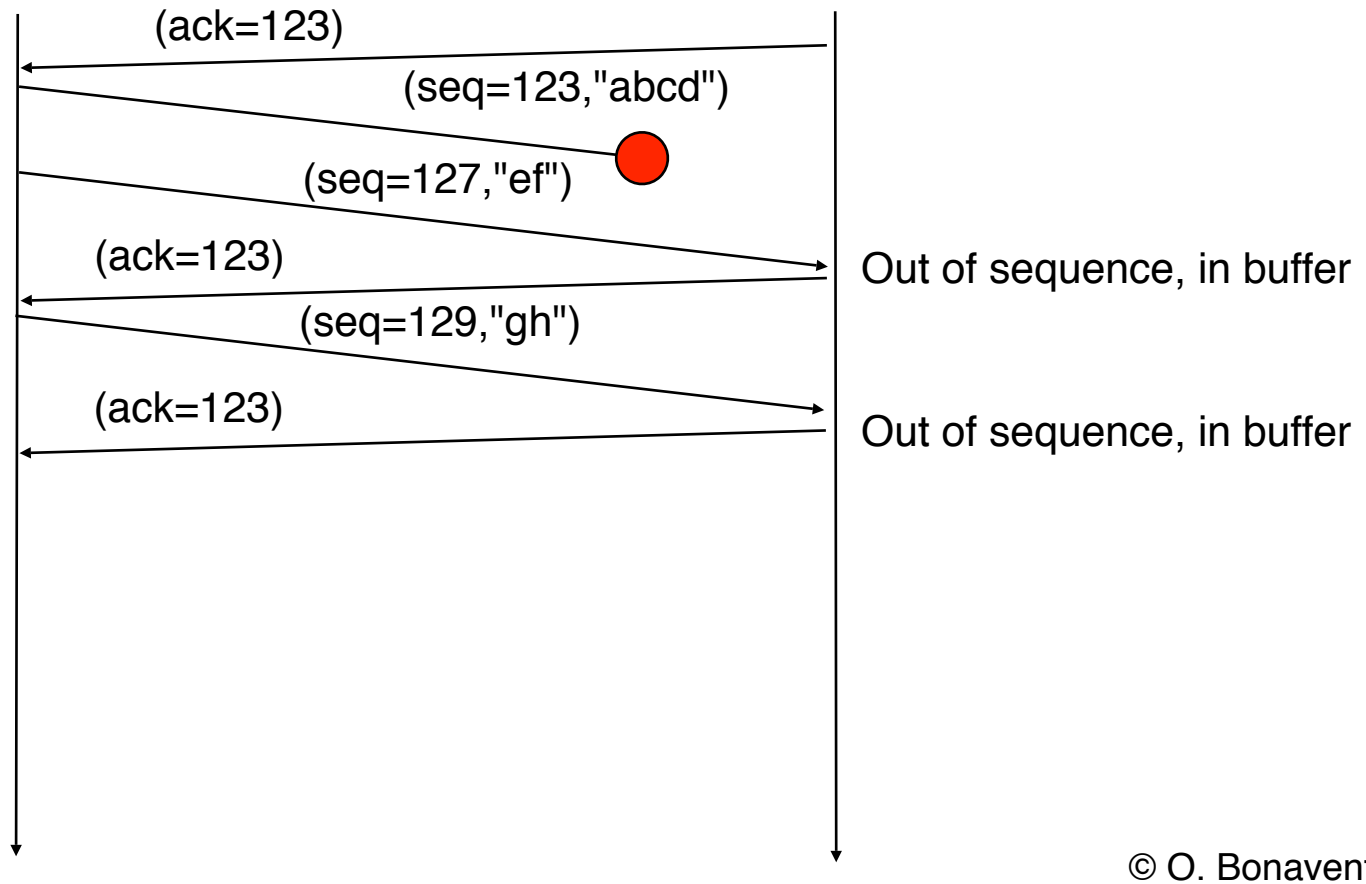

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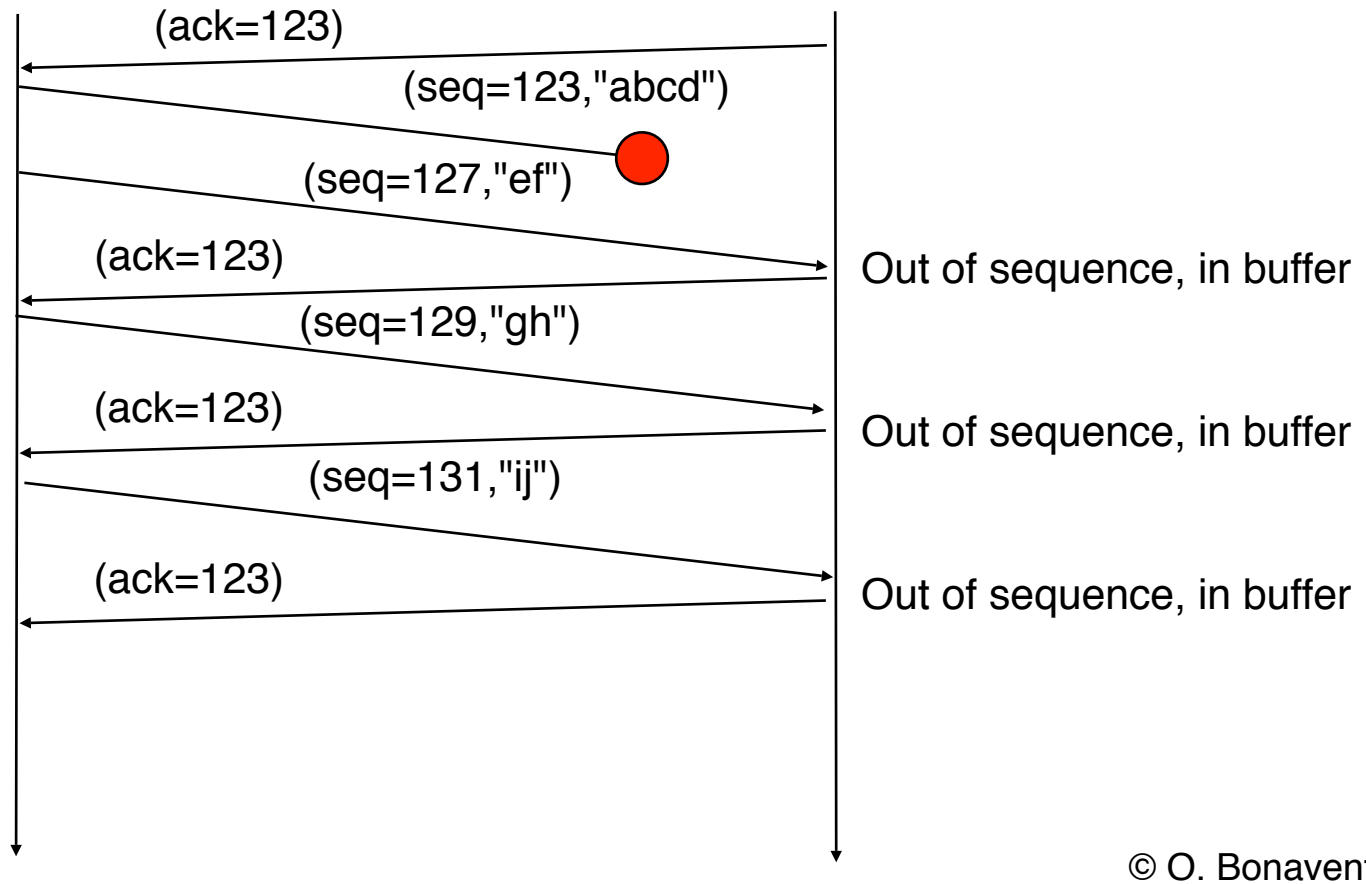

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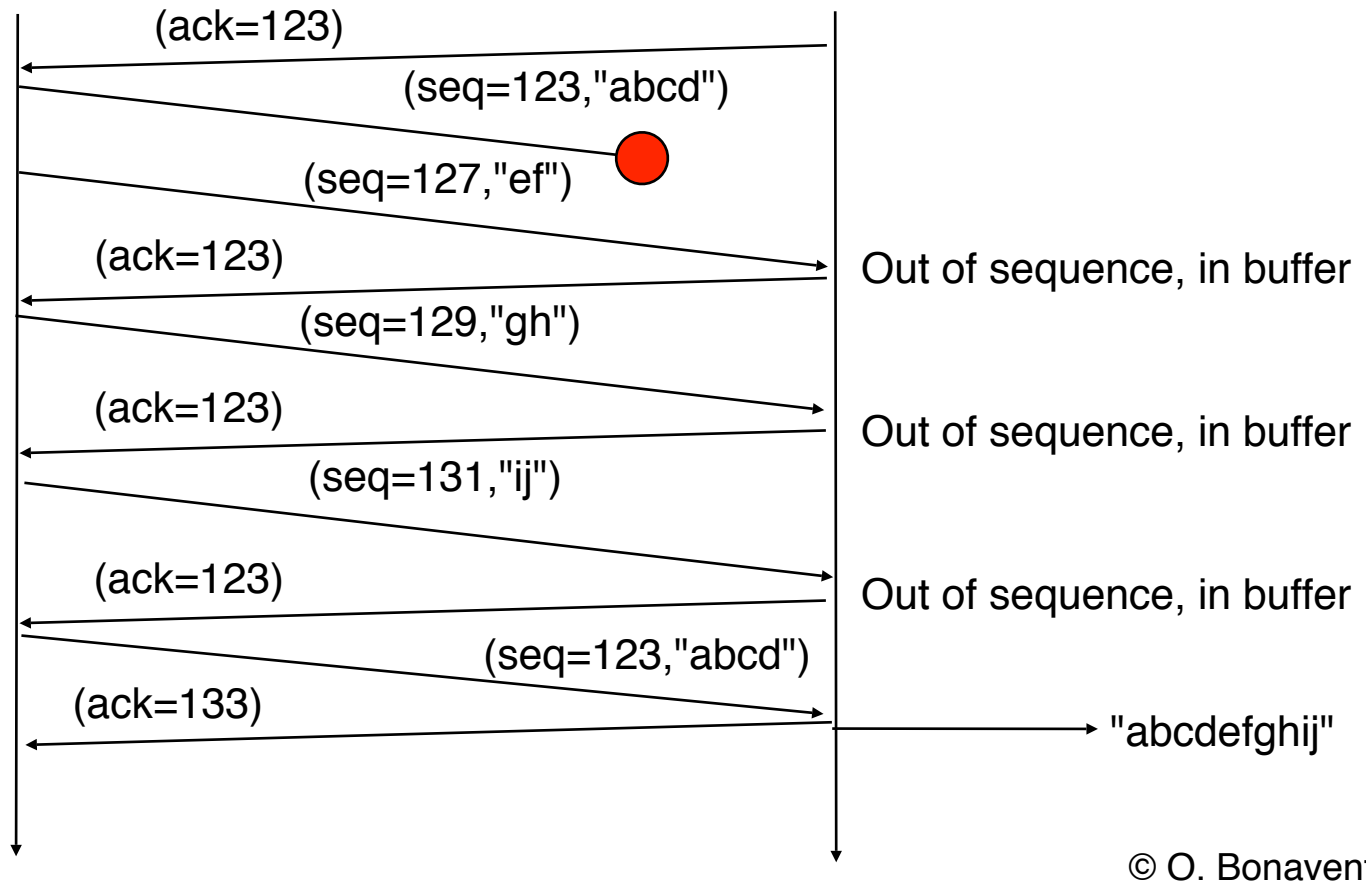
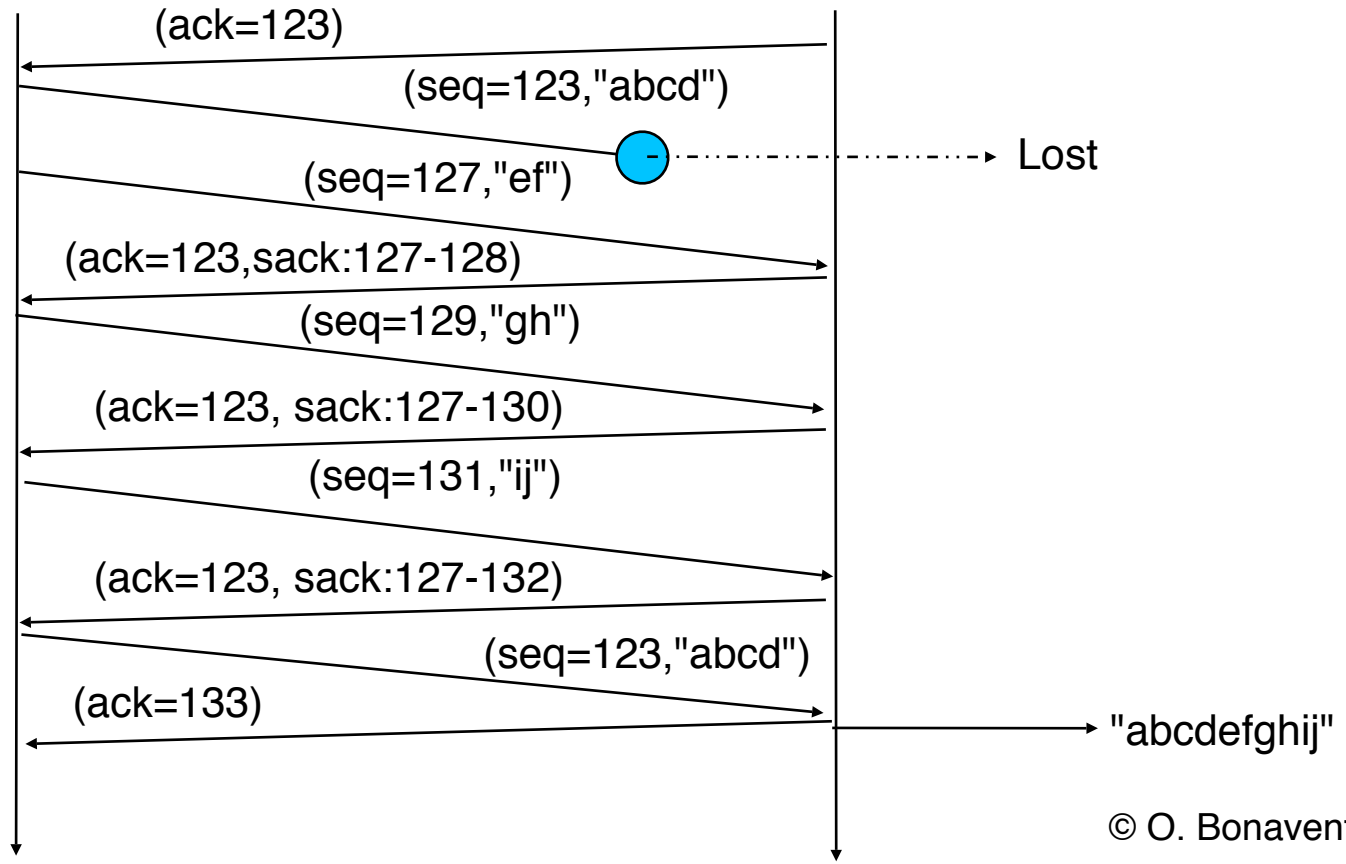


Improving the reliable data transfer

Selective acknowledgement

sack:[seq1-seq2];[seq3-seq4]



only 123-126 must be retransmitted