Computer Networking : Principles, Protocols and Practice

Part 3 : Transport Layer

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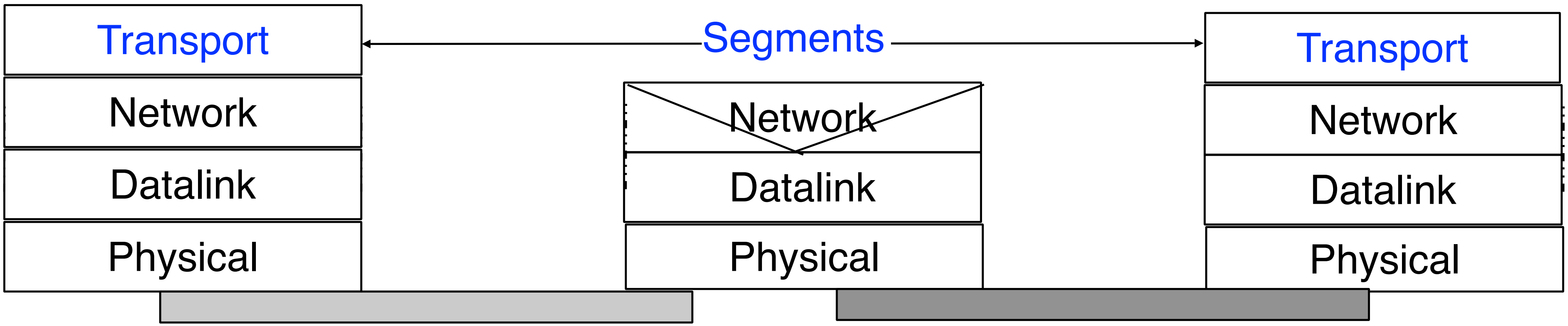
Module 3 : Transport Layer

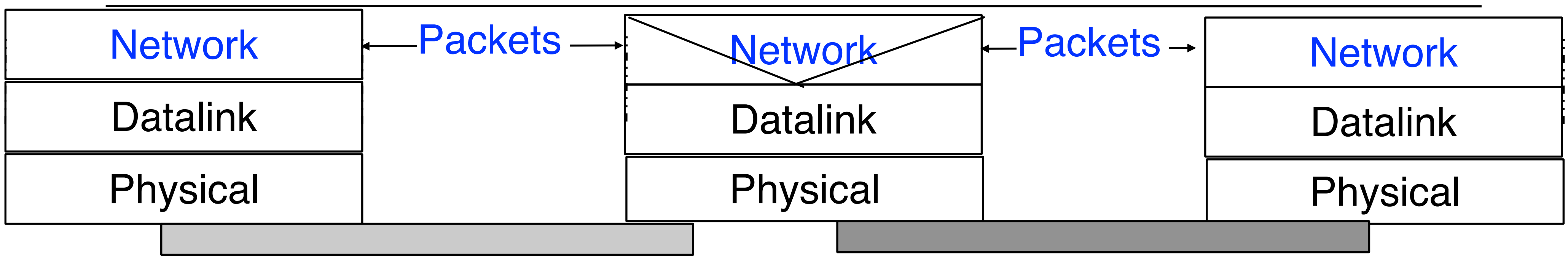
- Basics
- Building a reliable transport layer
  - Reliable data transmission
  - Connection establishment
  - Connection release
- UDP : a simple connectionless transport protocol
- TCP : a reliable connection oriented transport protocol

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



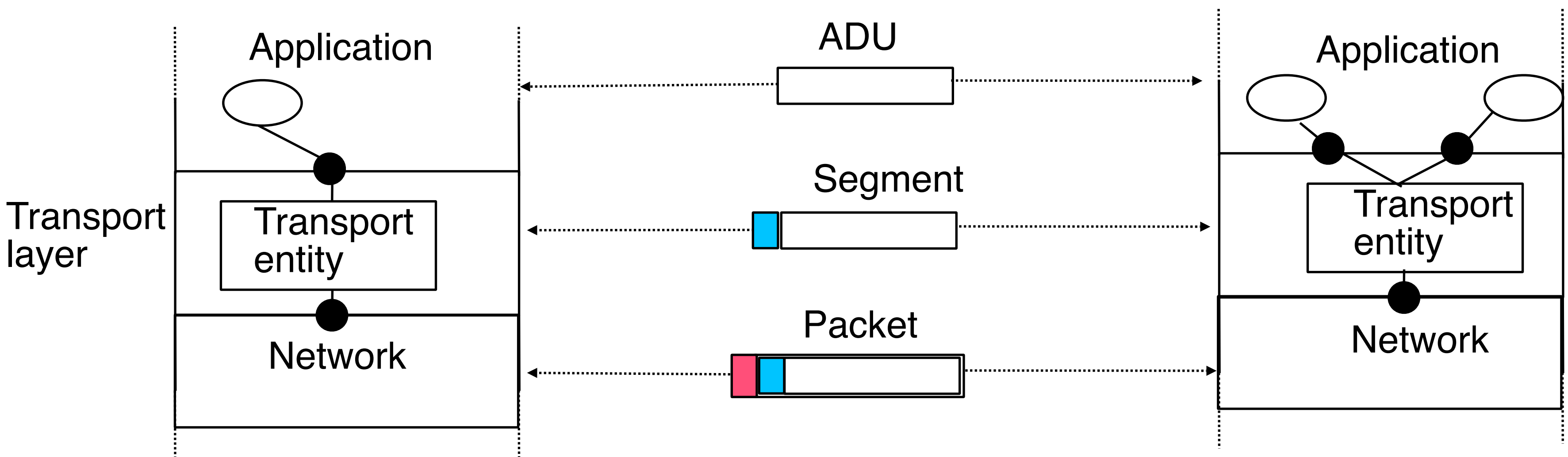
- Network layer service in Internet
  - Unreliable connectionless service
    - Packets can be lost
    - Packets can suffer from transmission errors
    - Packet ordering is not preserved
    - Packet can be duplicated
    - Packet size is limited to about 64 KBytes
  - How to build a service useable 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



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- Basics
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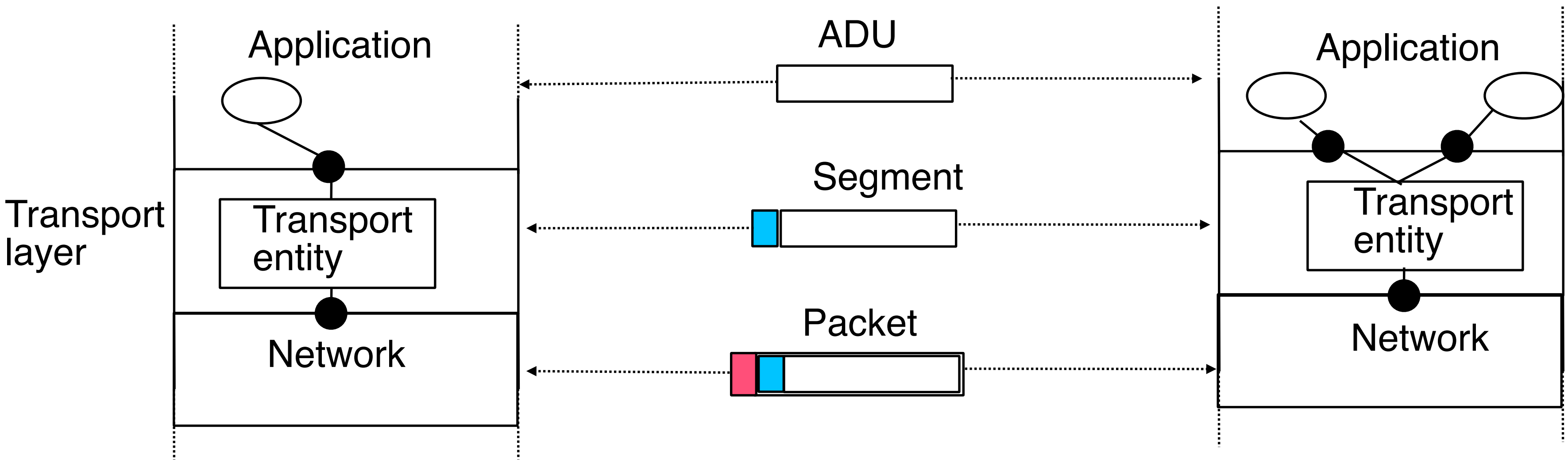
Transport layer protocols

- 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)`

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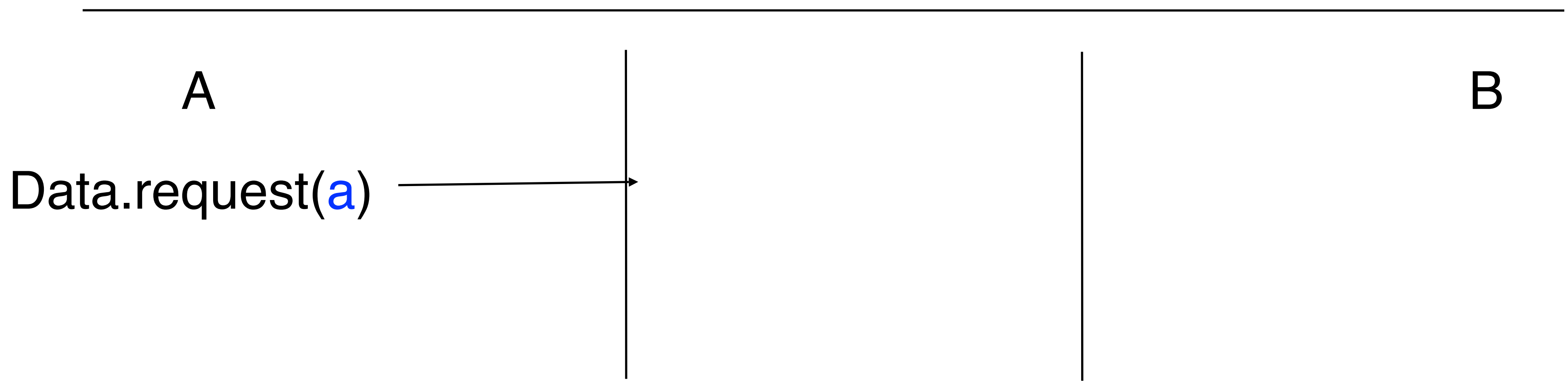

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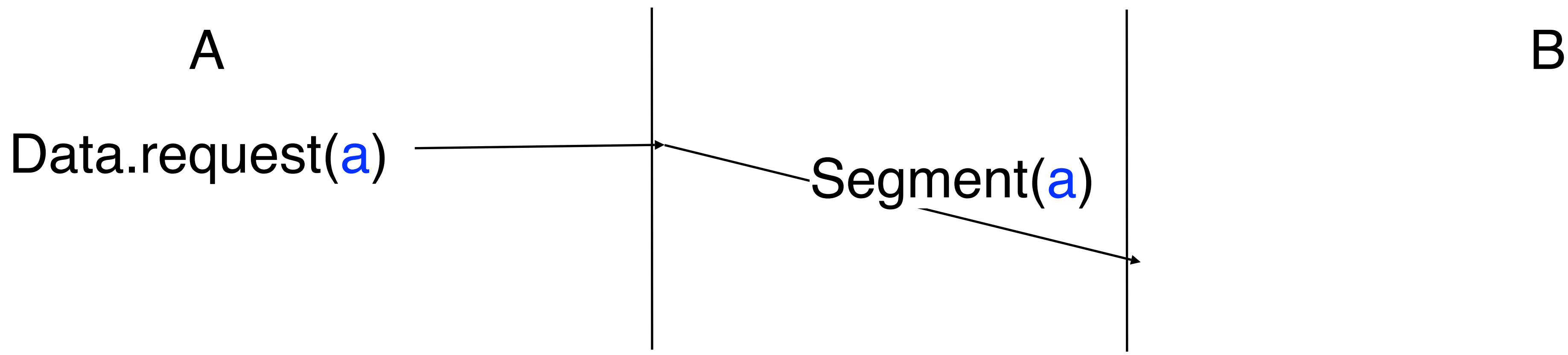

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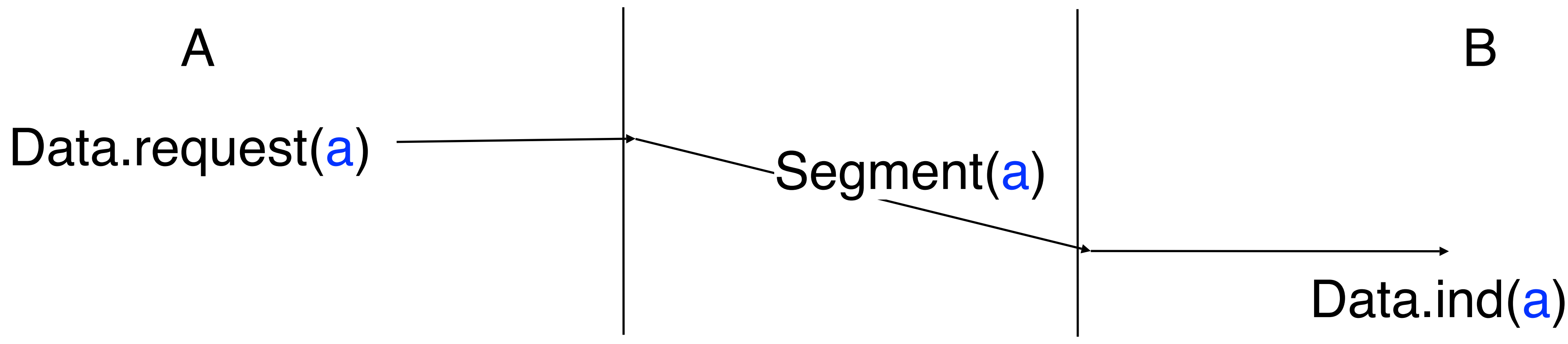

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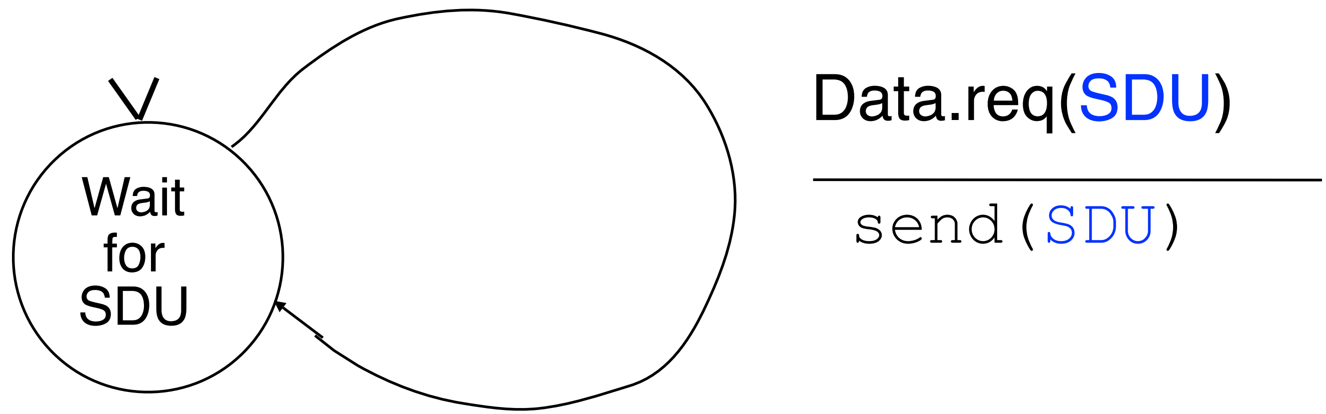
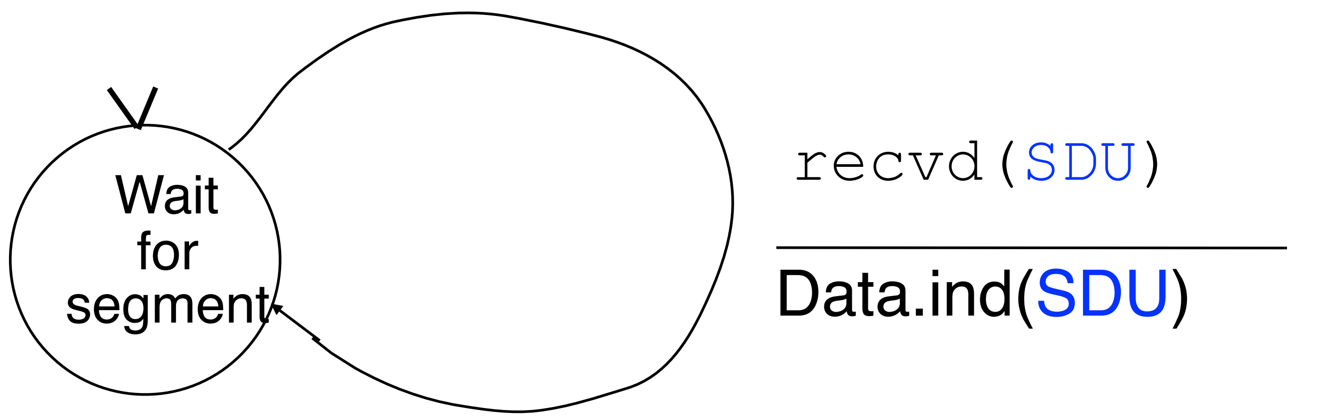
Protocol 1 as a FSM

- Sender



- Receiver



Protocol 1 : Example

A

B

- 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 ?

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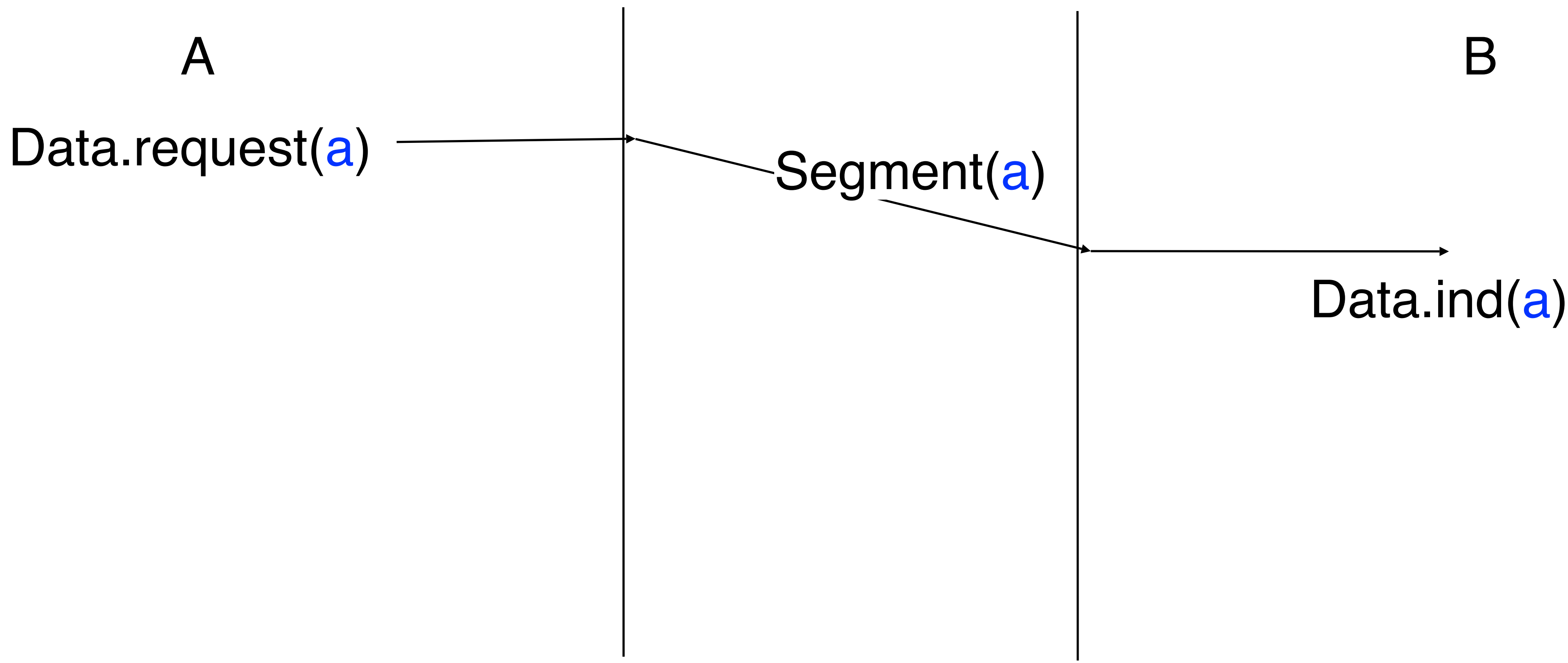

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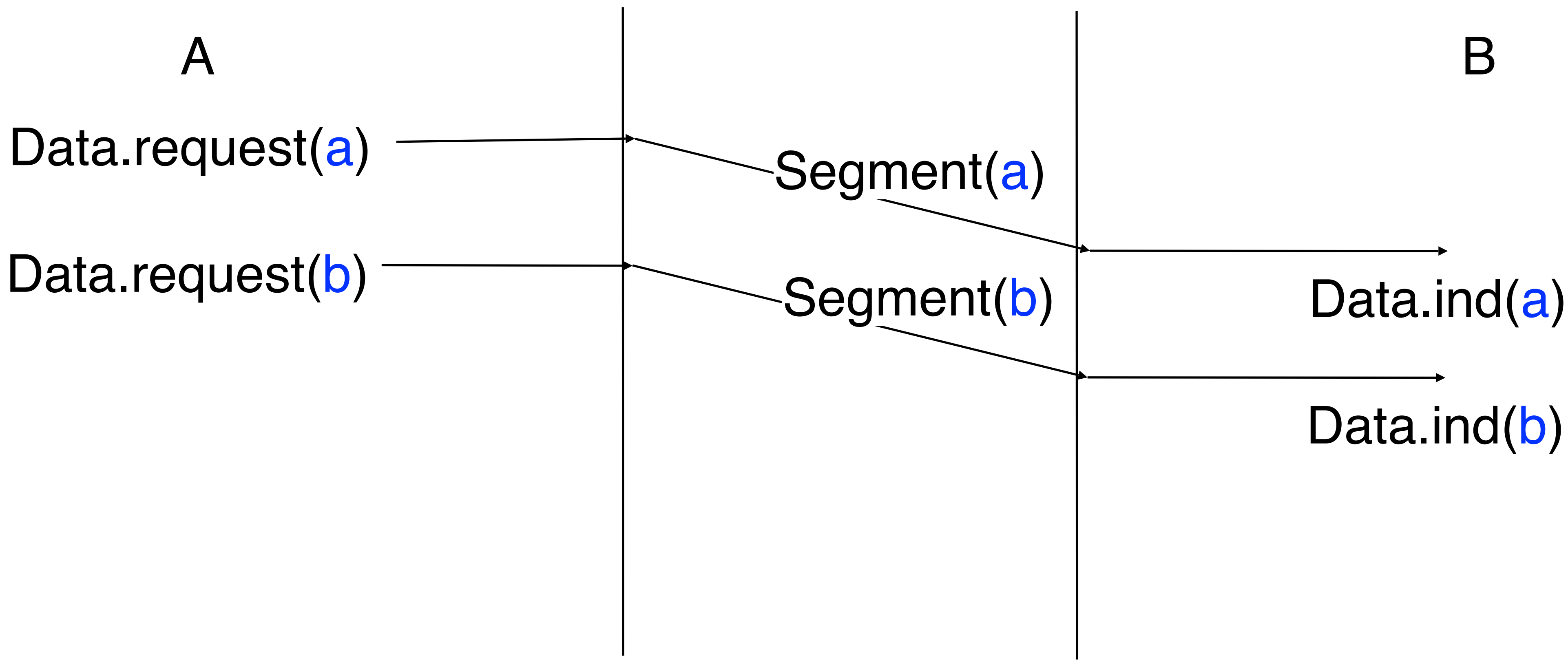

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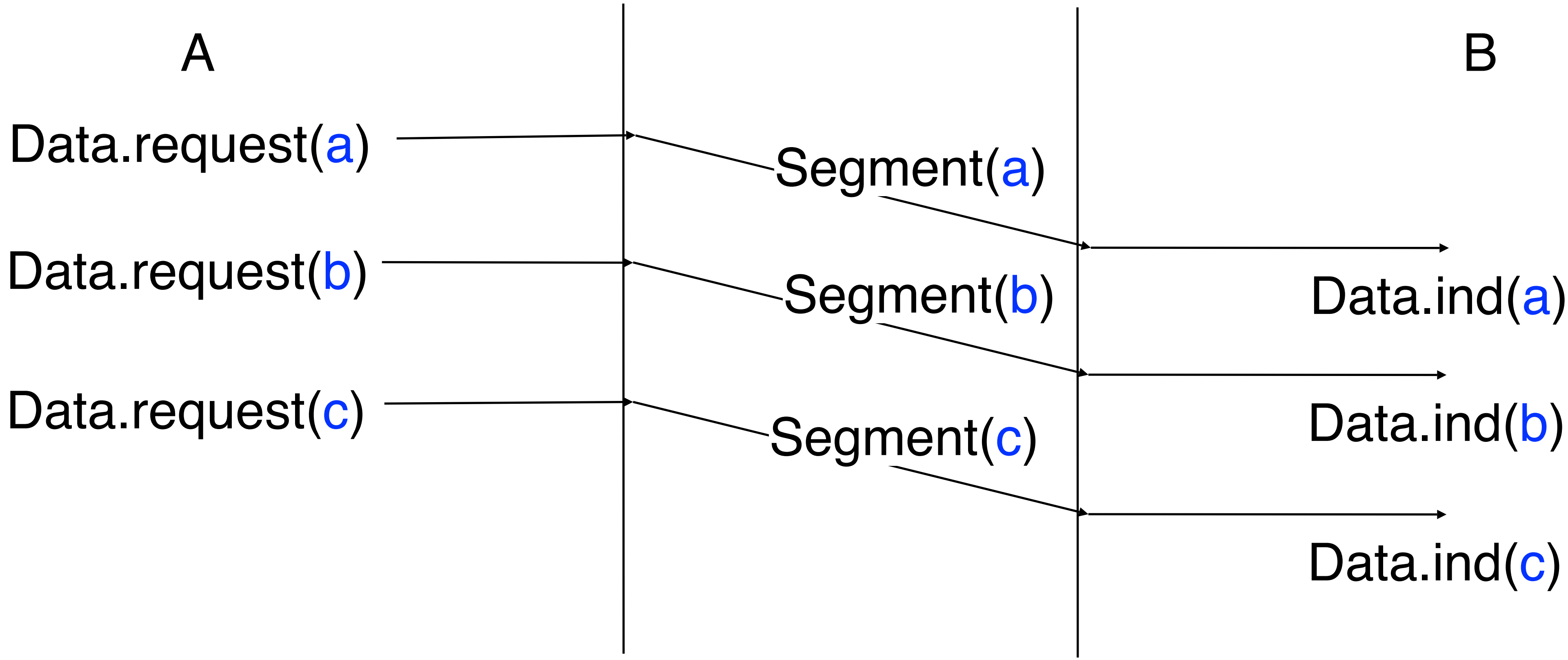


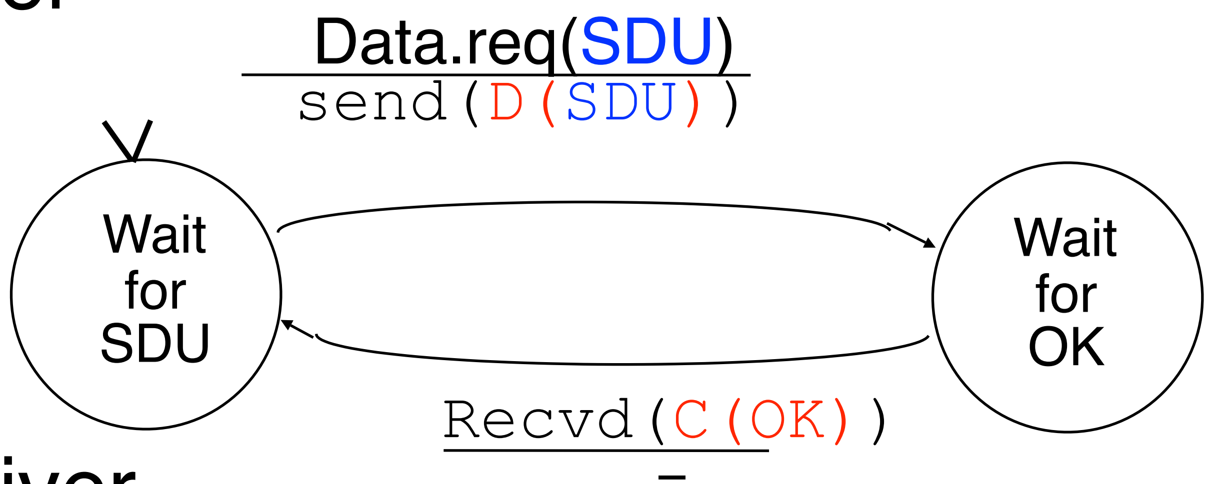
- Issue
  - What happens if the receiver is much slower than the sender ?
    - e.g. receiver can process one segment per second while sender is producing 10 segments per second ?

Protocol 2

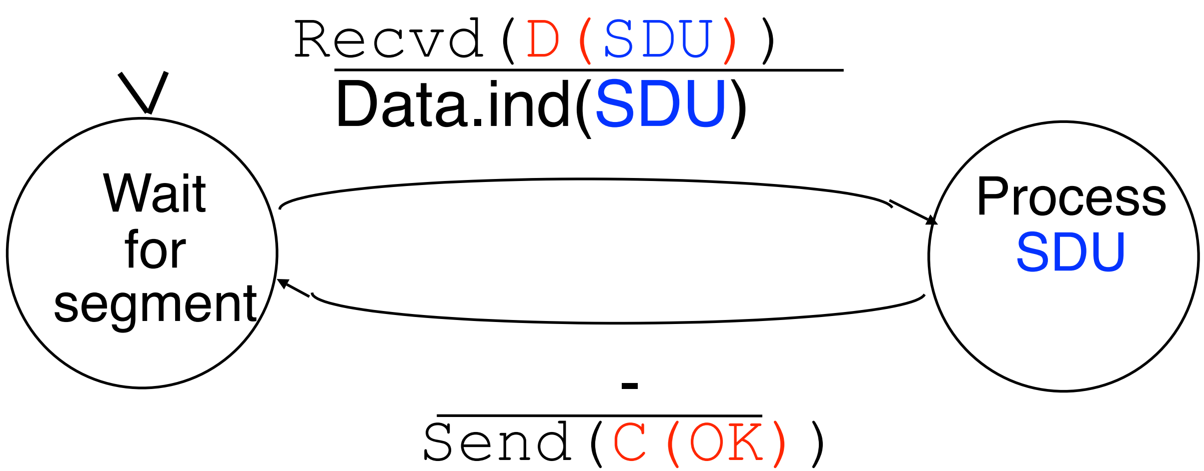
- Principle
  - Use a control segment (OK) that is sent by the receiver after having processed the received segment
  - creates a feedback loop between sender and receiver
- Consequences
  - Two types of segments
    - Data segment containing on SDU
      - Notation : D(SDU)
    - Control segment
      - 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

A

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The sender only sends segments when authorised by the receiver

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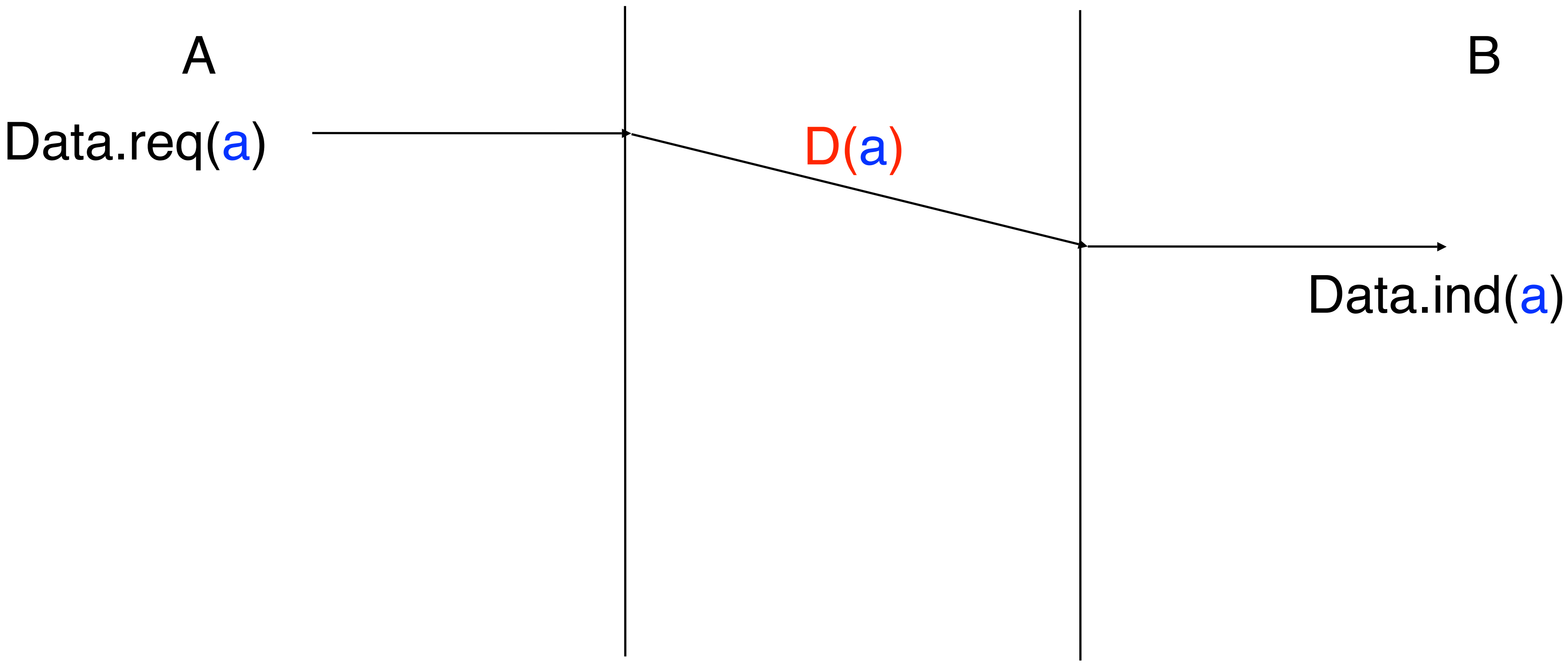

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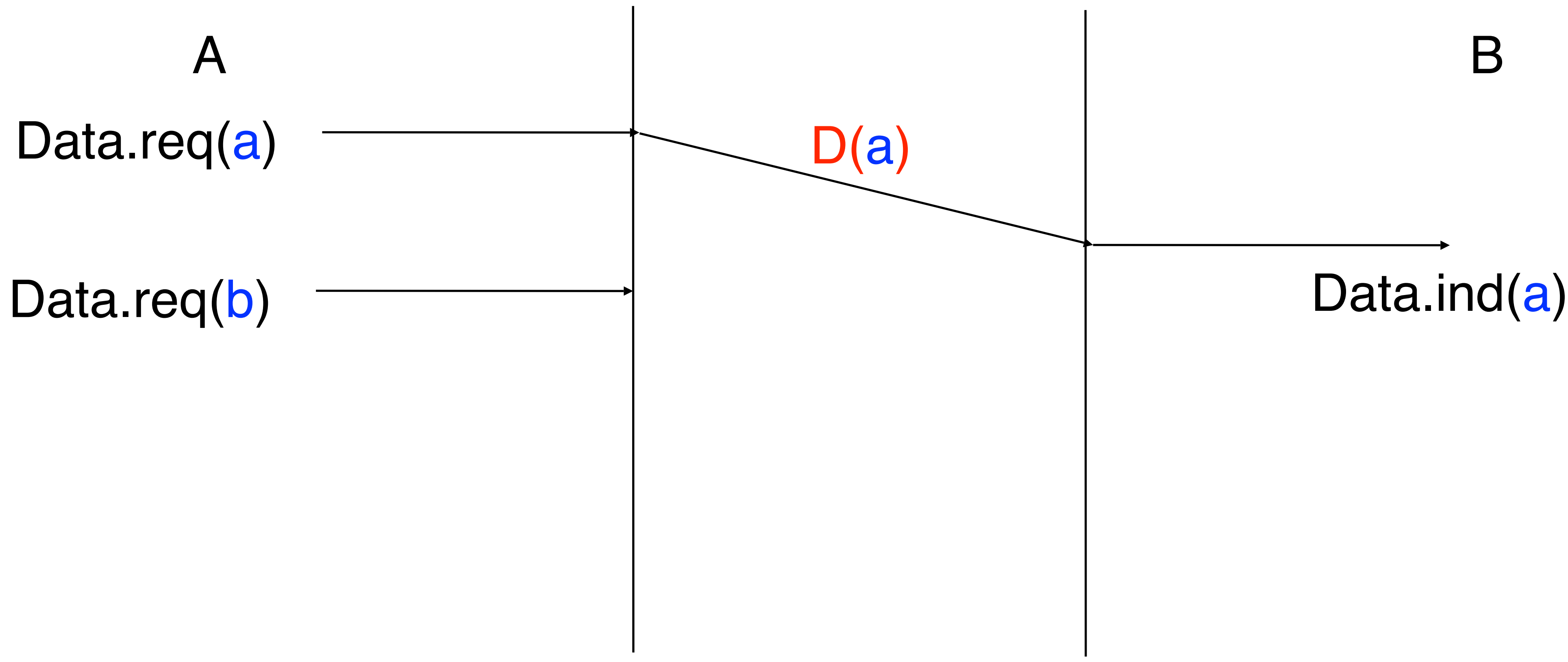

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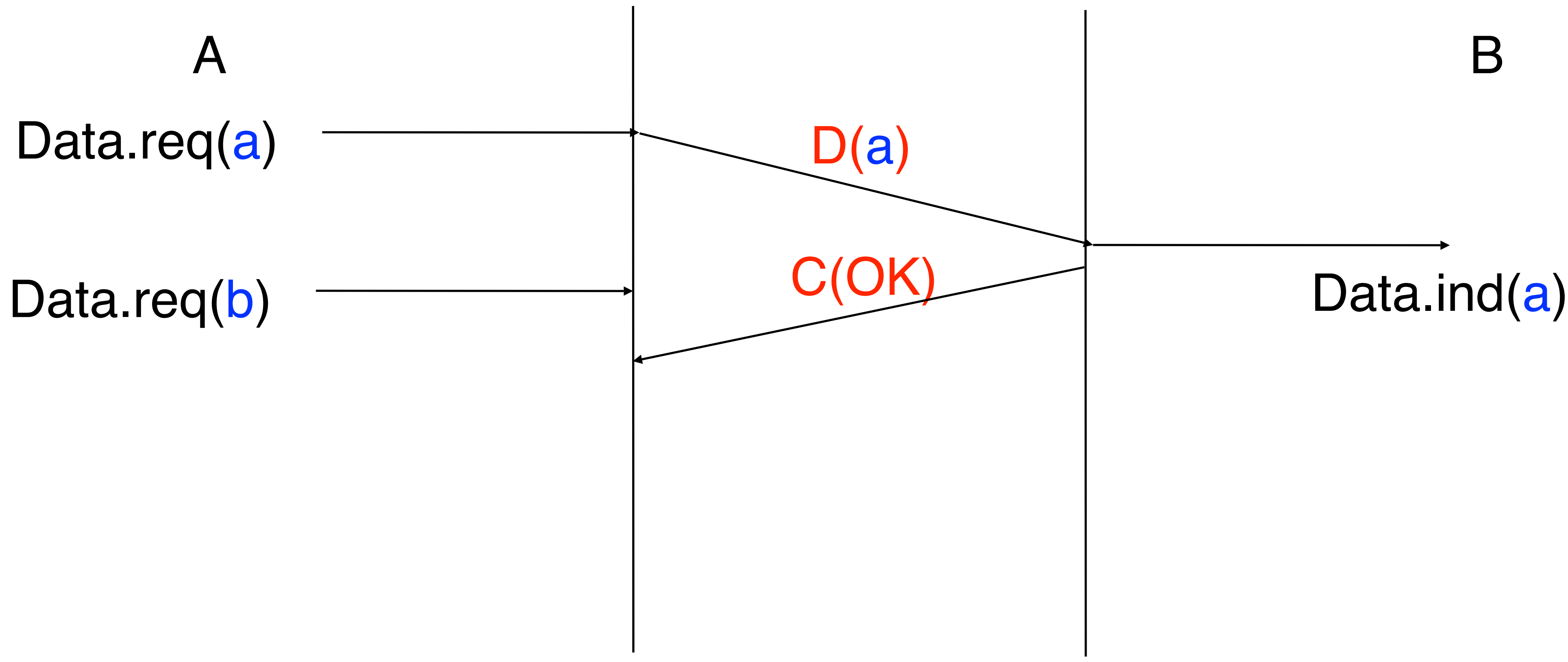

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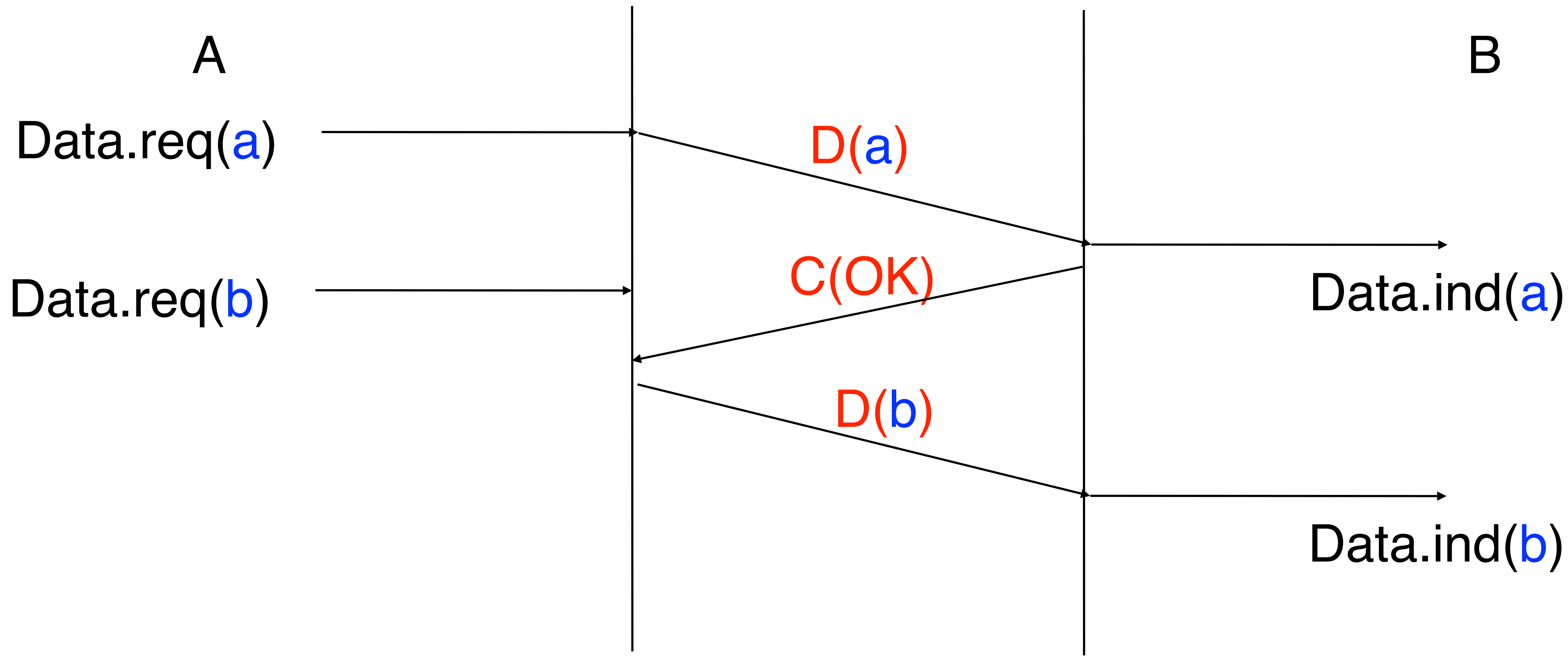

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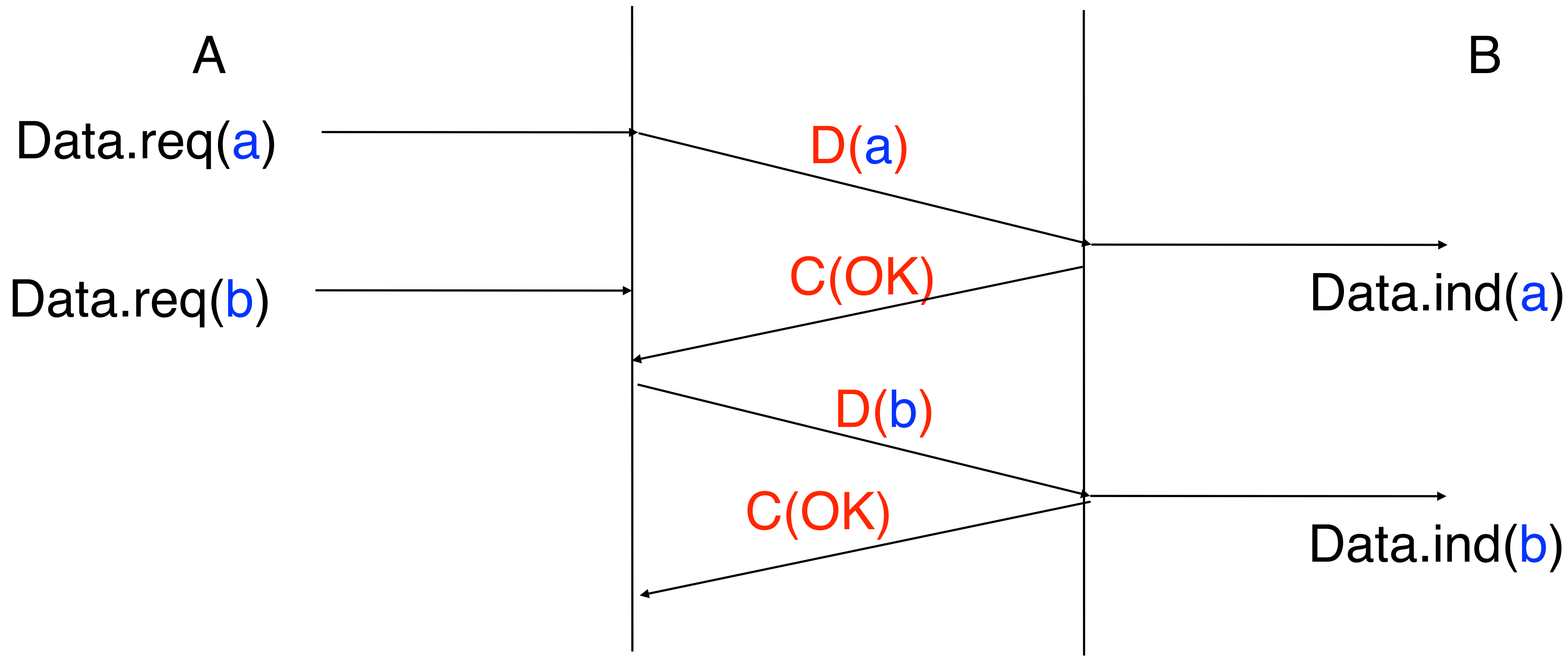

The sender only sends segments when authorised by the receiver

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
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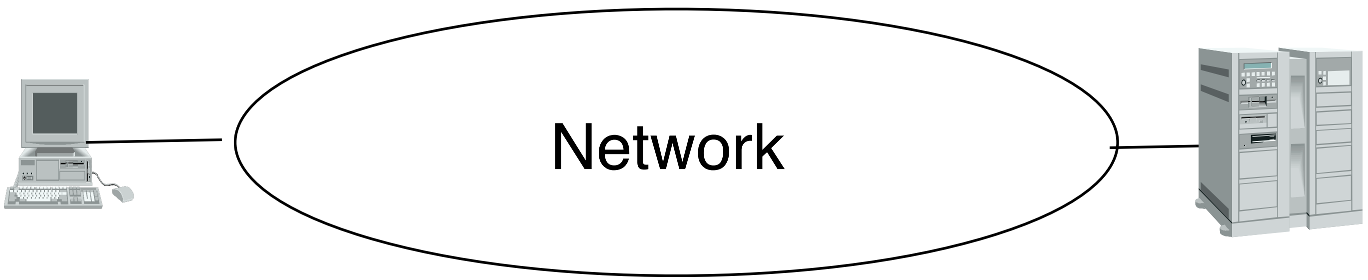
Transmission errors

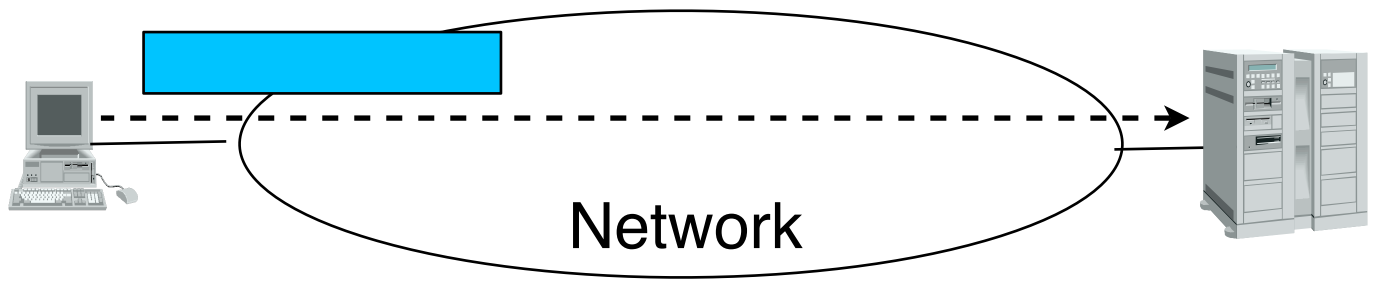
- Which types of transmission errors do we need to consider in the transport layer ?



- 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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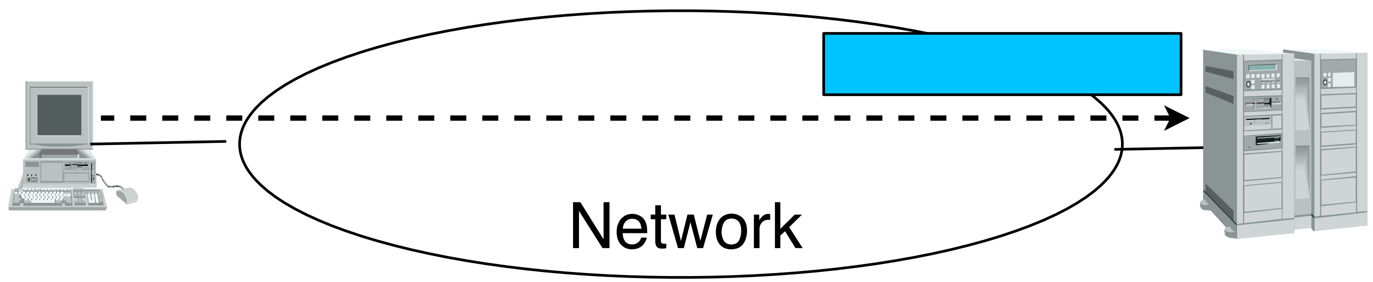

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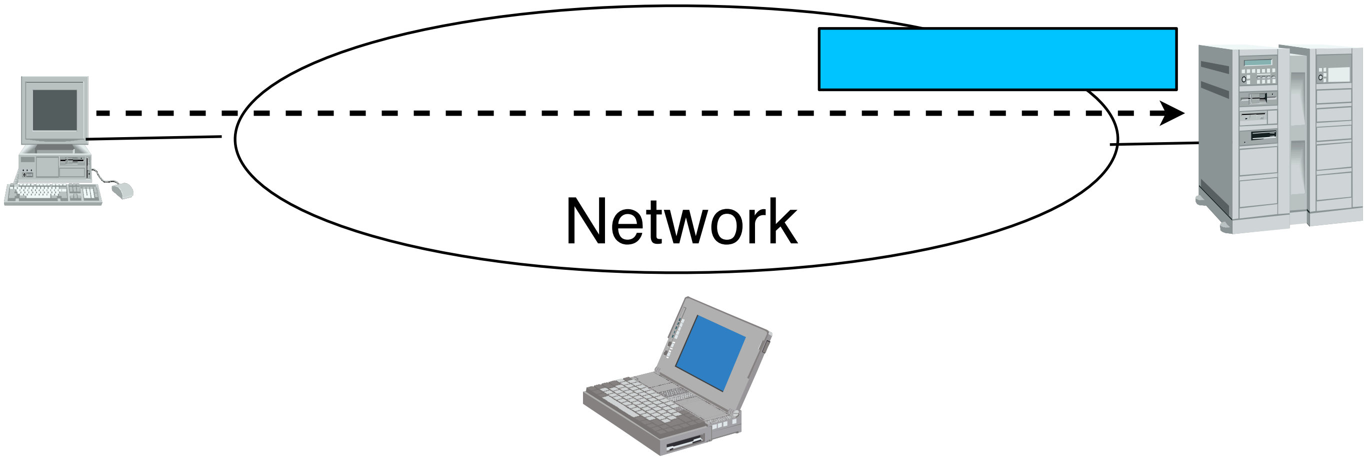

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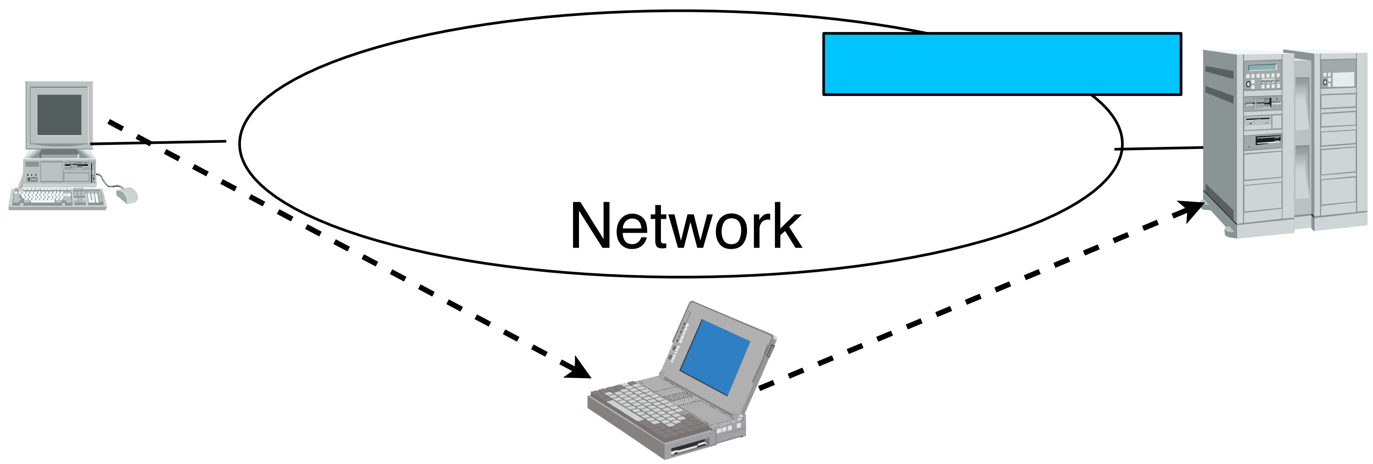

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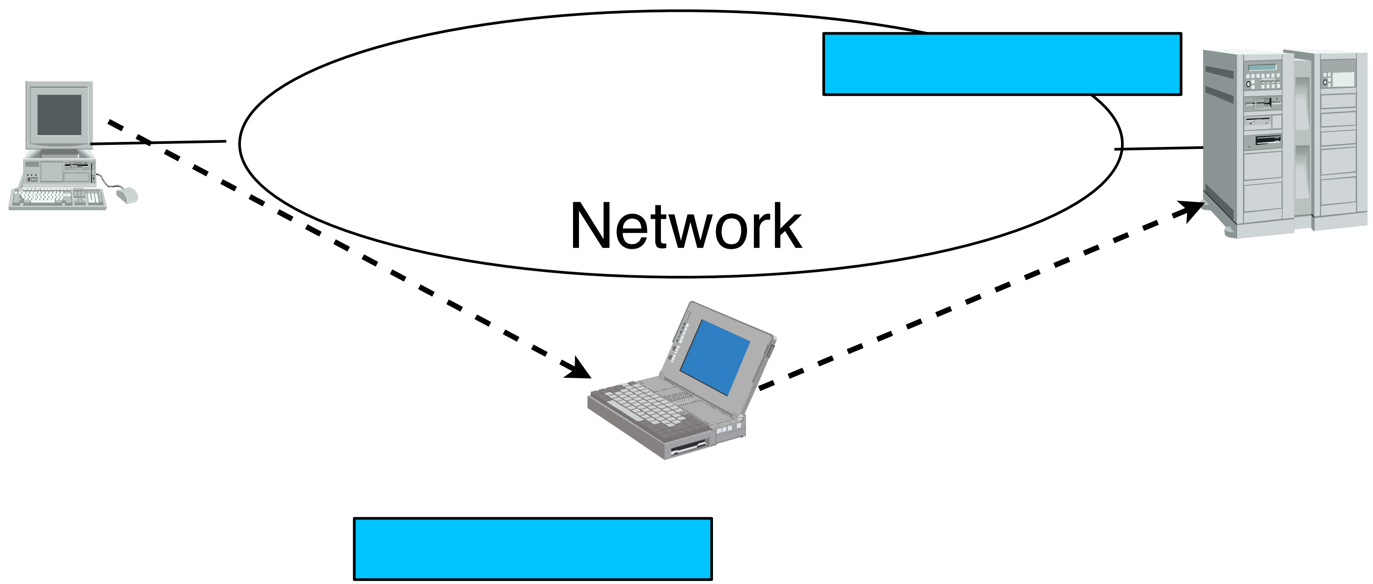

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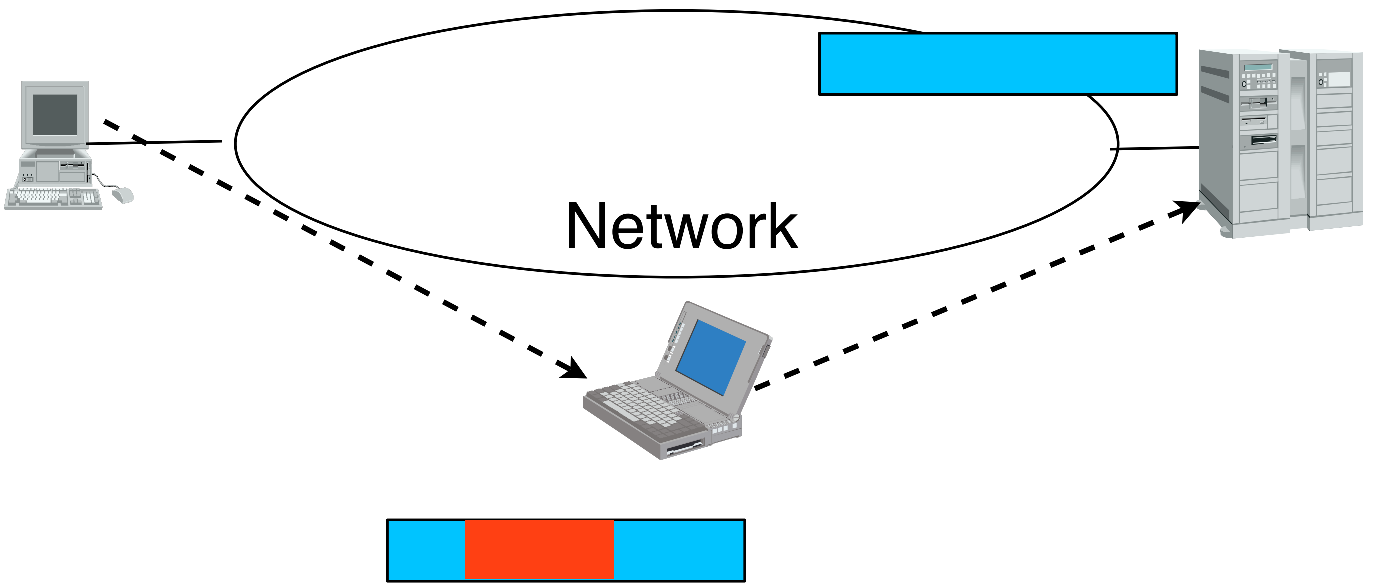

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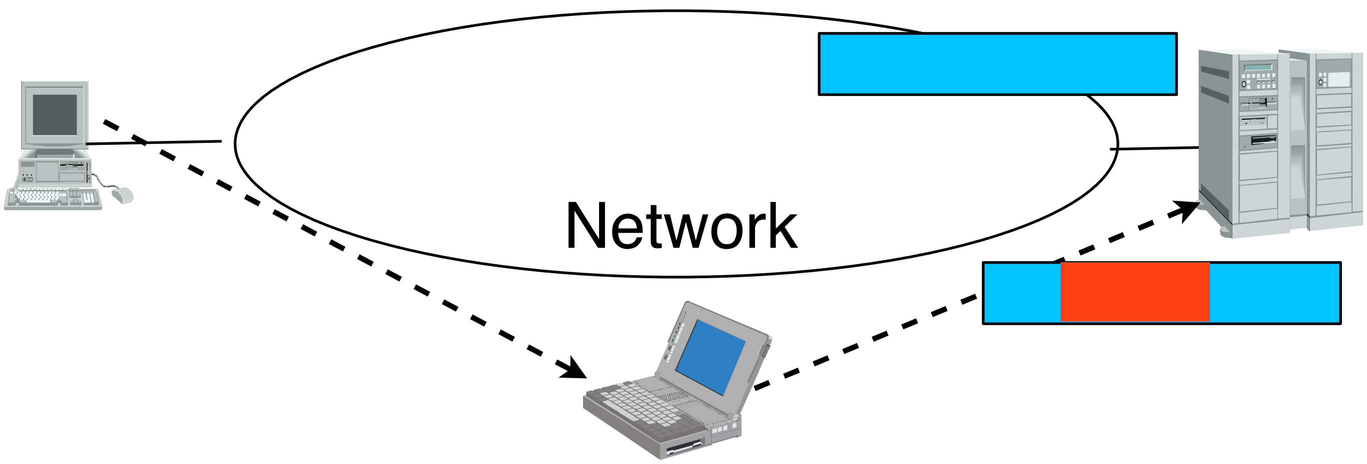

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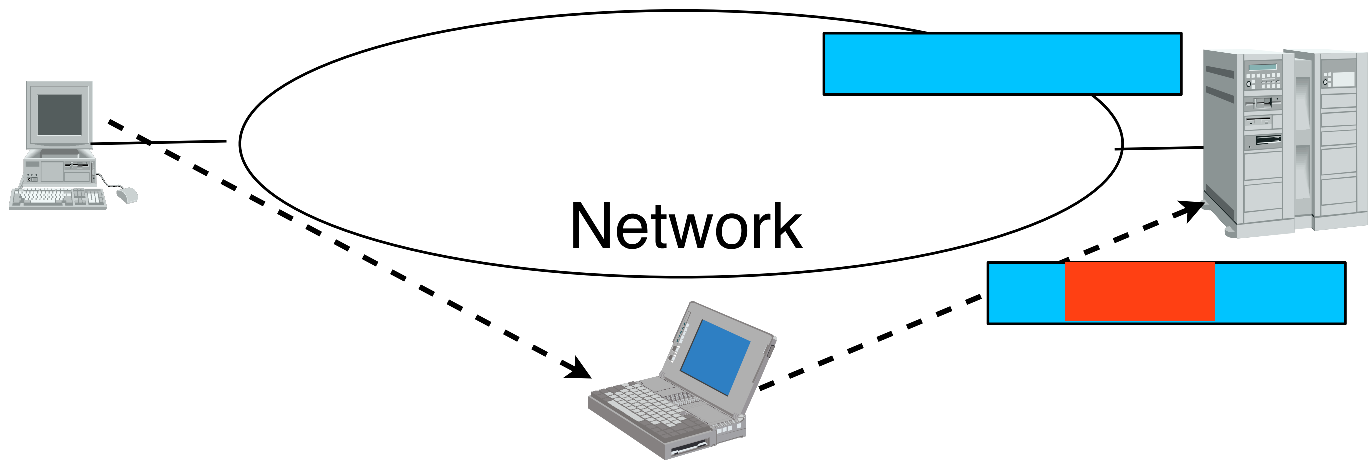

- These attacks are dealt by using special security protocols and mechanisms outside the transport layer

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

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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

Internet checksum : example

- Assume a segment composed of 48 bits

0110011001101100 0101010101010101 0000111100001111

Internet checksum : example

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0110011001101100 0000111100001111
0101010101010101

Internet checksum : example

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0110011001101100 0000111100001111

0101010101010101

1011101110111011

Internet checksum : example

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0110011001101100
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1100101011001010

Internet checksum : example

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0110011001101100
0101010101010101

1011101110111011
0000111100001111

1100101011001010　　0011010100110101

Cyclical Redundancy Check (CRC)

- Principle
  - Improve the performance of the Internet checksum by using polynomial codes
    - Sender and receiver agree on r+1 bits pattern called Generator (G)
    - Sender adds r bits of CRC to a d bits data segment such that the d+r bits pattern is exactly divisible by G using modulo 2 arithmetic
      - D * 2^r XOR R = n*G

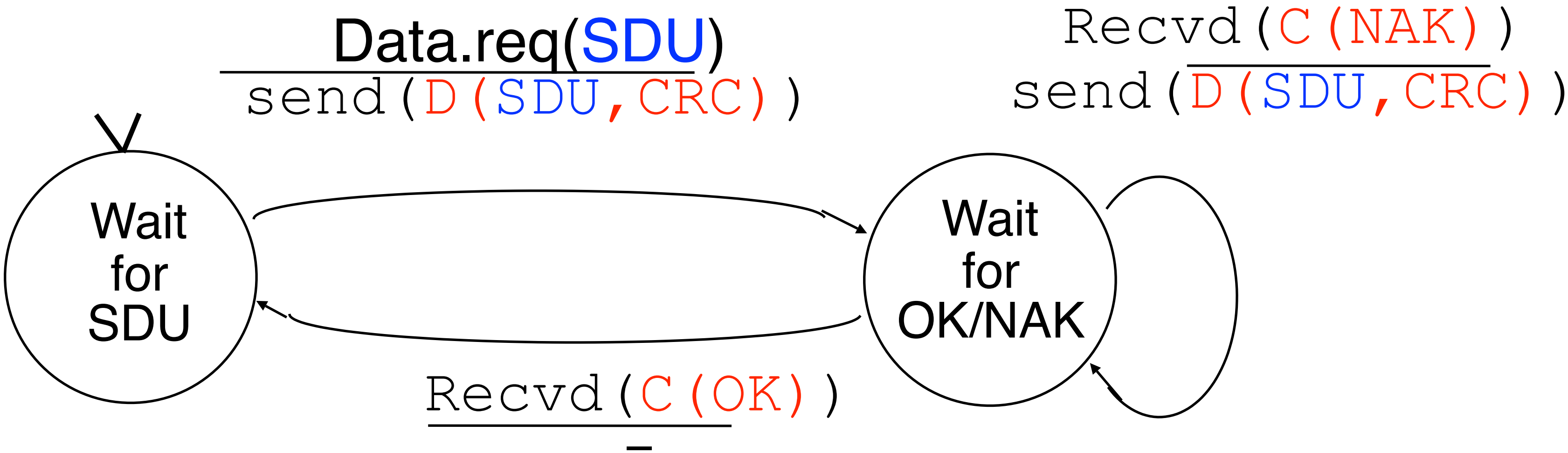
    - All computations are done in modulo 2 arithmetic by using XOR
      - 1011 + 0101 = 1110   1001 + 1101 = 0100
      - 1011 - 0101 = 1110   1001 - 1101 = 0100

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



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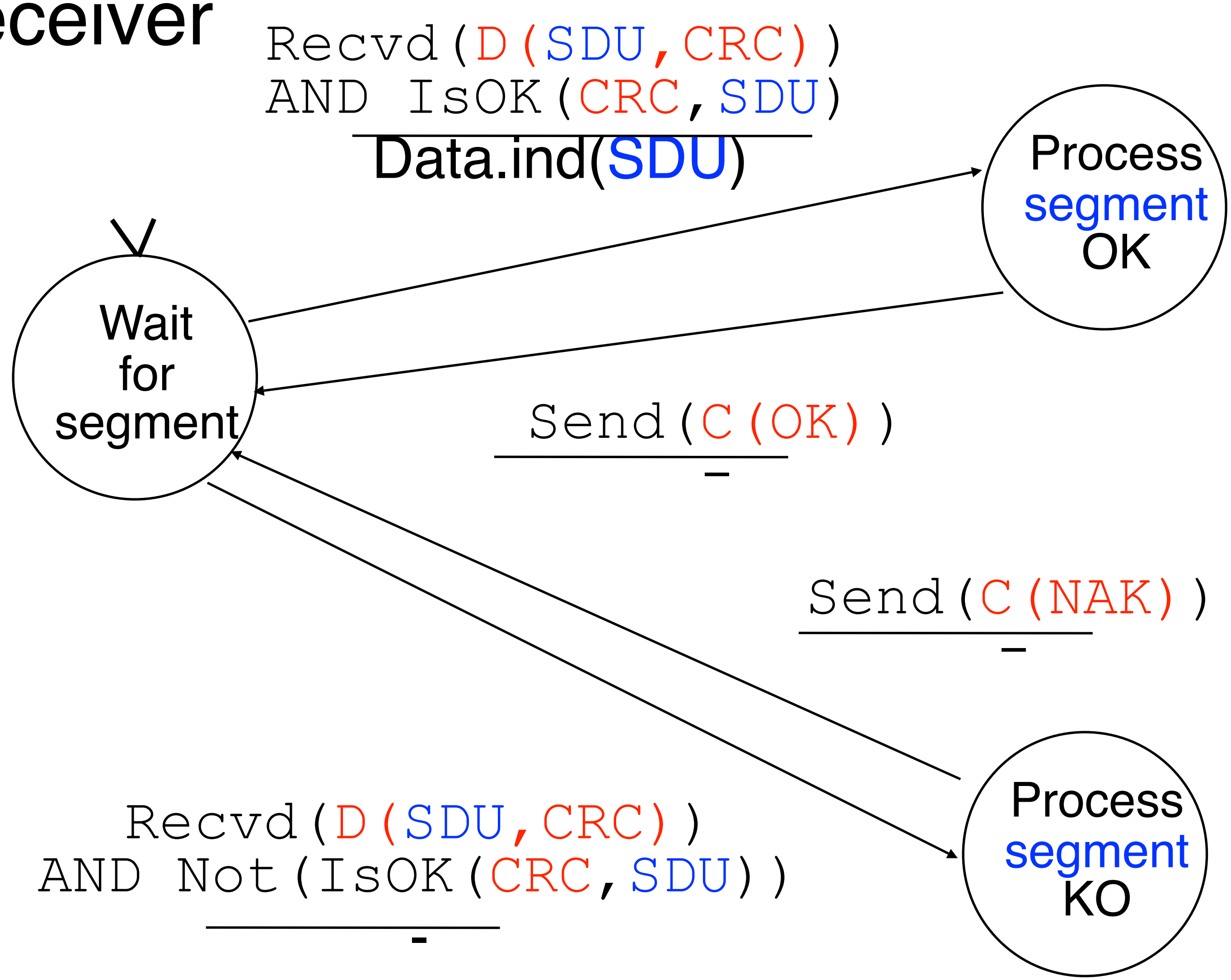

Protocol 3a : Example

A

B

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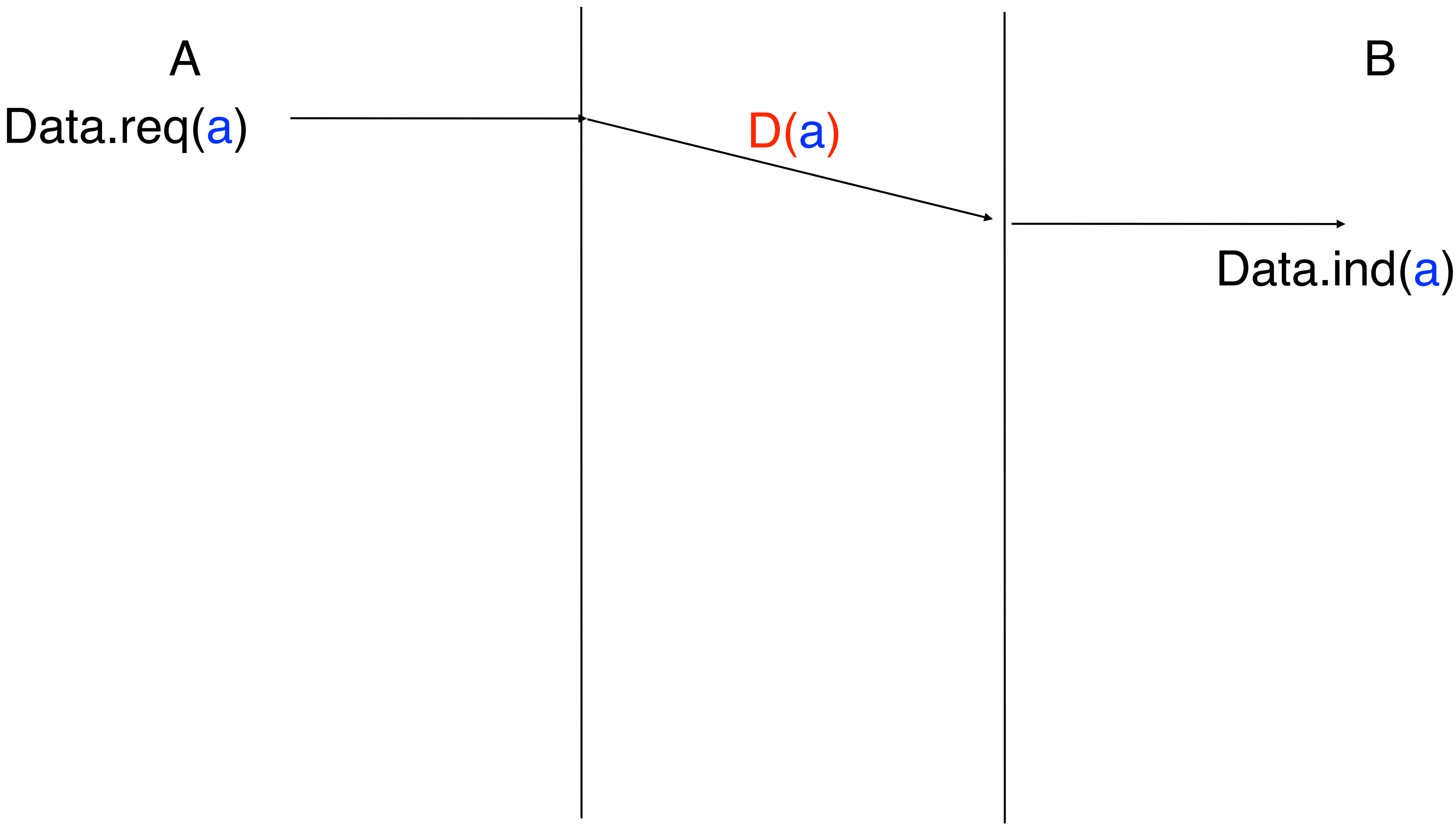

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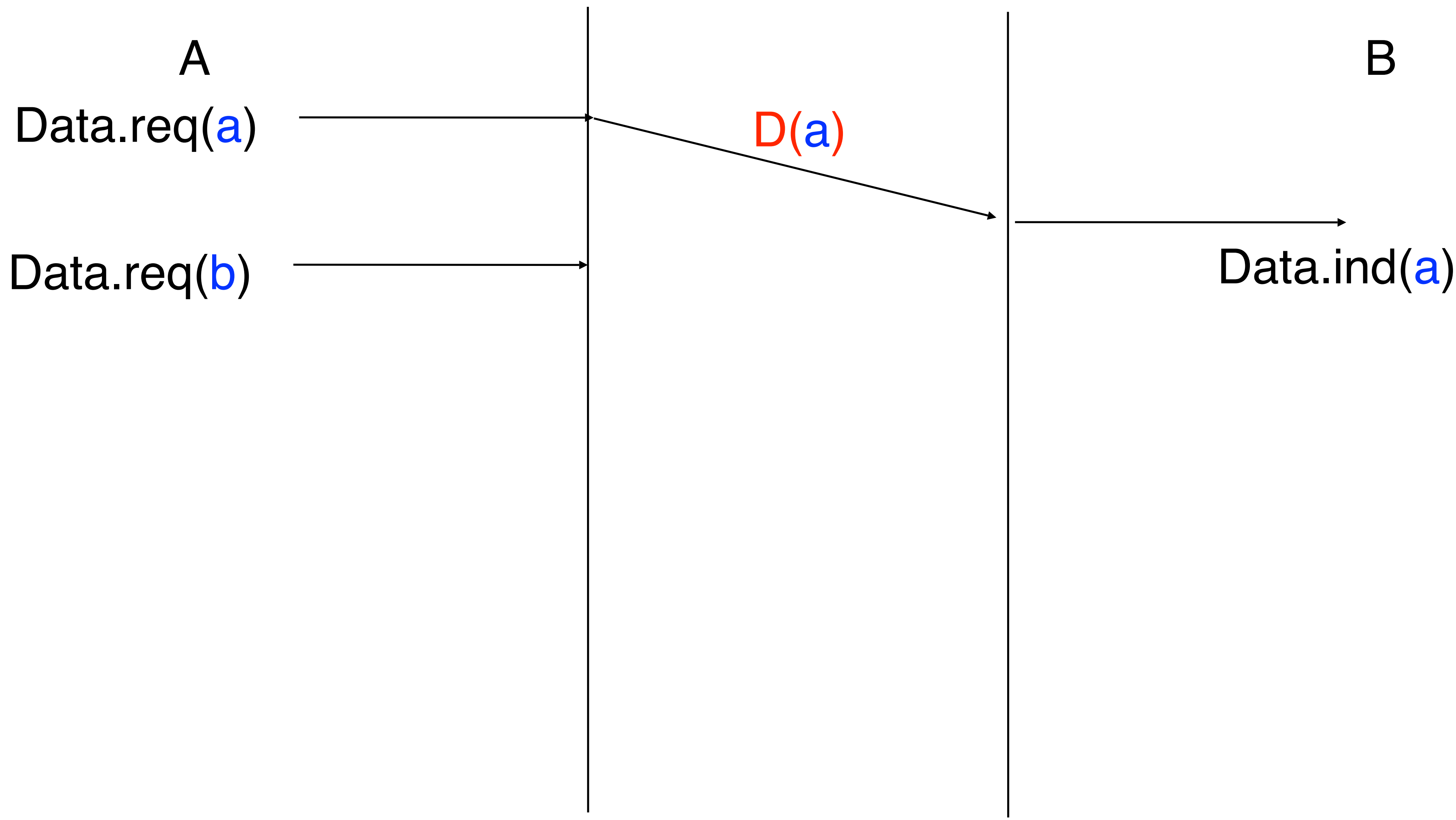

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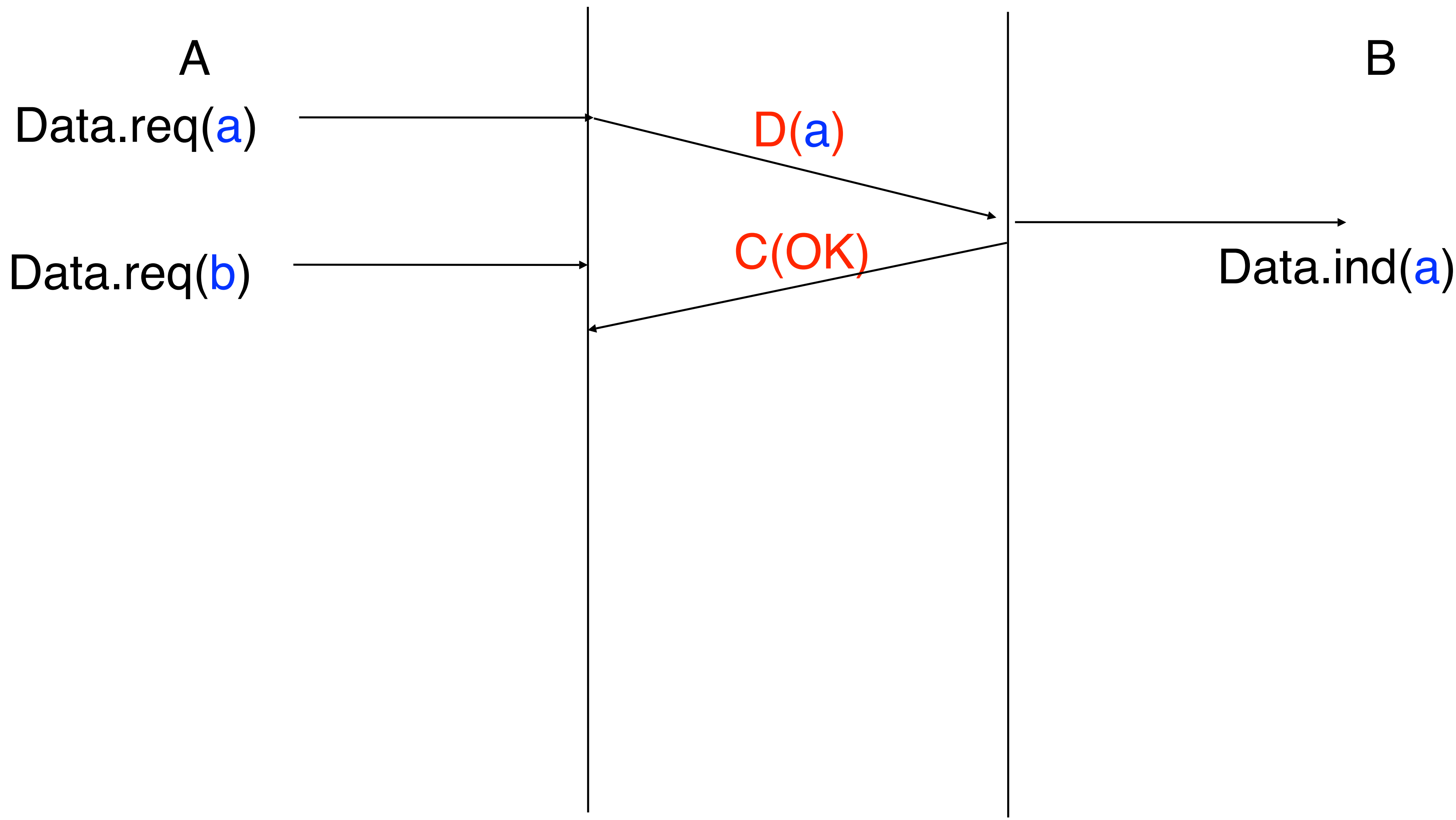

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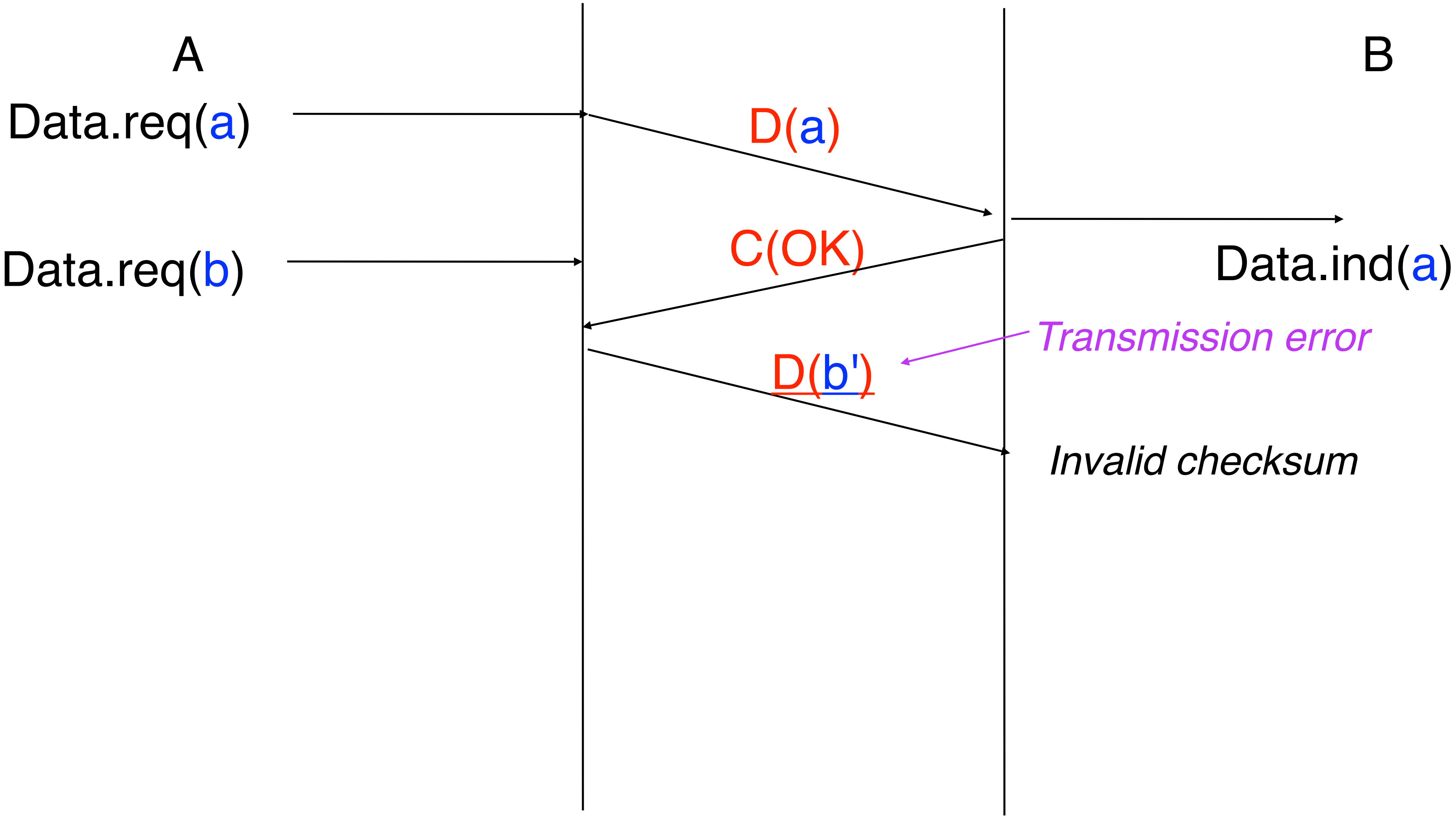

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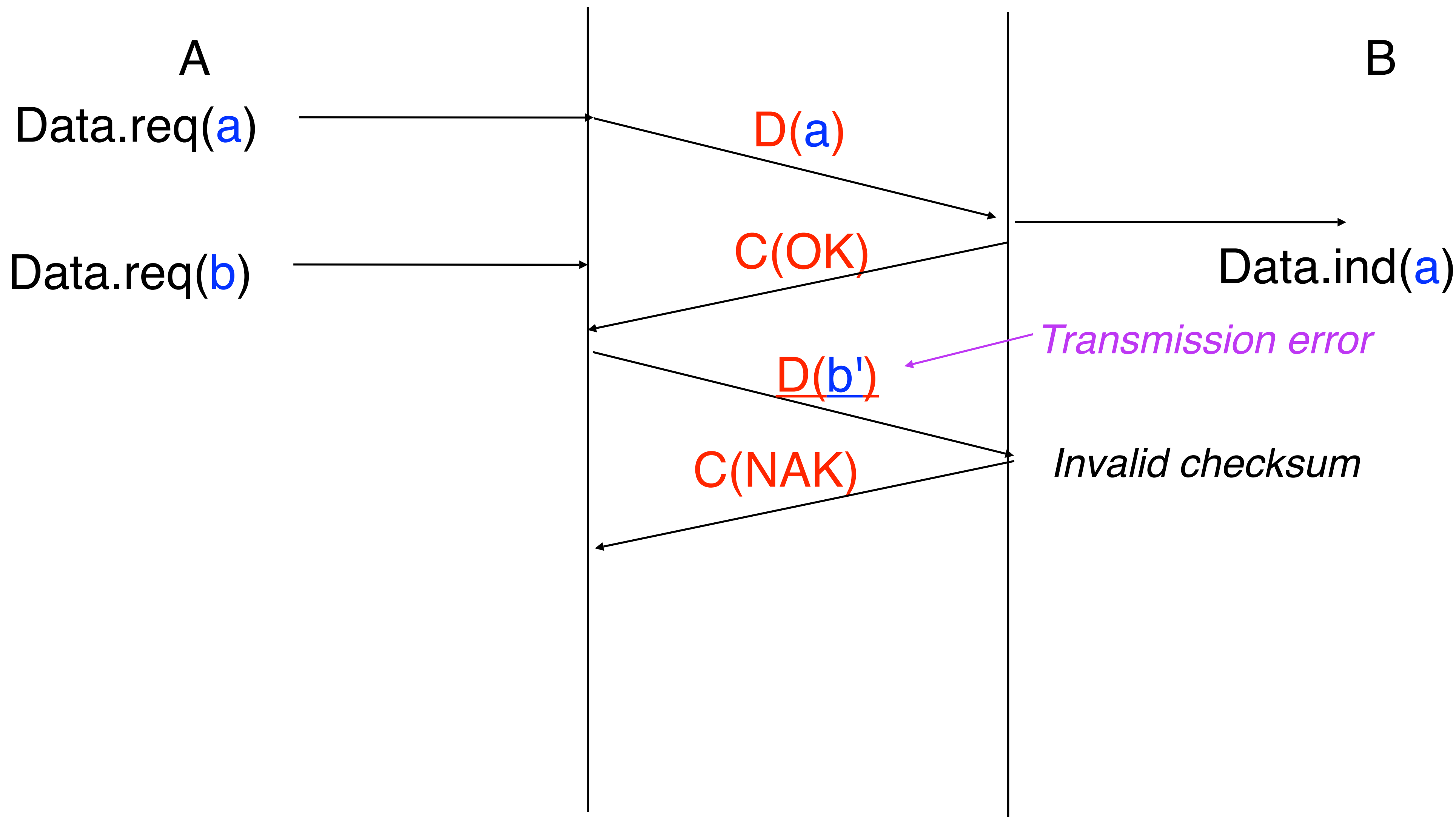

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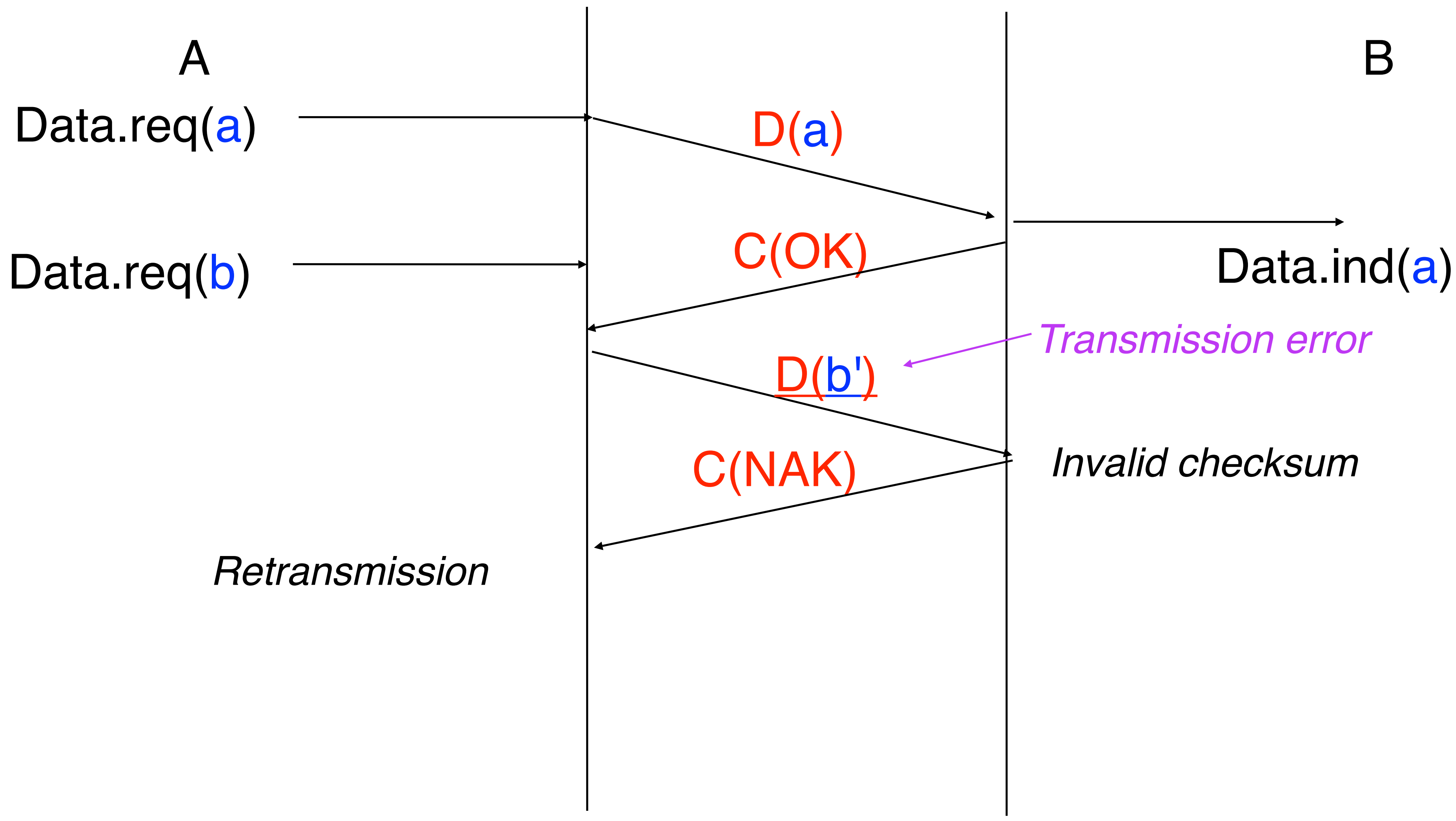

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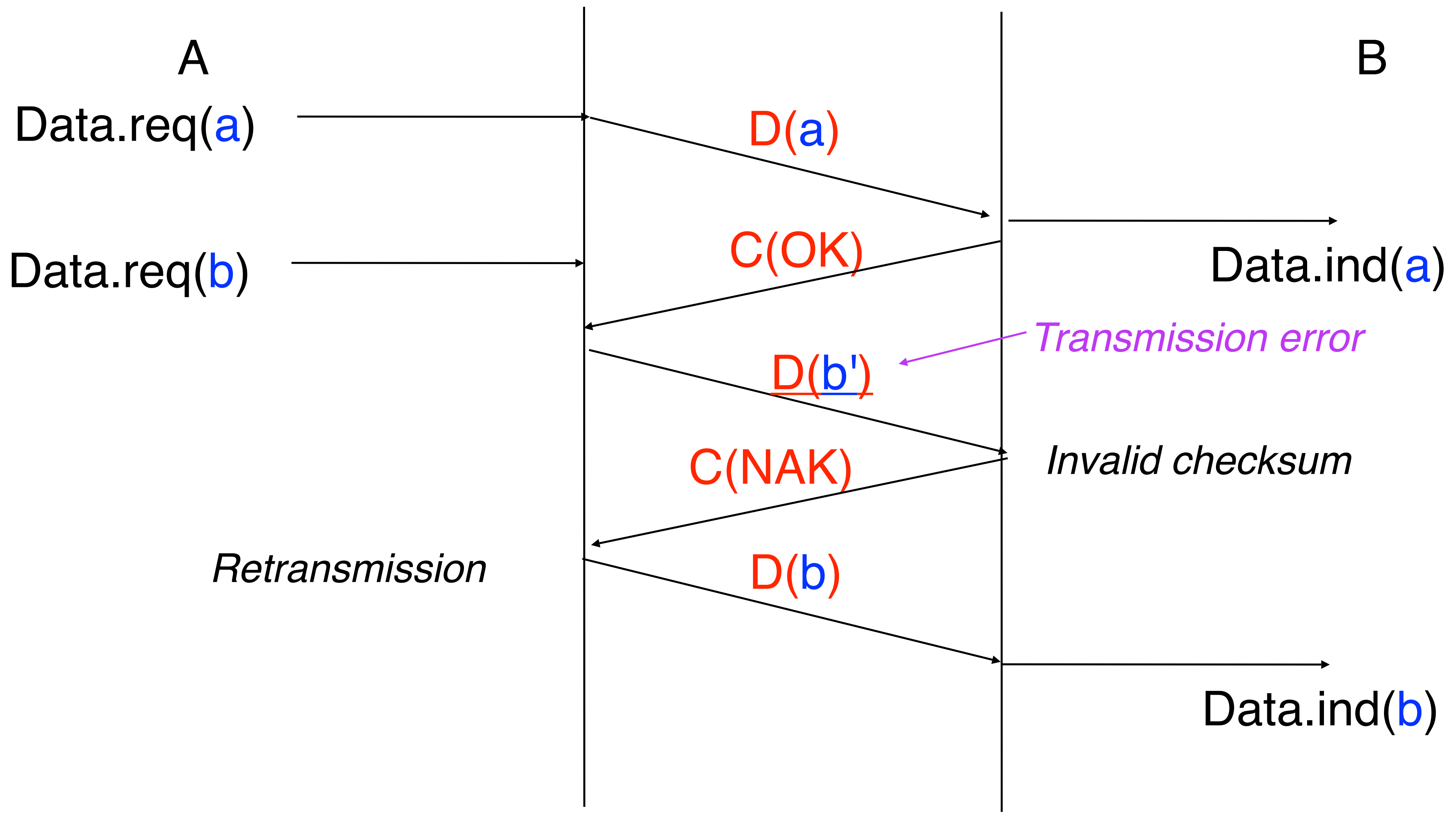

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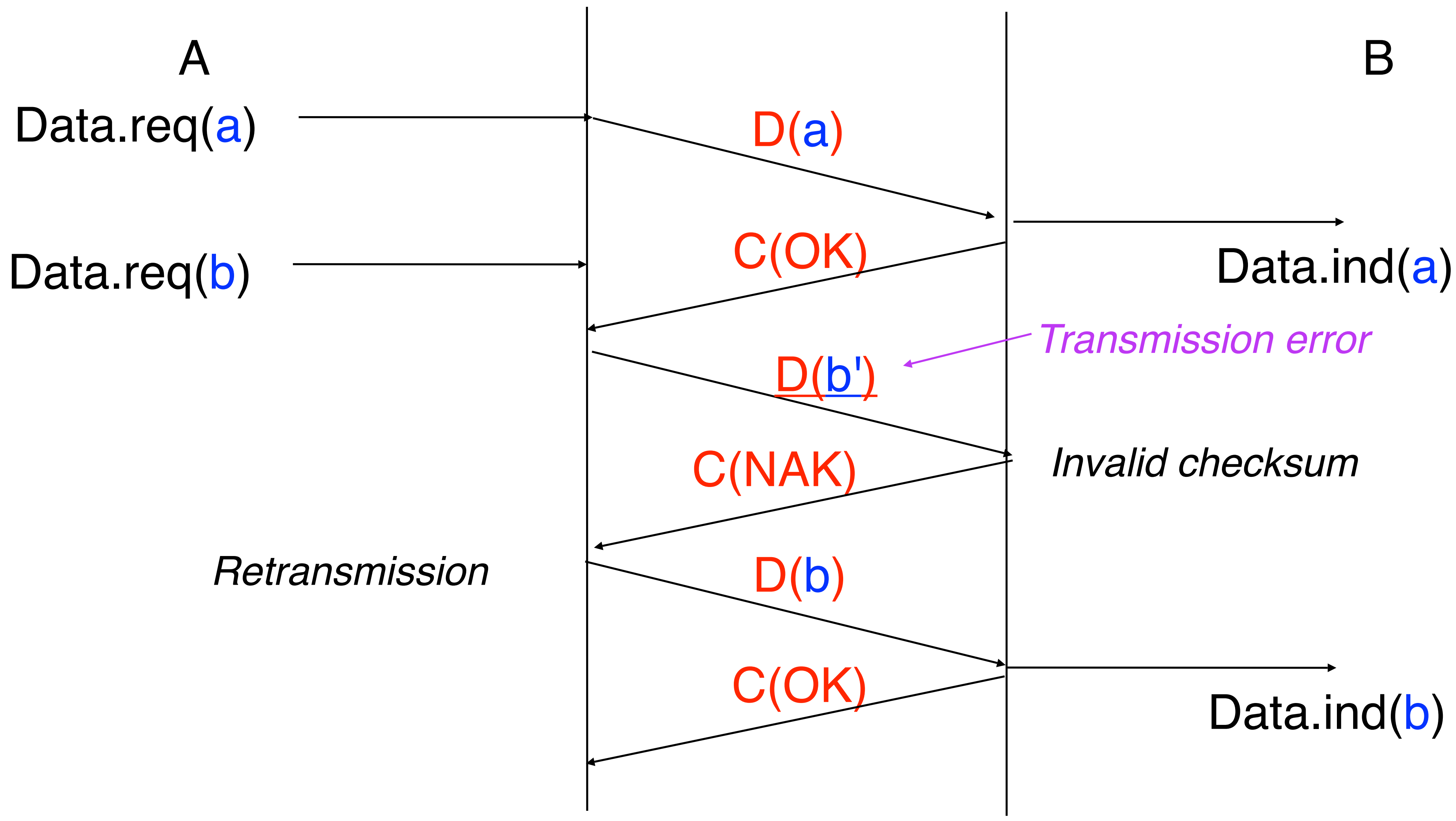

Protocol 3b

- How can we provide a reliable service in the transport layer ?
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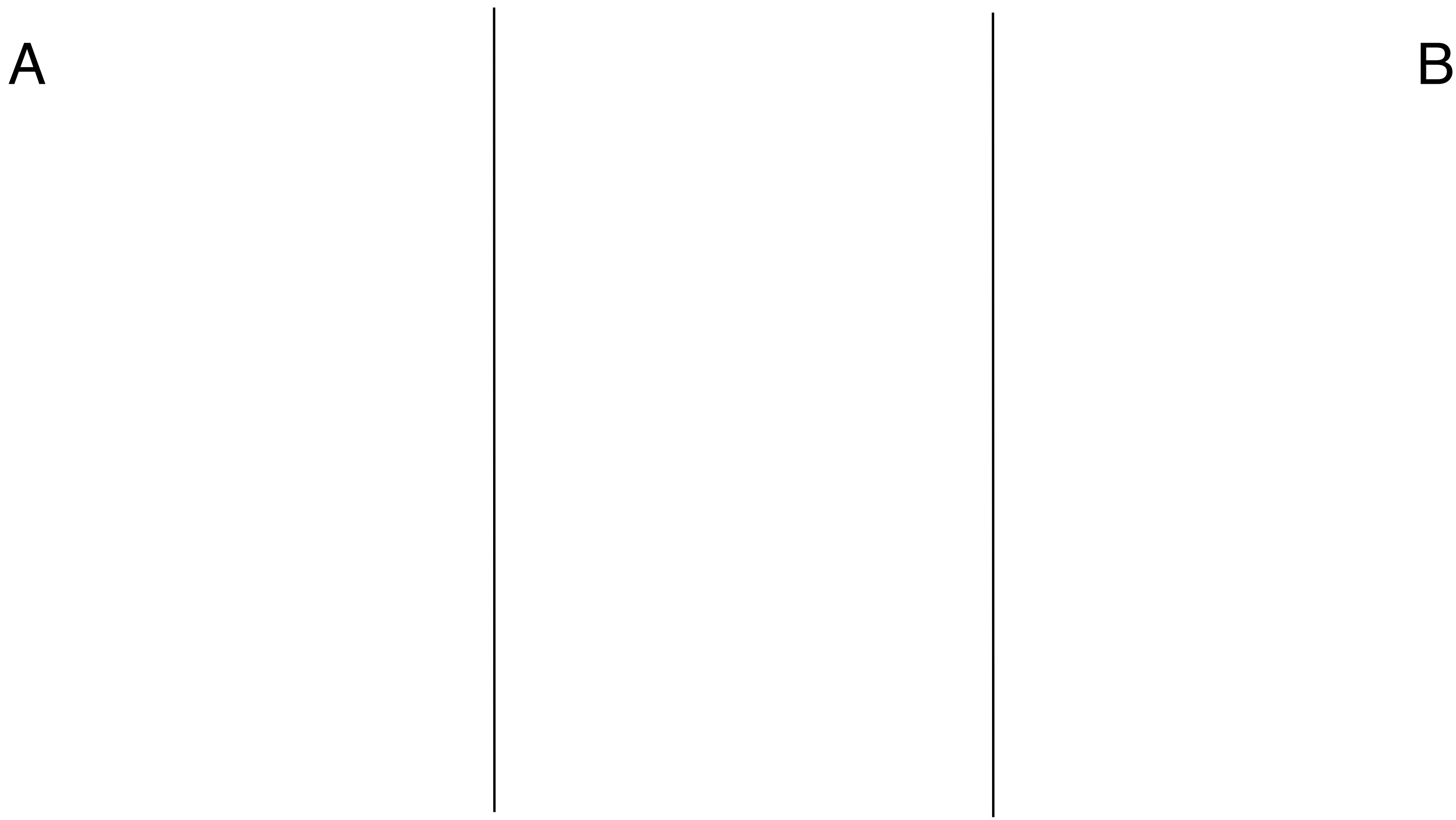
2. How to deal with these problems ?

Protocol 3a and segment losses

- How do segment losses affect protocol 3a ?



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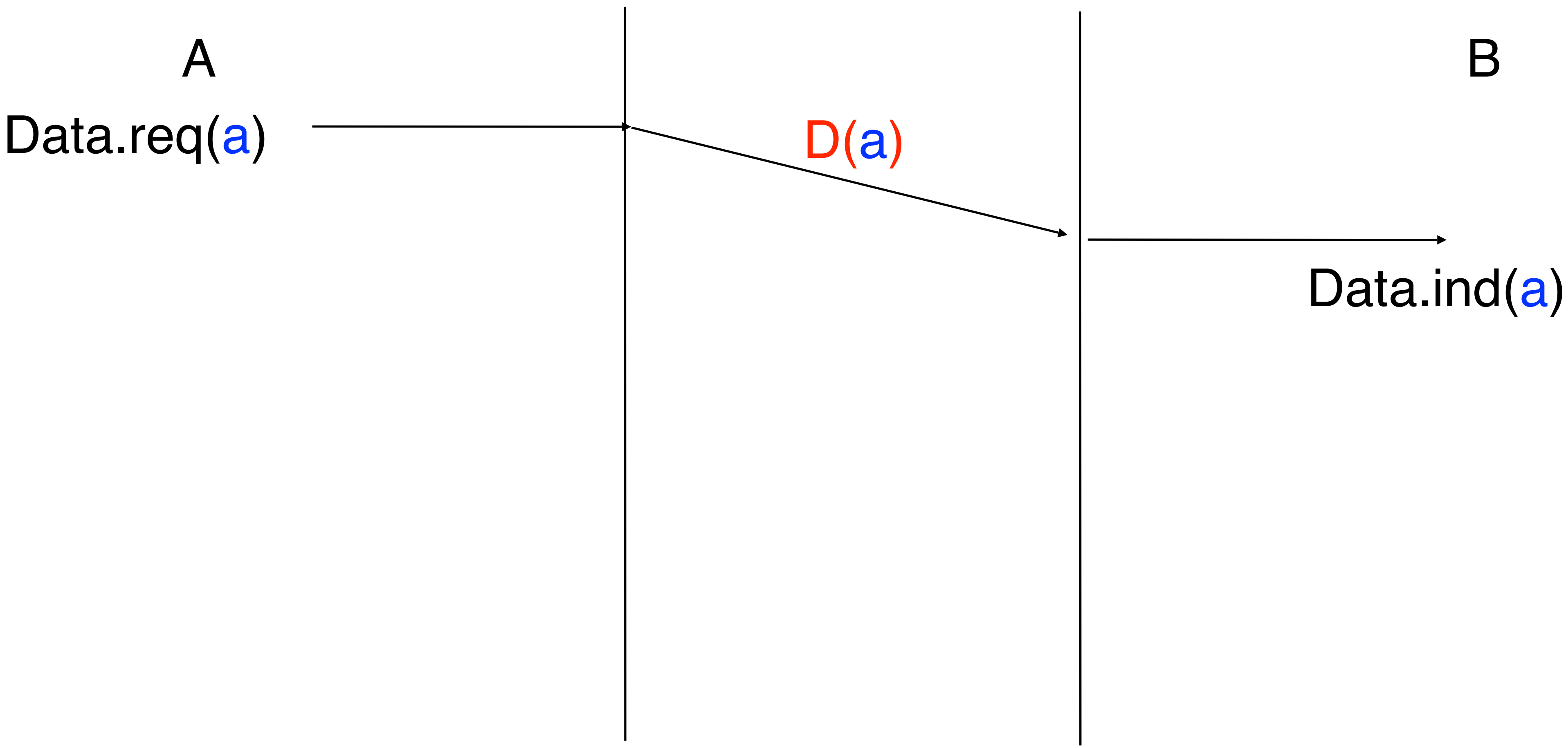

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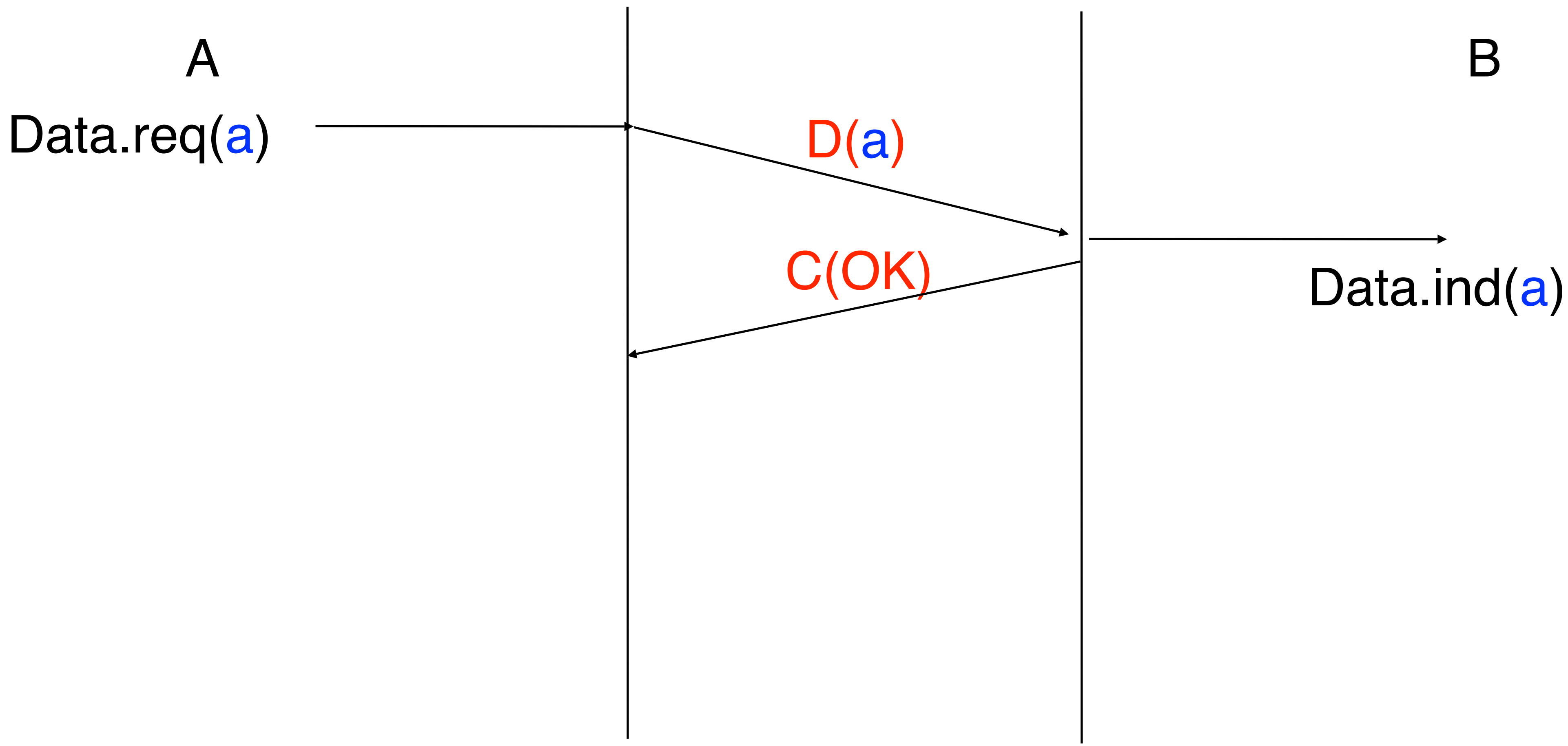

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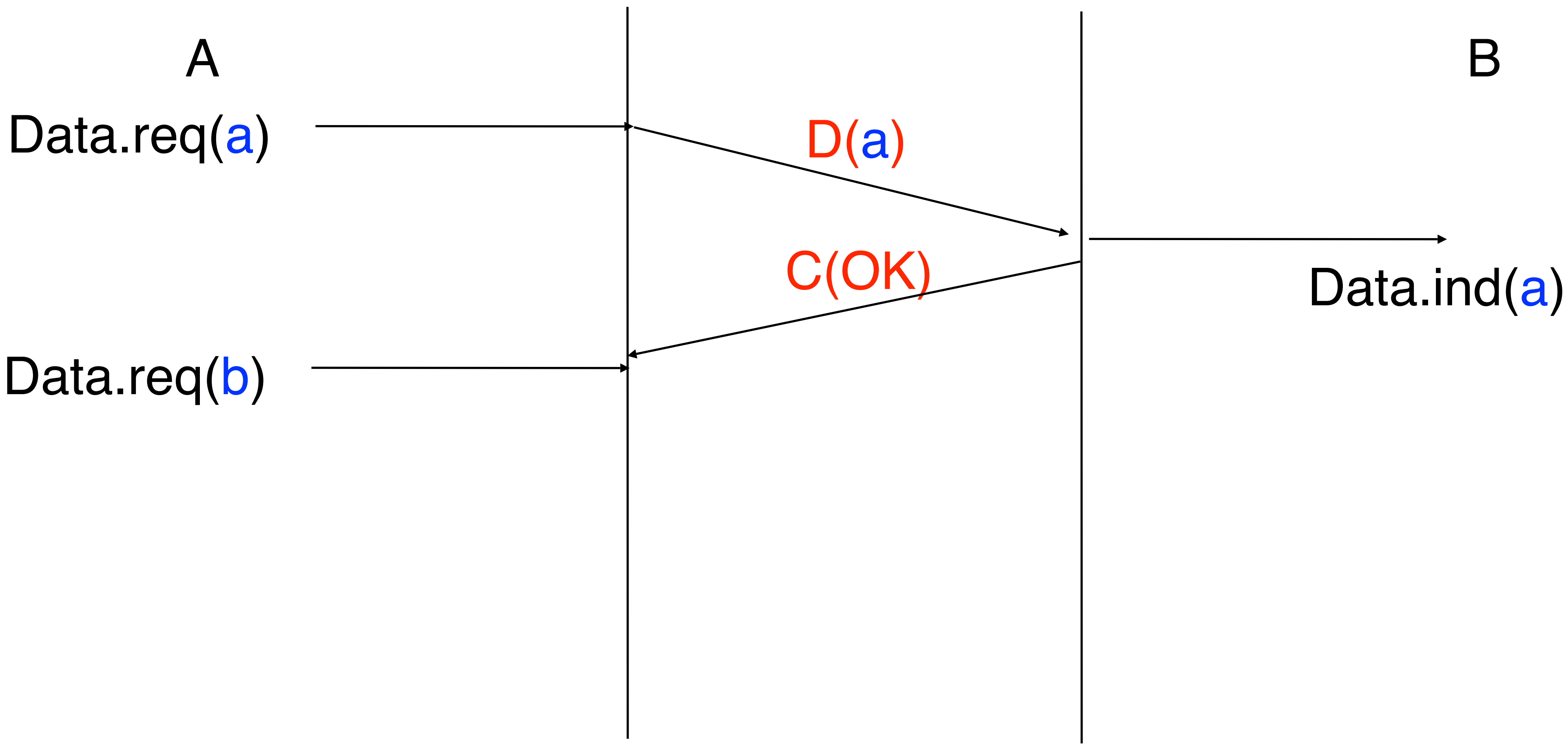

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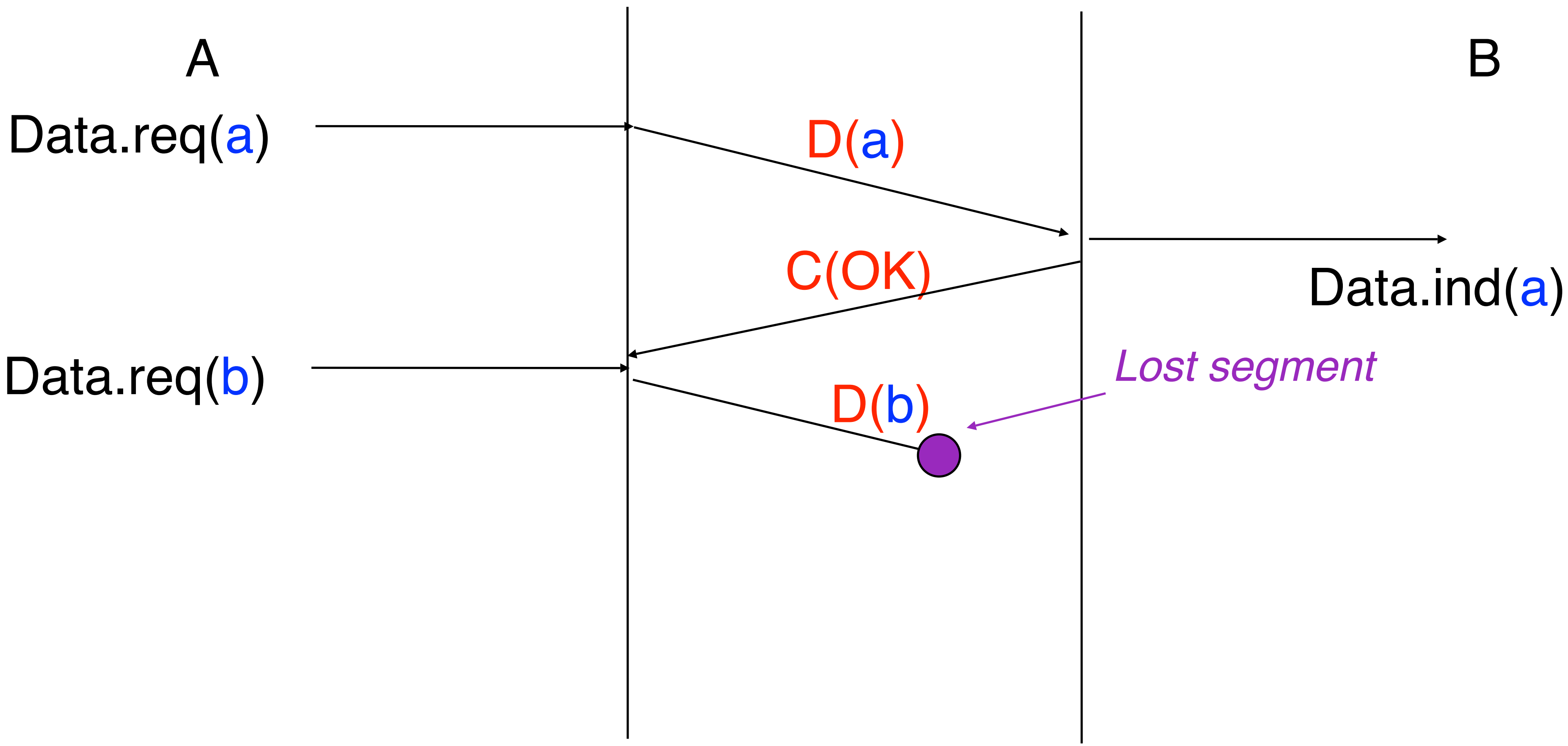

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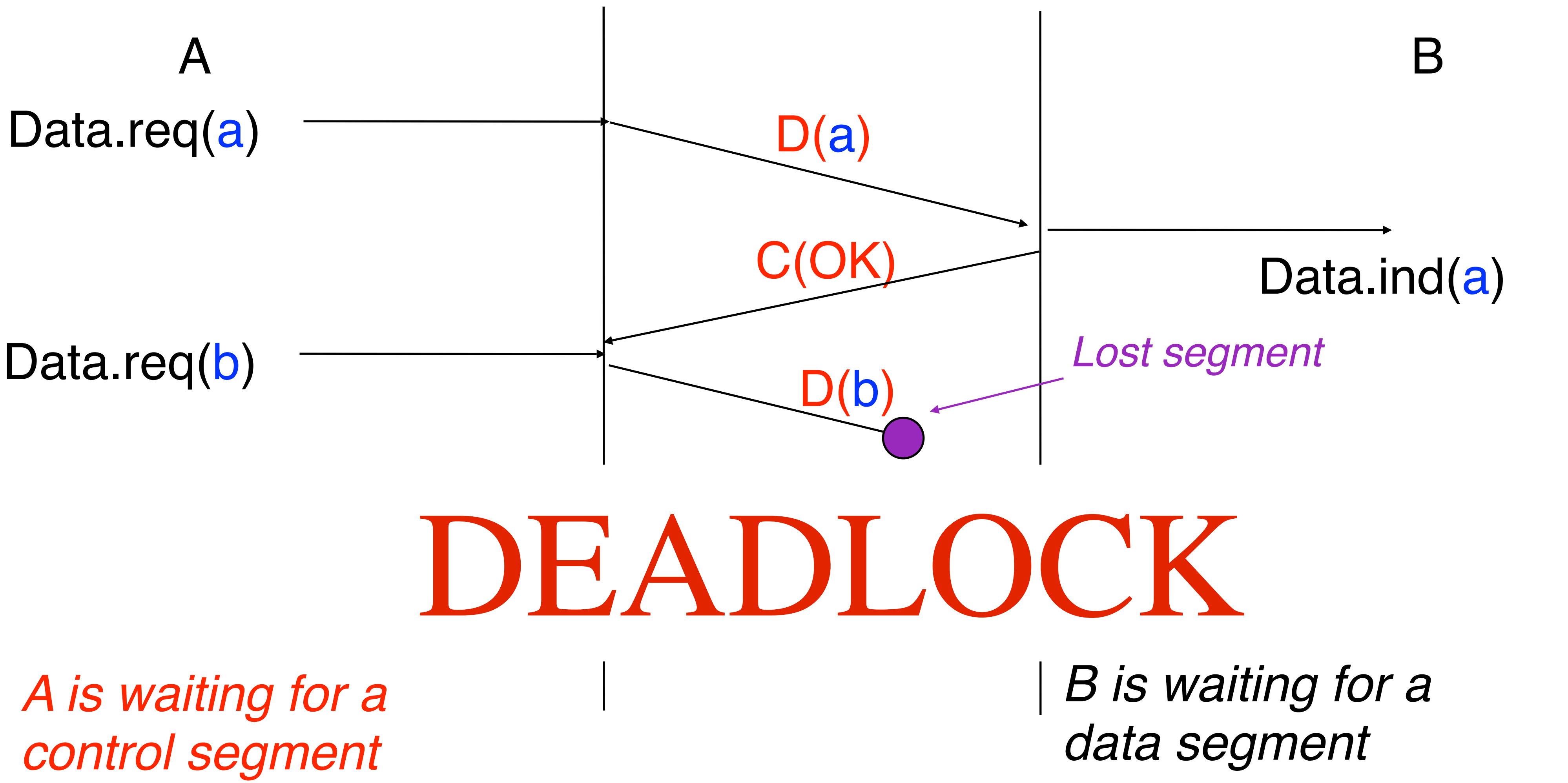
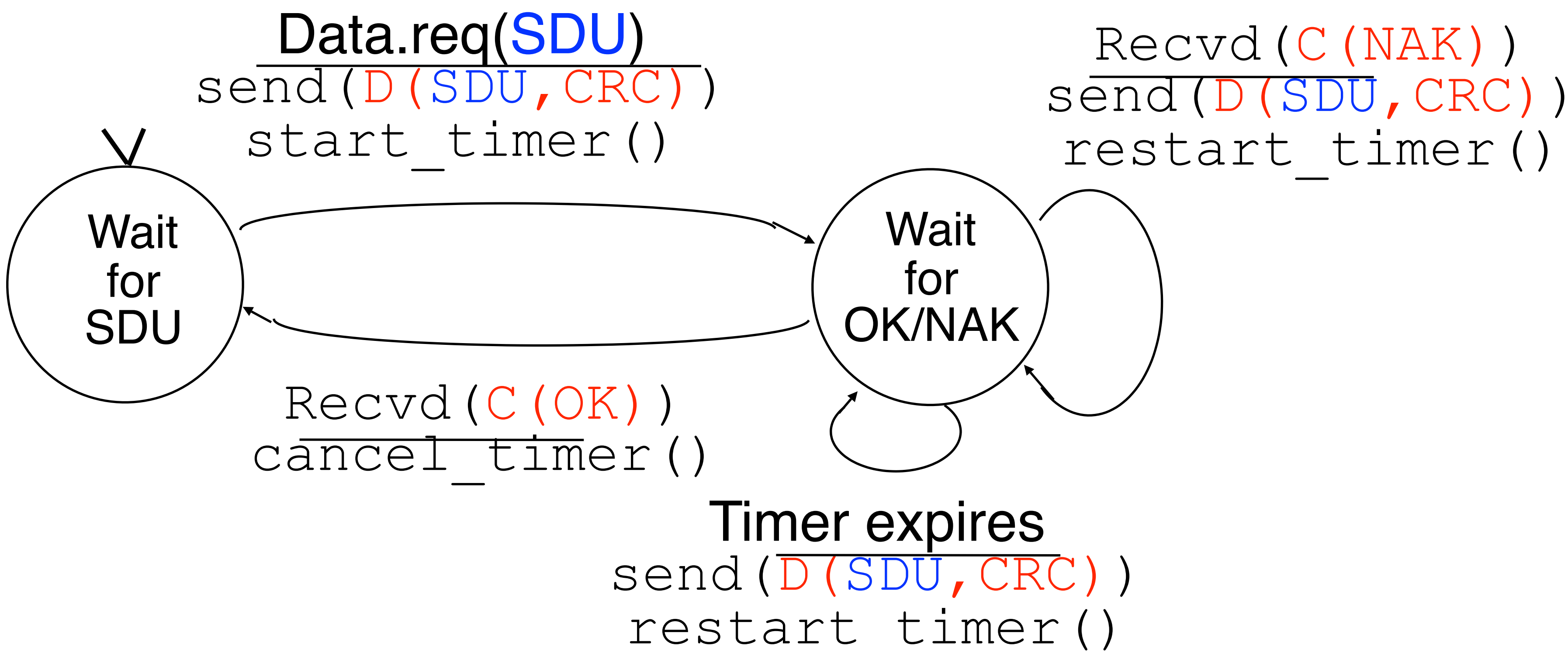


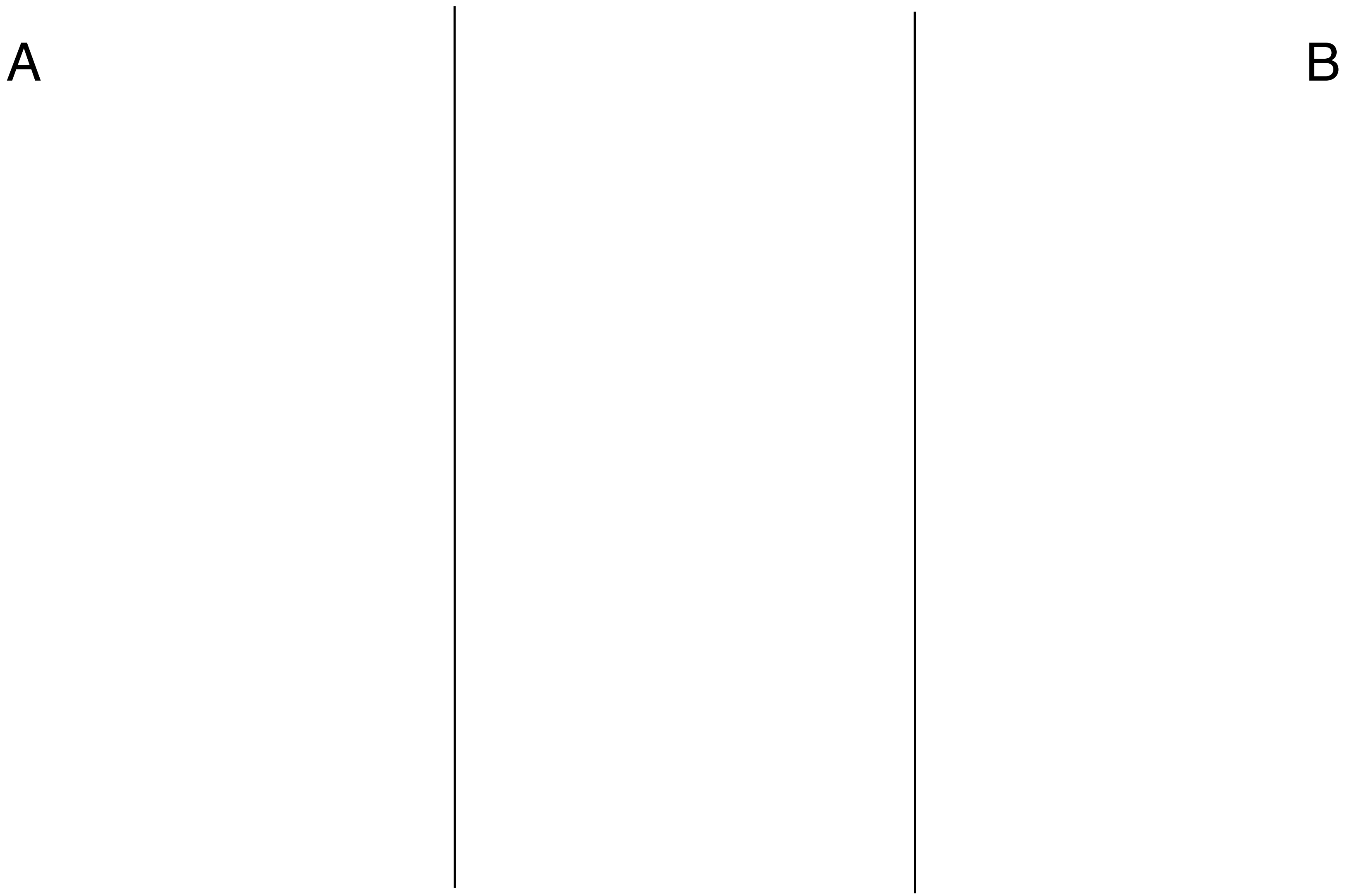
Protocol 3b

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



- No modification to the receiver

Protocol 3b : Example



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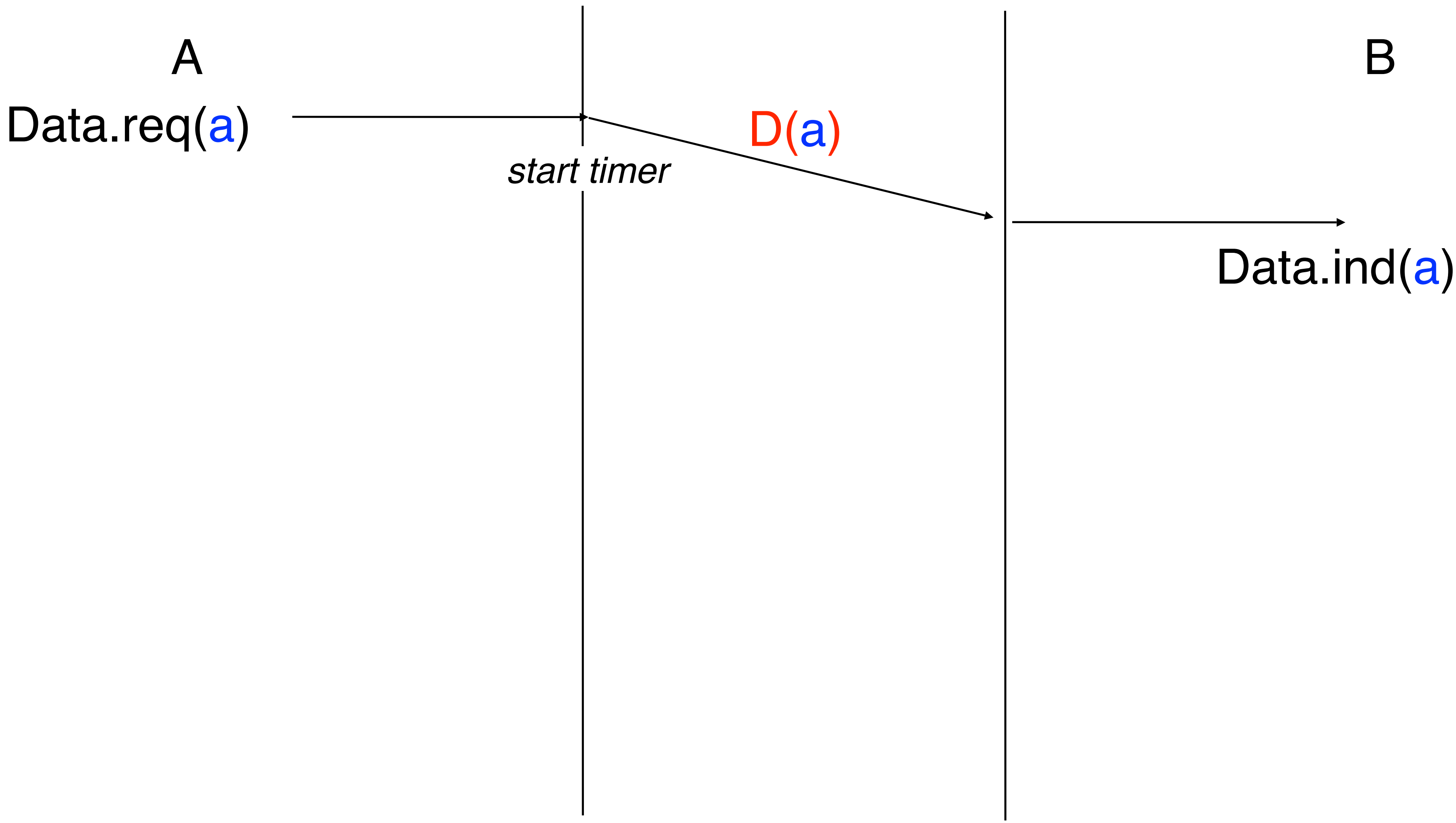
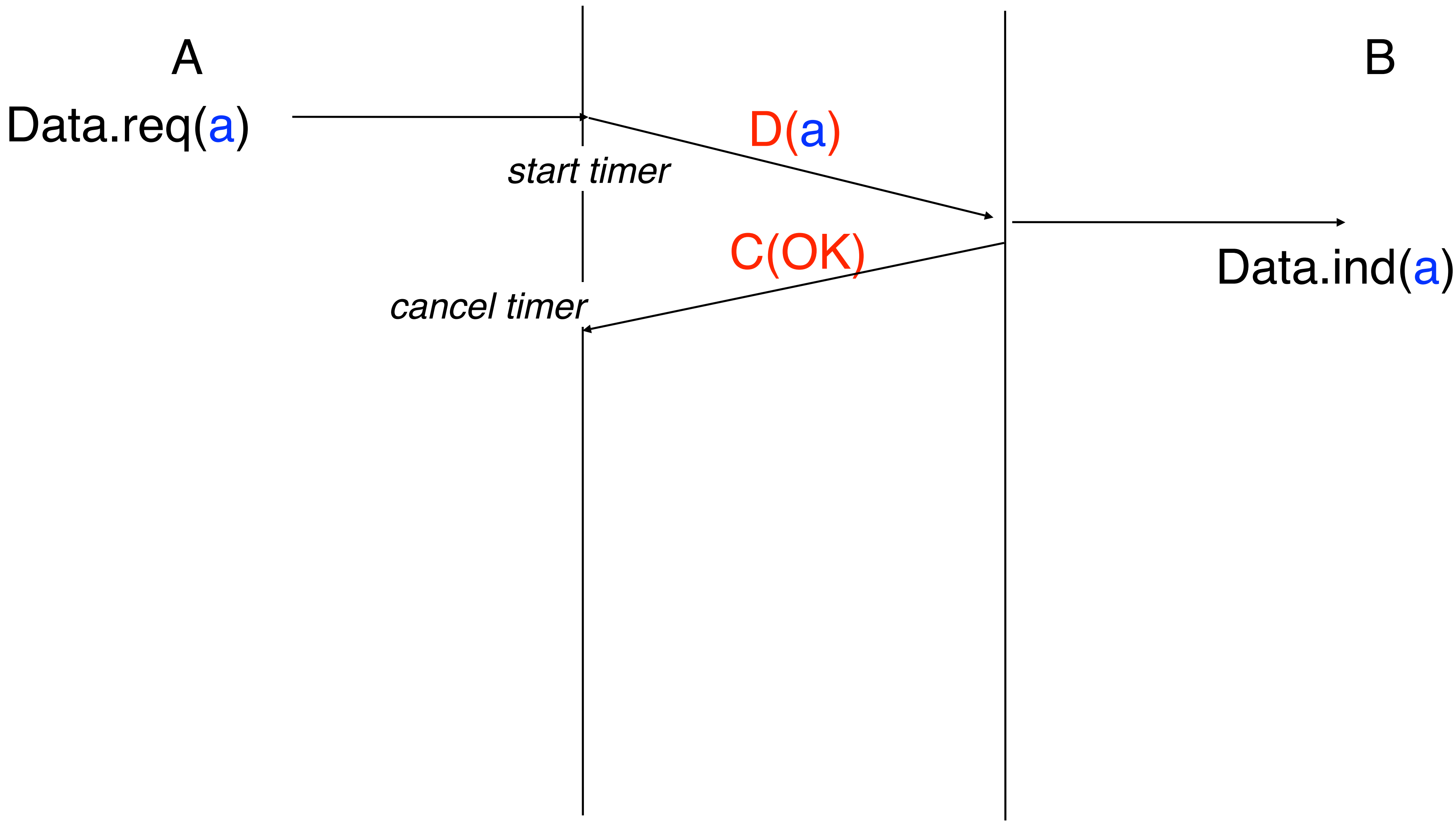


Protocol 3b : Example



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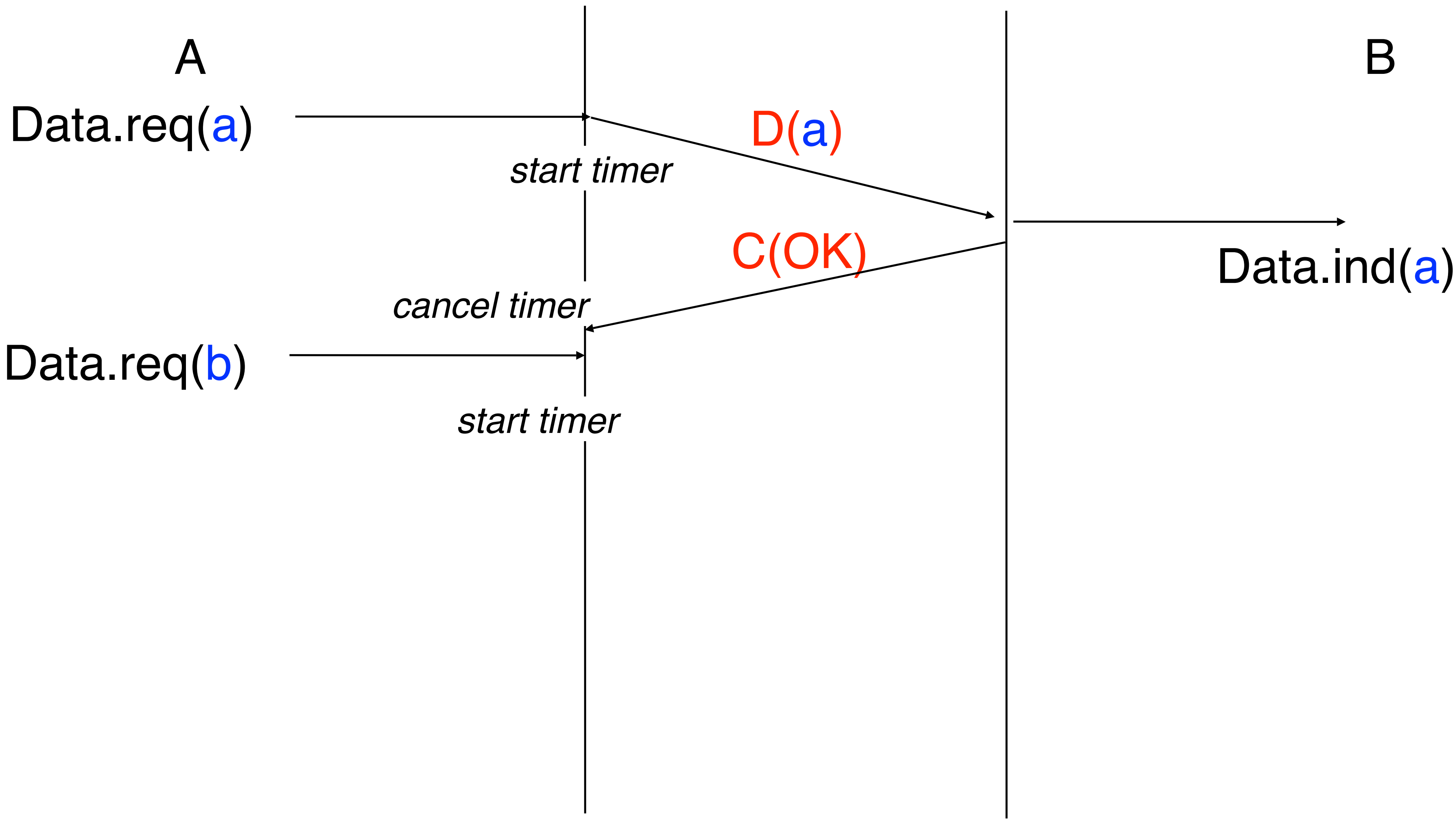

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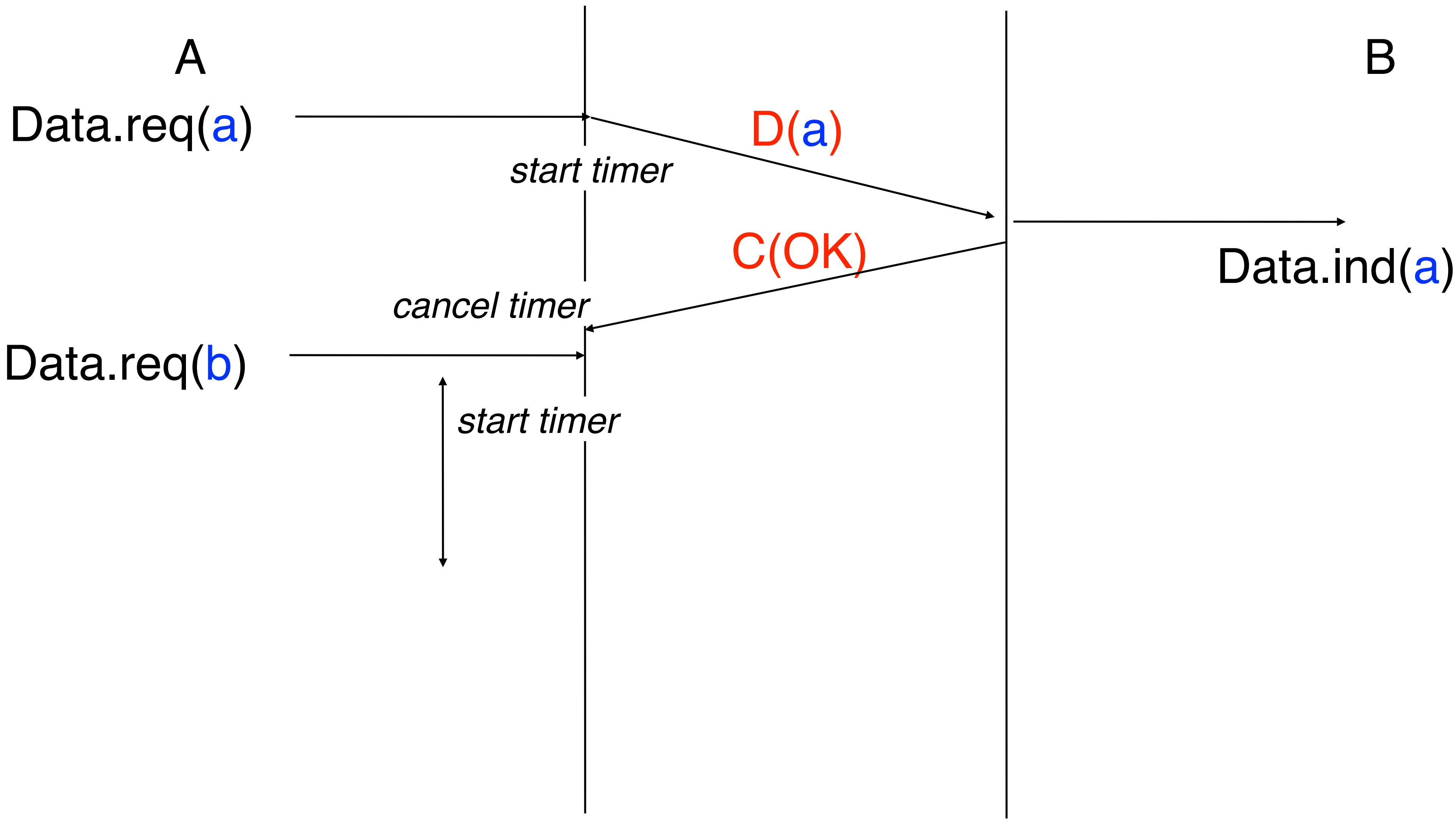

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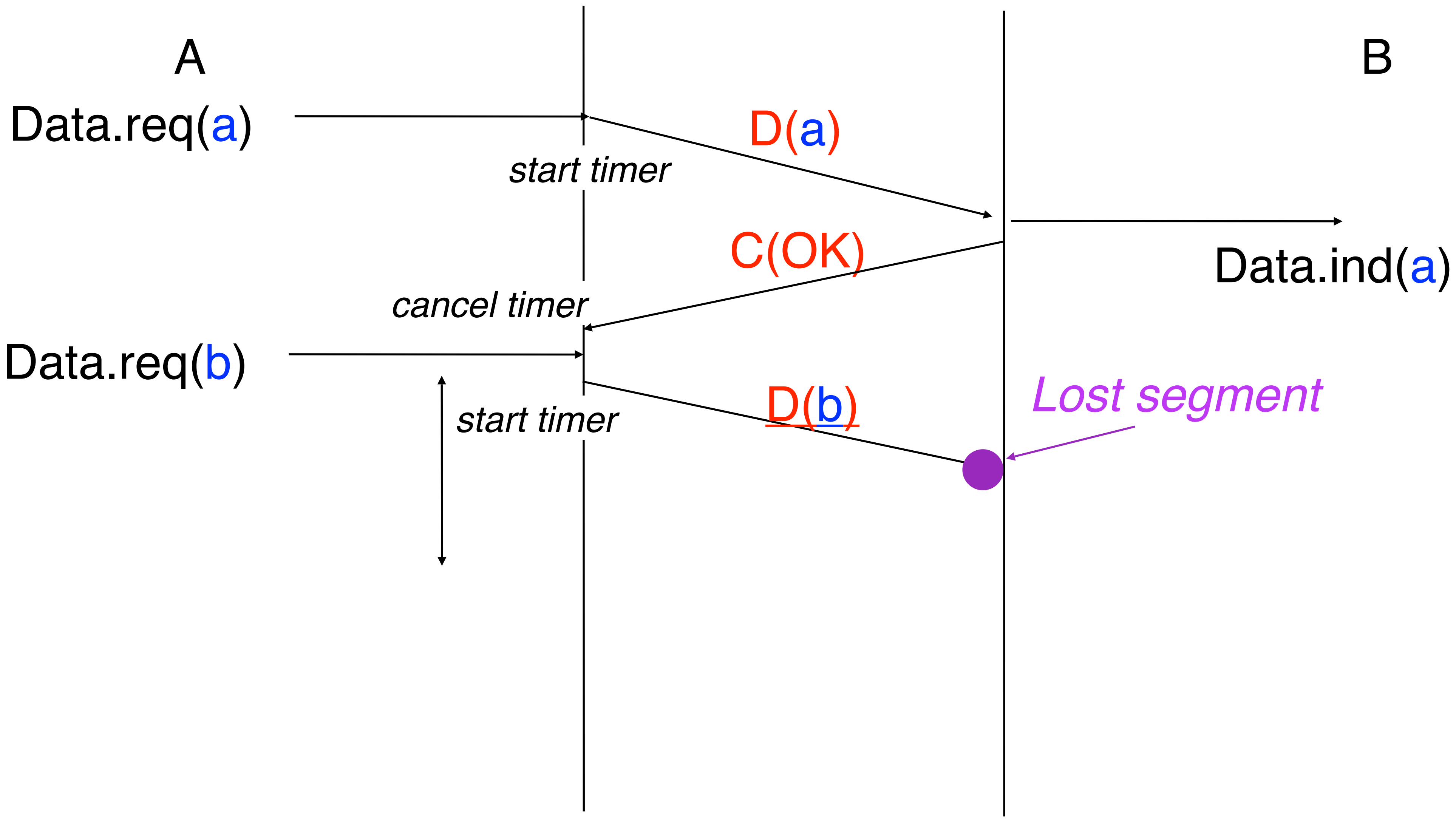

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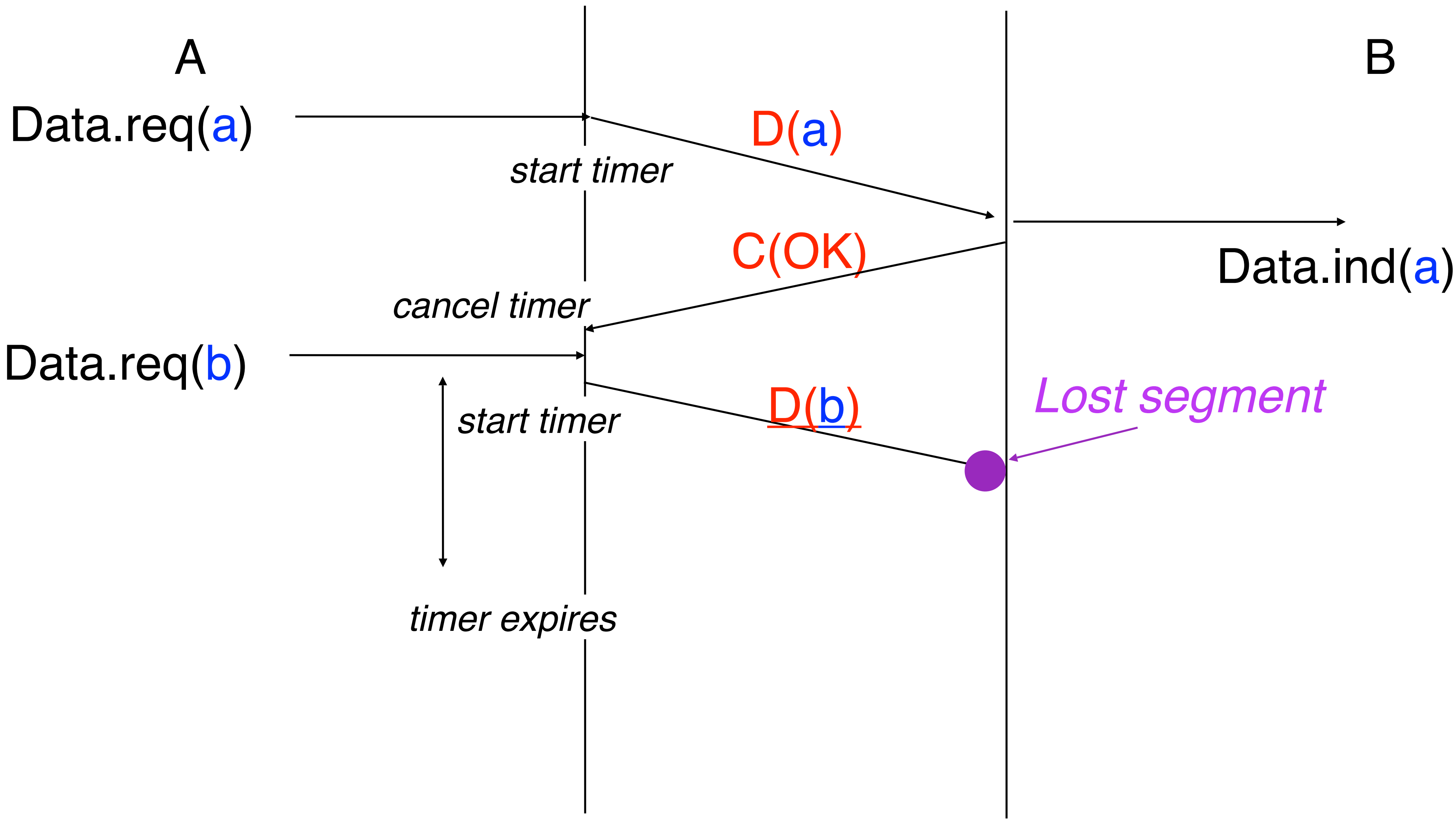

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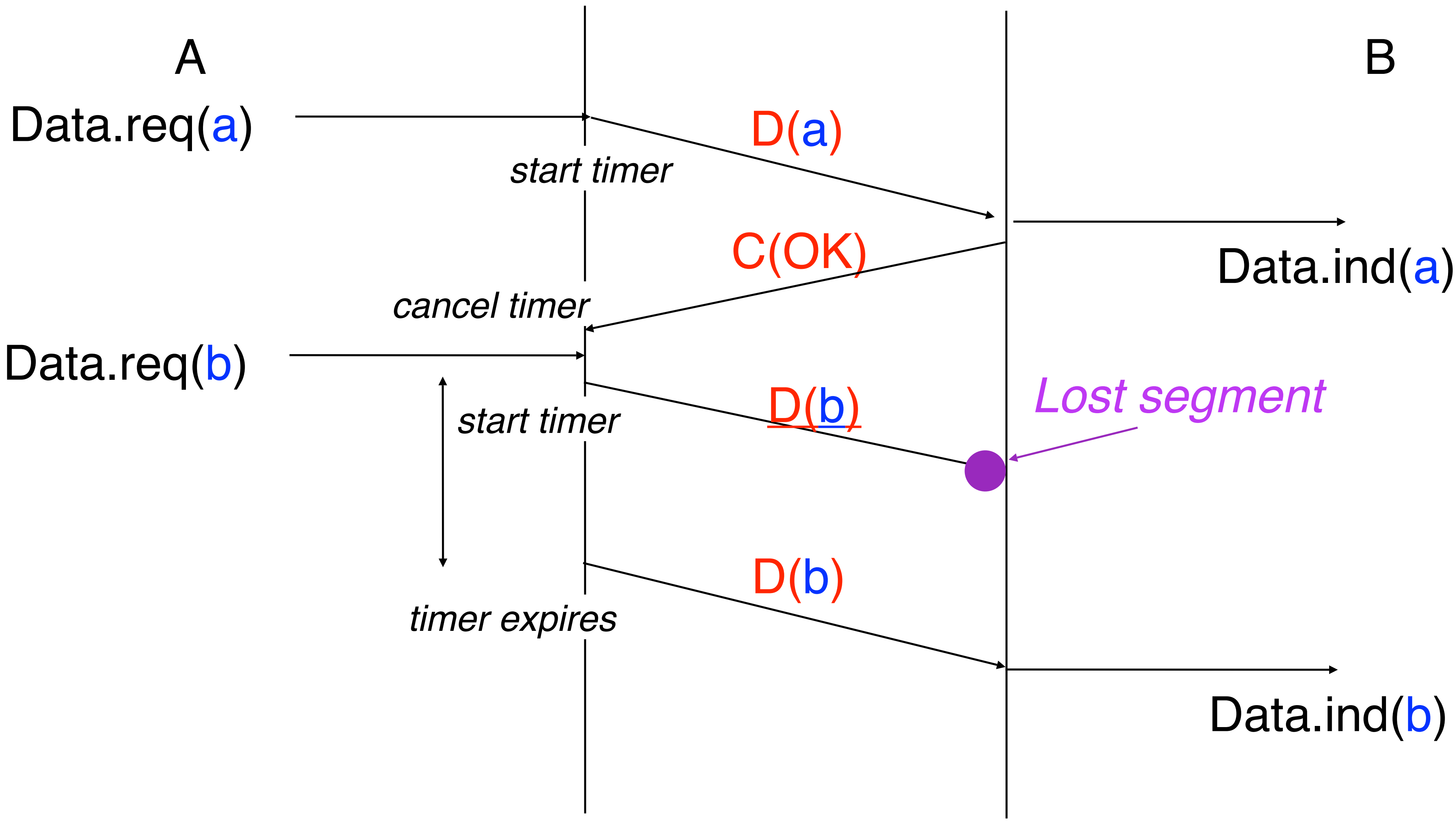

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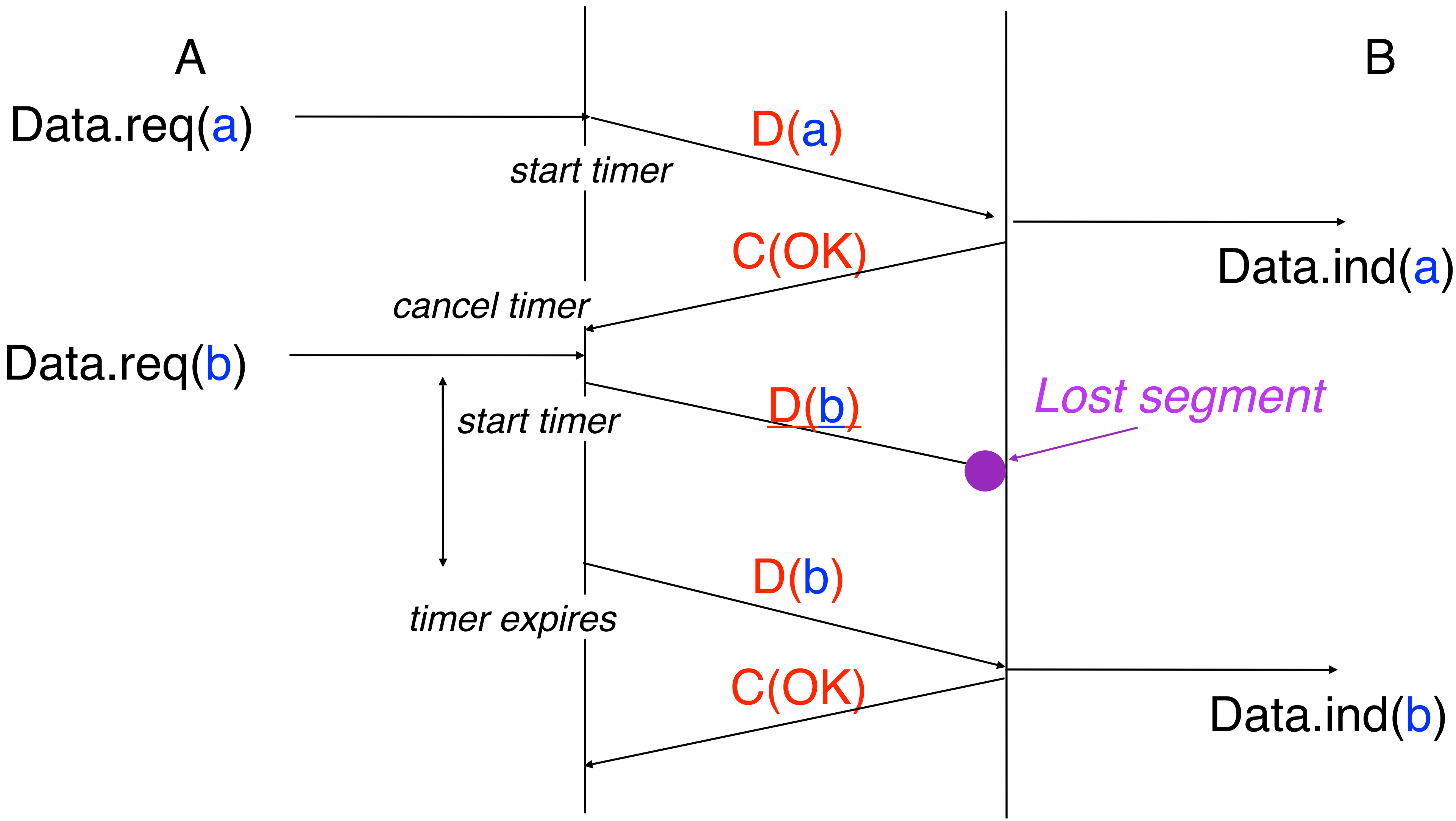

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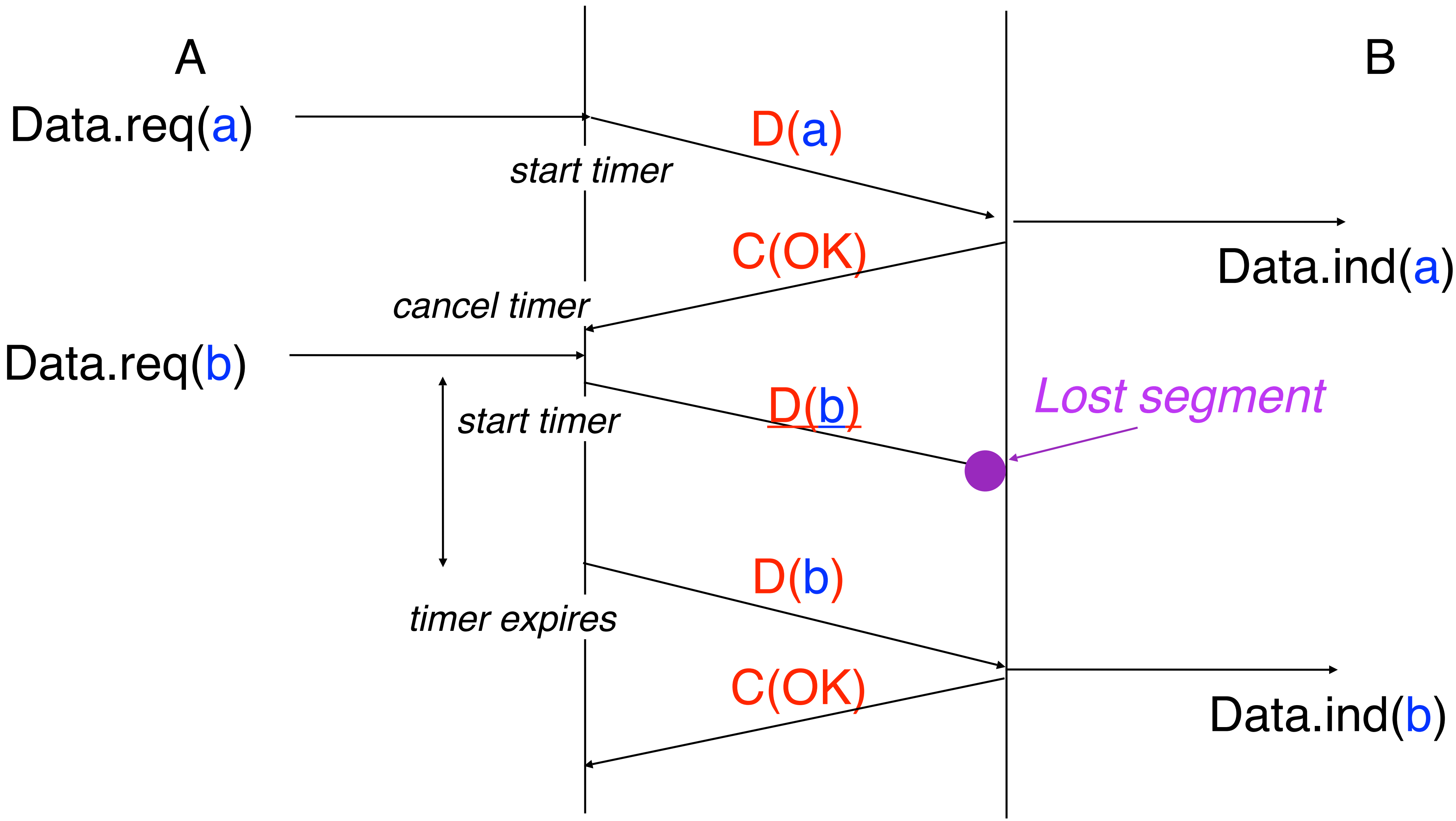
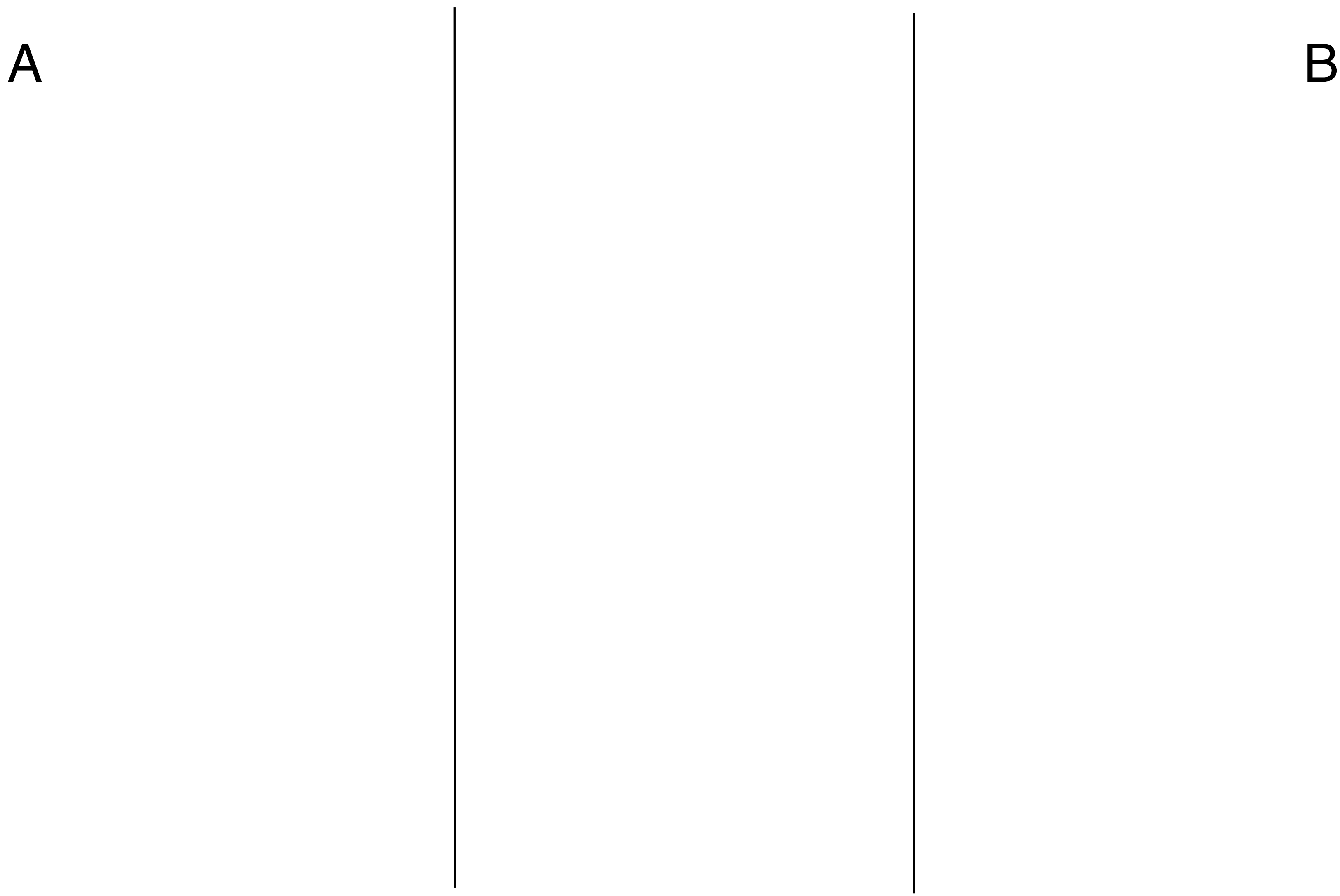


- Does this protocol always work ?

Protocol 3b : Example



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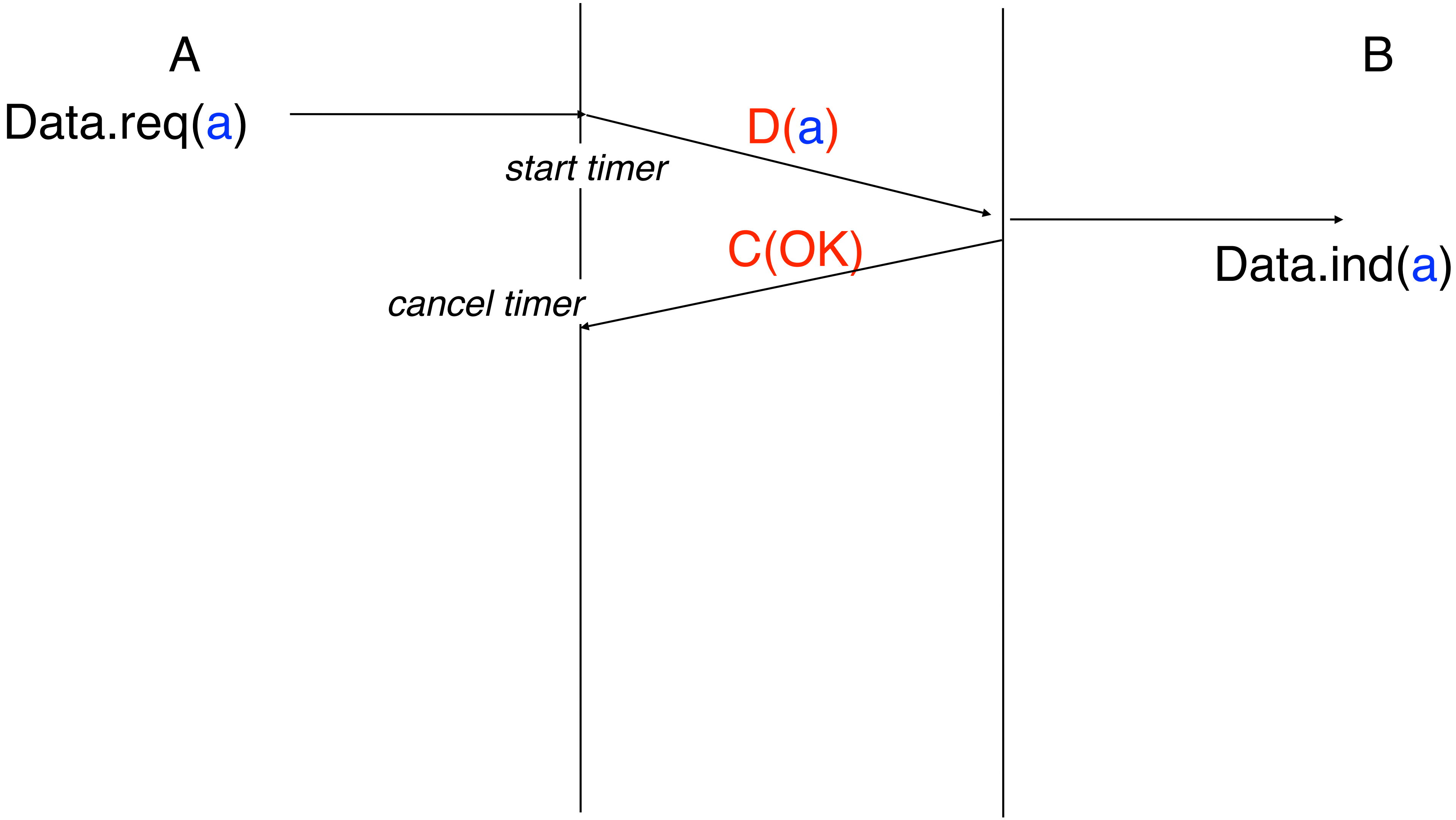

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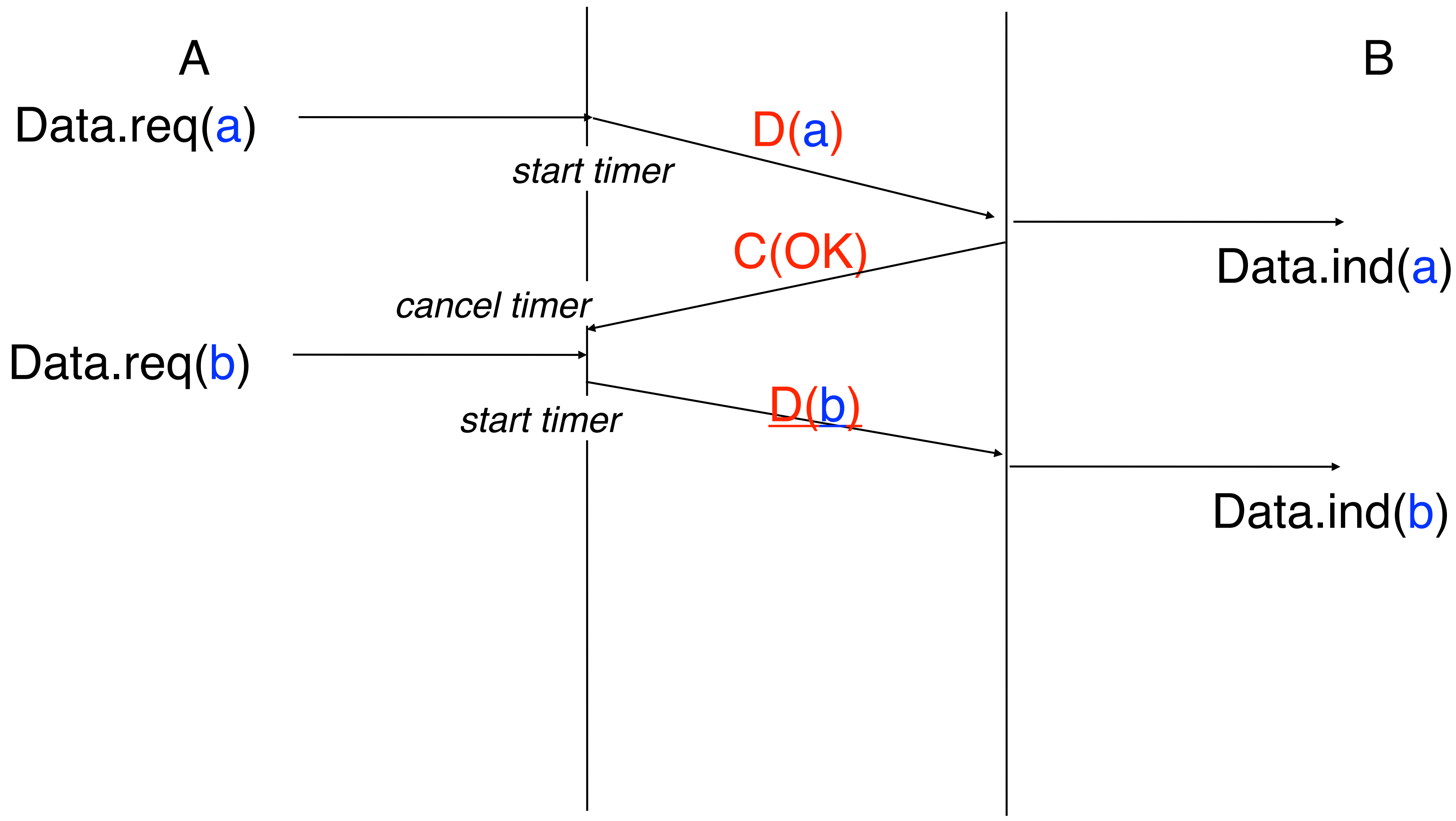

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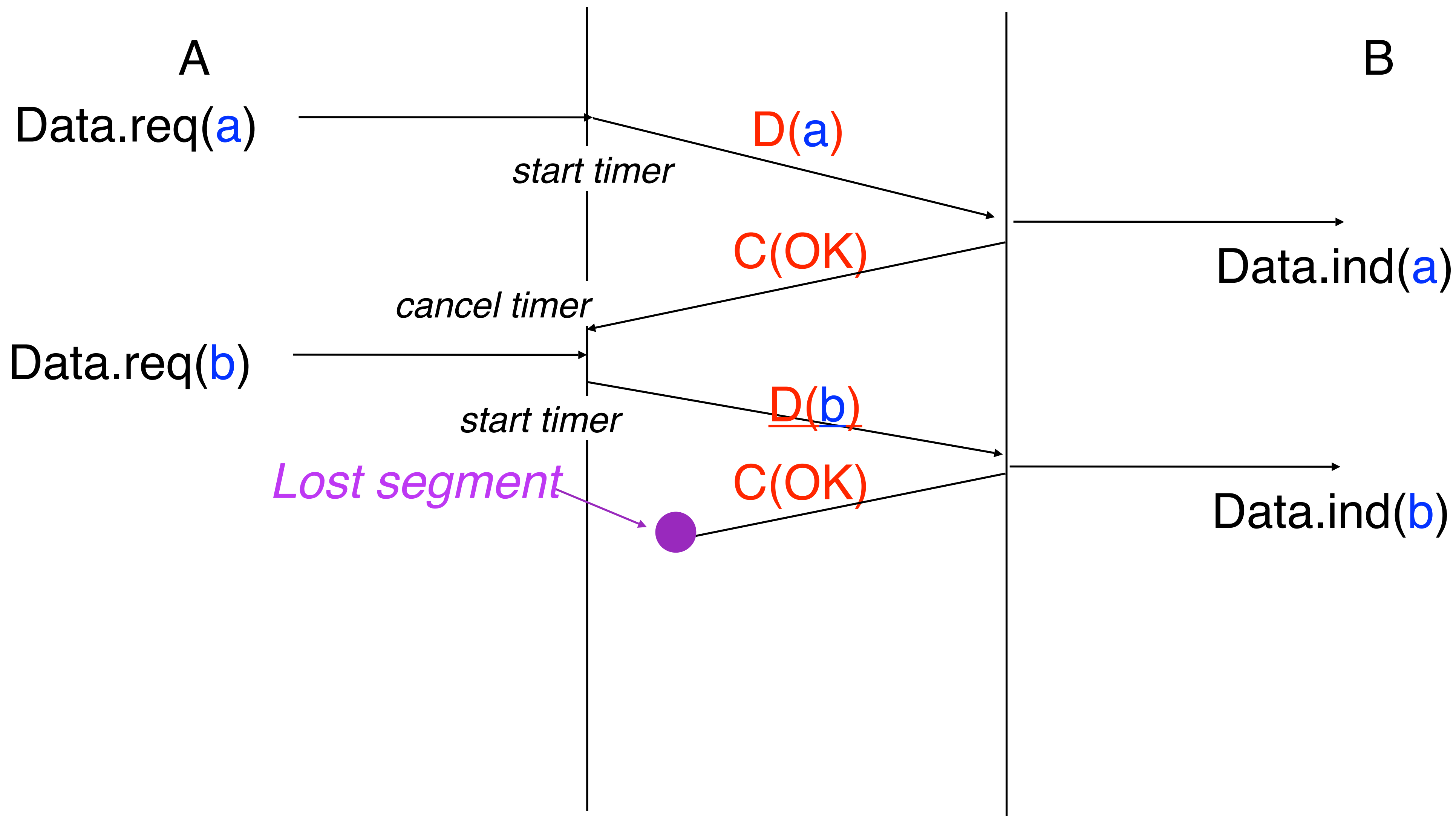

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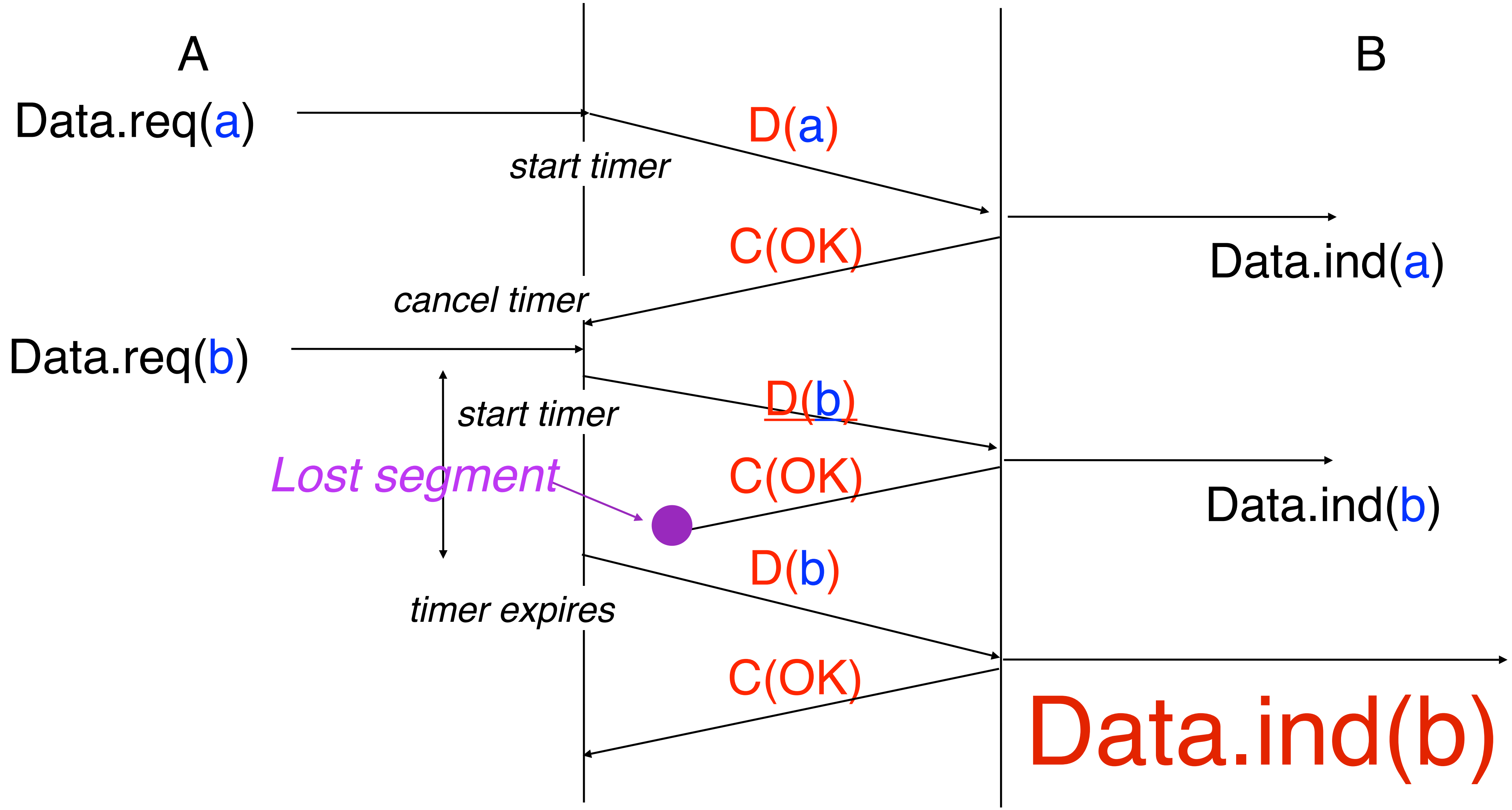

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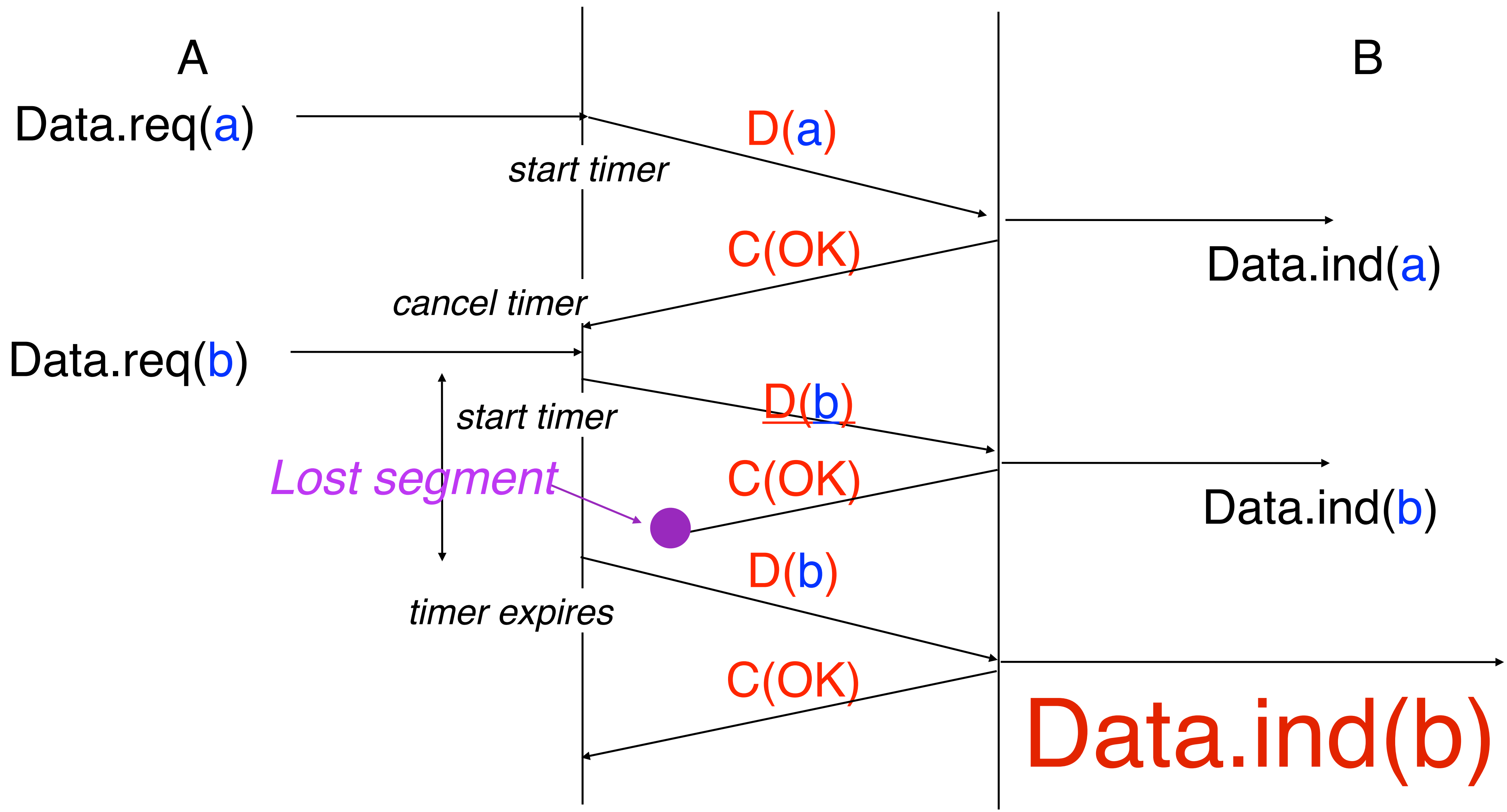
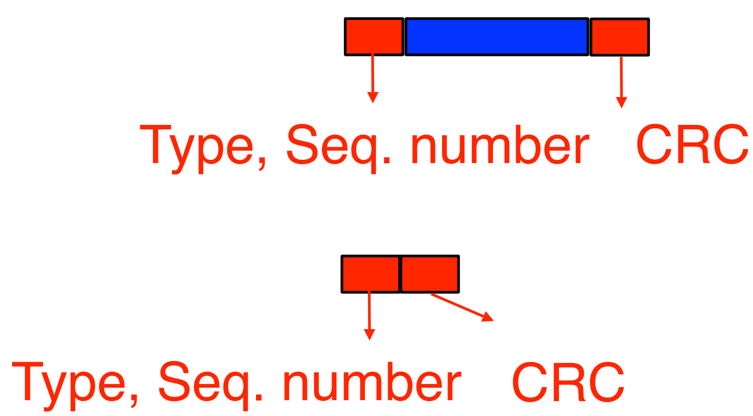


- How to solve this problem ?

Alternating bit protocol

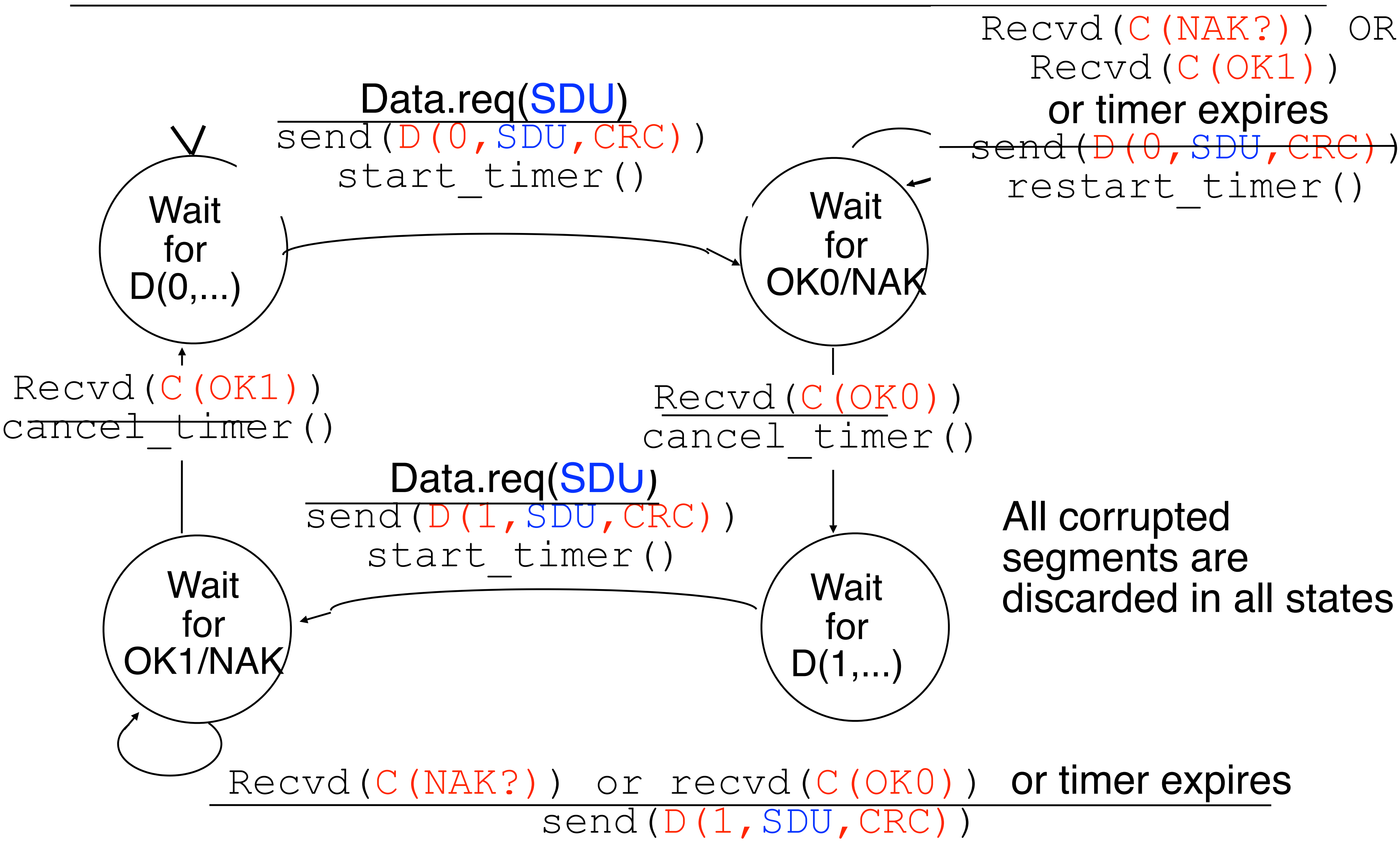
- Principles of the solution
  - Add sequence numbers to each data segment sent by sender
  - By looking at the sequence number, the receiver can check whether it has already received this segment

- Contents of each segment
  - Data segments
  - Control segments



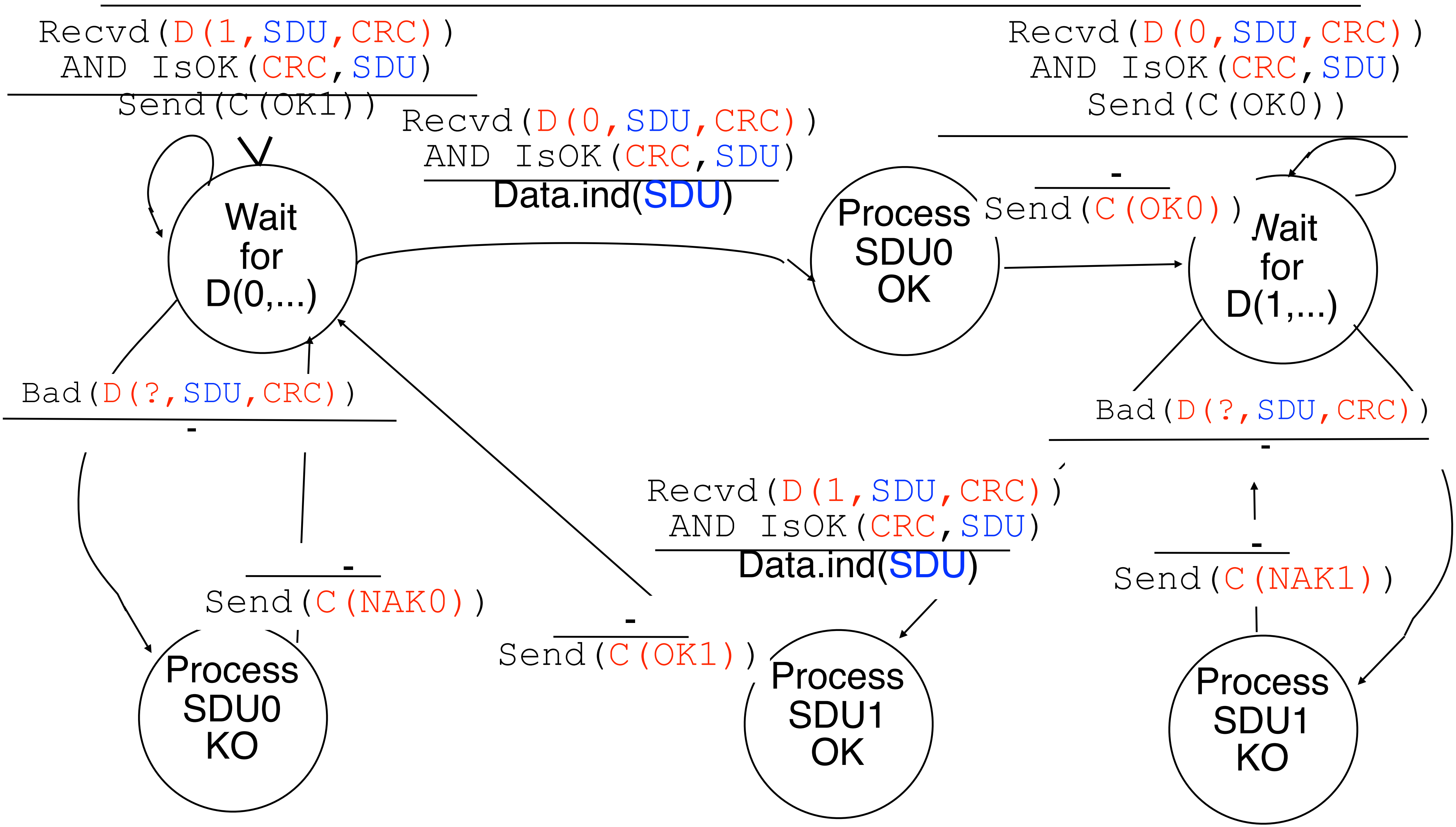
  - How many bits do we need for the sequence number?
    - a single bit is enough

Alternating bit protocol Sender



All corrupted segments are discarded in all states

Alternating bit protocol Receiver

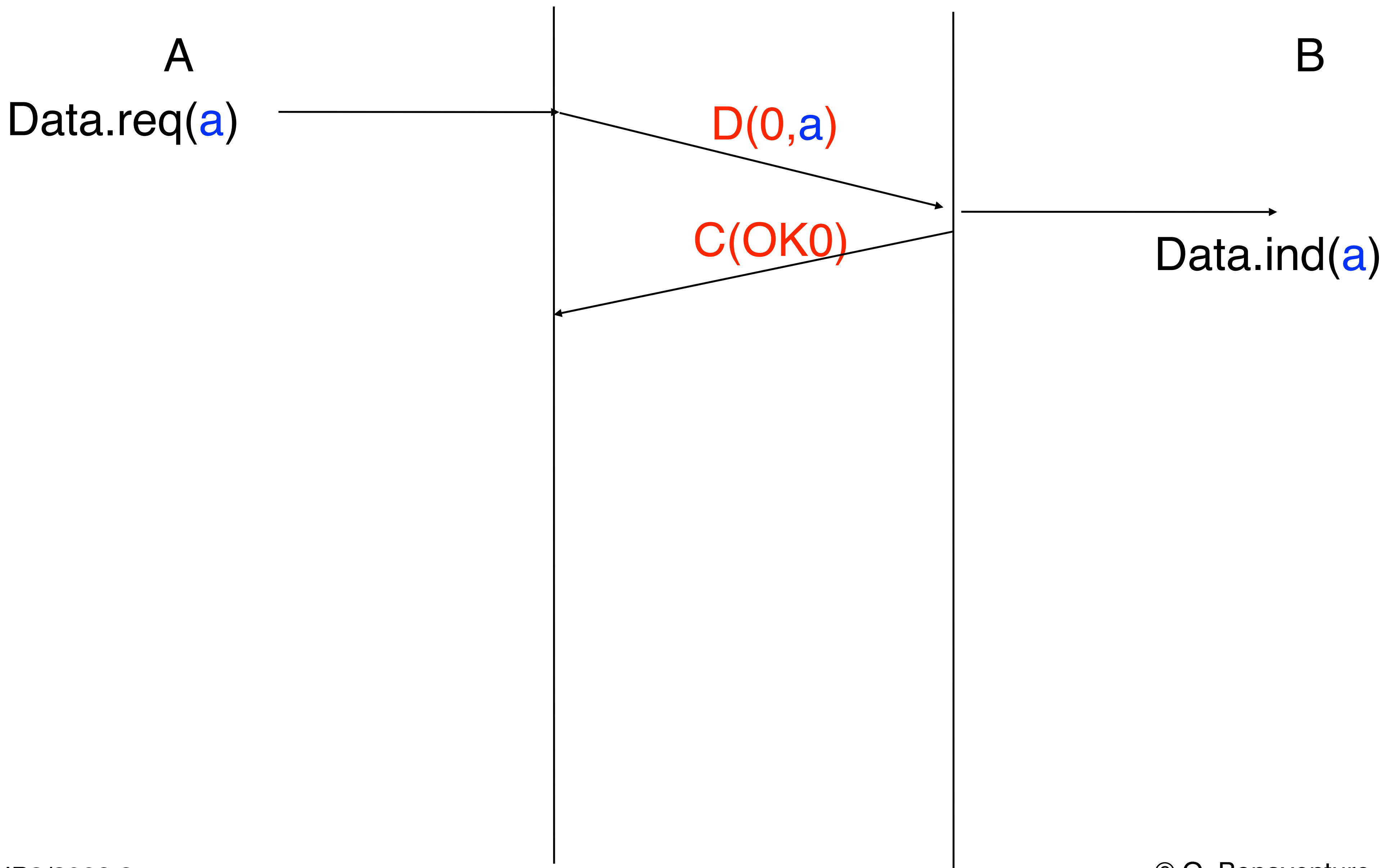


Alternating bit protocol
Example

A

B

Alternating bit protocol Example



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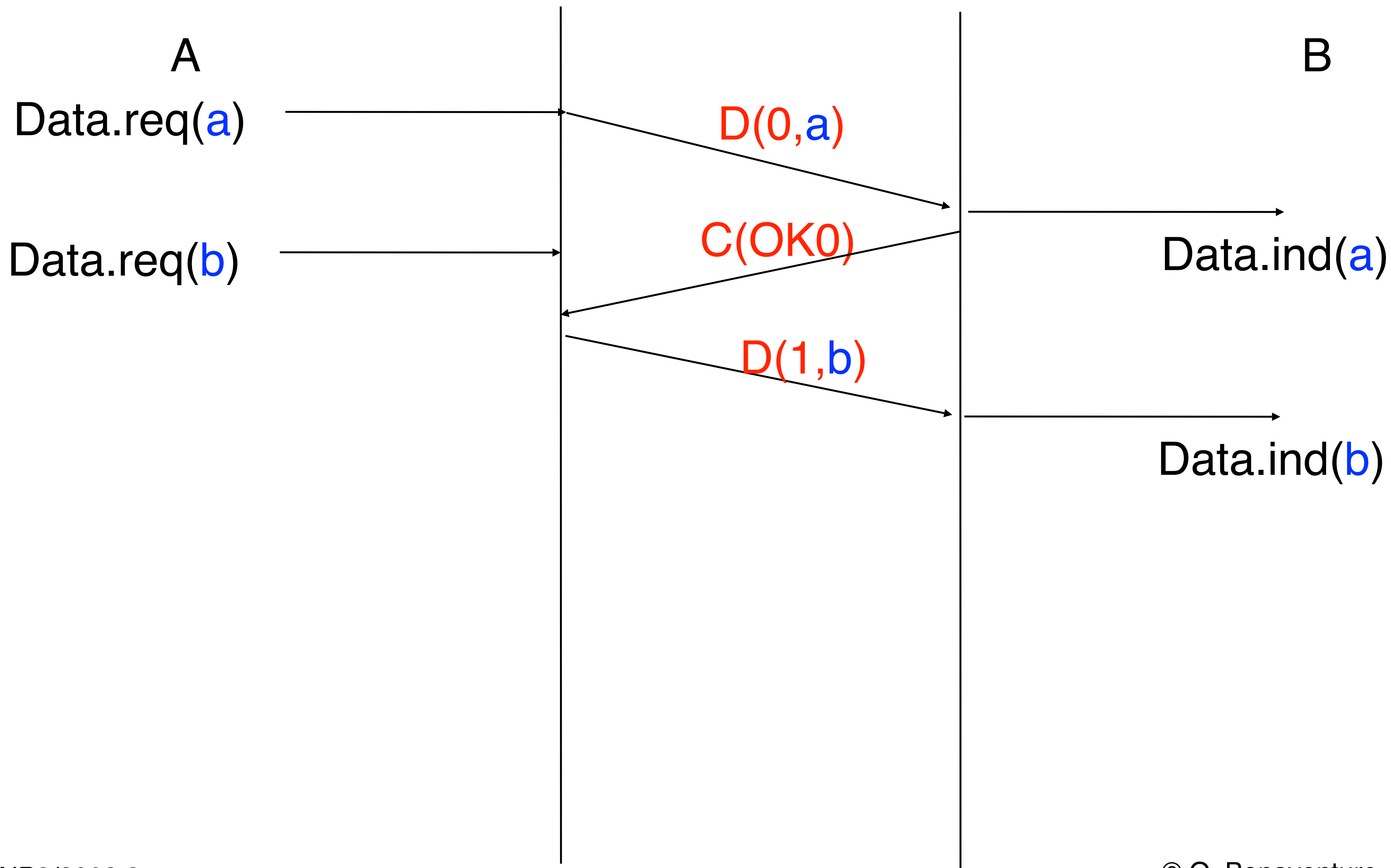

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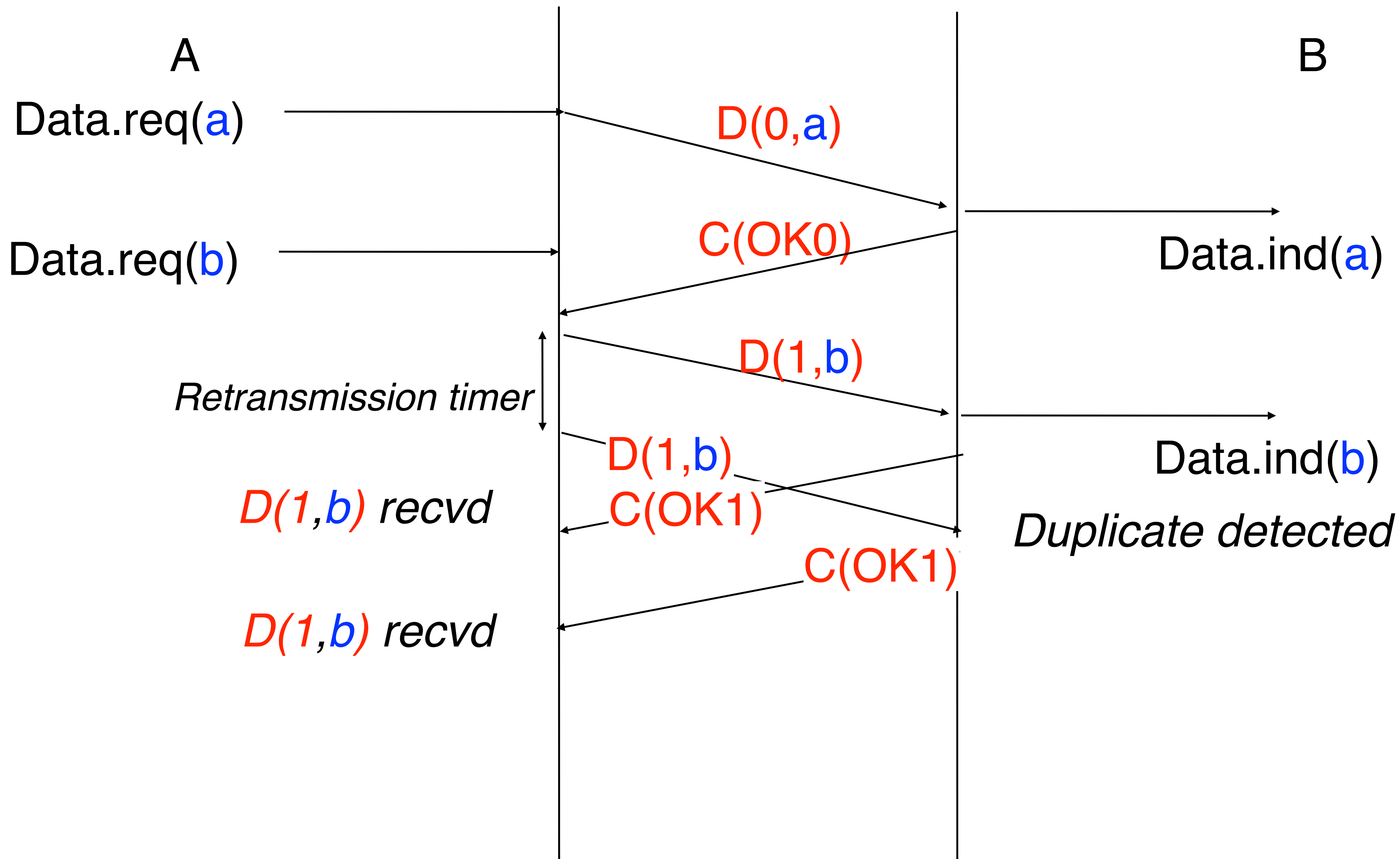

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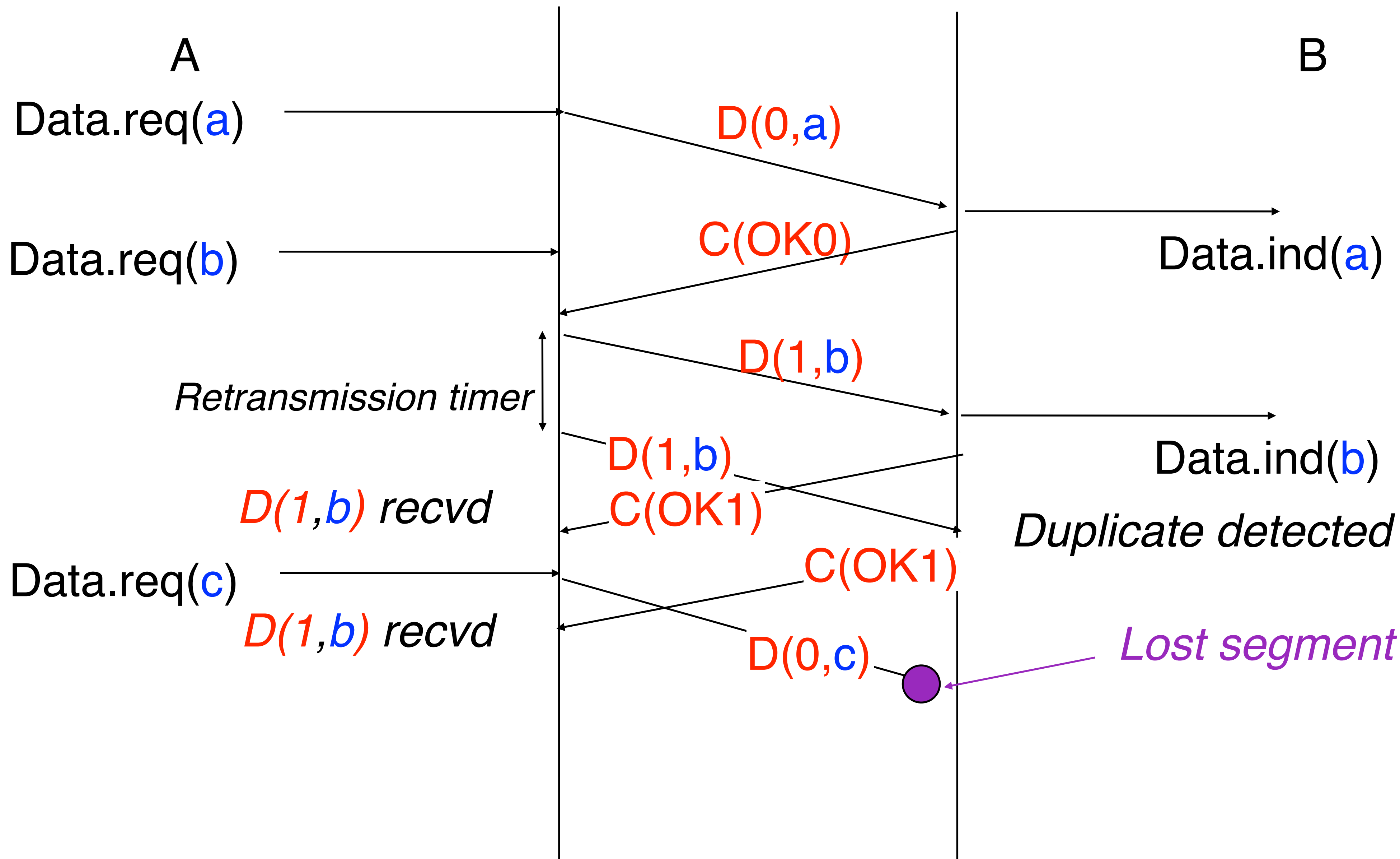

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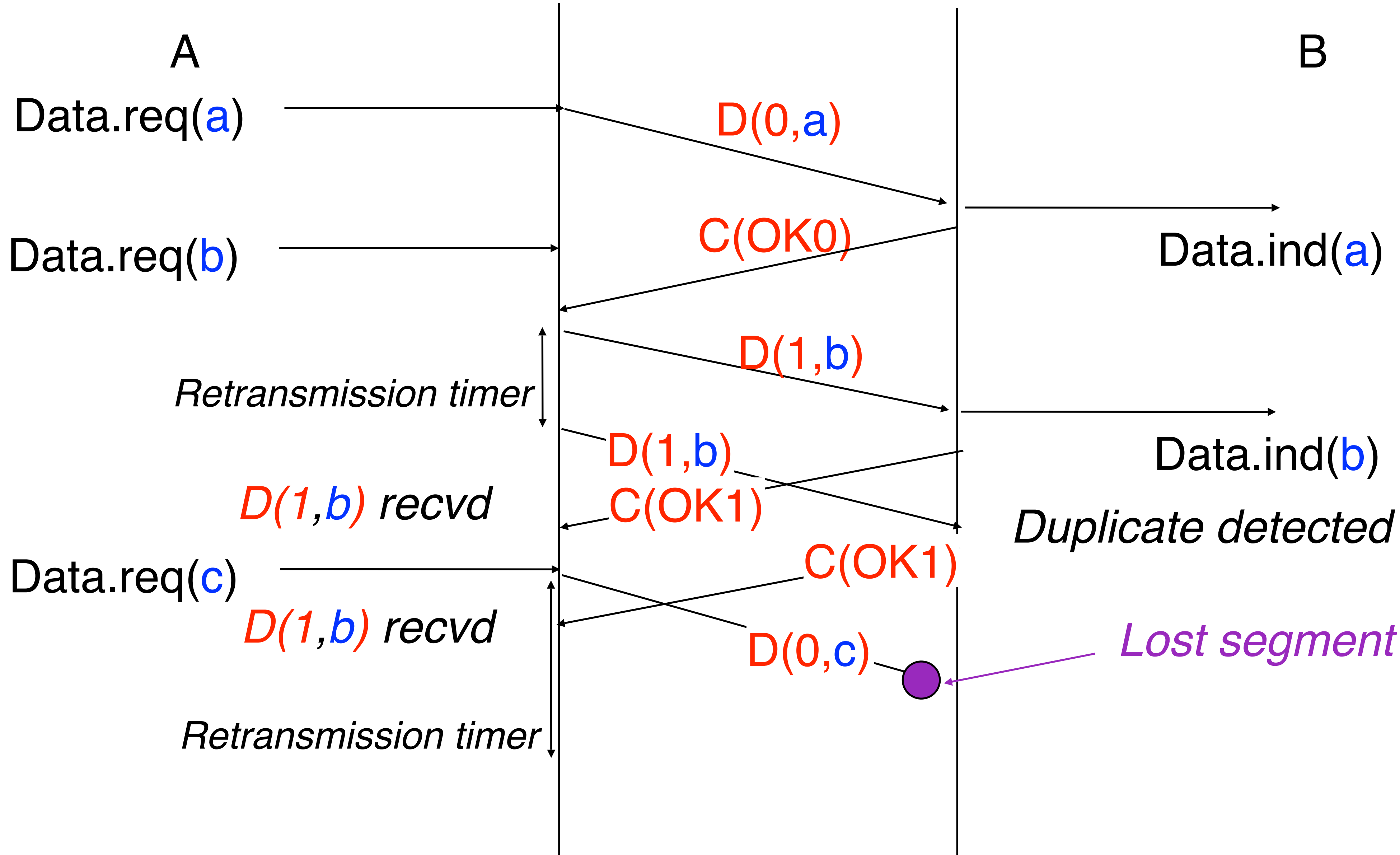

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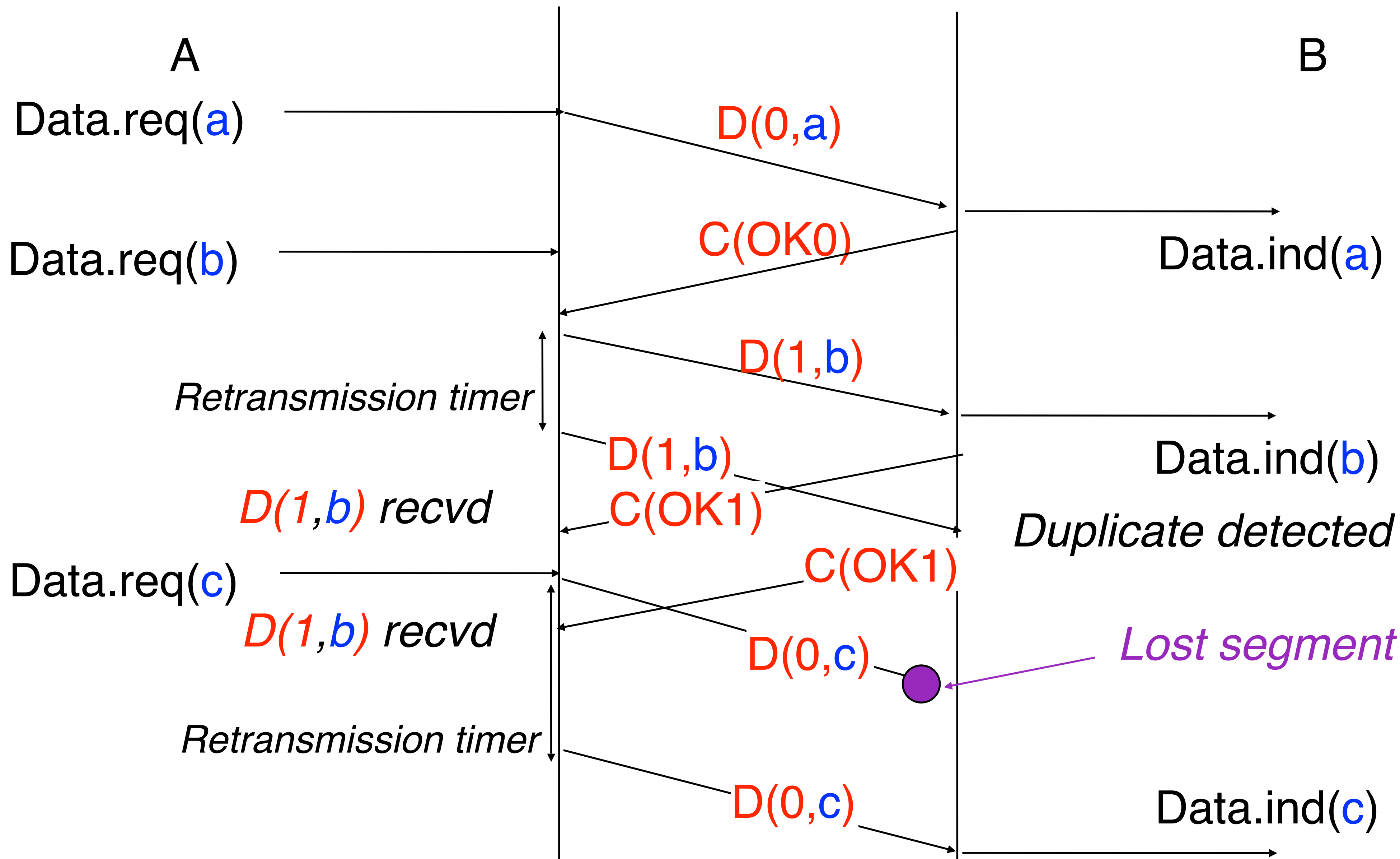

Performance of the alternating bit protocol

- What is the performance of the ABP in this case
  - One-way delay : 250 msec
  - Physical layer throughput : 50 kbps
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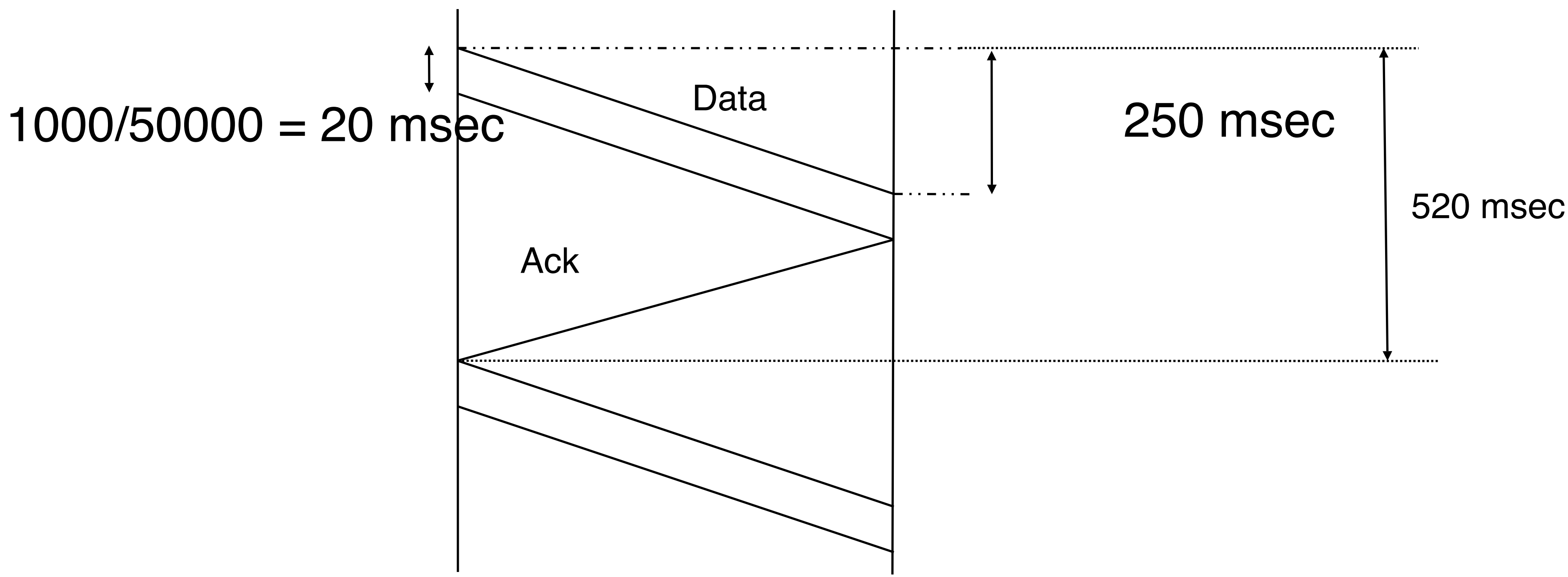

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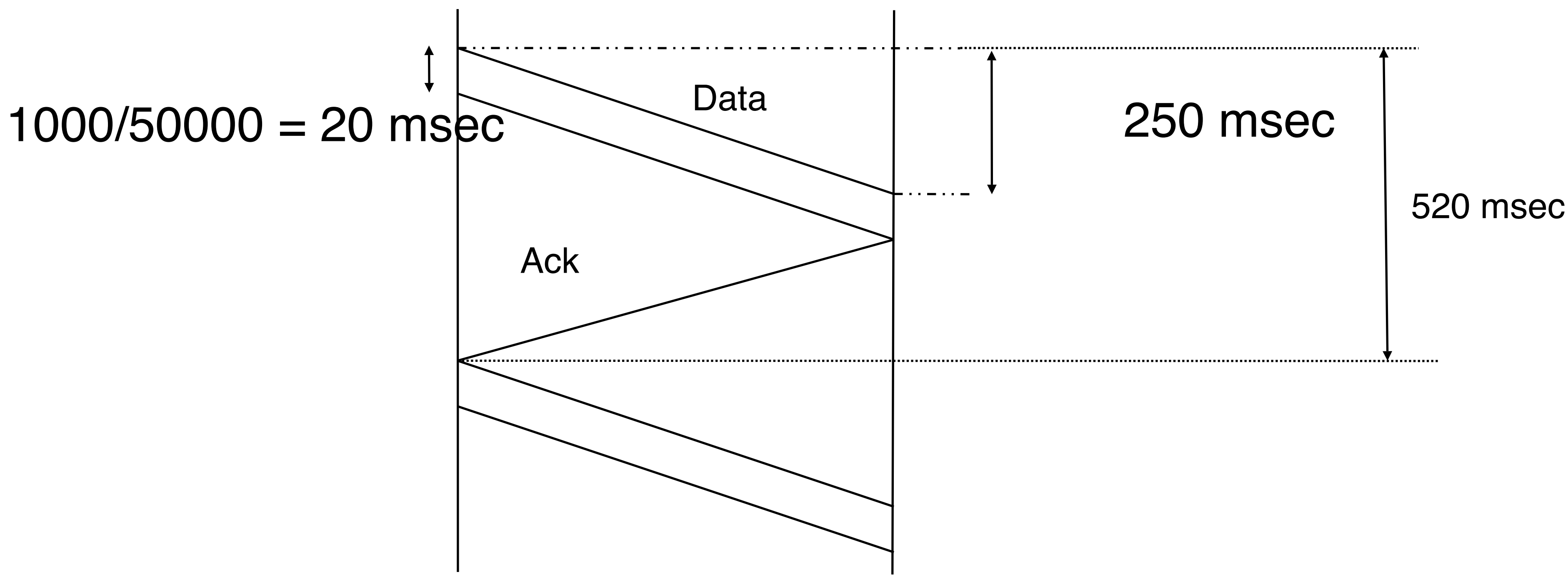

- -> Performance is function of *bandwidth * round-trip-time*

How to improve the alternating bit protocol ?

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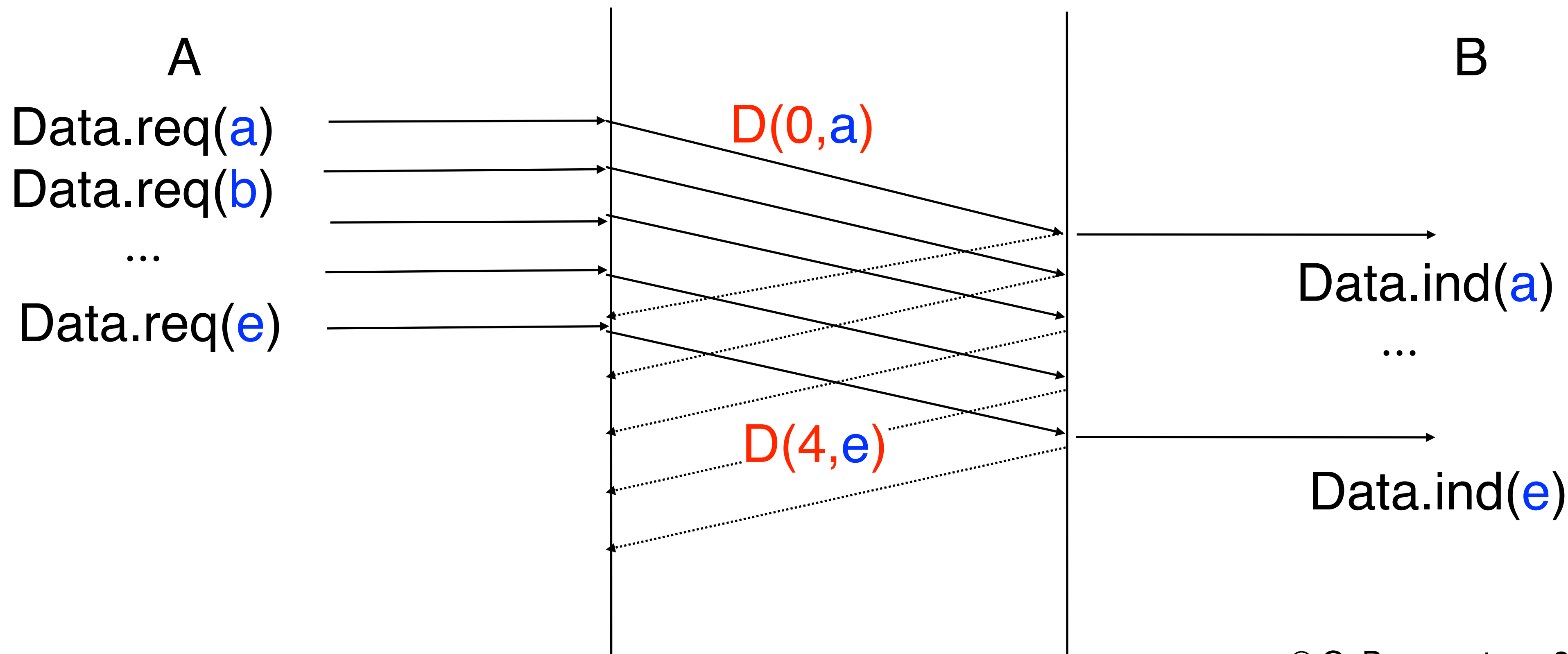

How to improve the alternating bit protocol ? (2)

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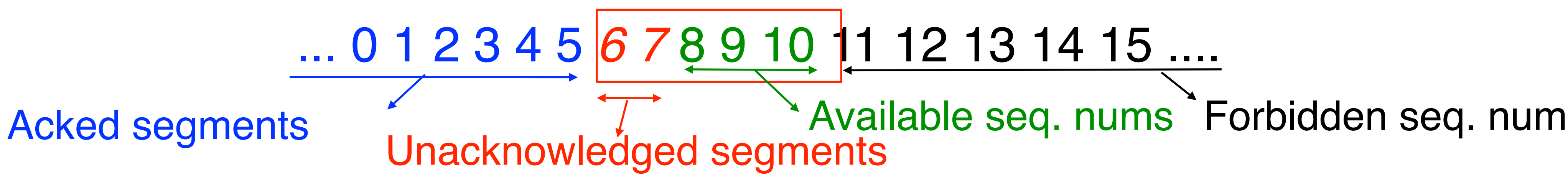
How to avoid an overflow of the receiver's buffers ?

Sliding window

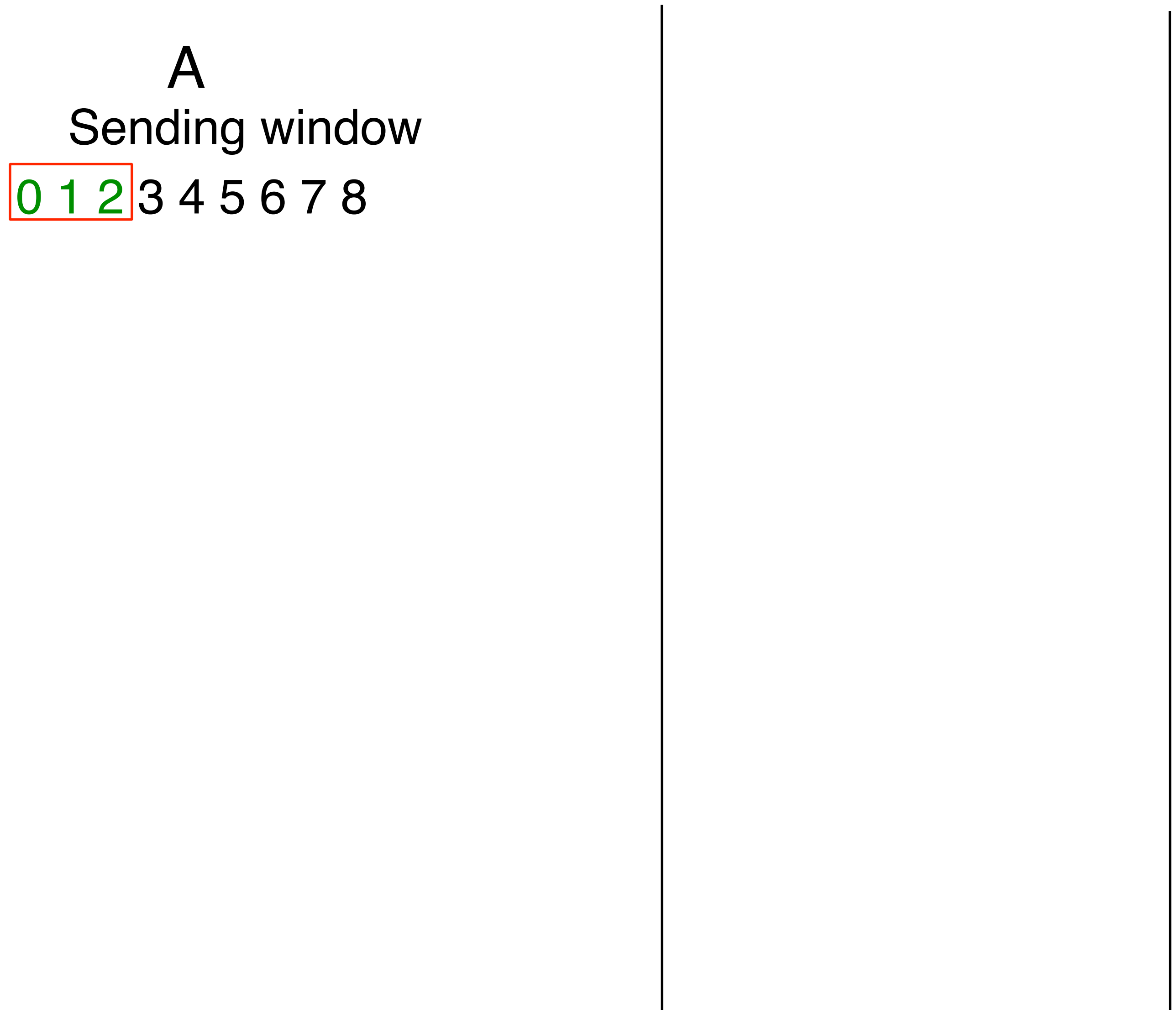
- Principle
  - Sender keeps a list of all the segments that it is allowed to send
    - `sending_window`



  - 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



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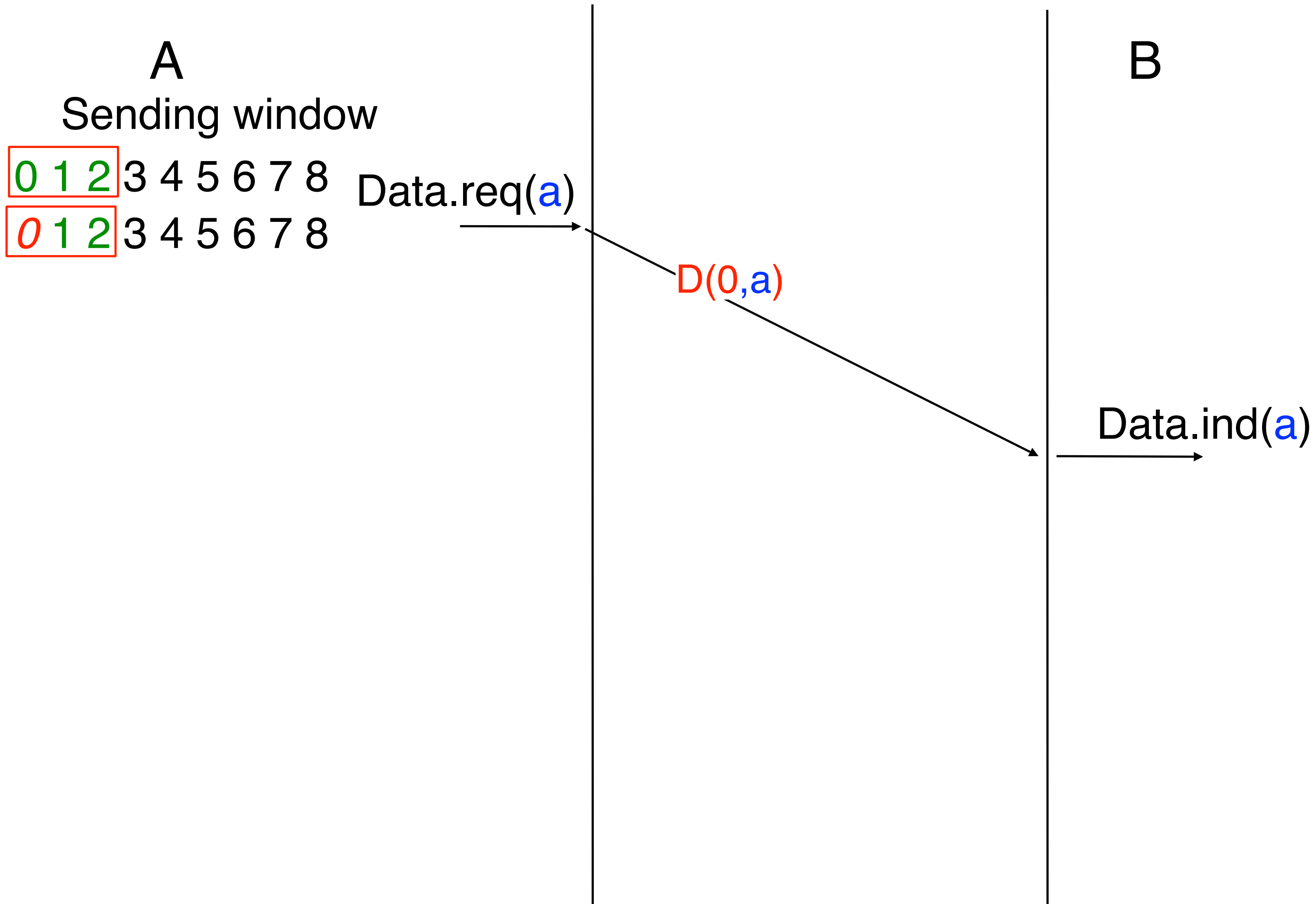

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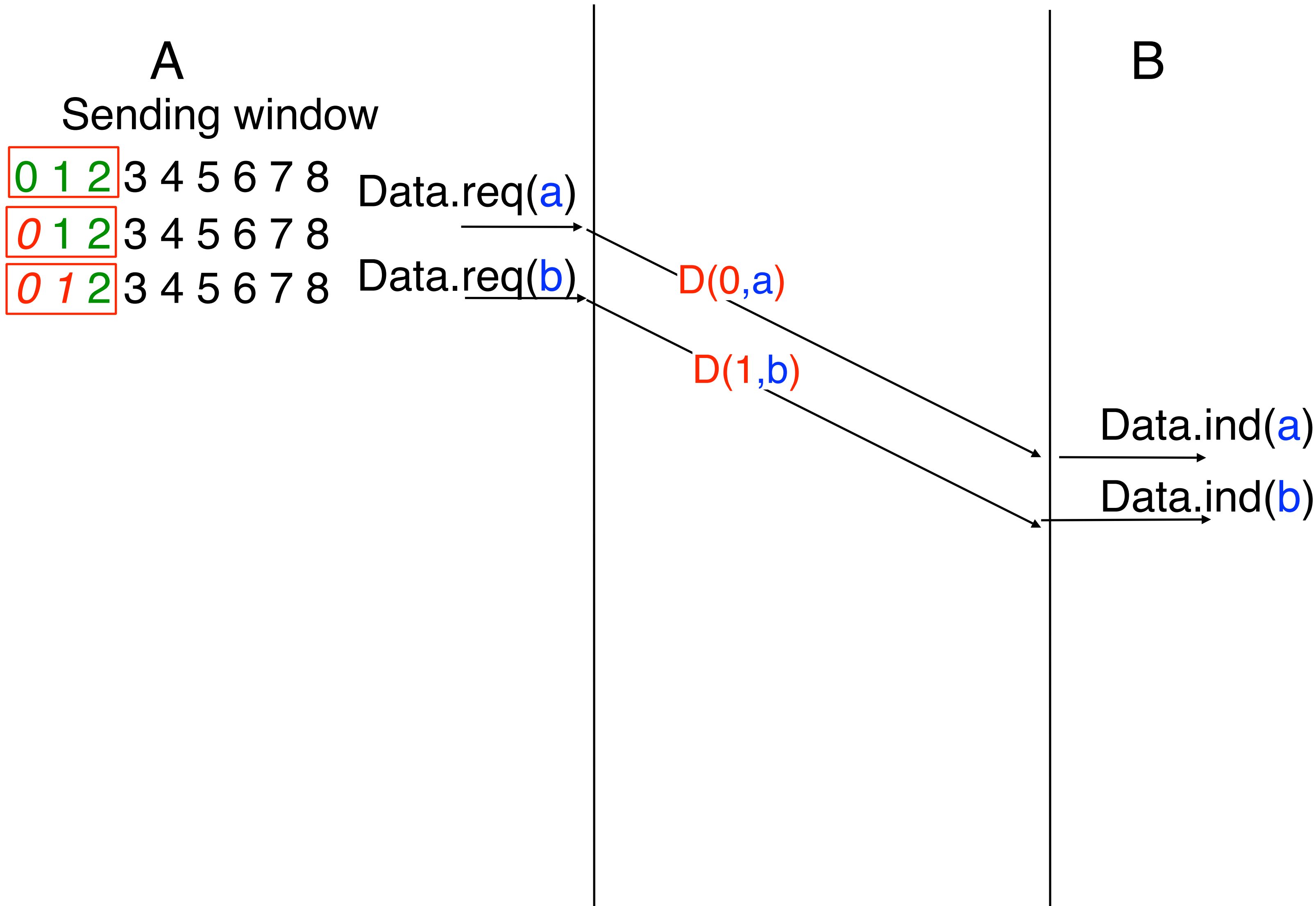

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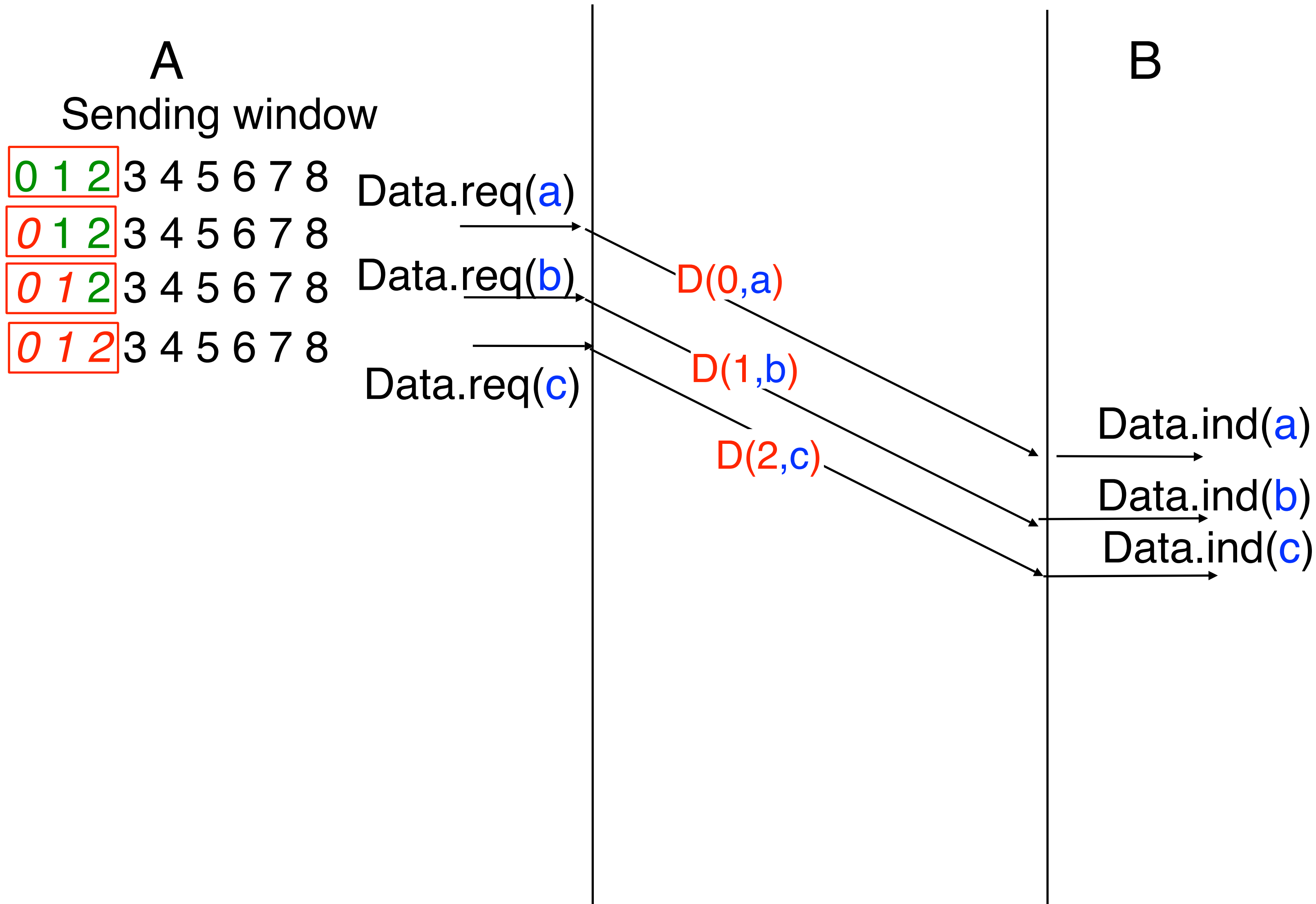

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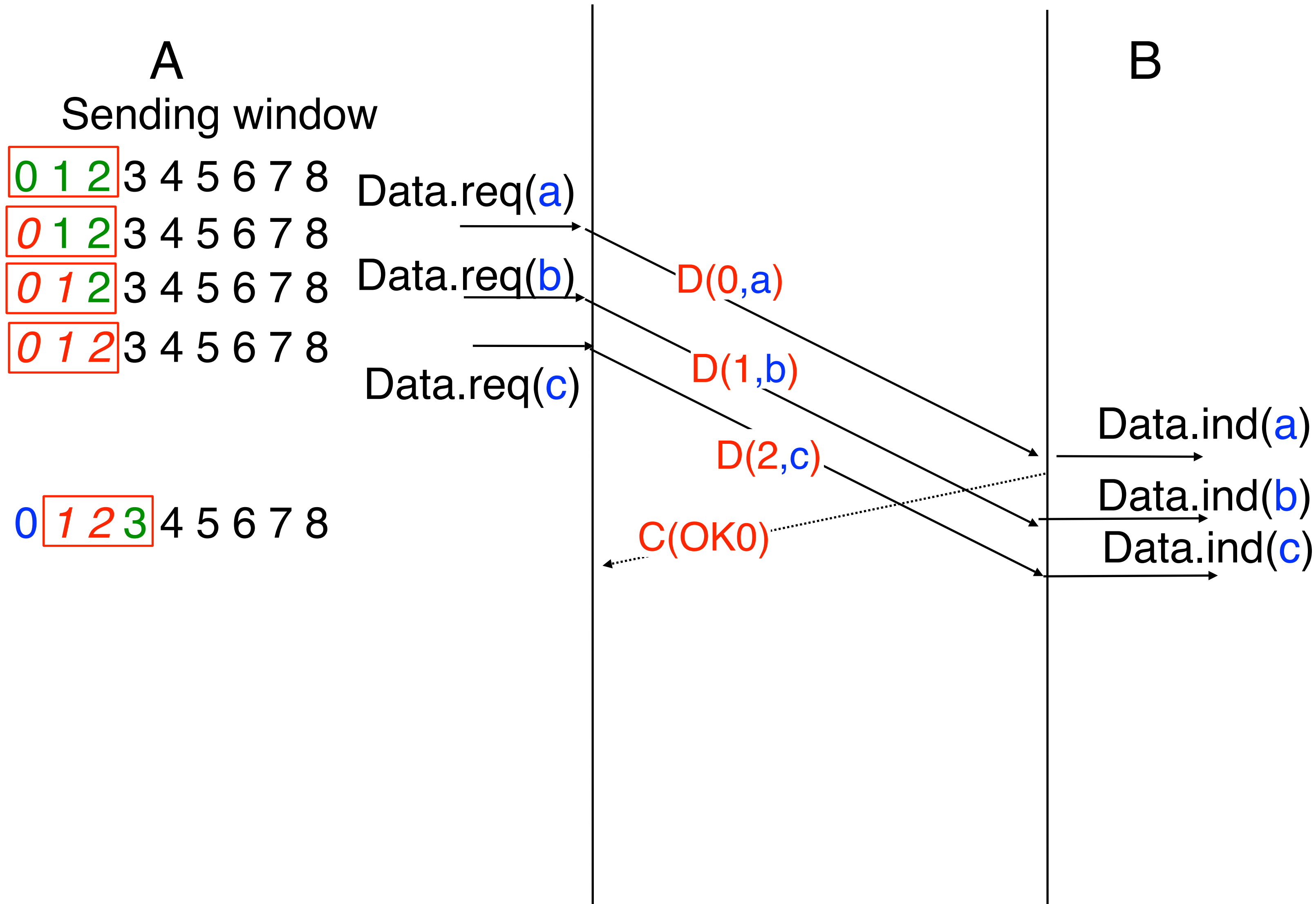

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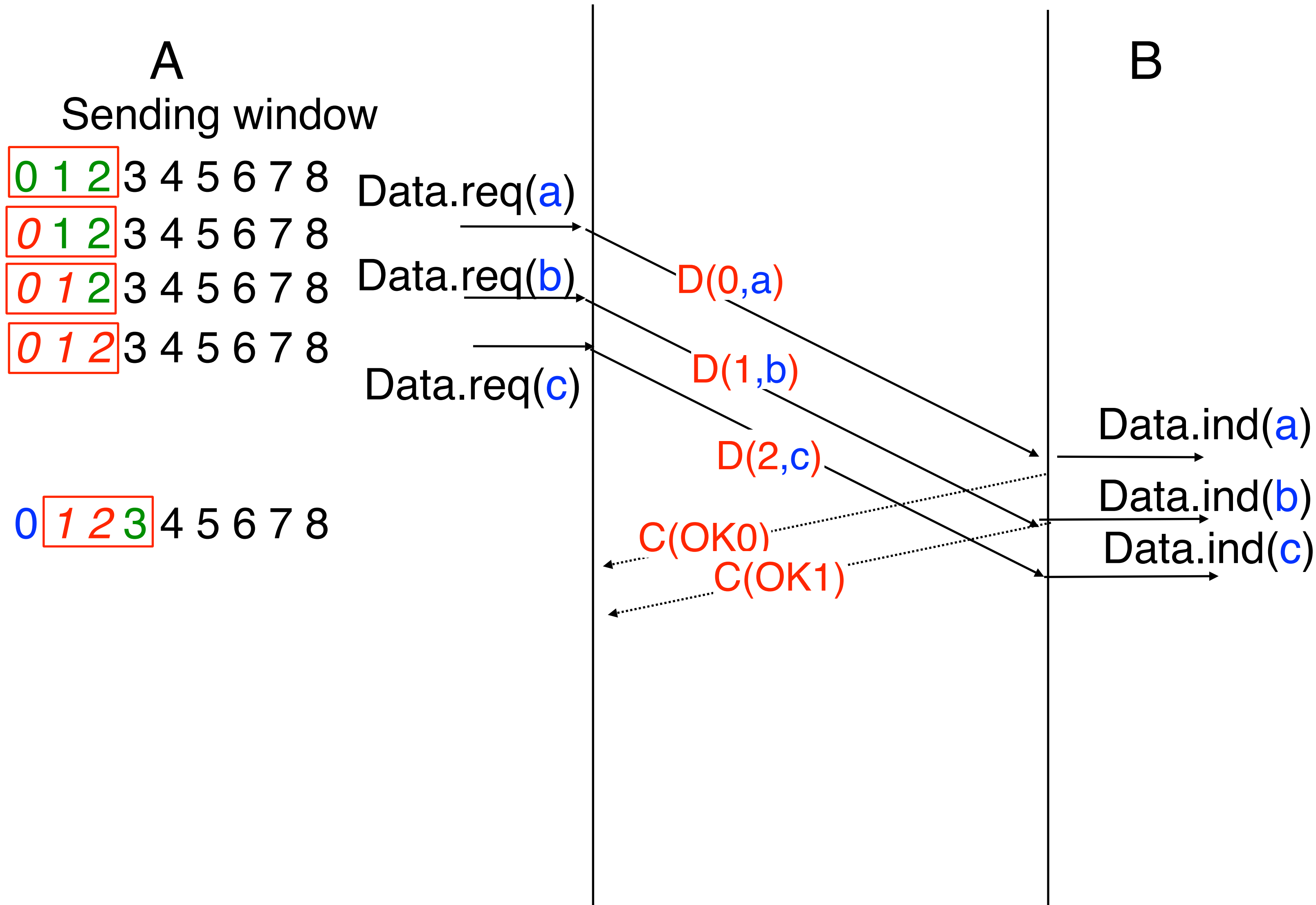

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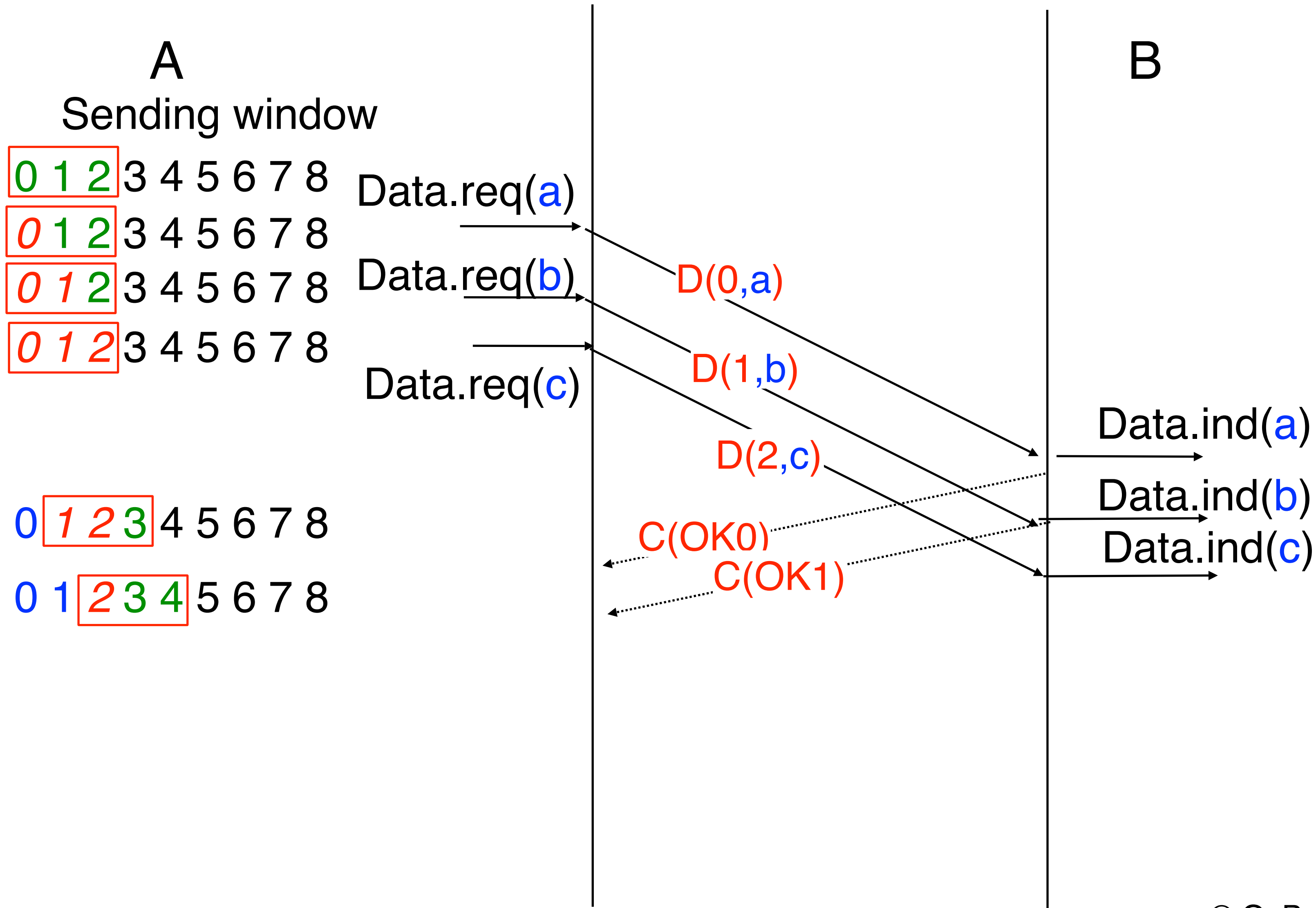

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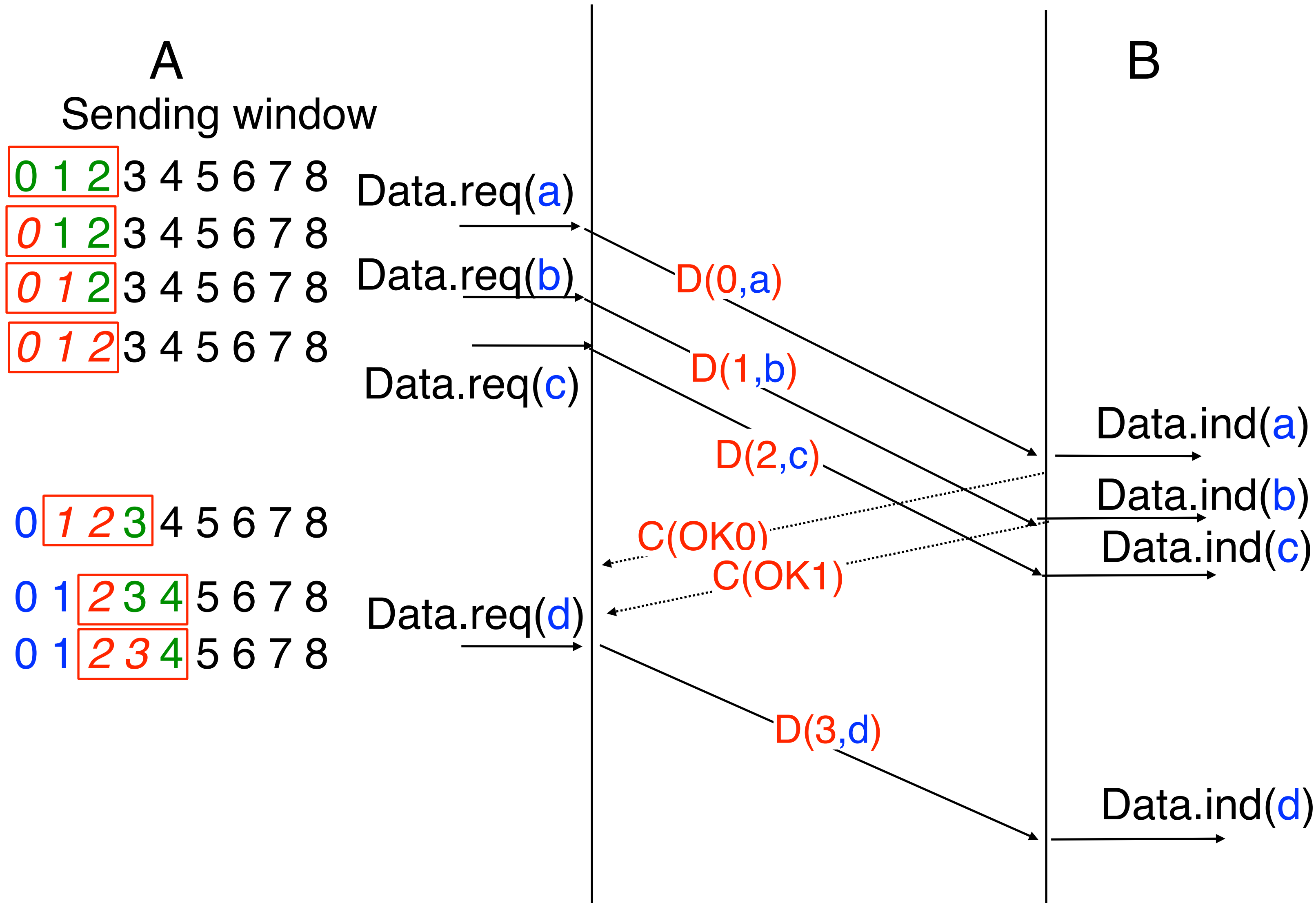

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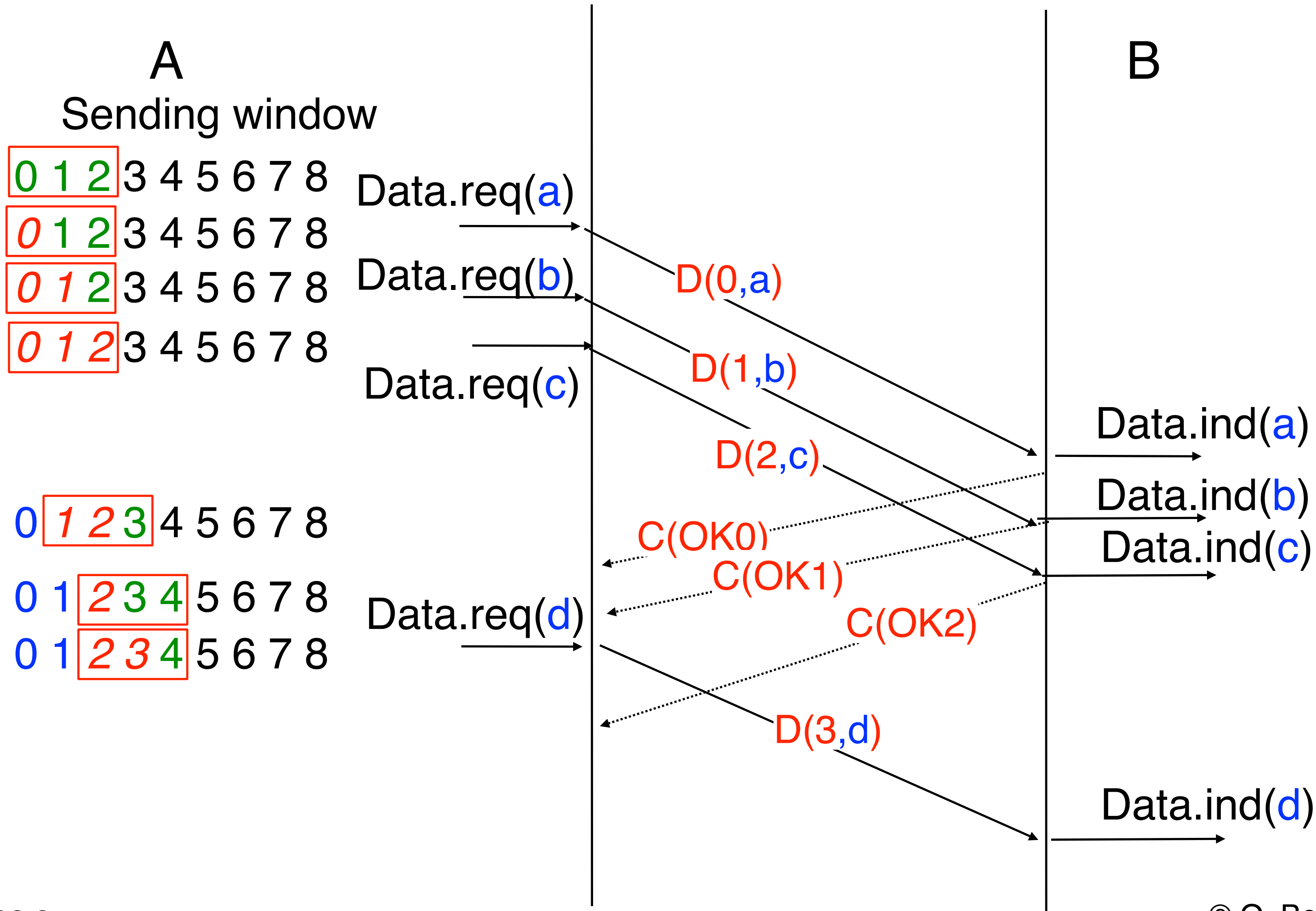

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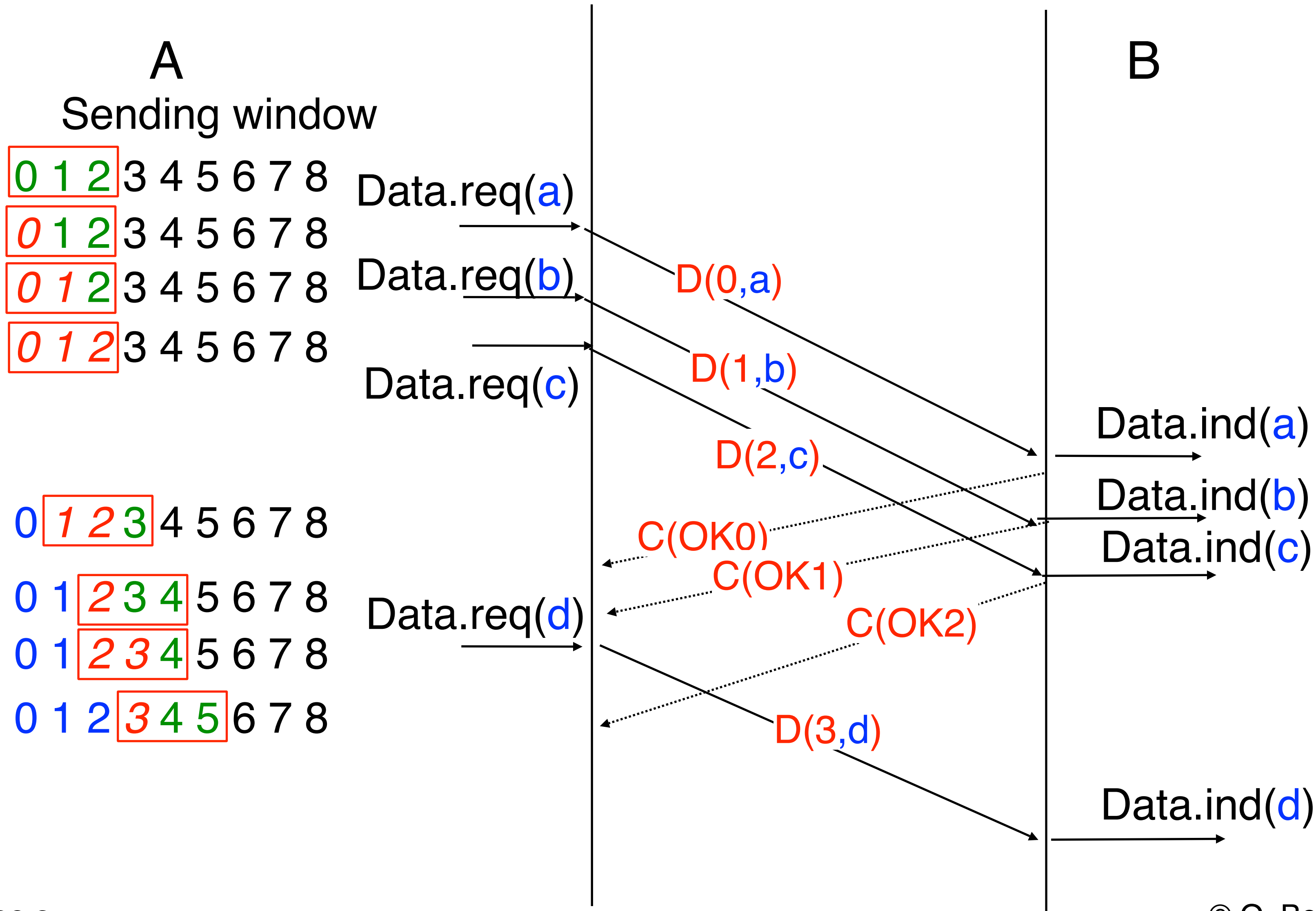

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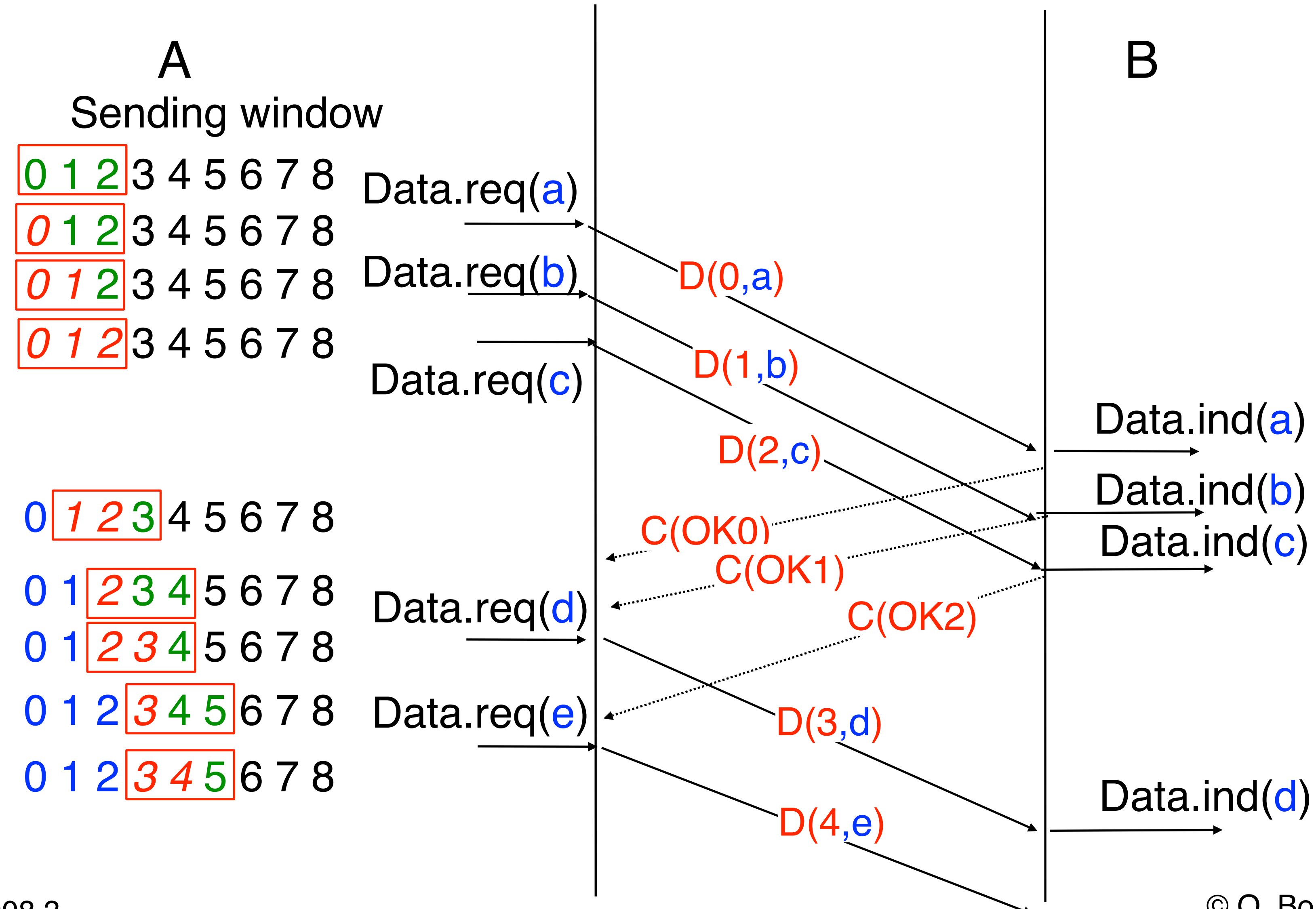
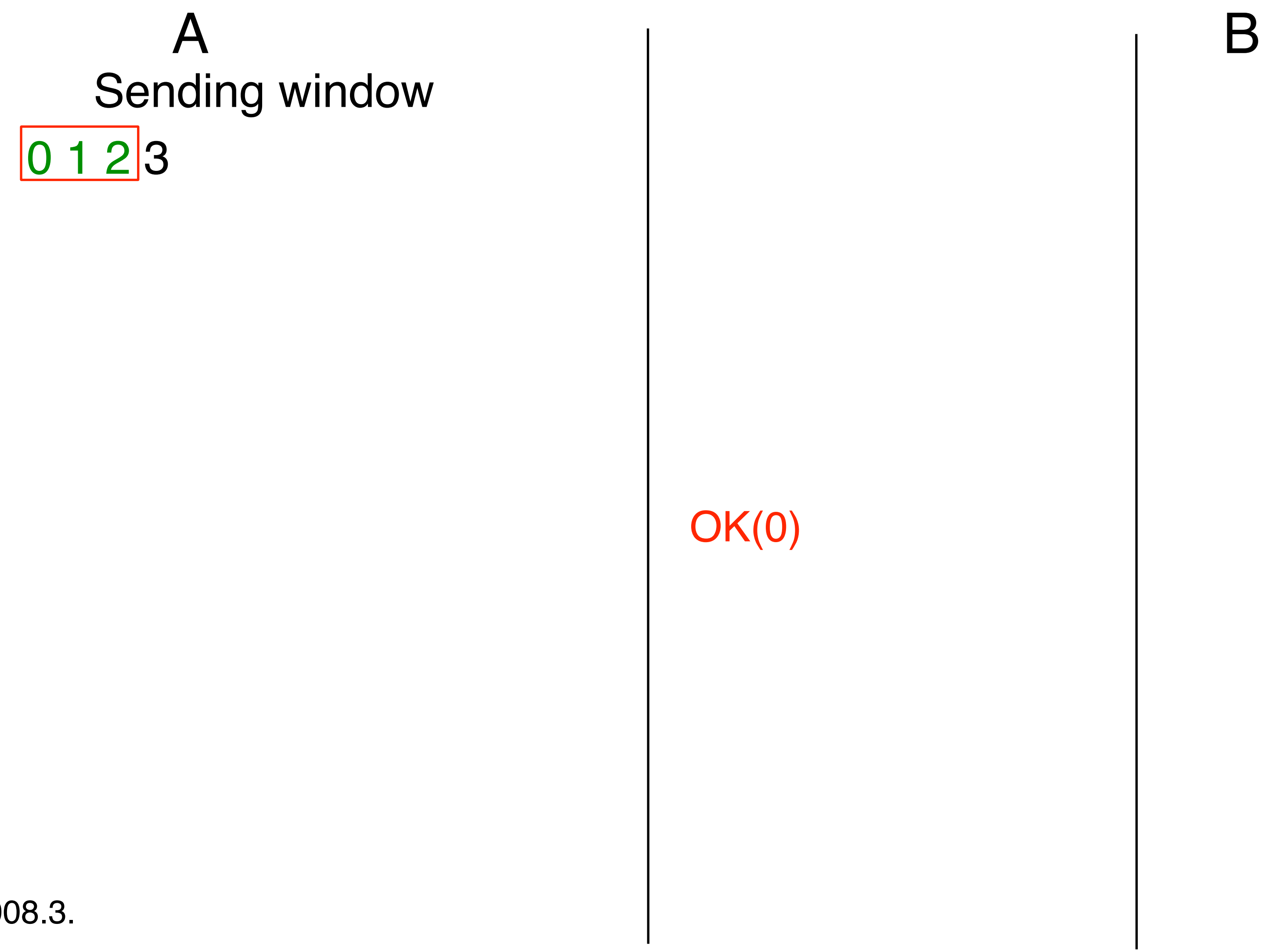


Encoding sequence numbers

- 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



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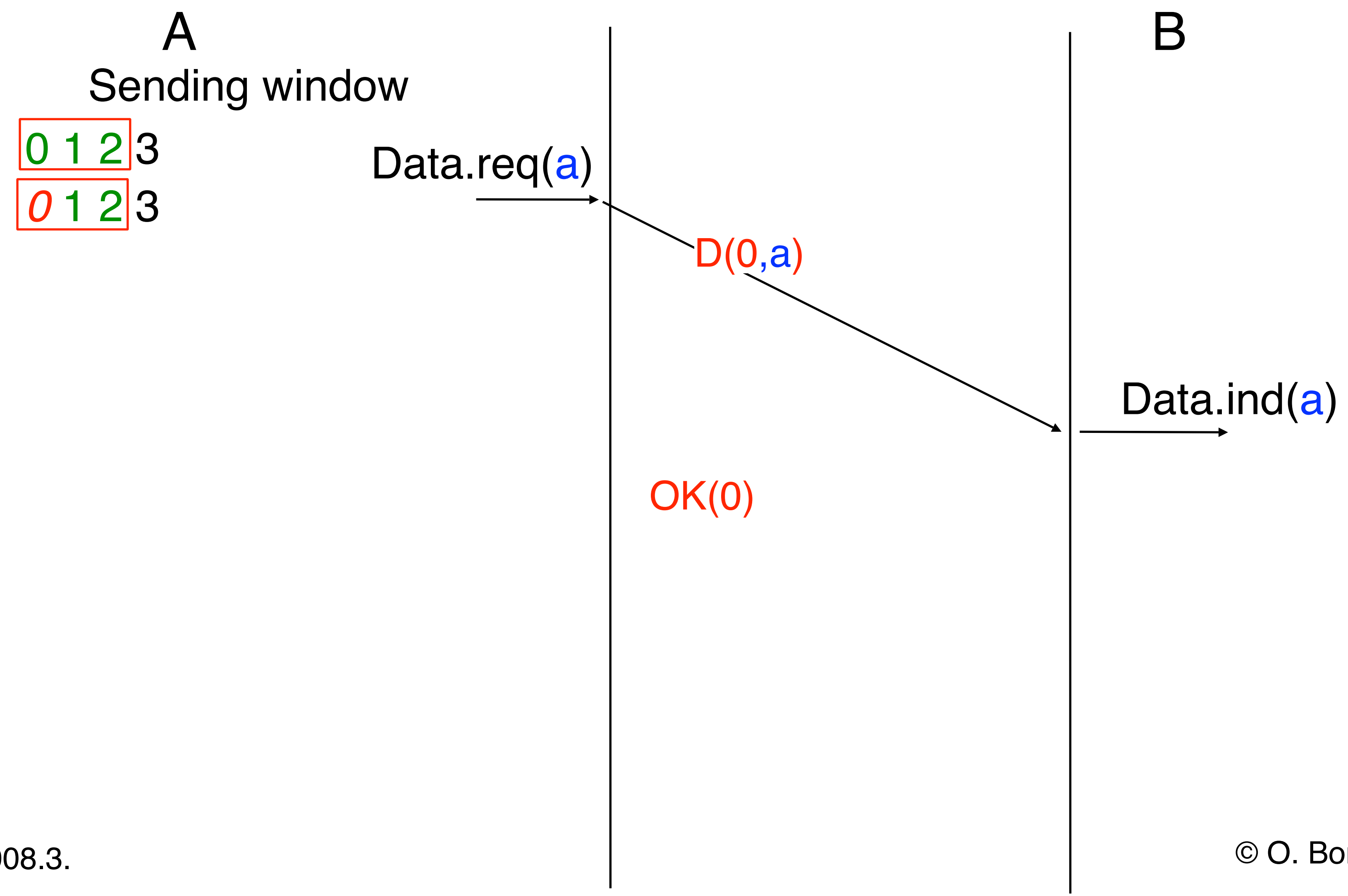

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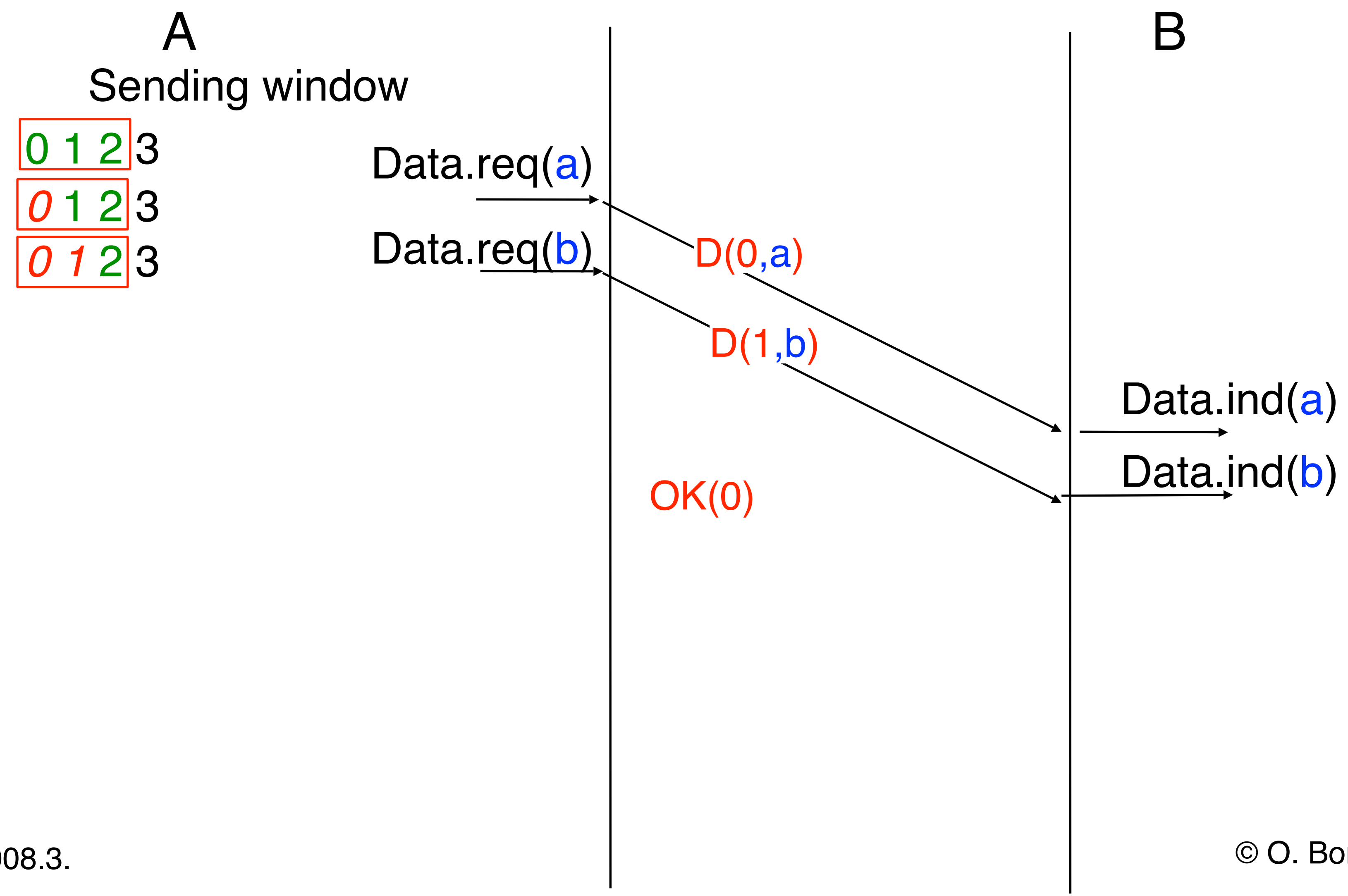

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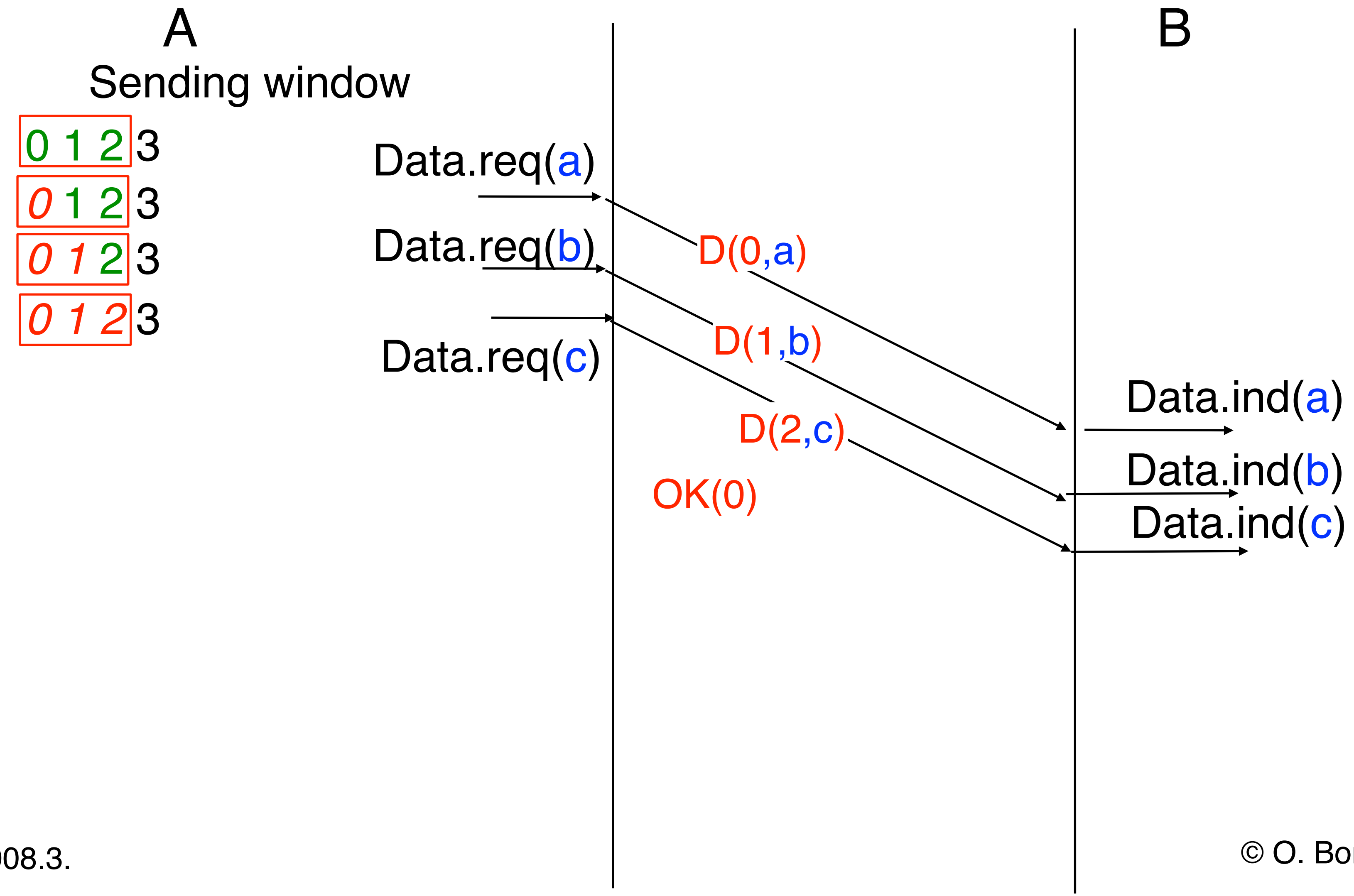

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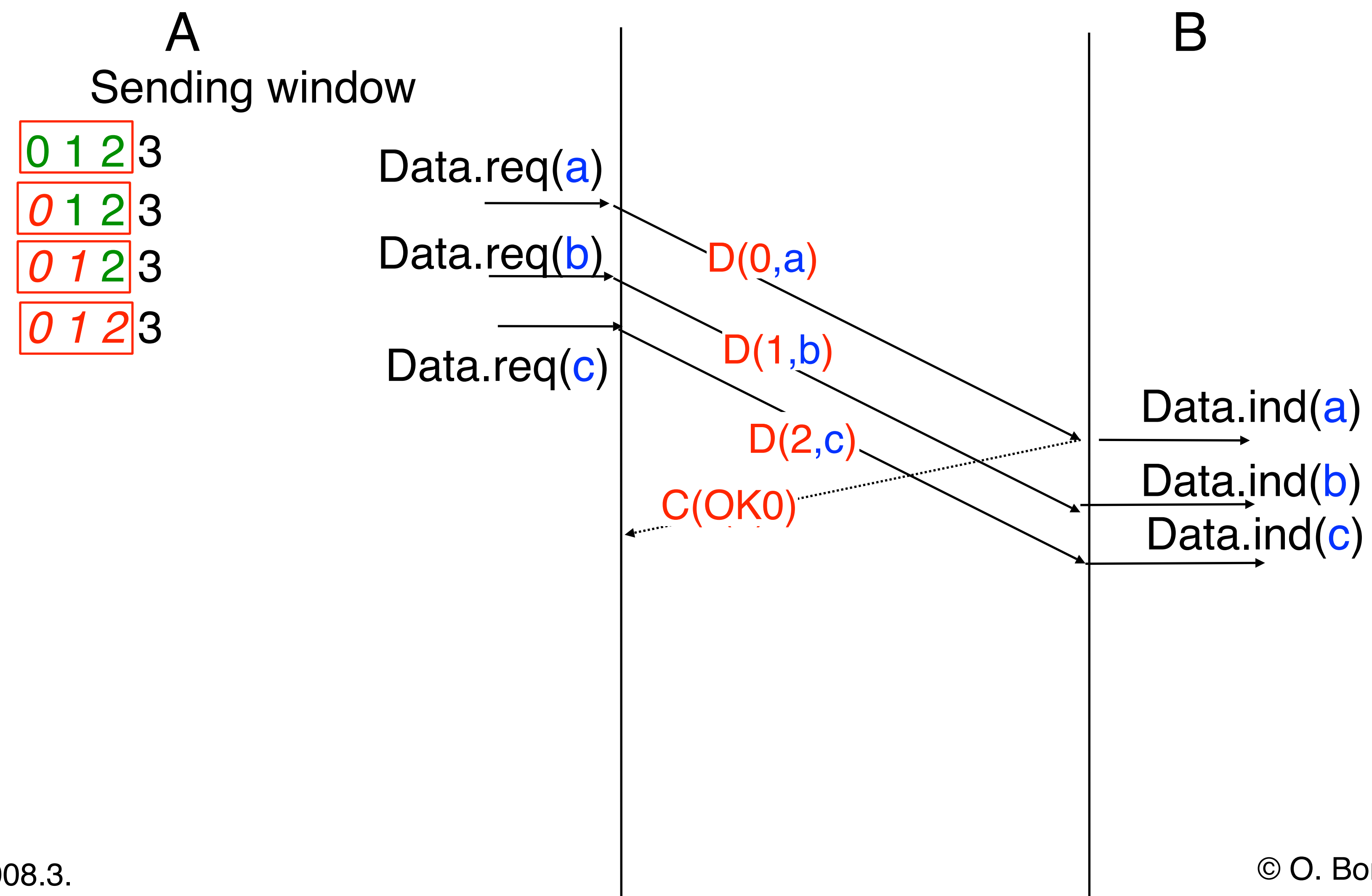

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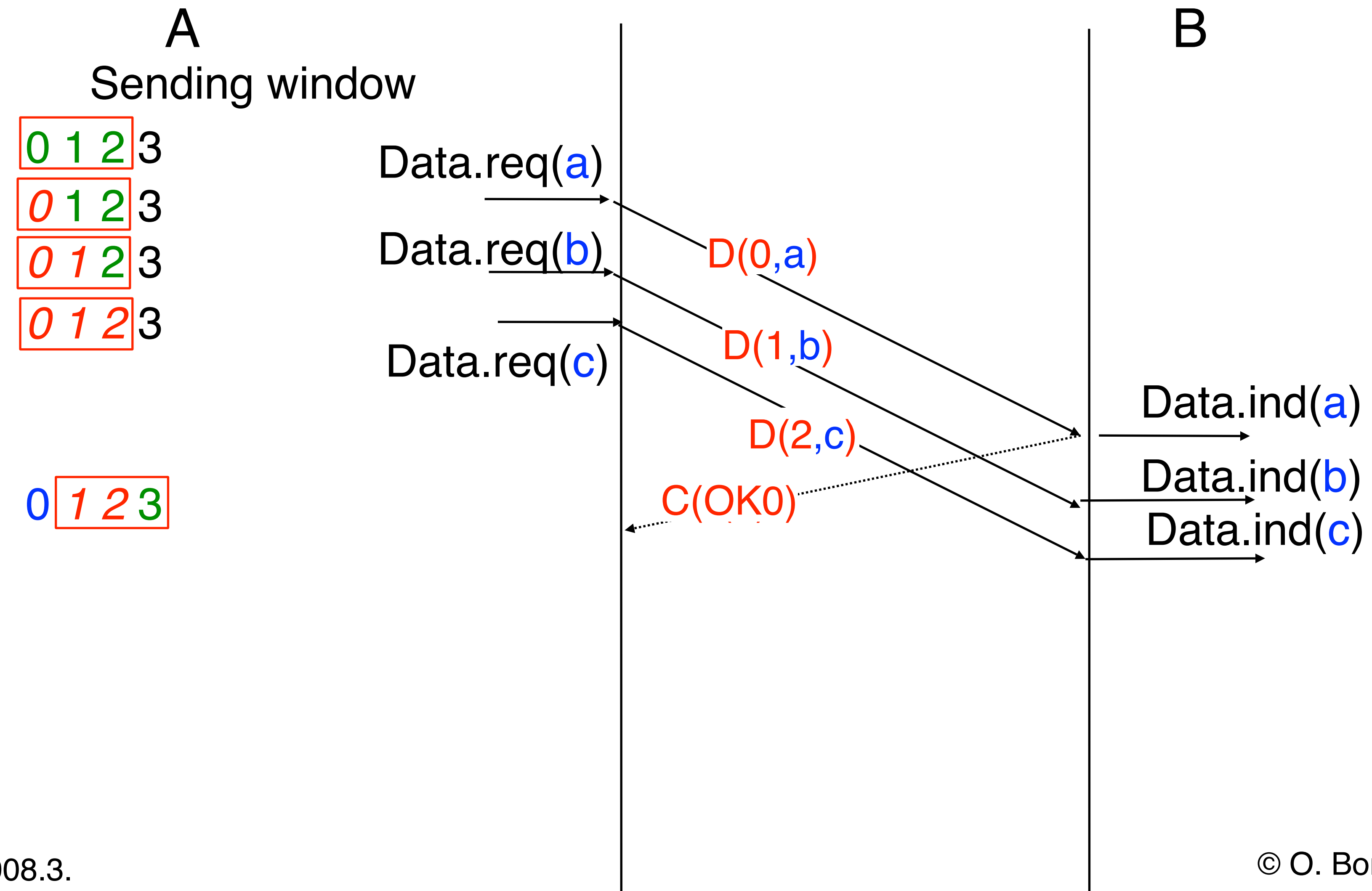

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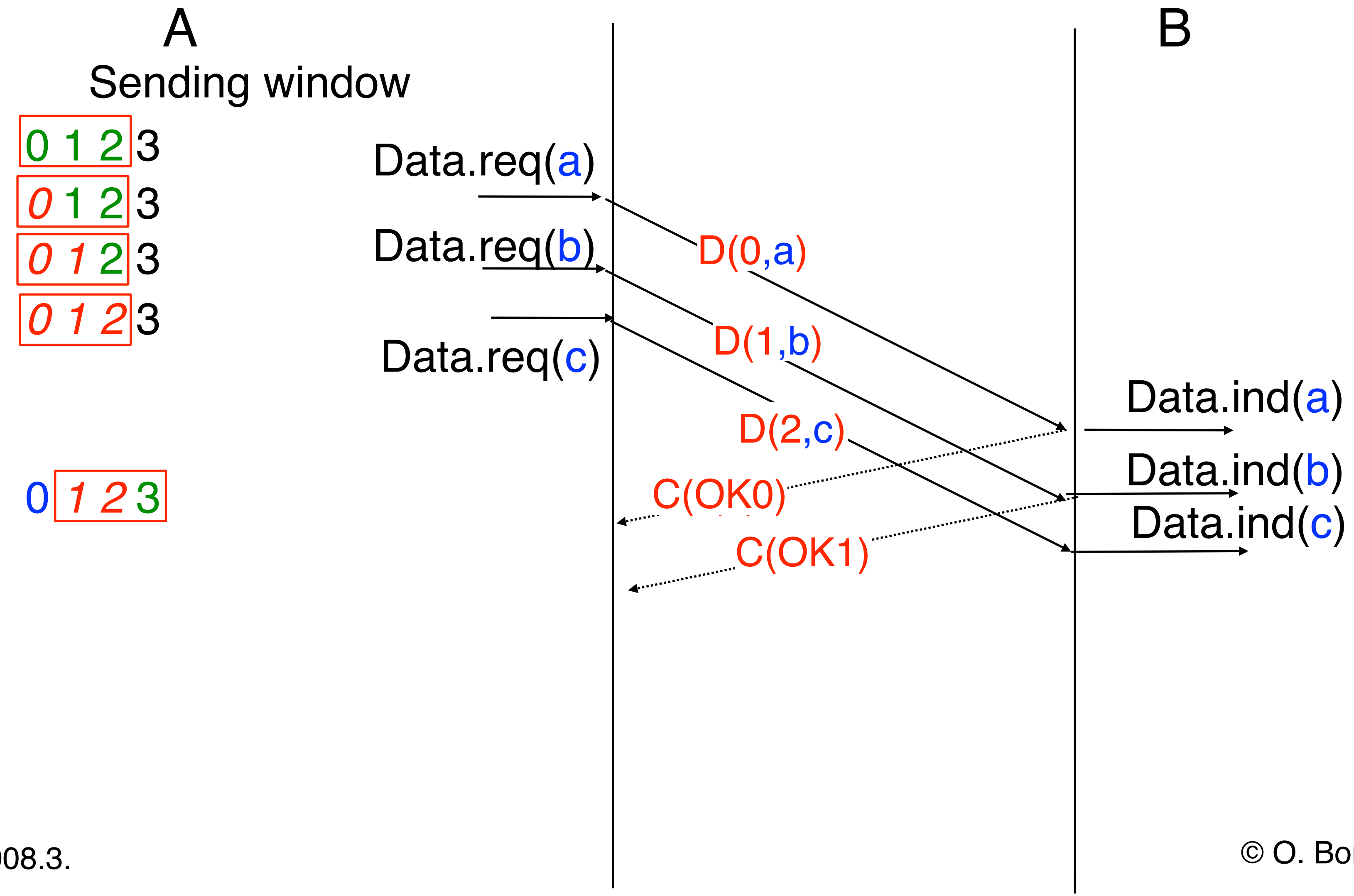

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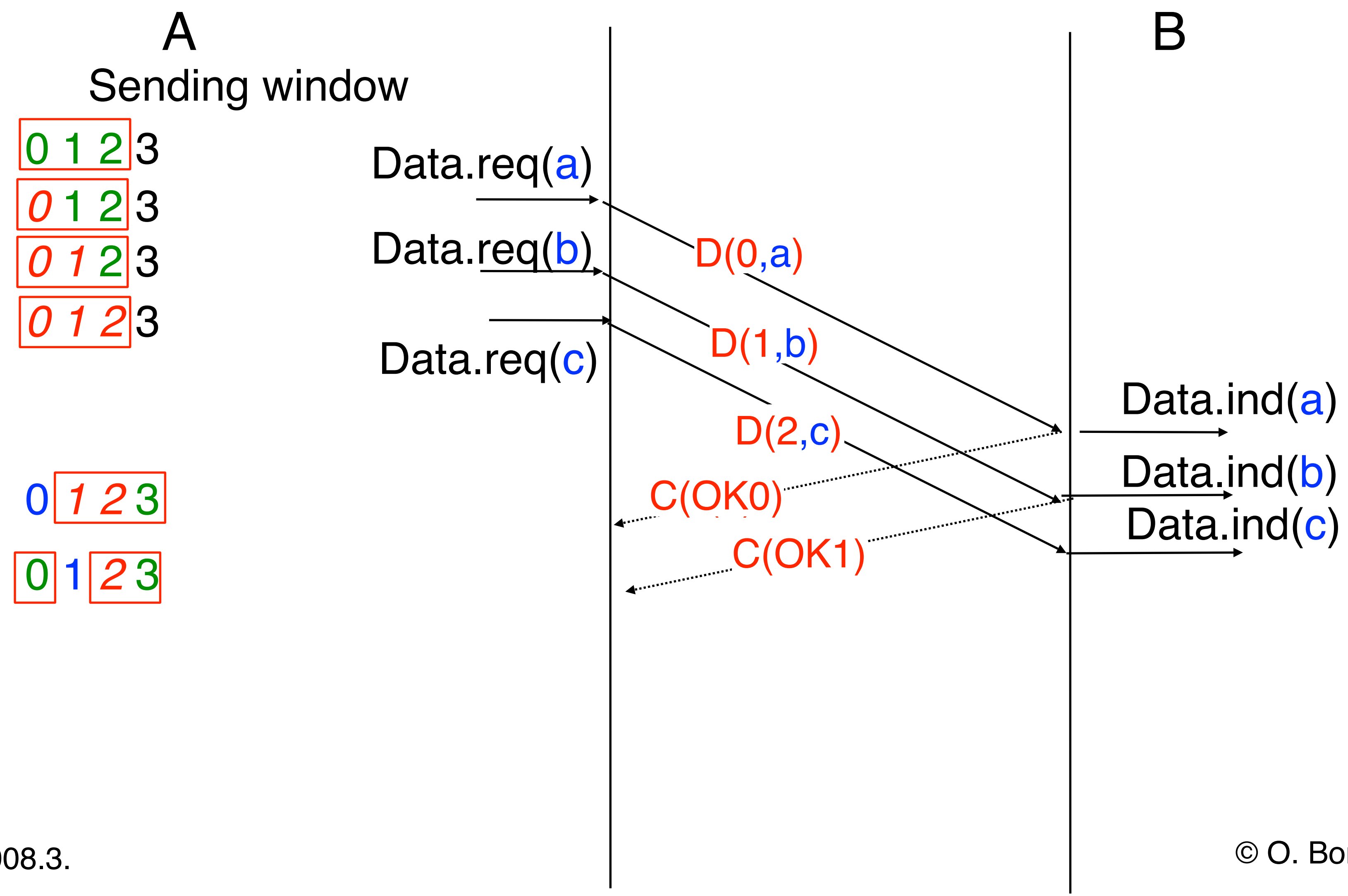

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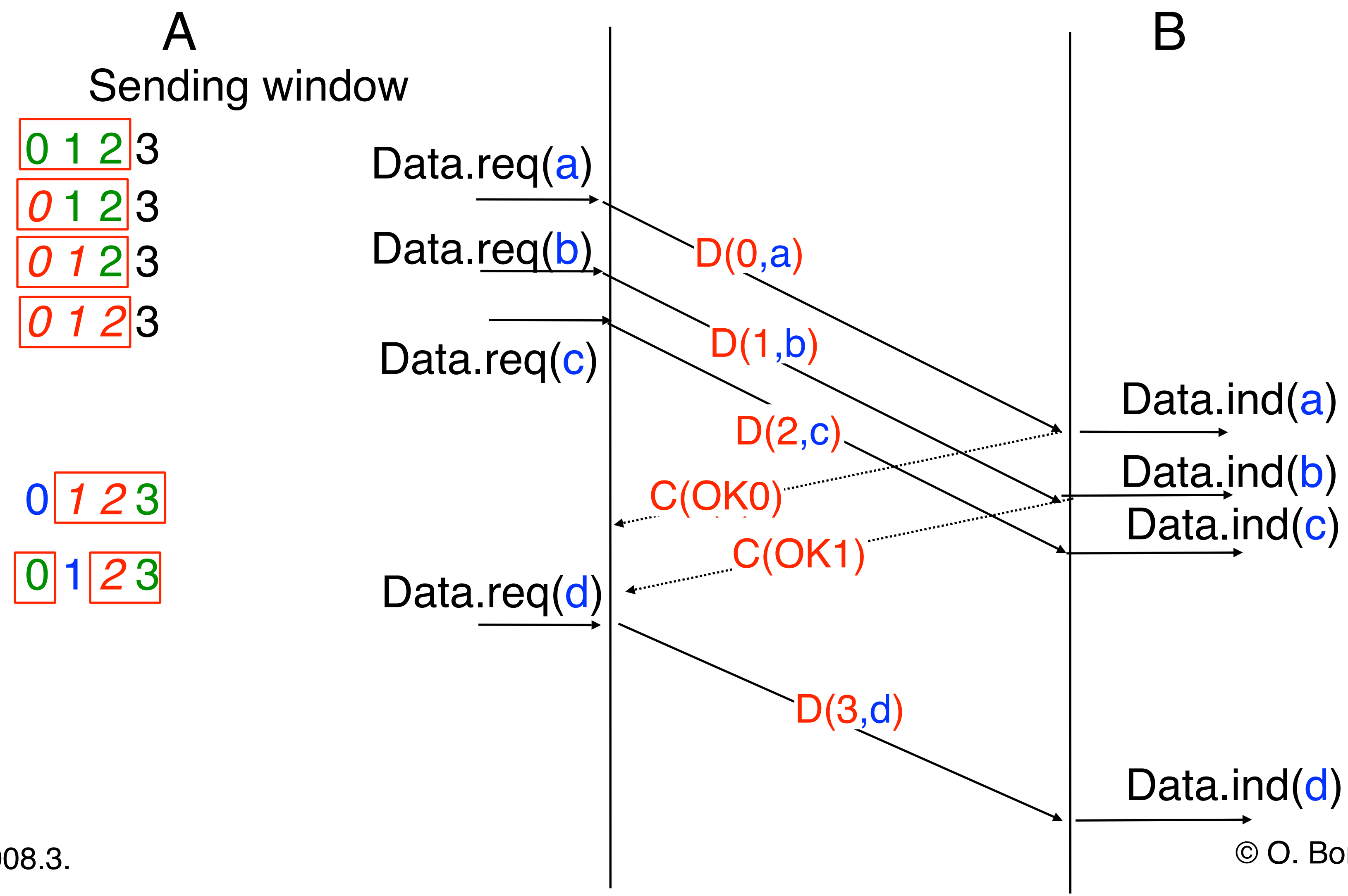

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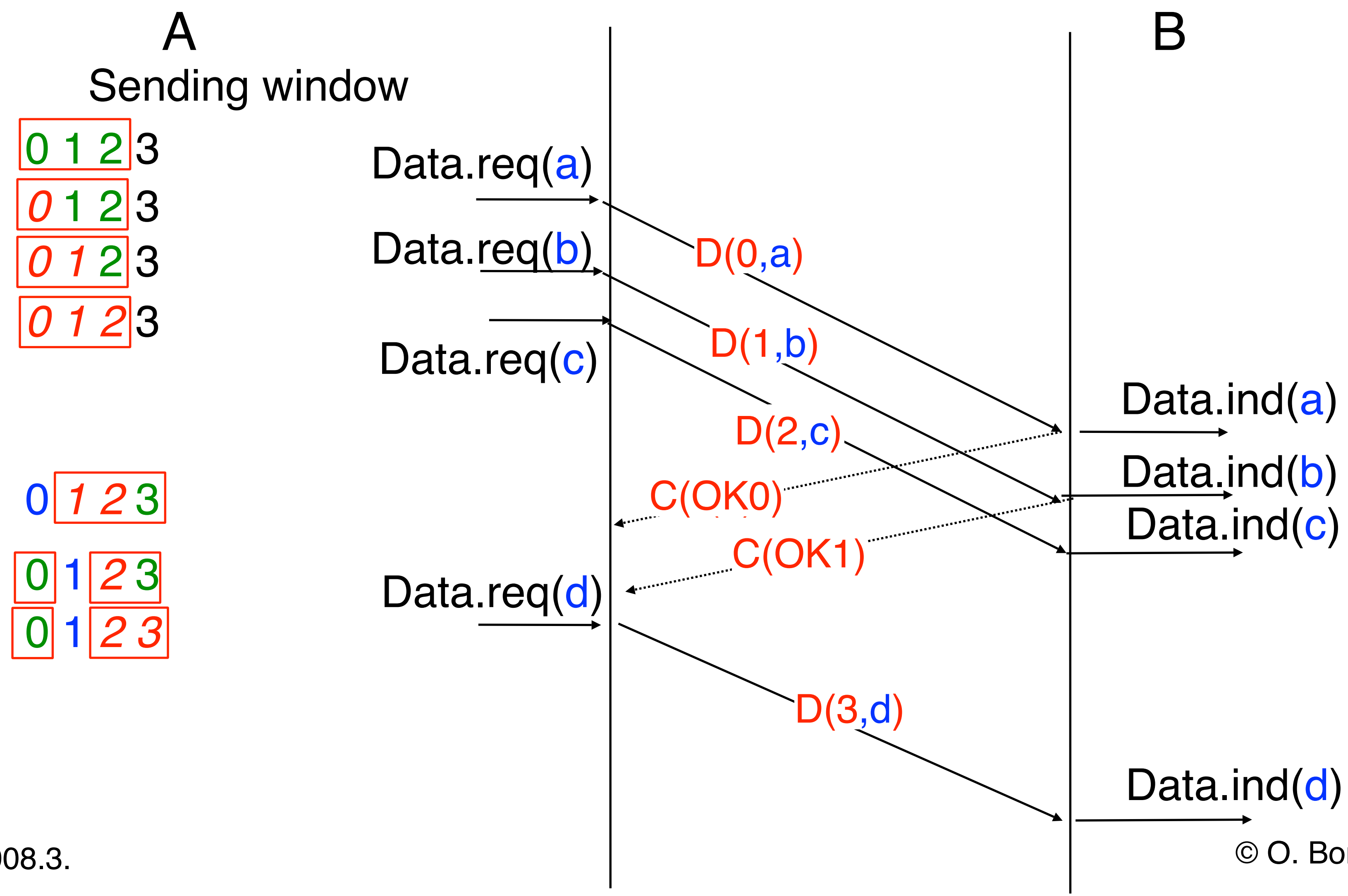

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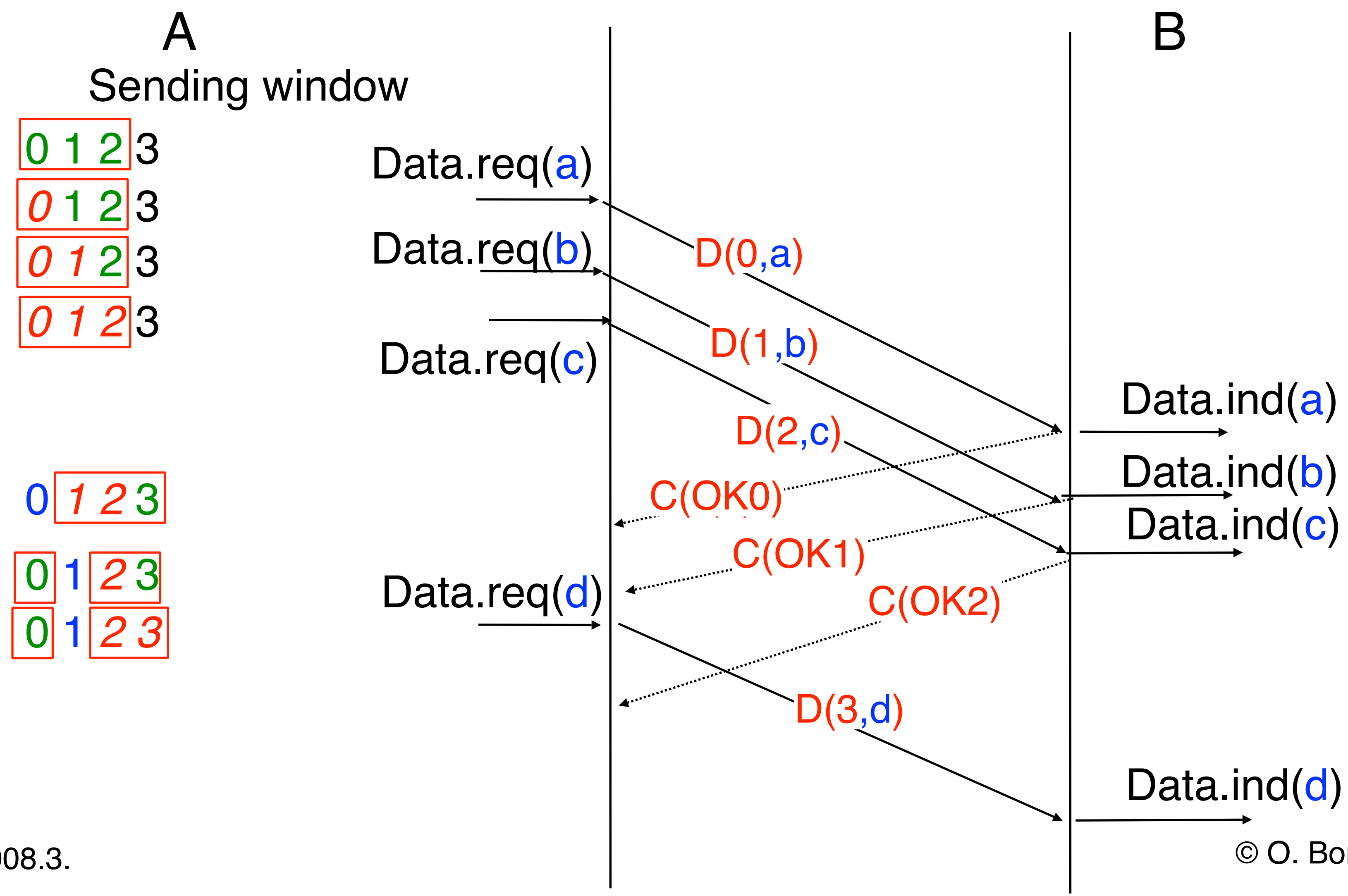

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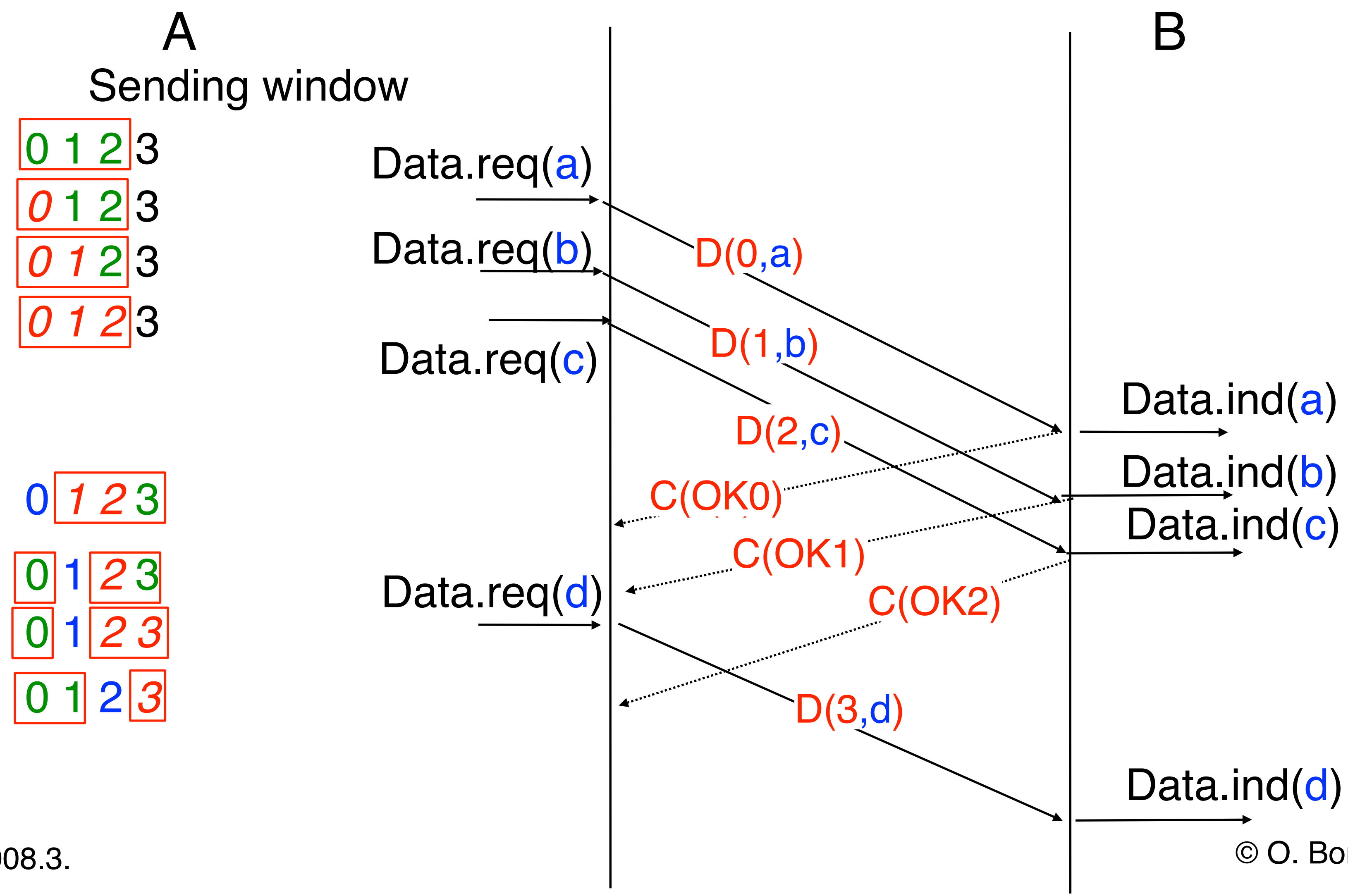

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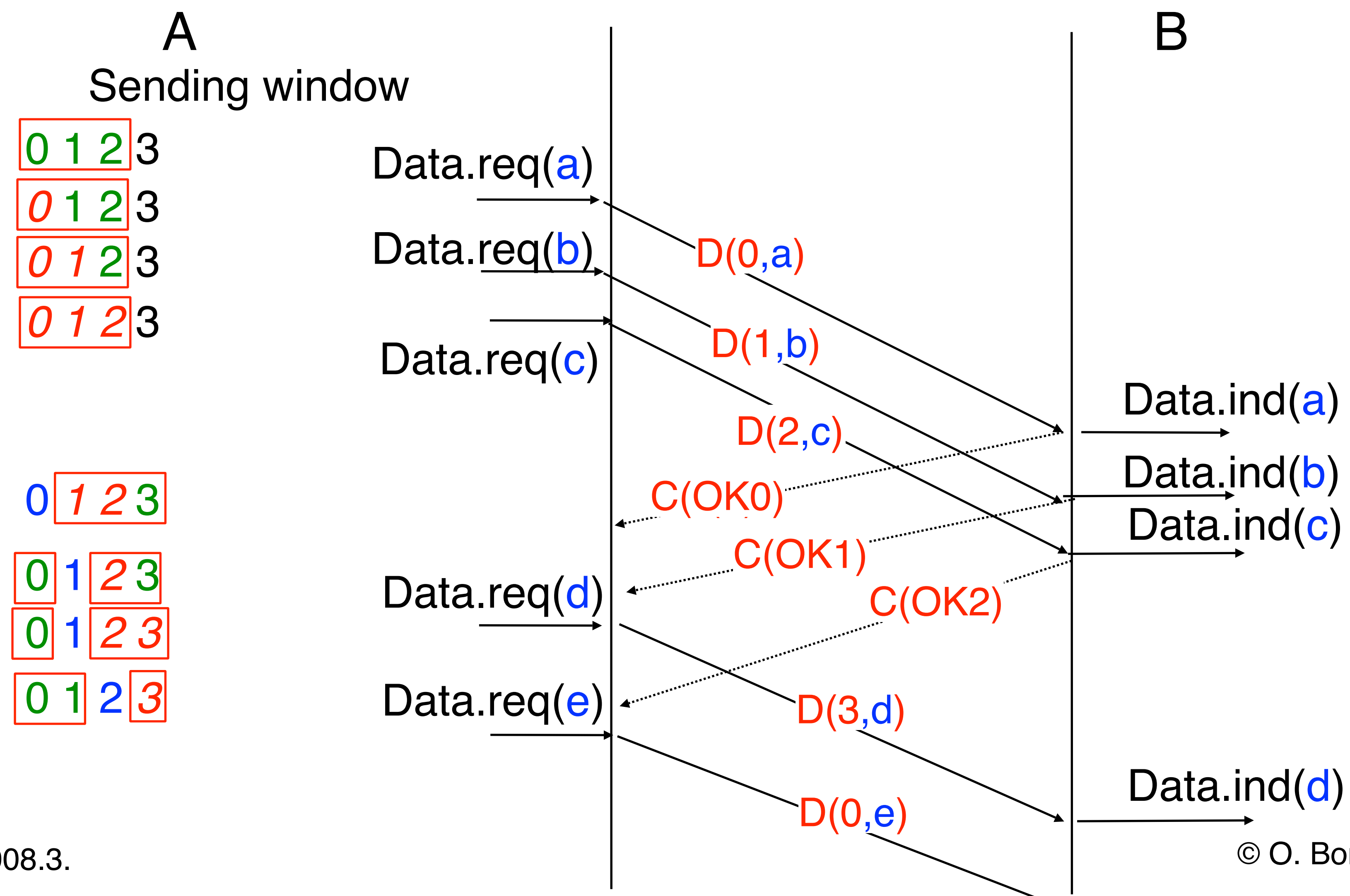

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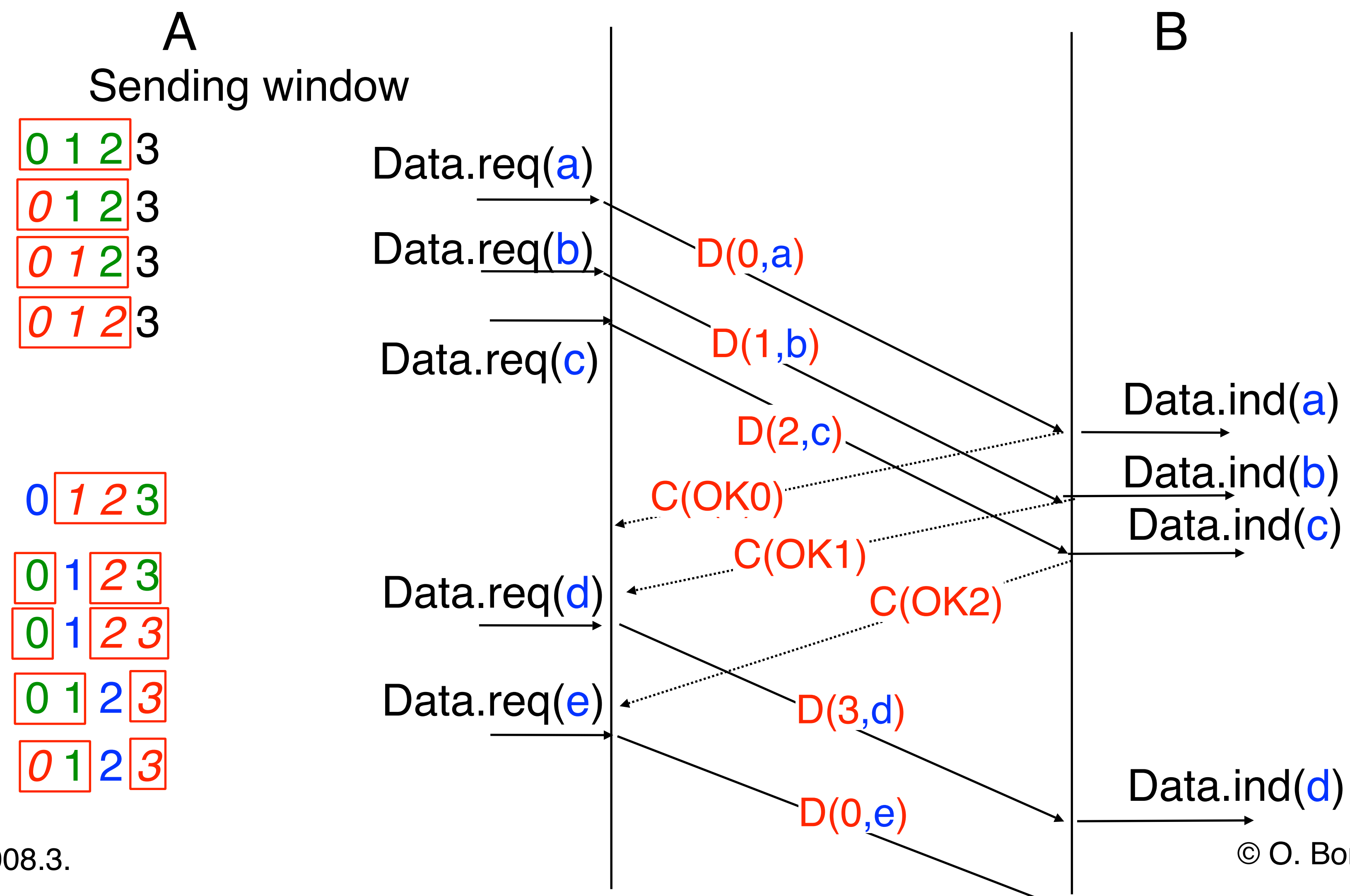


Reliable transfer with a sliding window

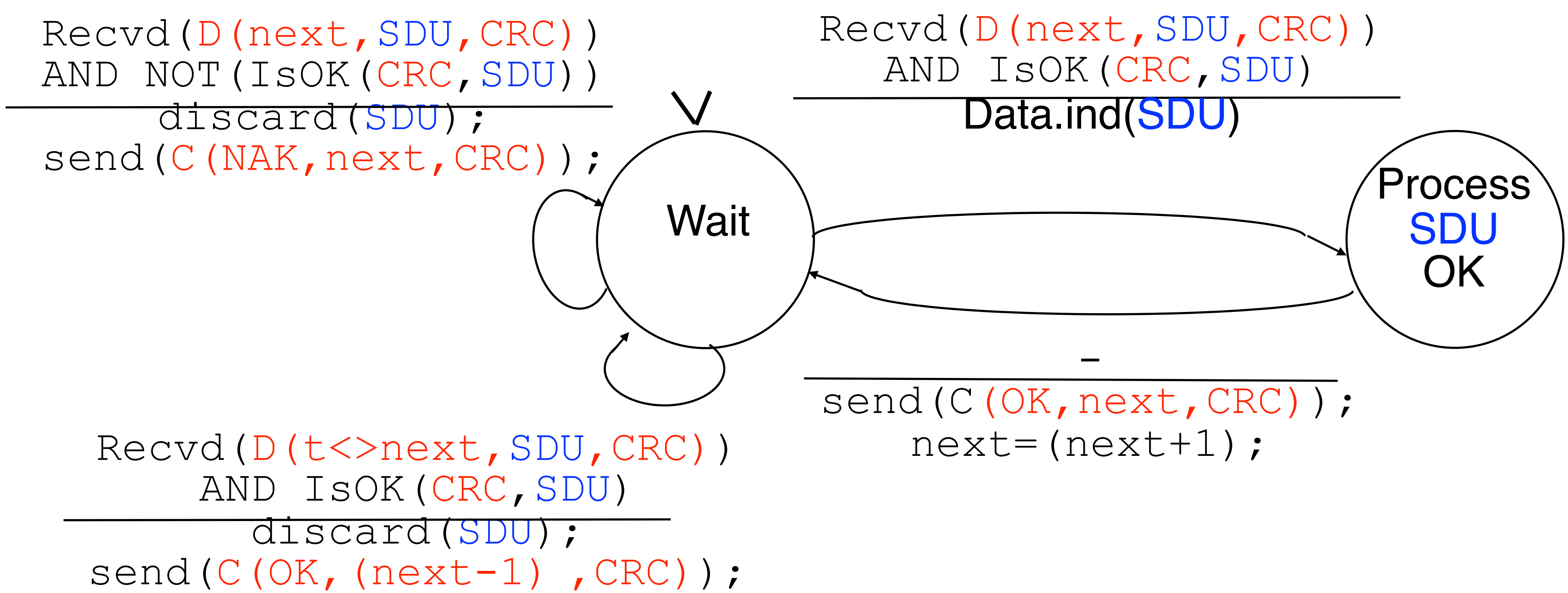
- How to provide a reliable data transfer with a sliding window
  - How to react upon reception of a control segment ?
  - Sender's and receiver's behaviours
- Basic solutions
  - Go-Back-N
    - simple implementation, in particular on receiving side
    - throughput will be limited when losses occur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

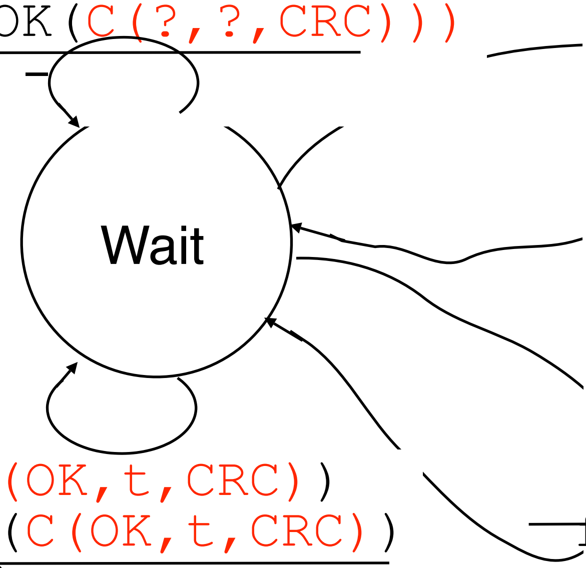
Go-Back-N : Receiver

- 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(); }
```

Go-Back-N : Example

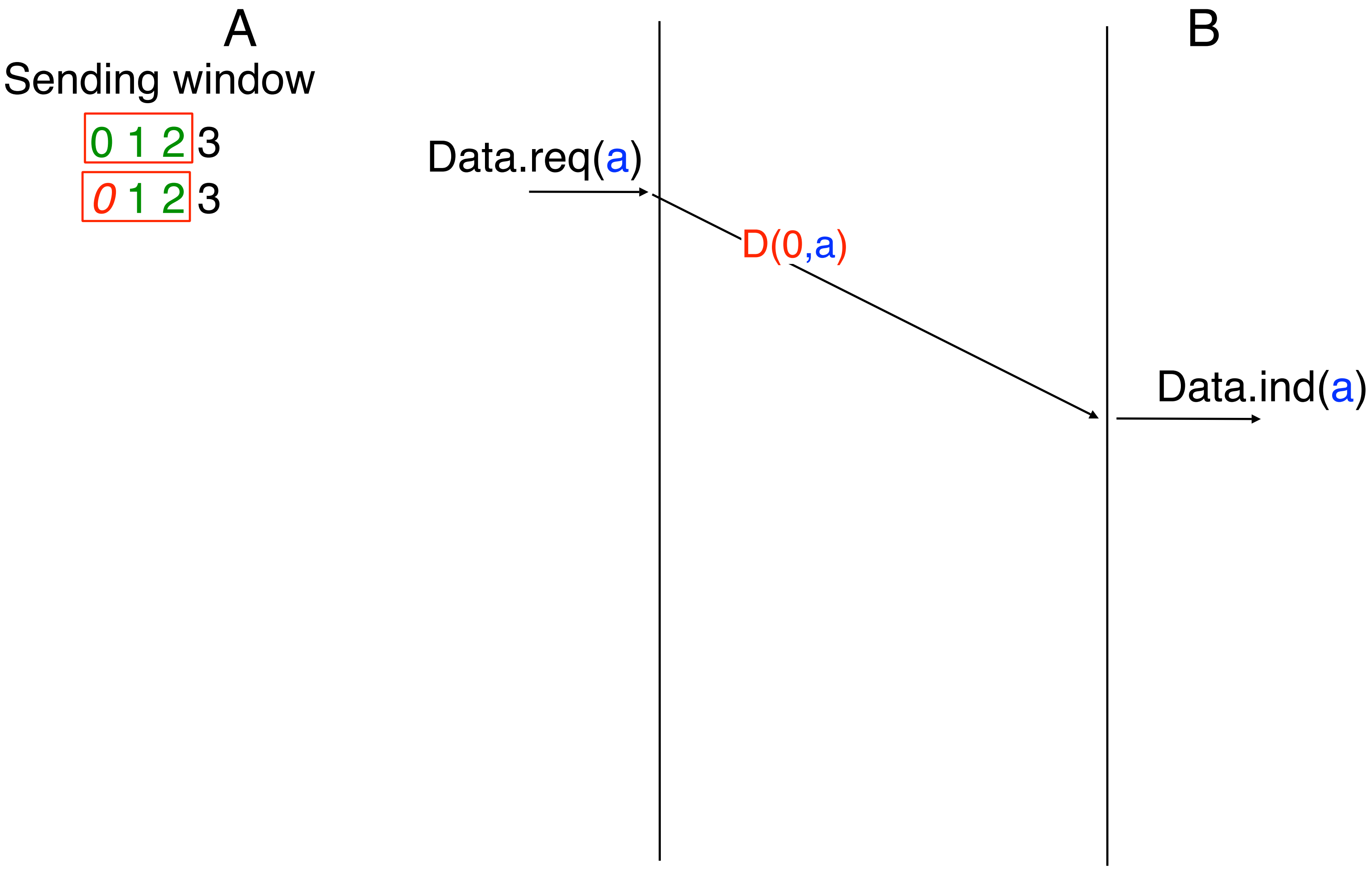
A

Sending window

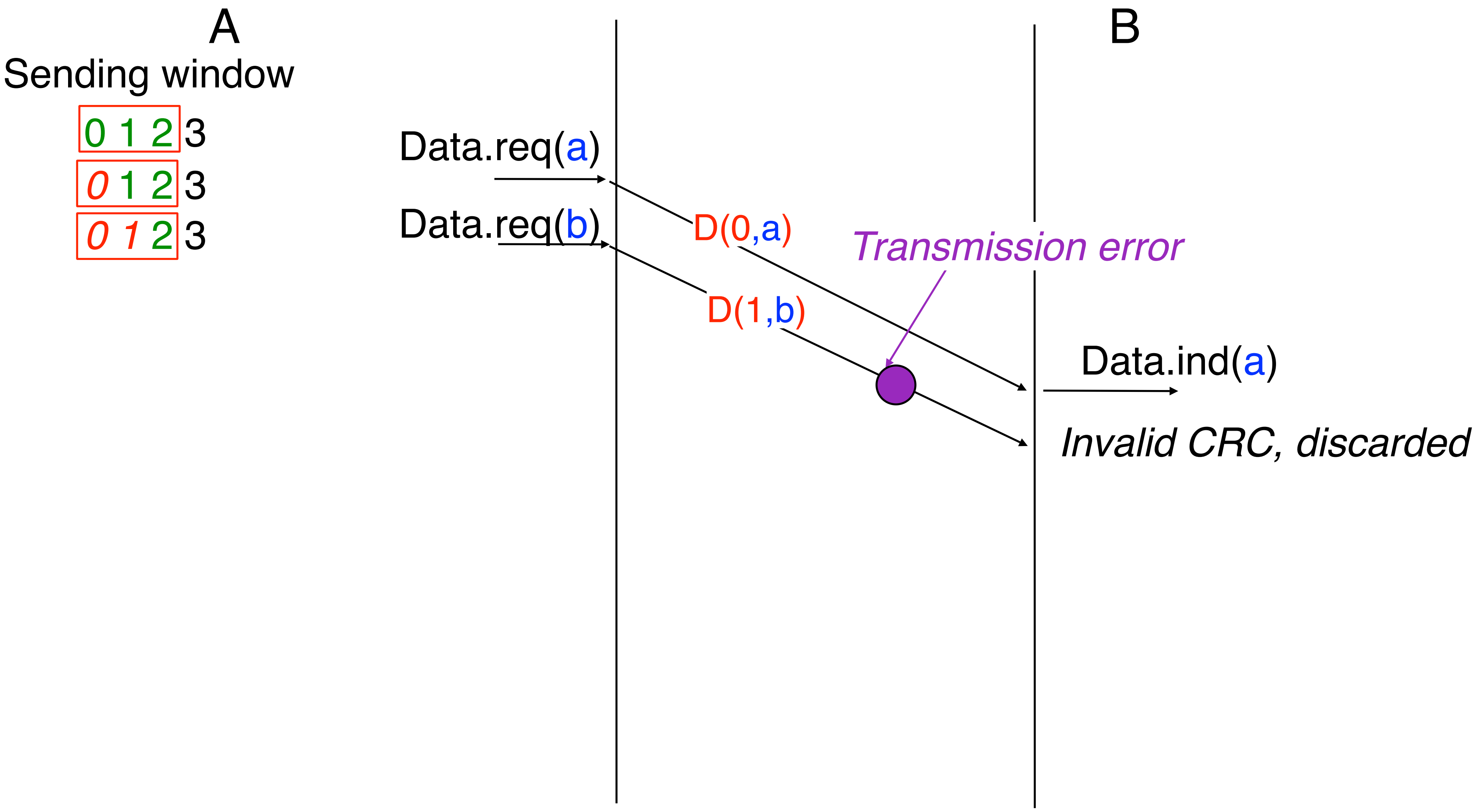
$\boxed{0\ 1\ 2}\ 3$

B

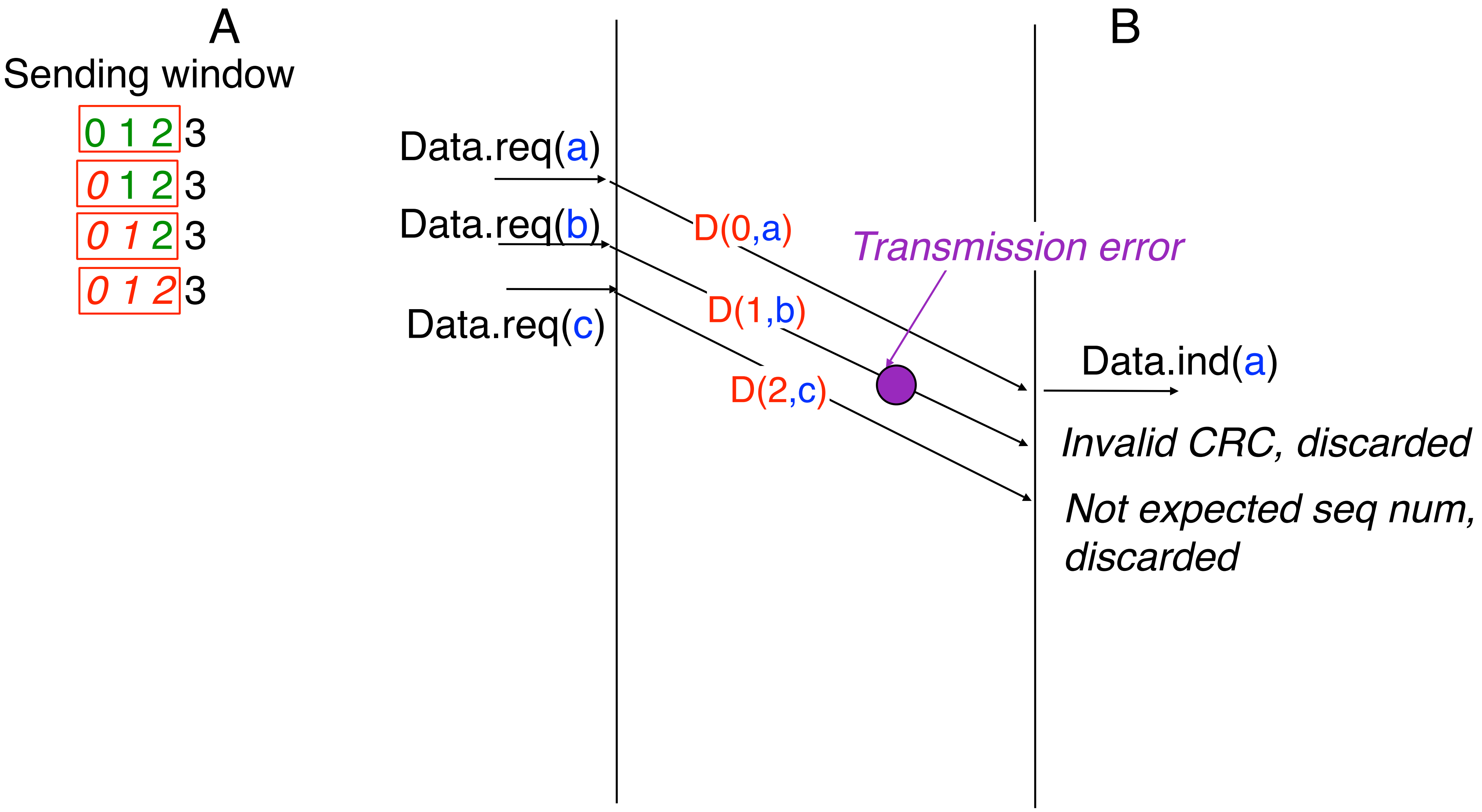
Go-Back-N : Example



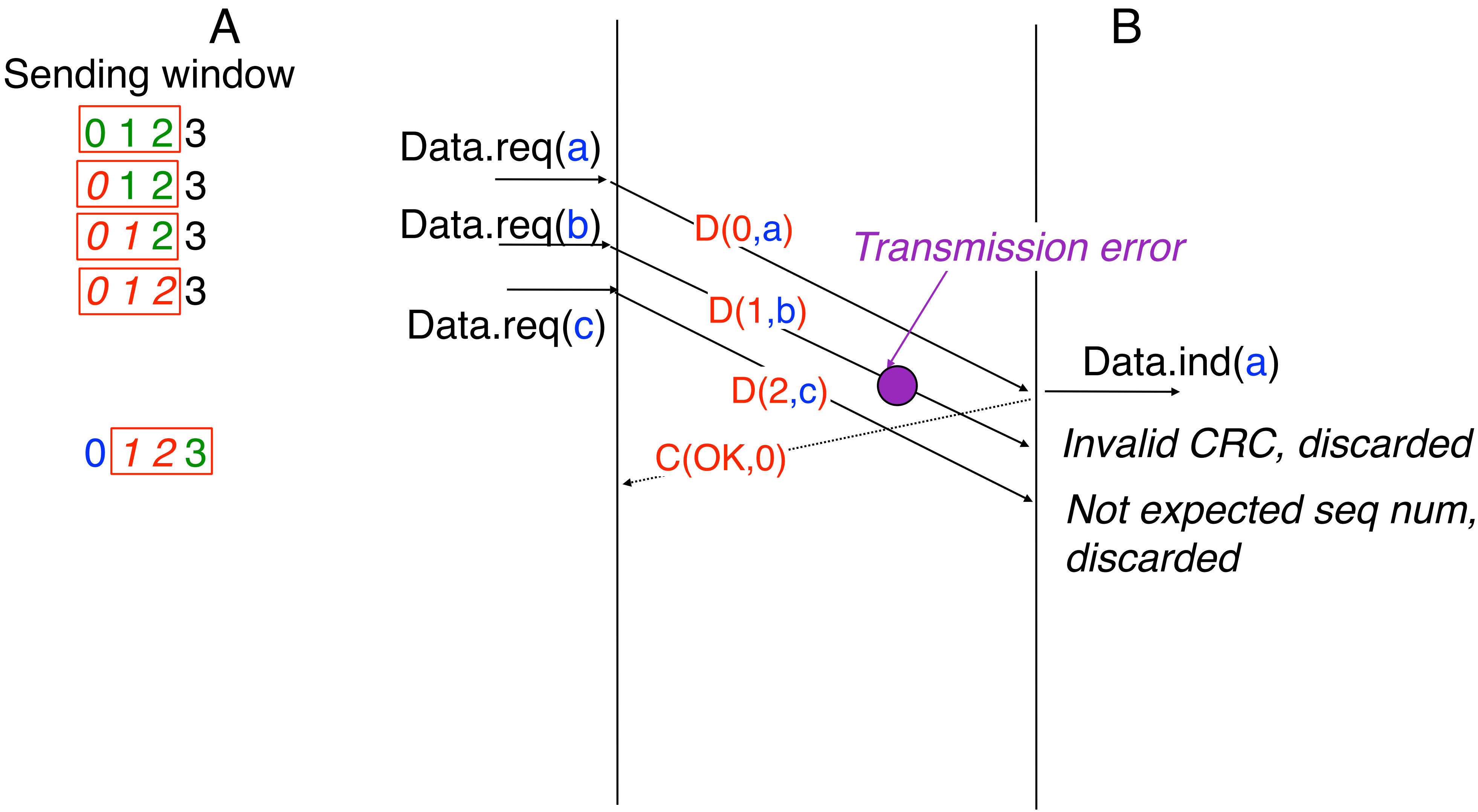
Go-Back-N : Example



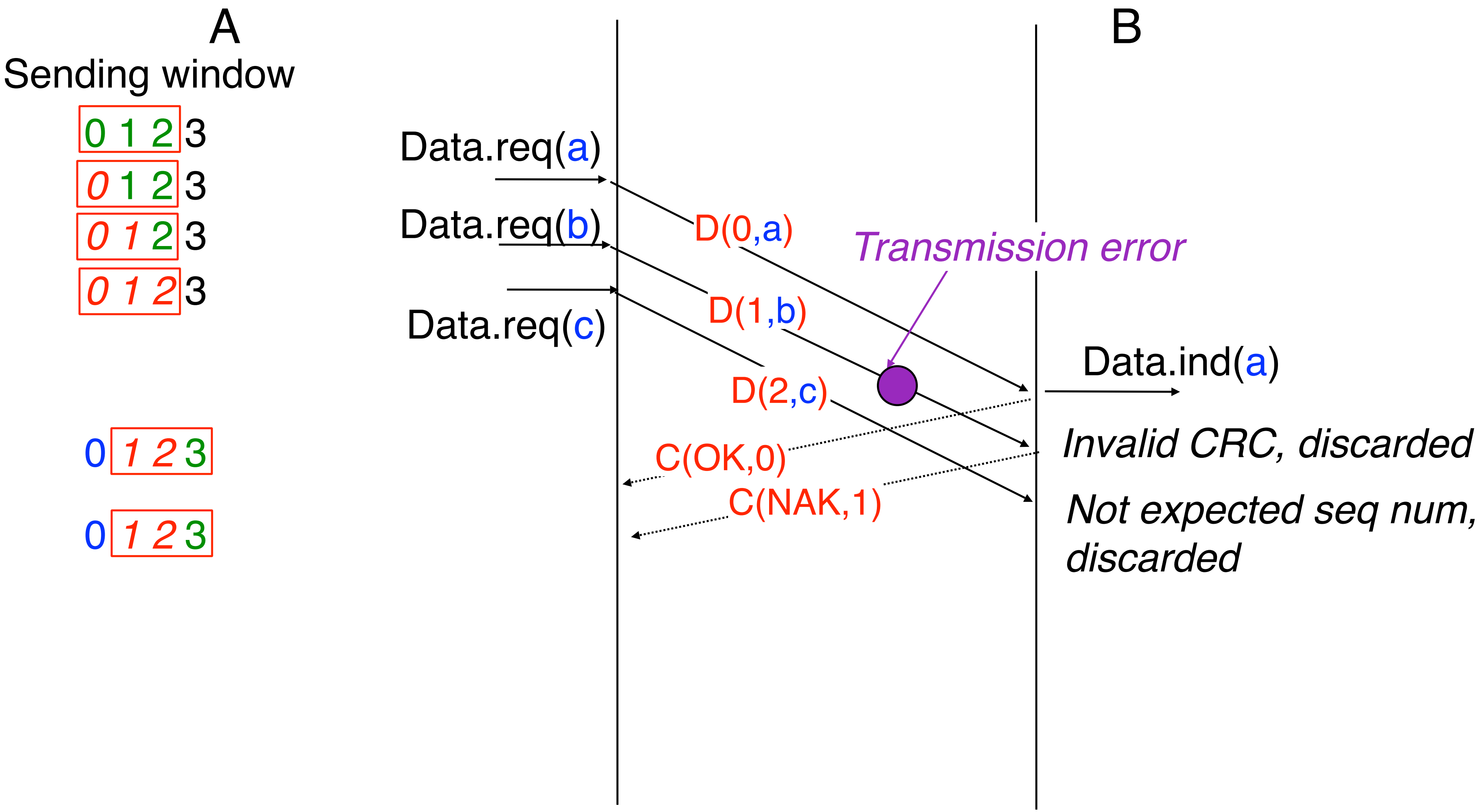
Go-Back-N : Example



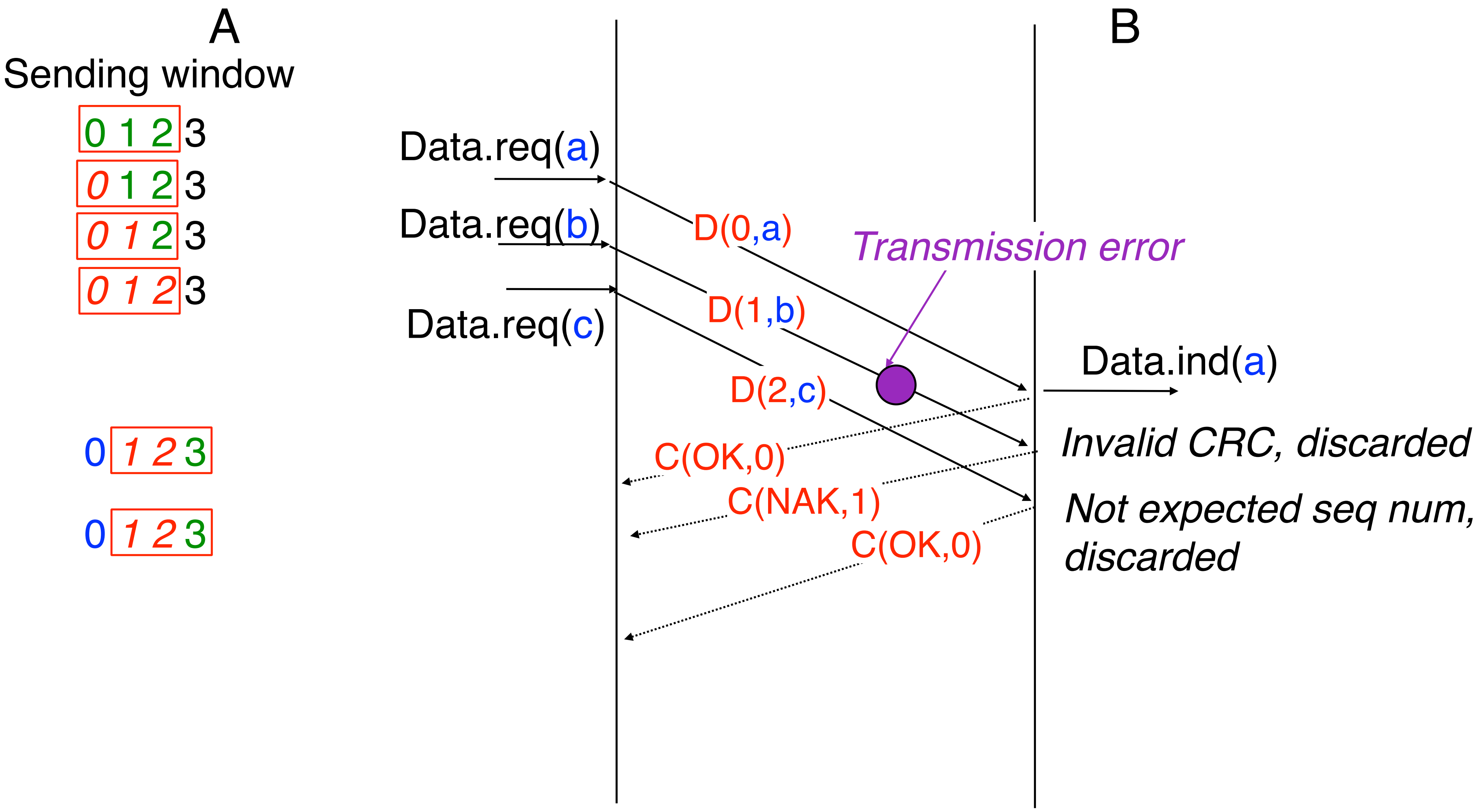
Go-Back-N : Example



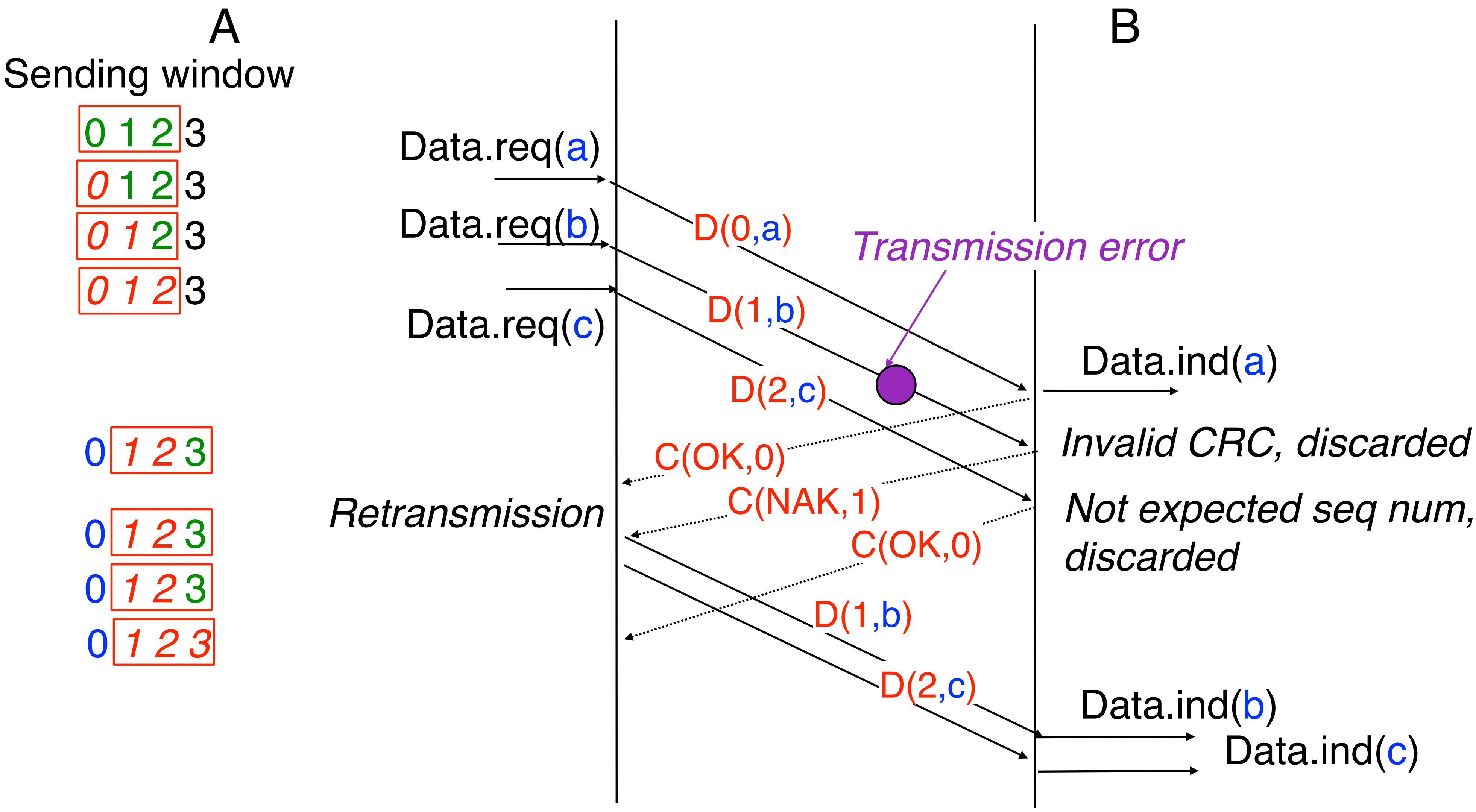
Go-Back-N : Example



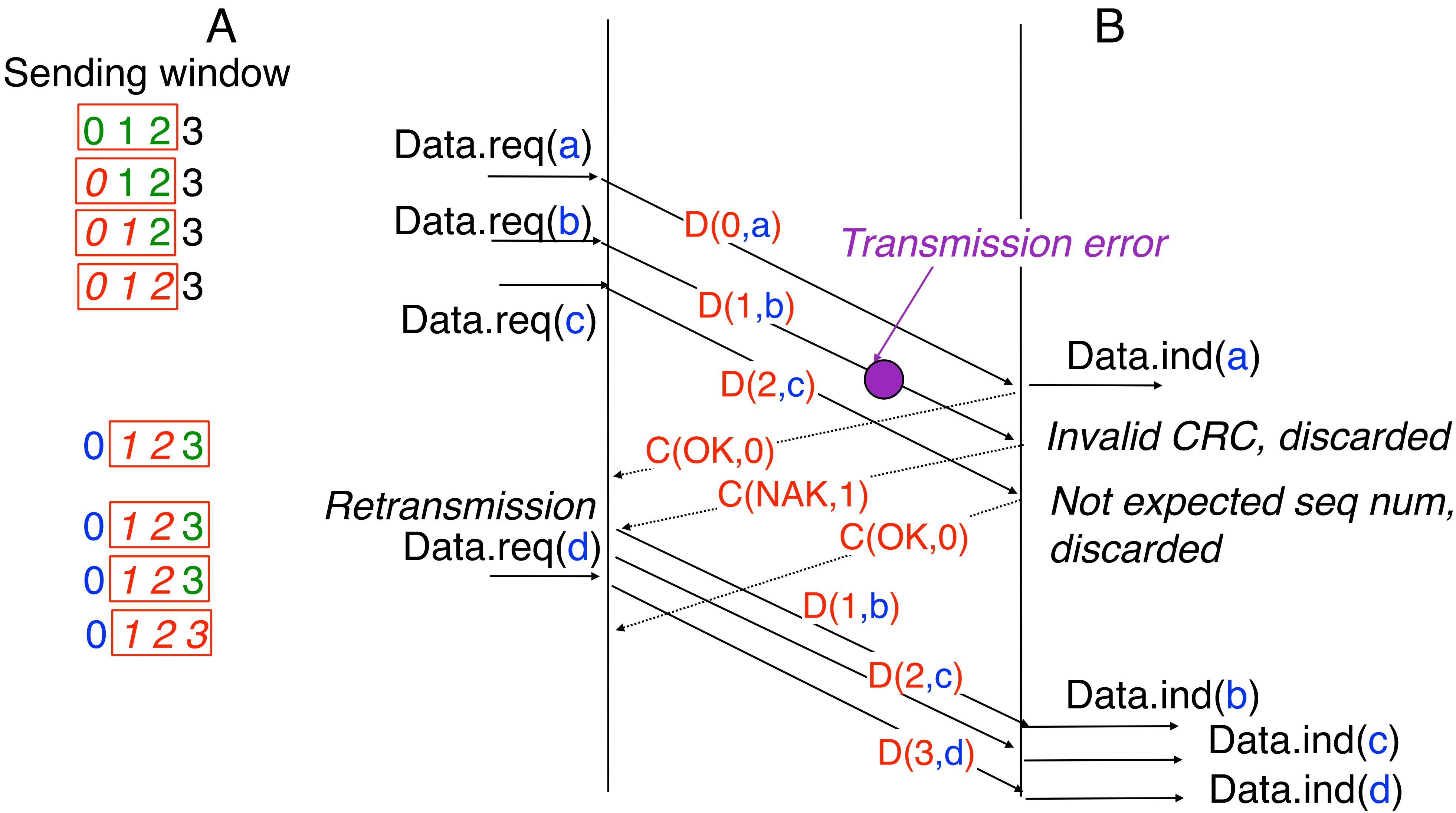
Go-Back-N : Example



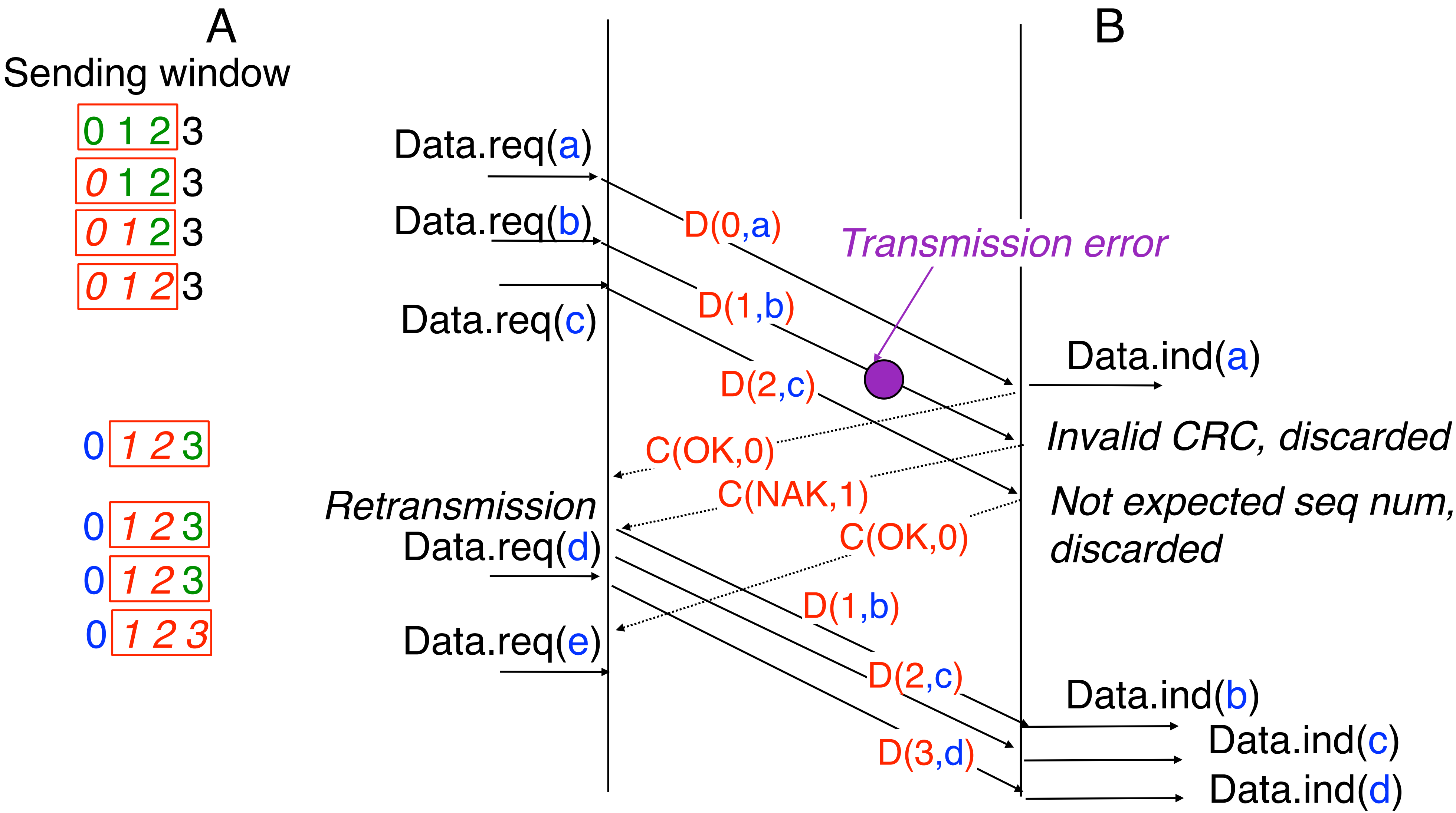
Go-Back-N : Example



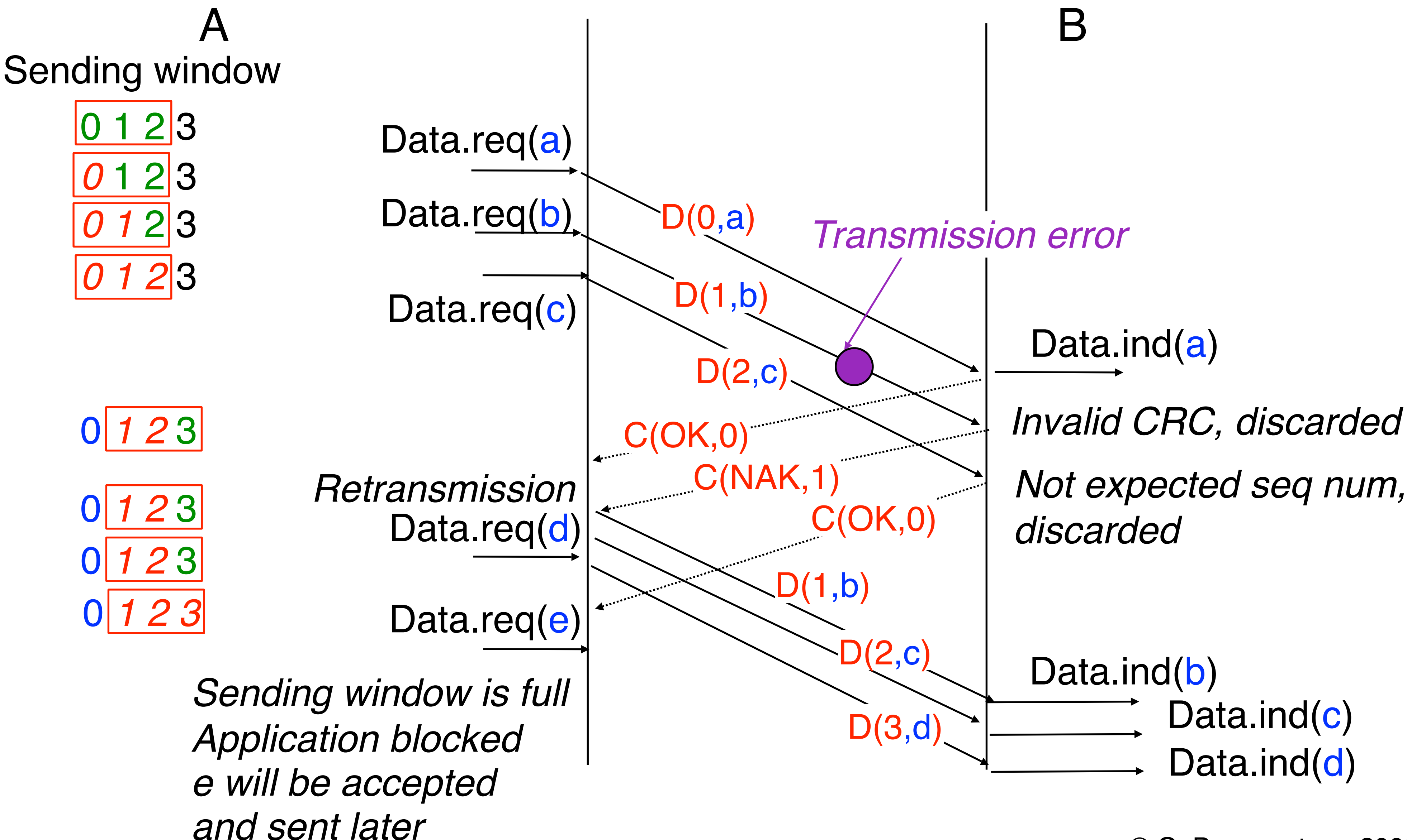
Go-Back-N : Example



Go-Back-N : Example



Go-Back-N : Example



Go-Back-N : Example (2)

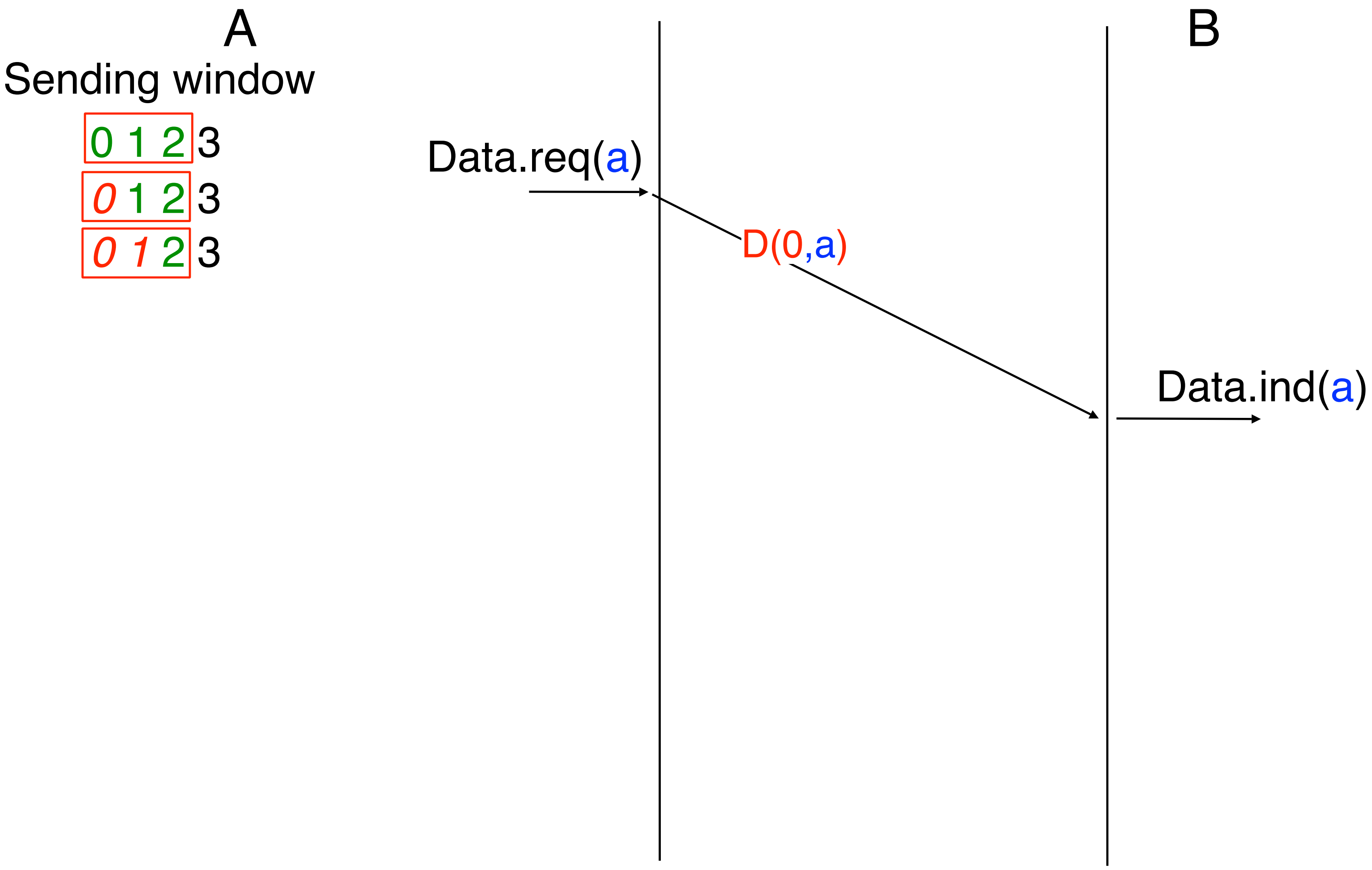
A

Sending window

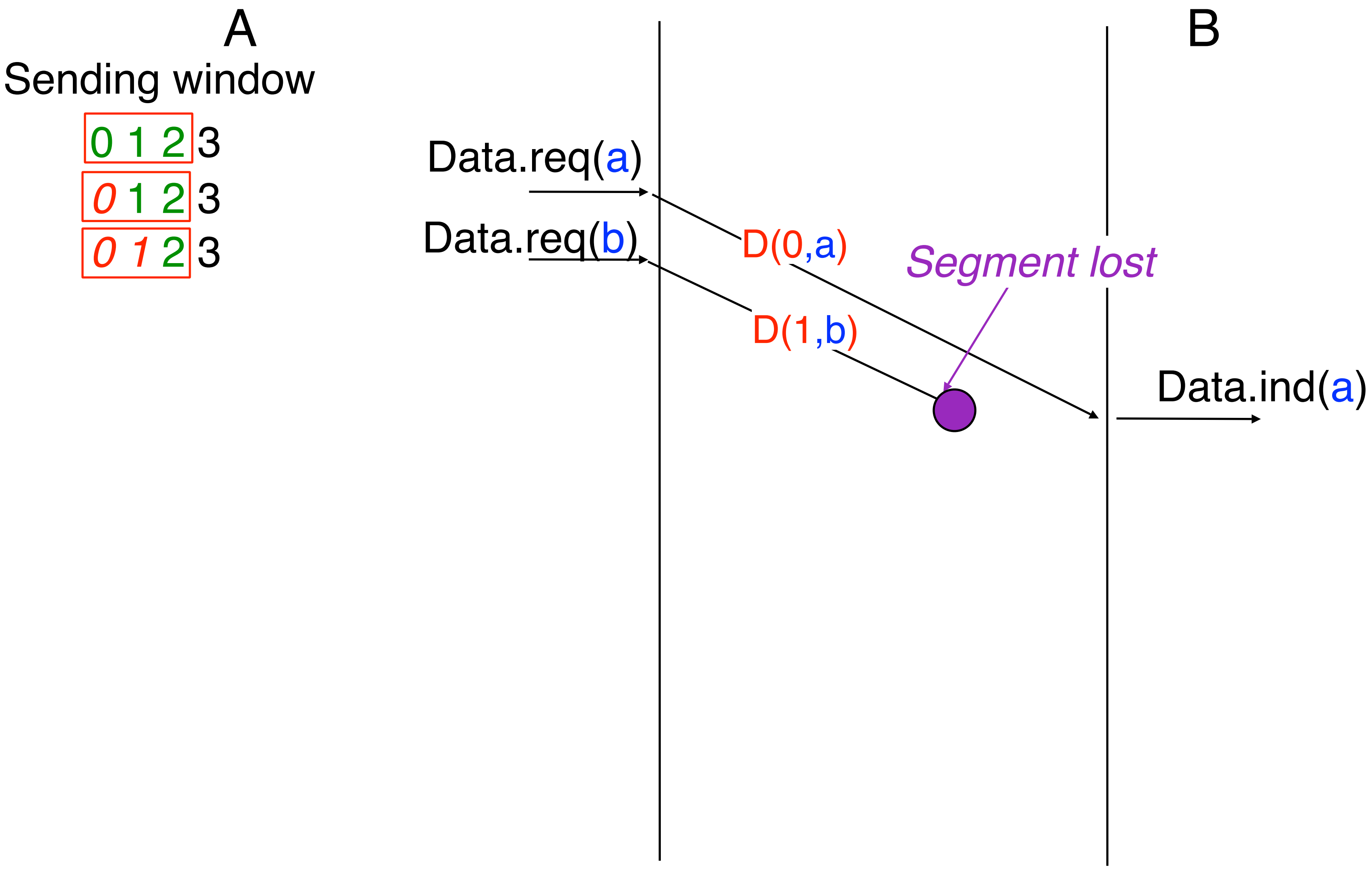
$\boxed{0\ 1\ 2}\ 3$

B

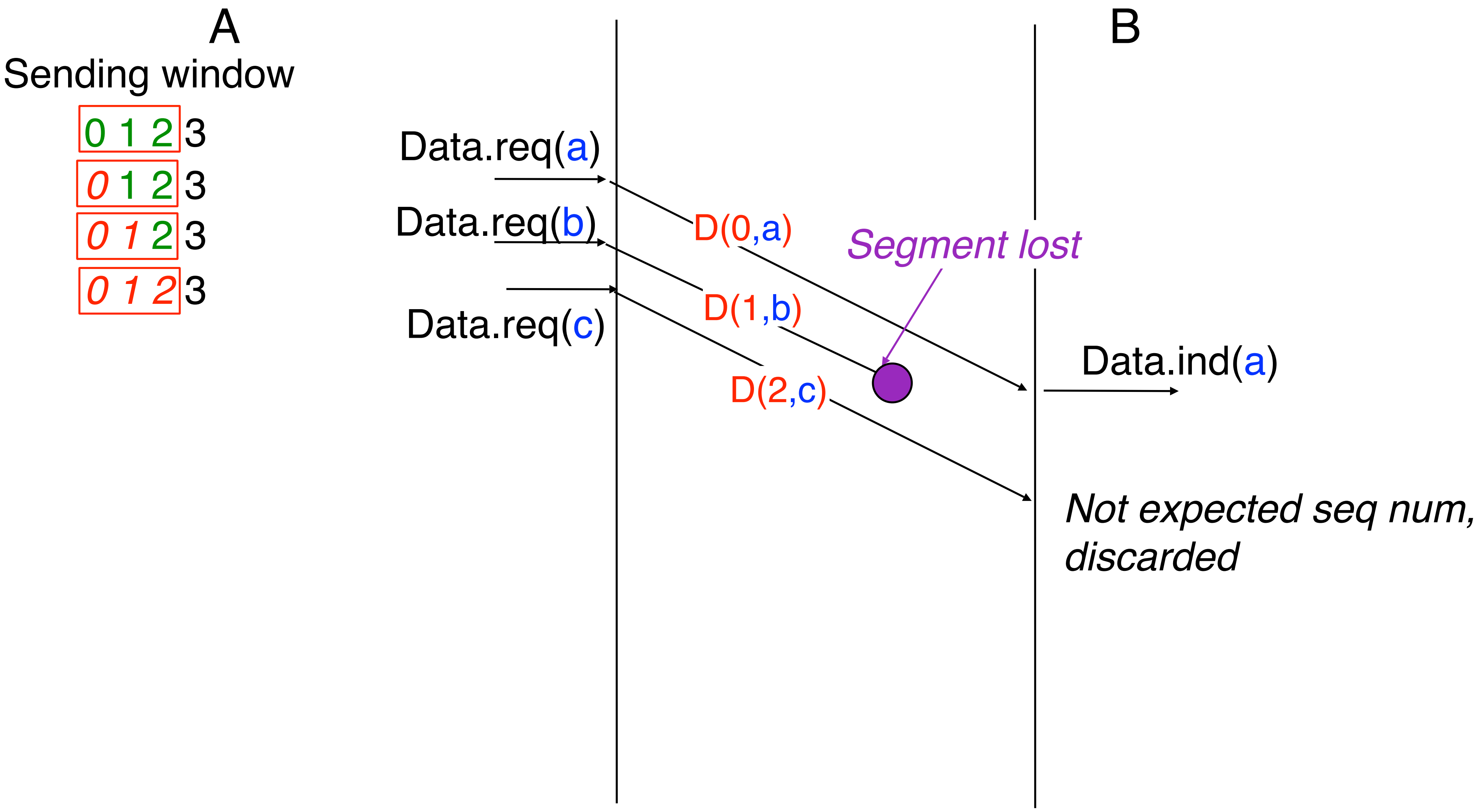
Go-Back-N : Example (2)



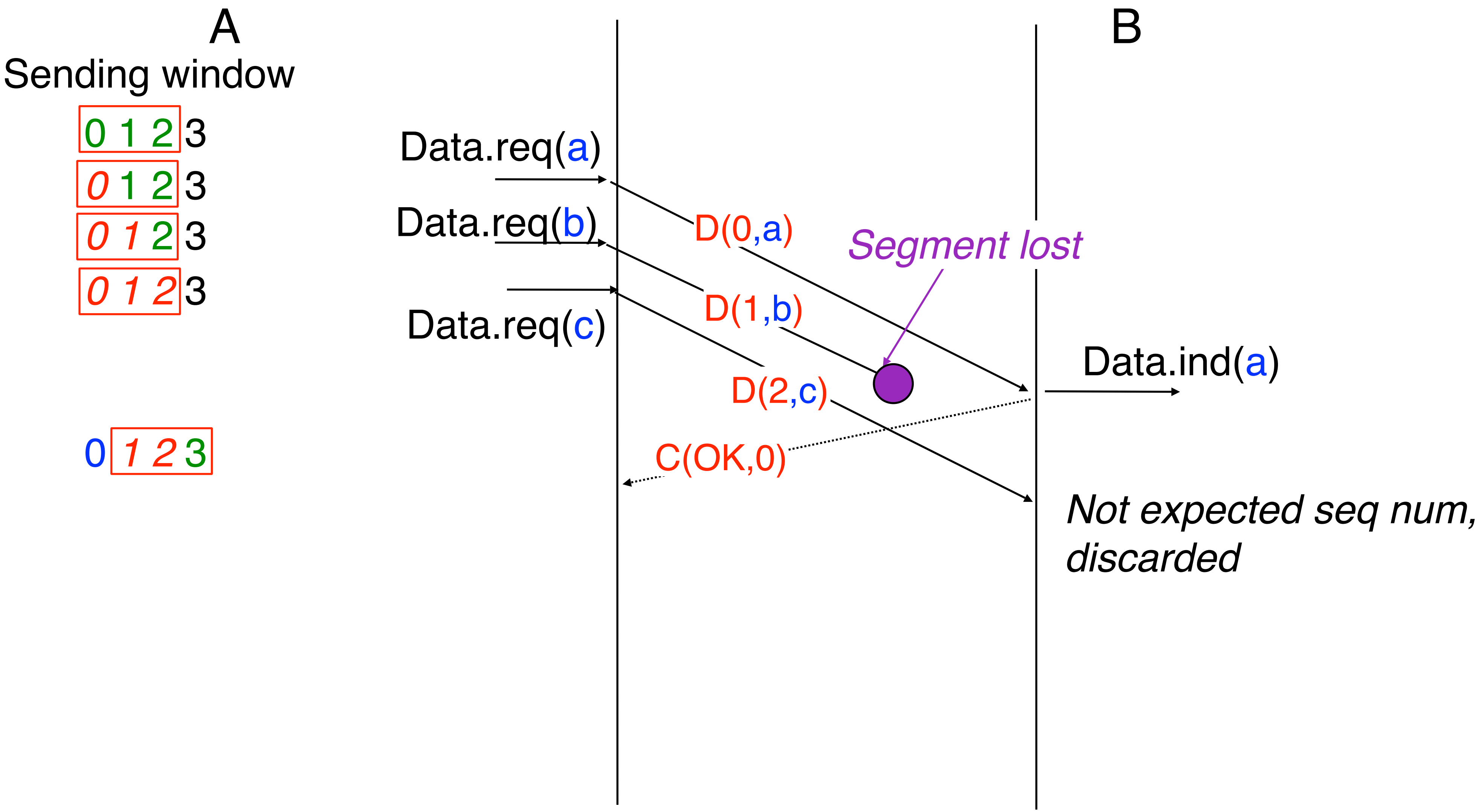
Go-Back-N : Example (2)



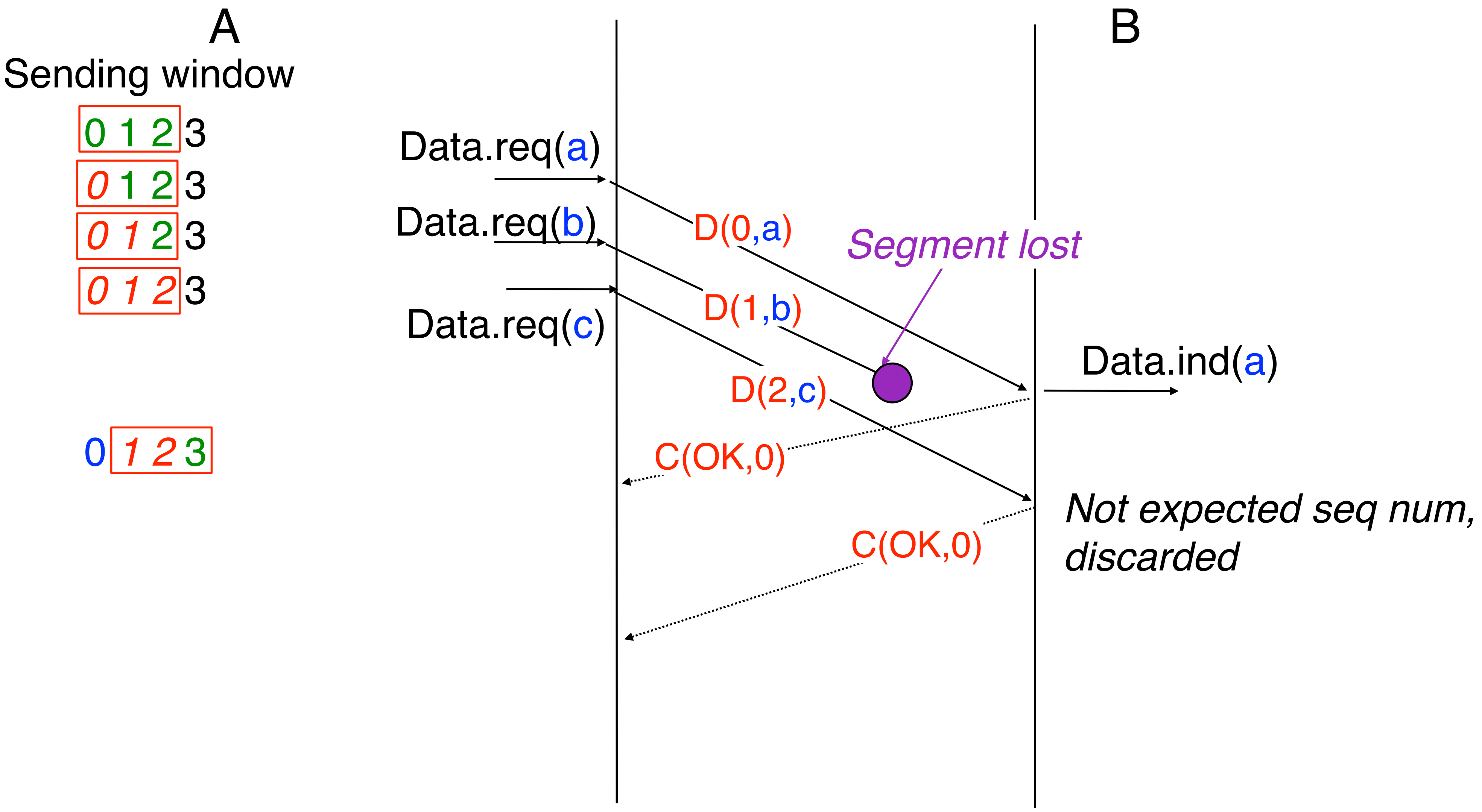
Go-Back-N : Example (2)



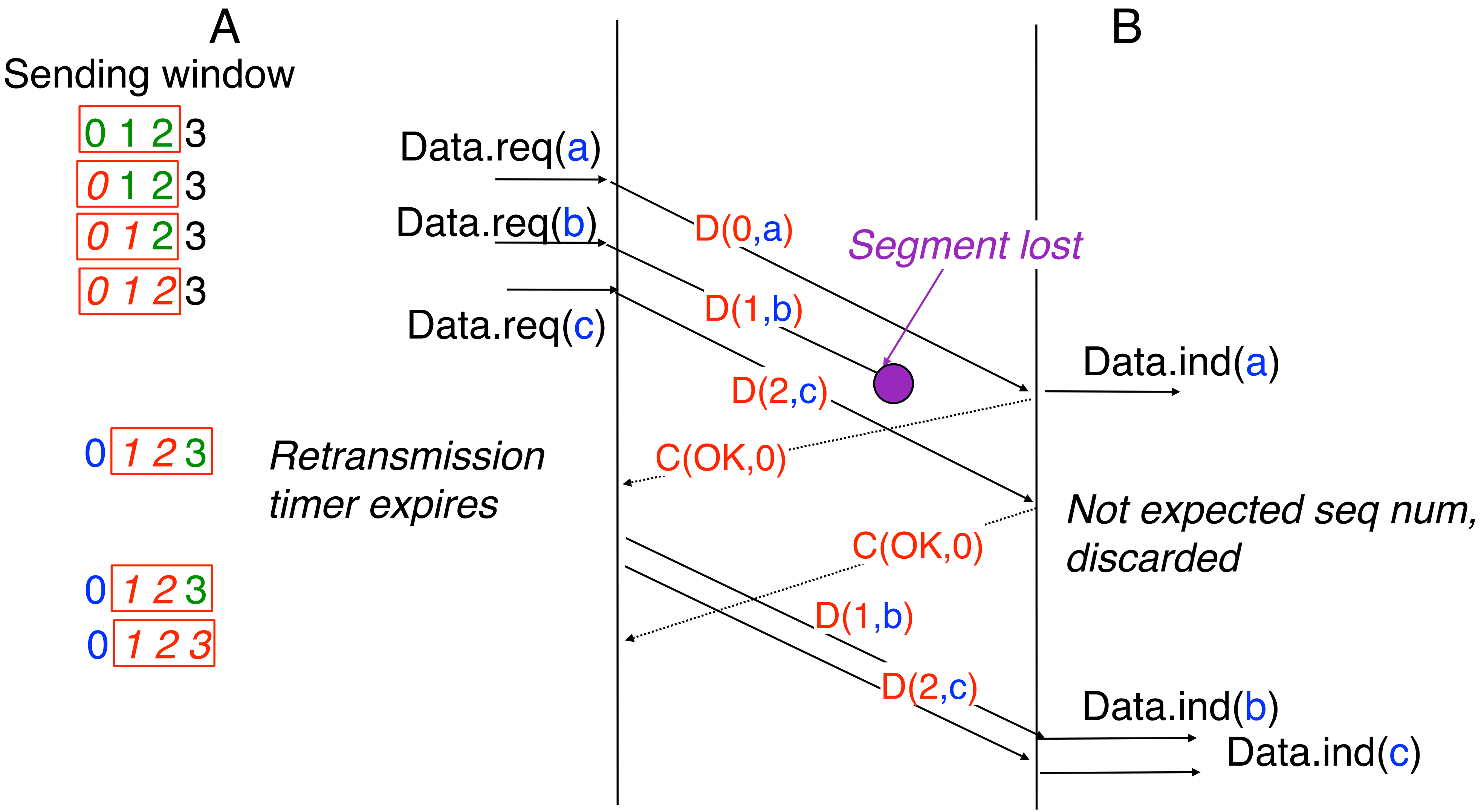
Go-Back-N : Example (2)



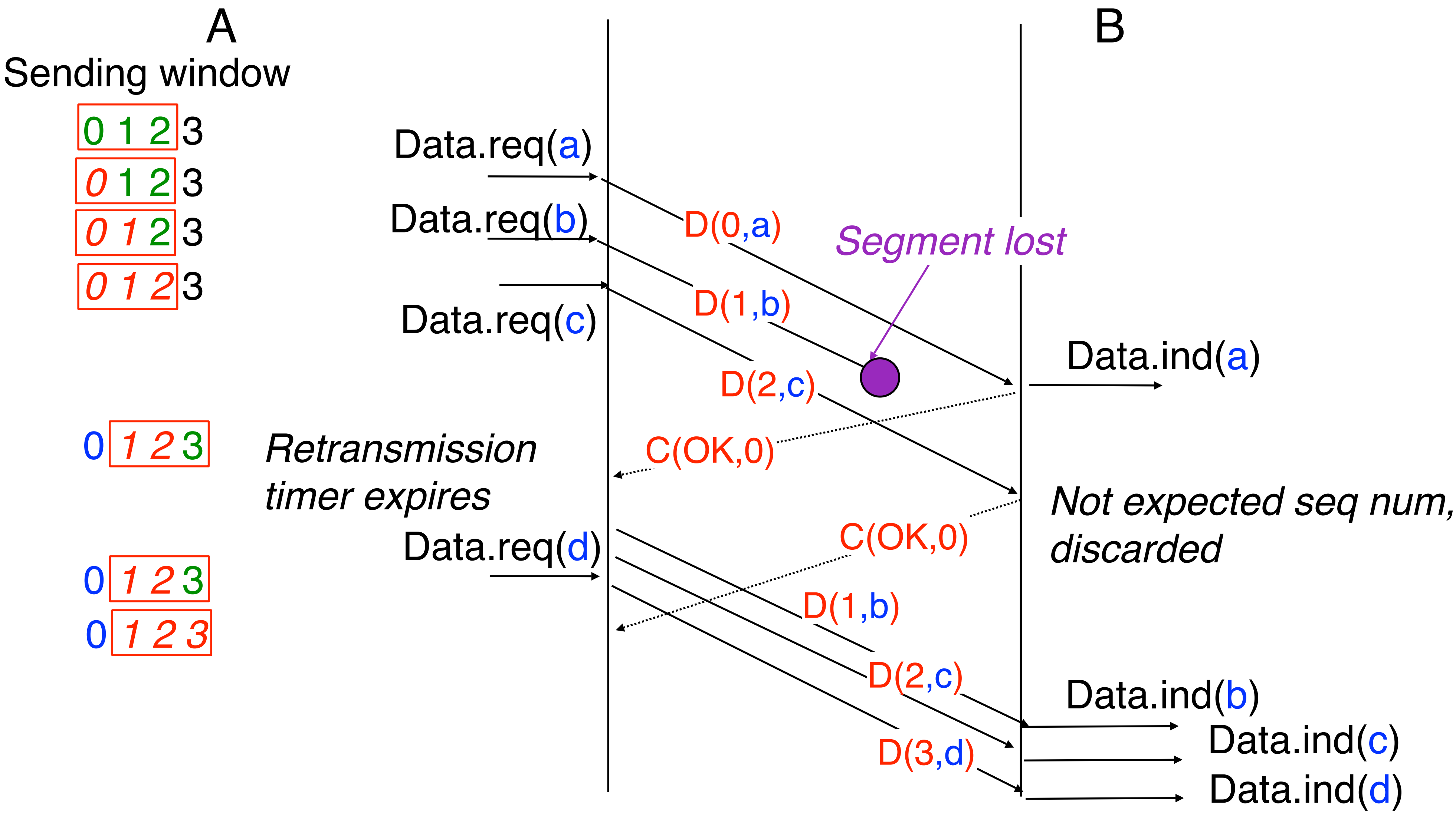
Go-Back-N : Example (2)



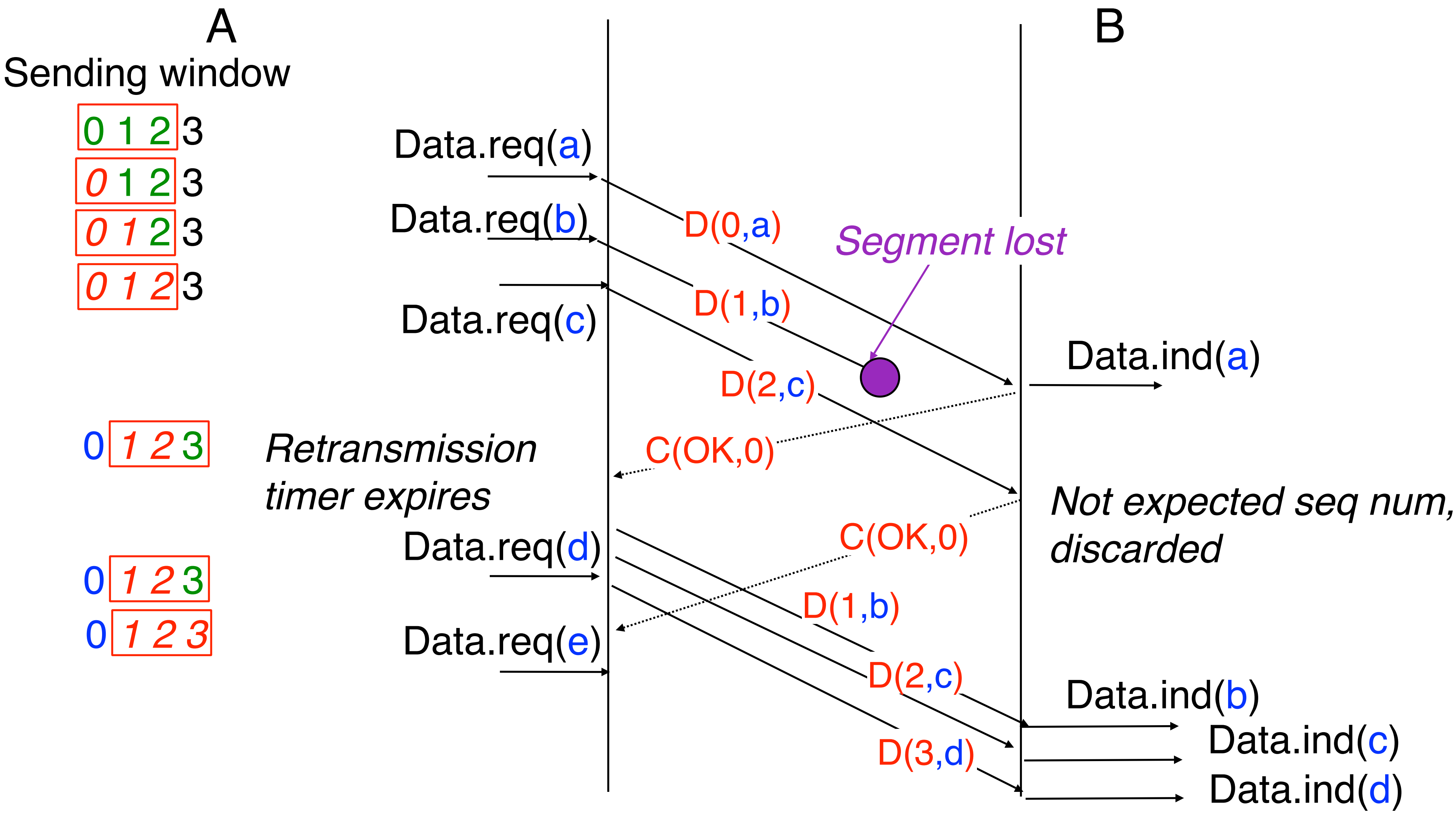
Go-Back-N : Example (2)



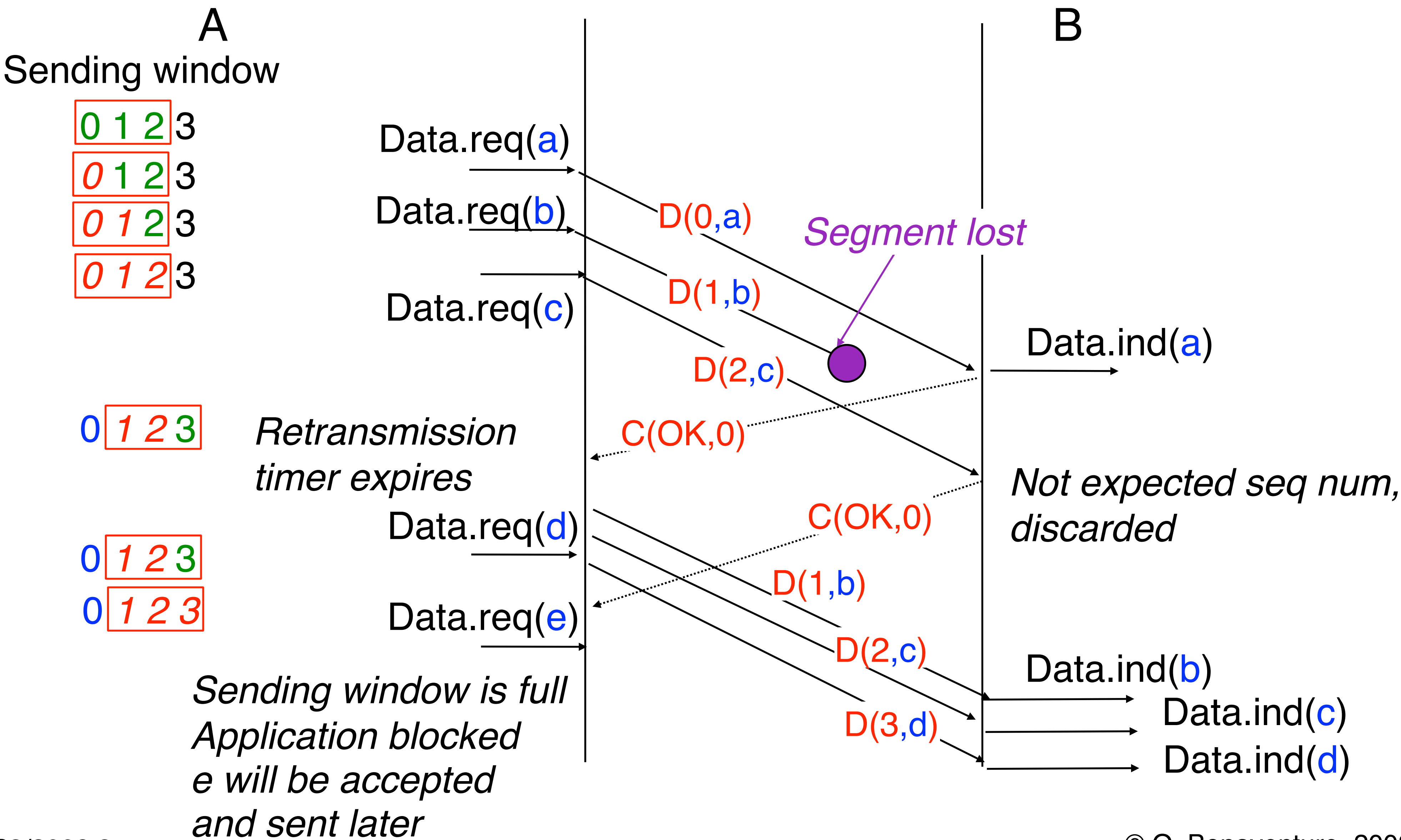
Go-Back-N : Example (2)



Go-Back-N : Example (2)

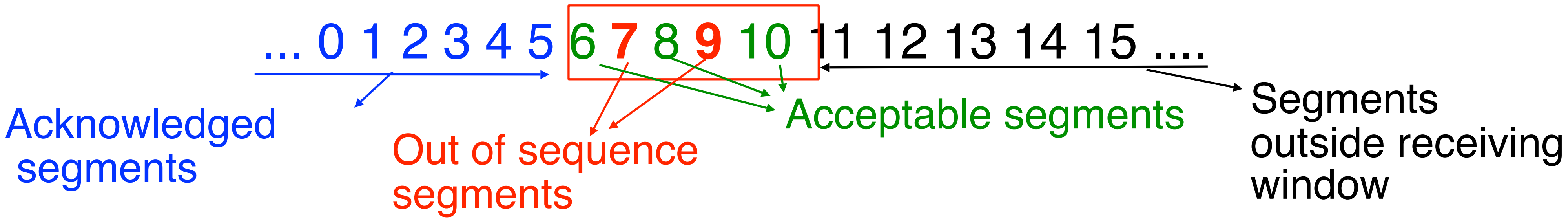


Go-Back-N : Example (2)



Selective Repeat

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



Selective Repeat

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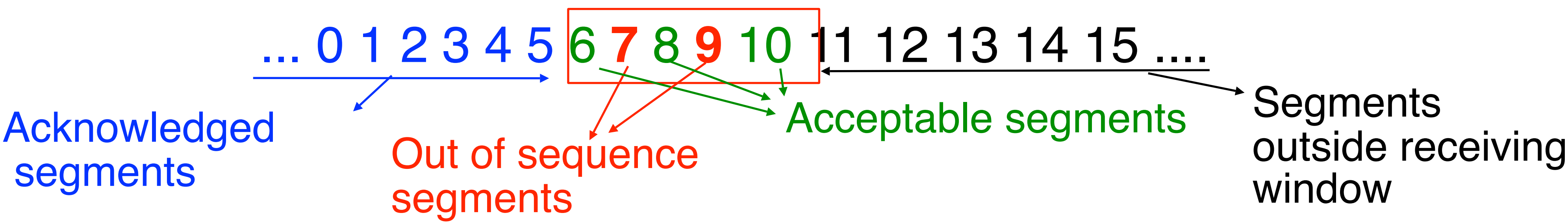
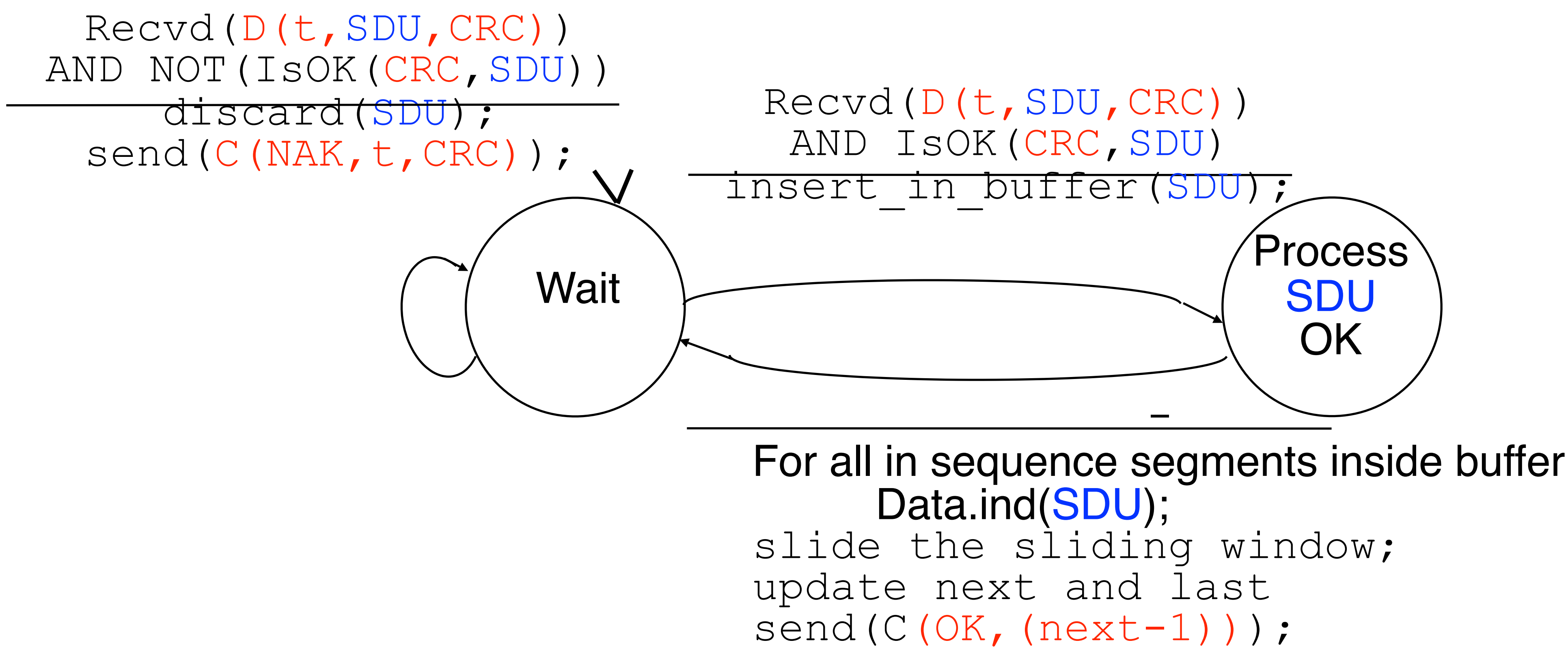


- Semantics of the control segments
  - OKX
    - The segments up to and including sequence number X have been received
  - NAKX
    - The segment with sequence number X was errored
- Sender
  - Upon detection of an errored or lost segment, sender retransmits only this segment
    - may require one retransmission timer per segment

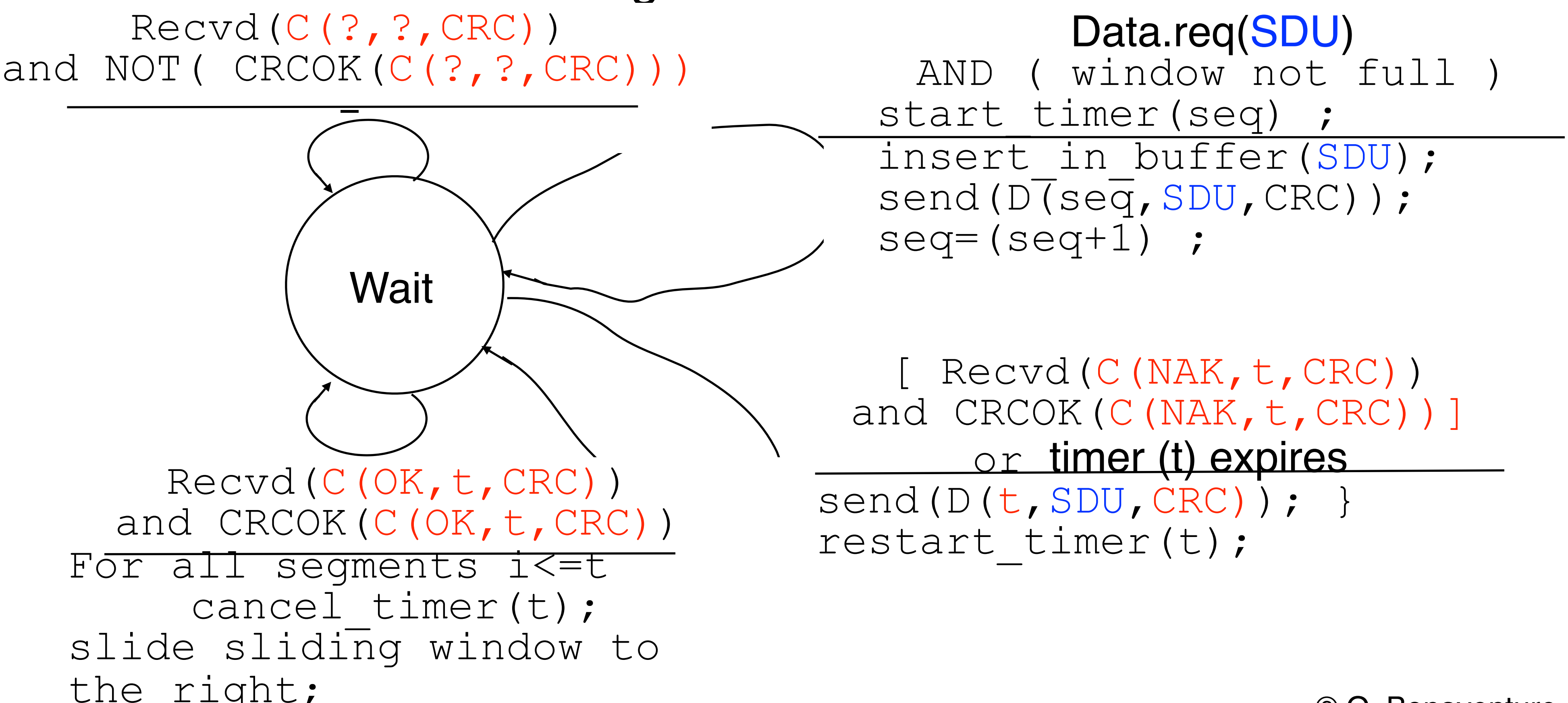
Selective-Repeat : Receiver

- State variable
  - `next` : sequence number of expected data segment
  - `Last` : last received in-sequence segment



Selective Repeat : Sender

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



Selective Repeat : Example

A

Sending window

0 1 2 3

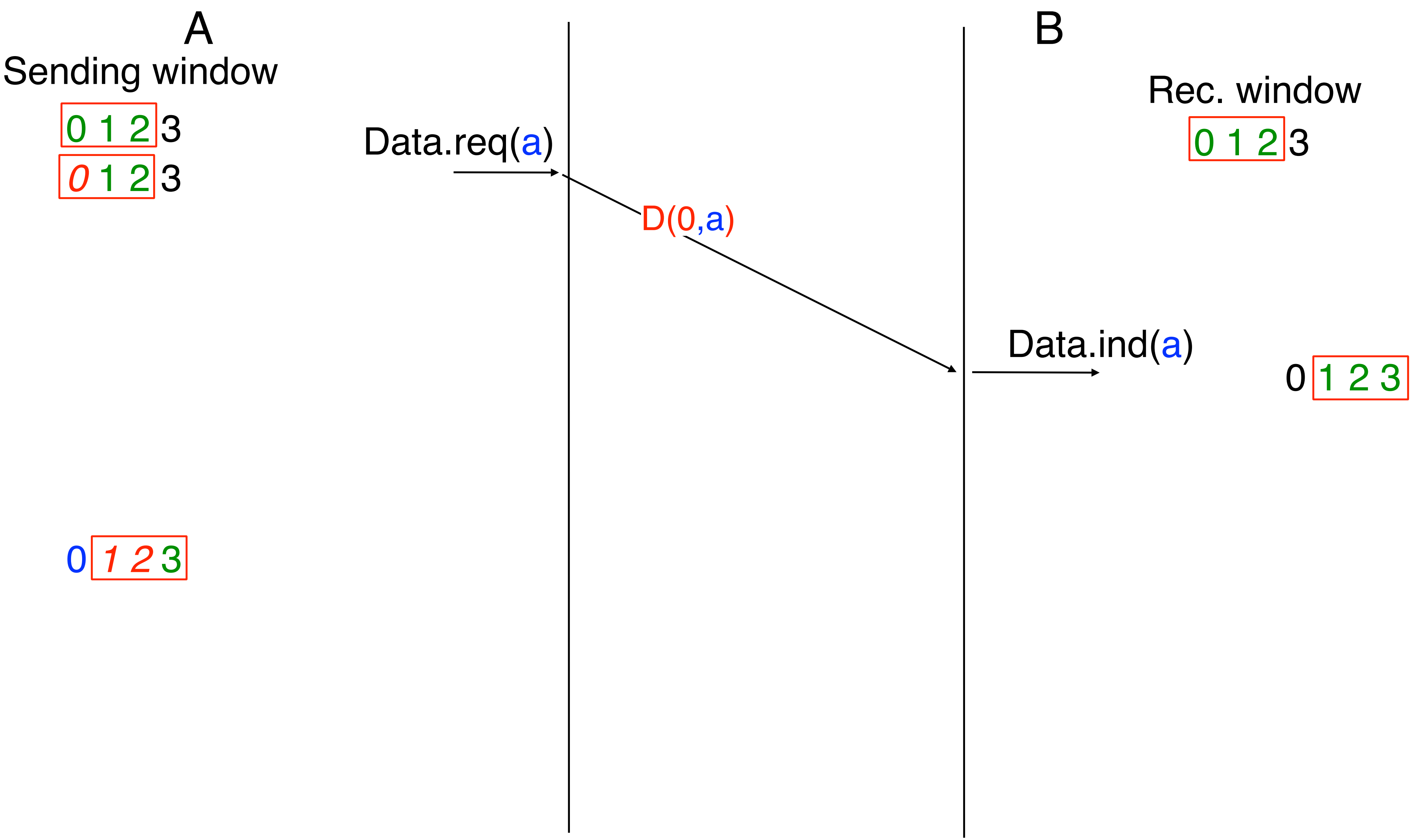
B

Rec. window

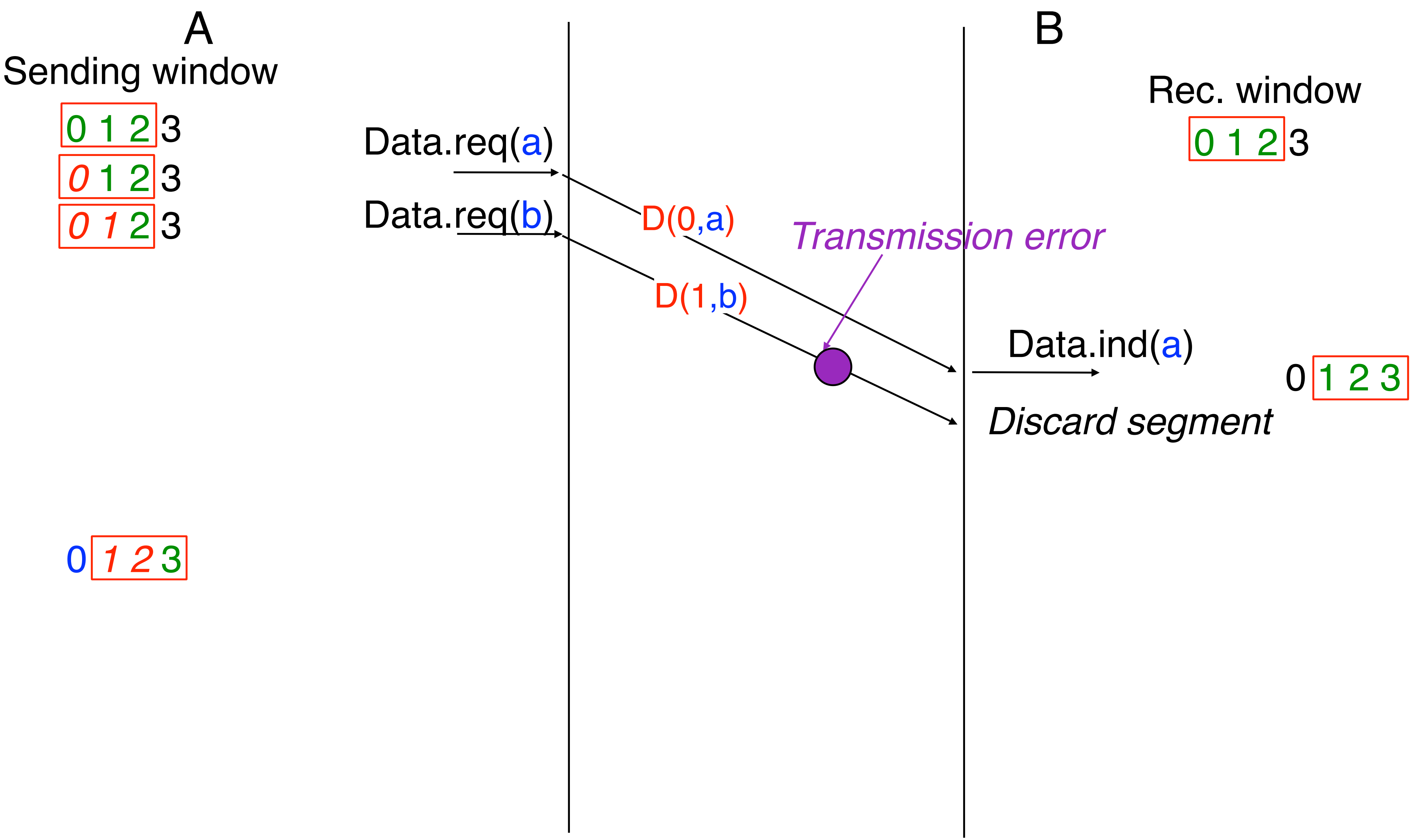
0 1 2 3

0 *1 2* 3

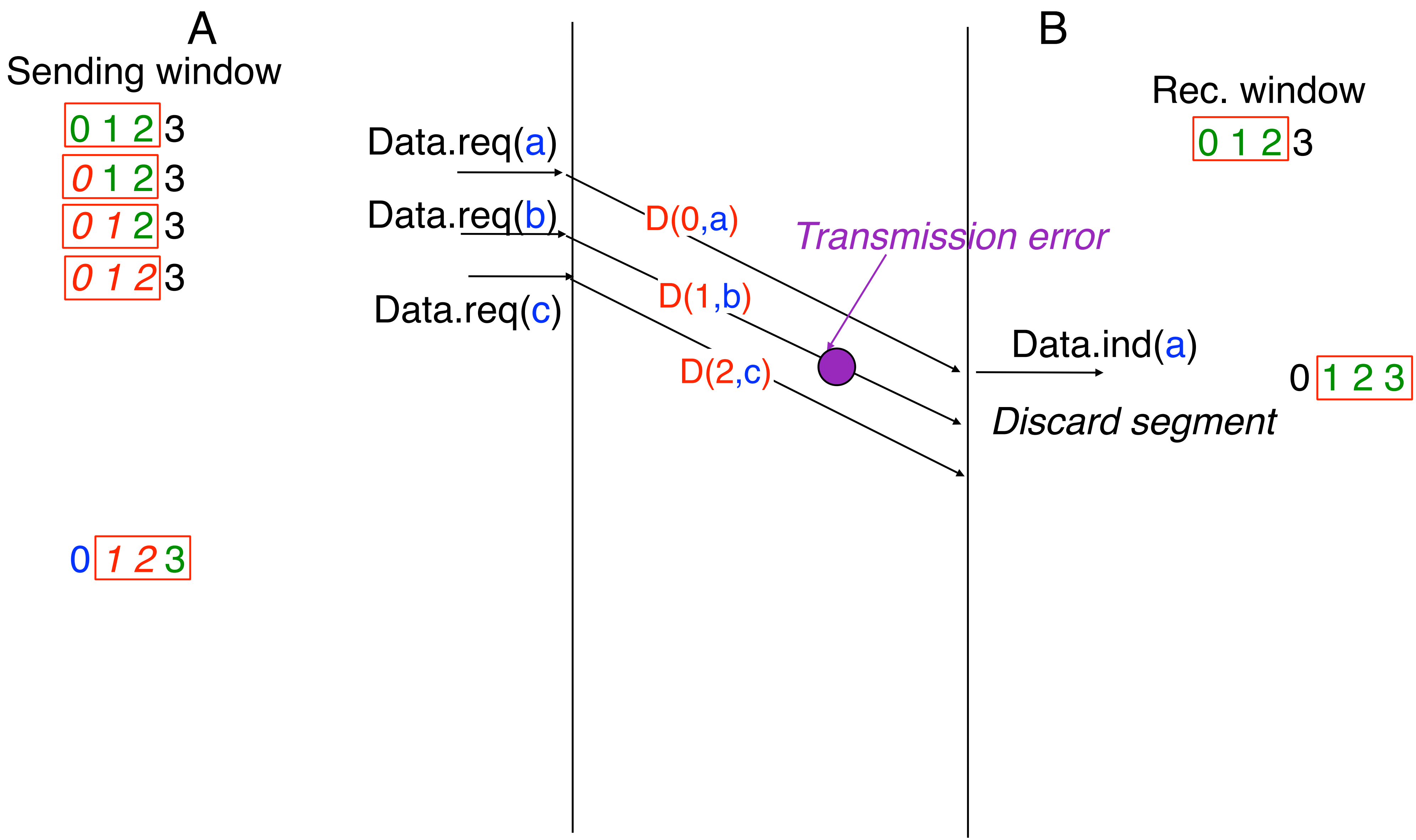
Selective Repeat : Example



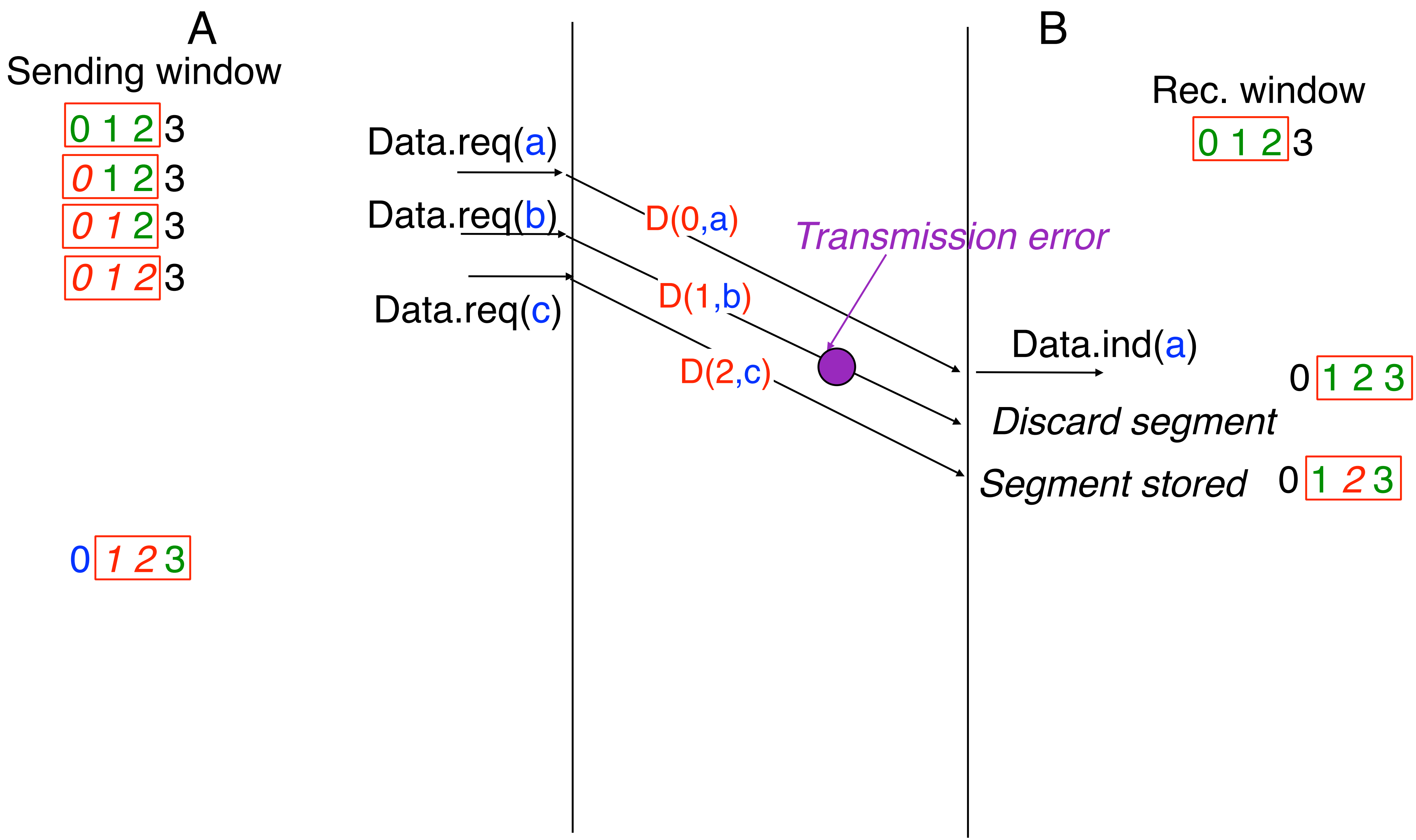
Selective Repeat : Example



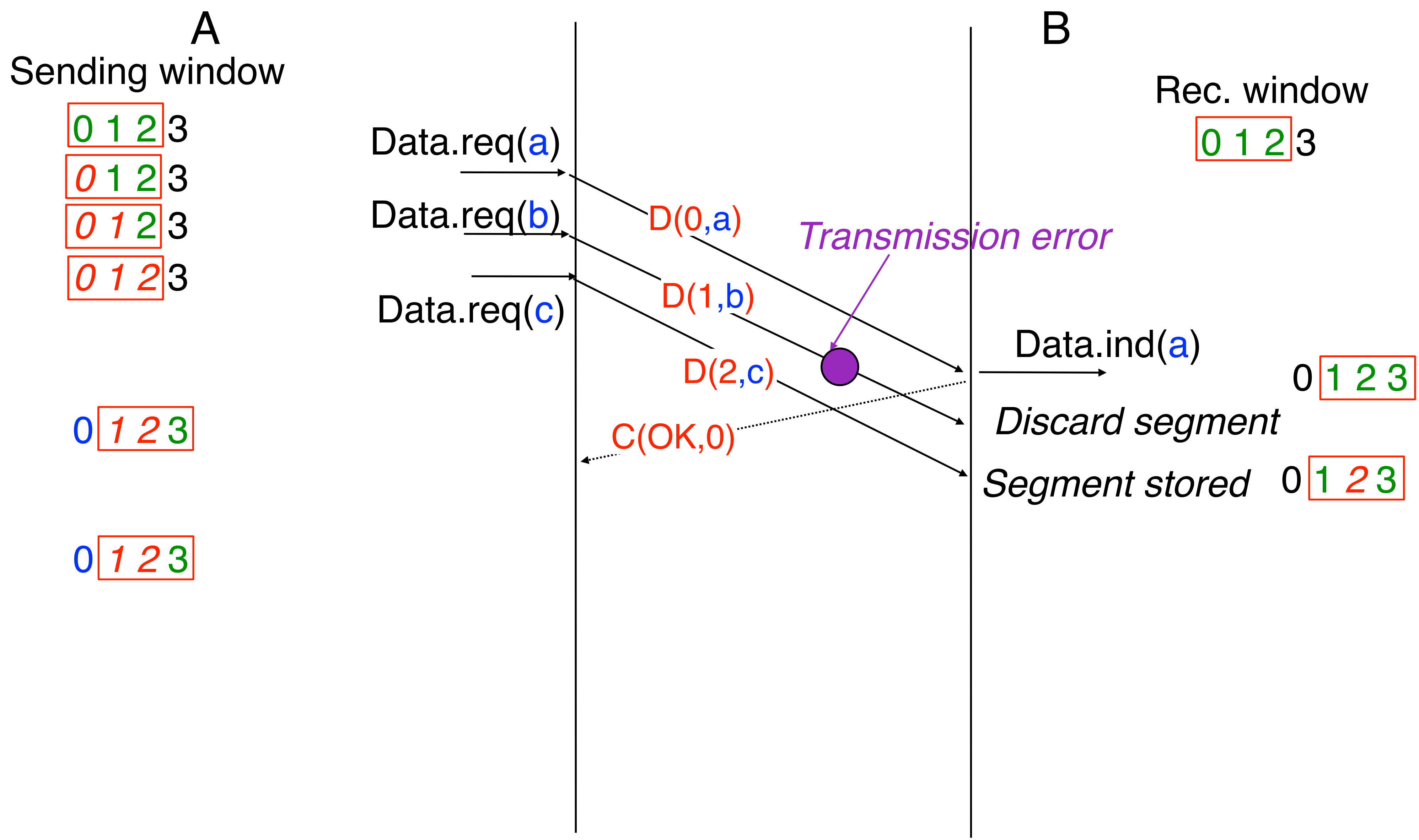
Selective Repeat : Example



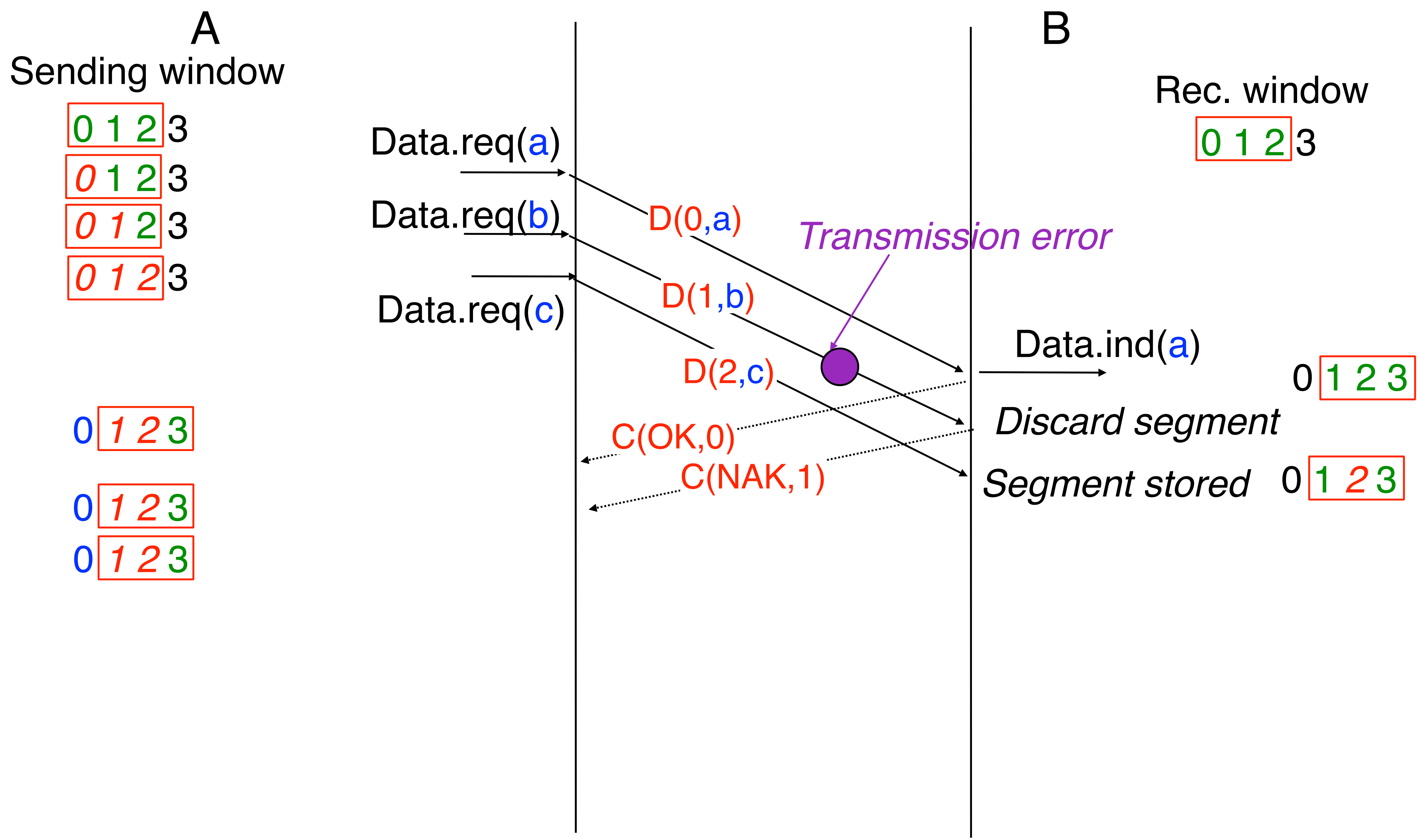
Selective Repeat : Example



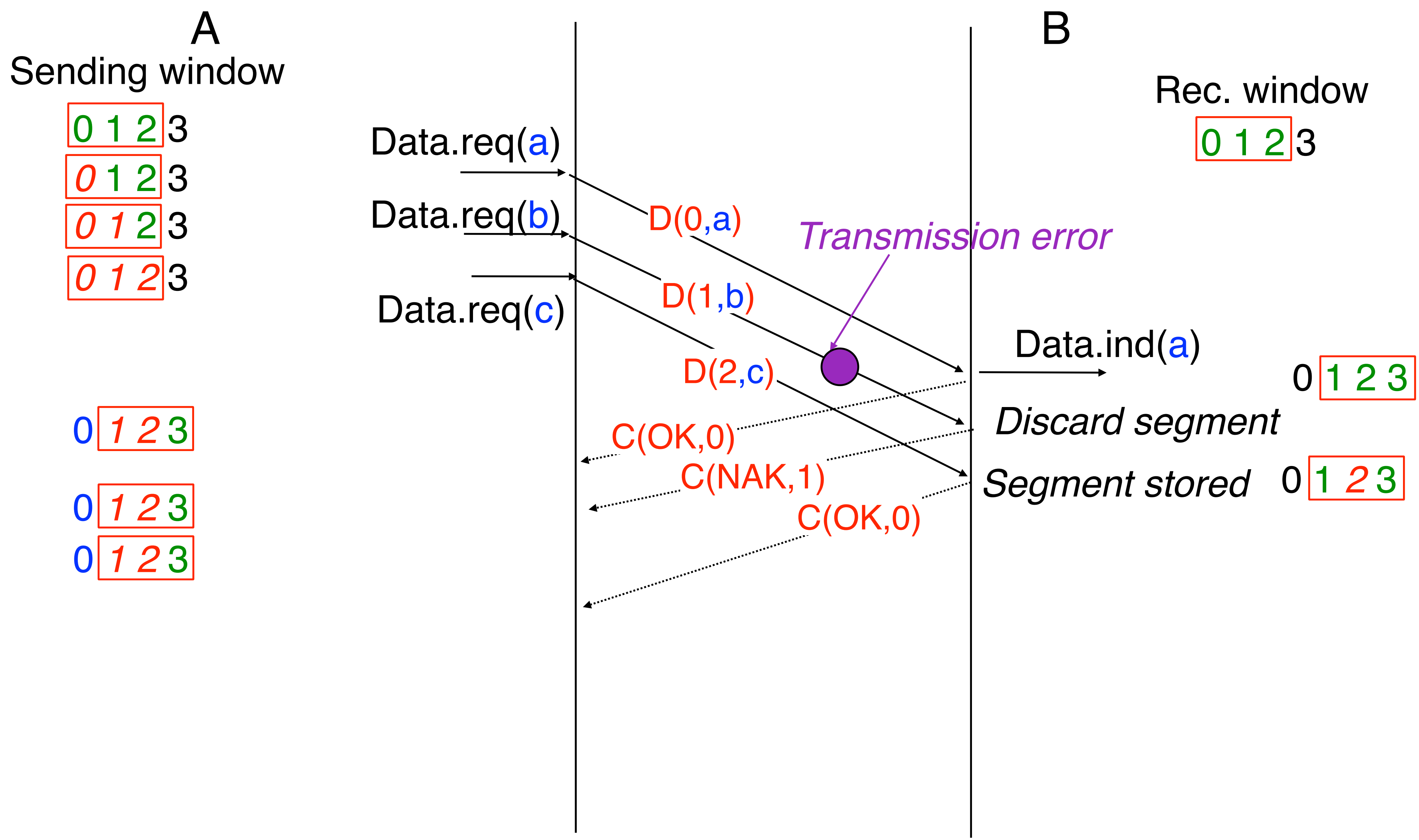
Selective Repeat : Example



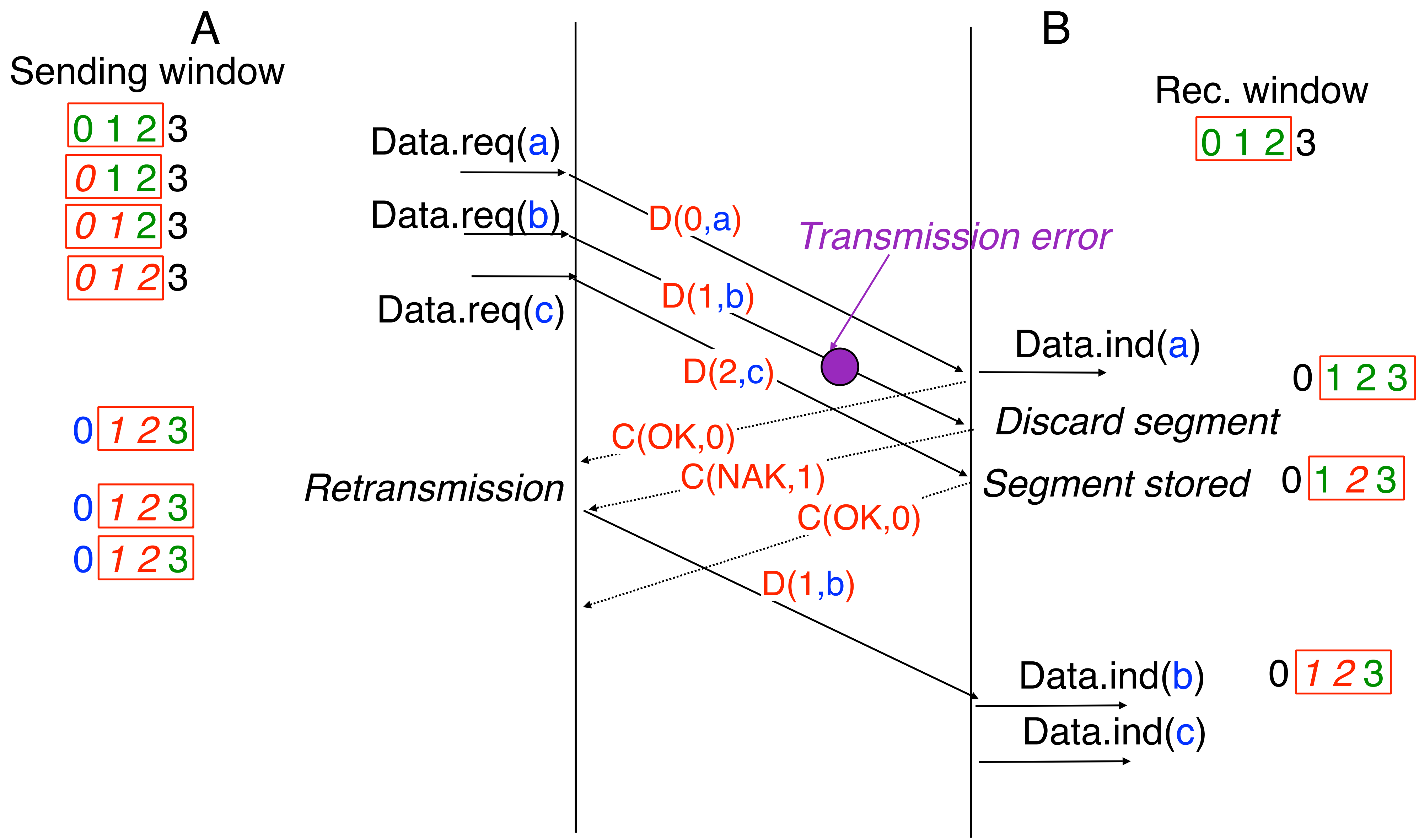
Selective Repeat : Example



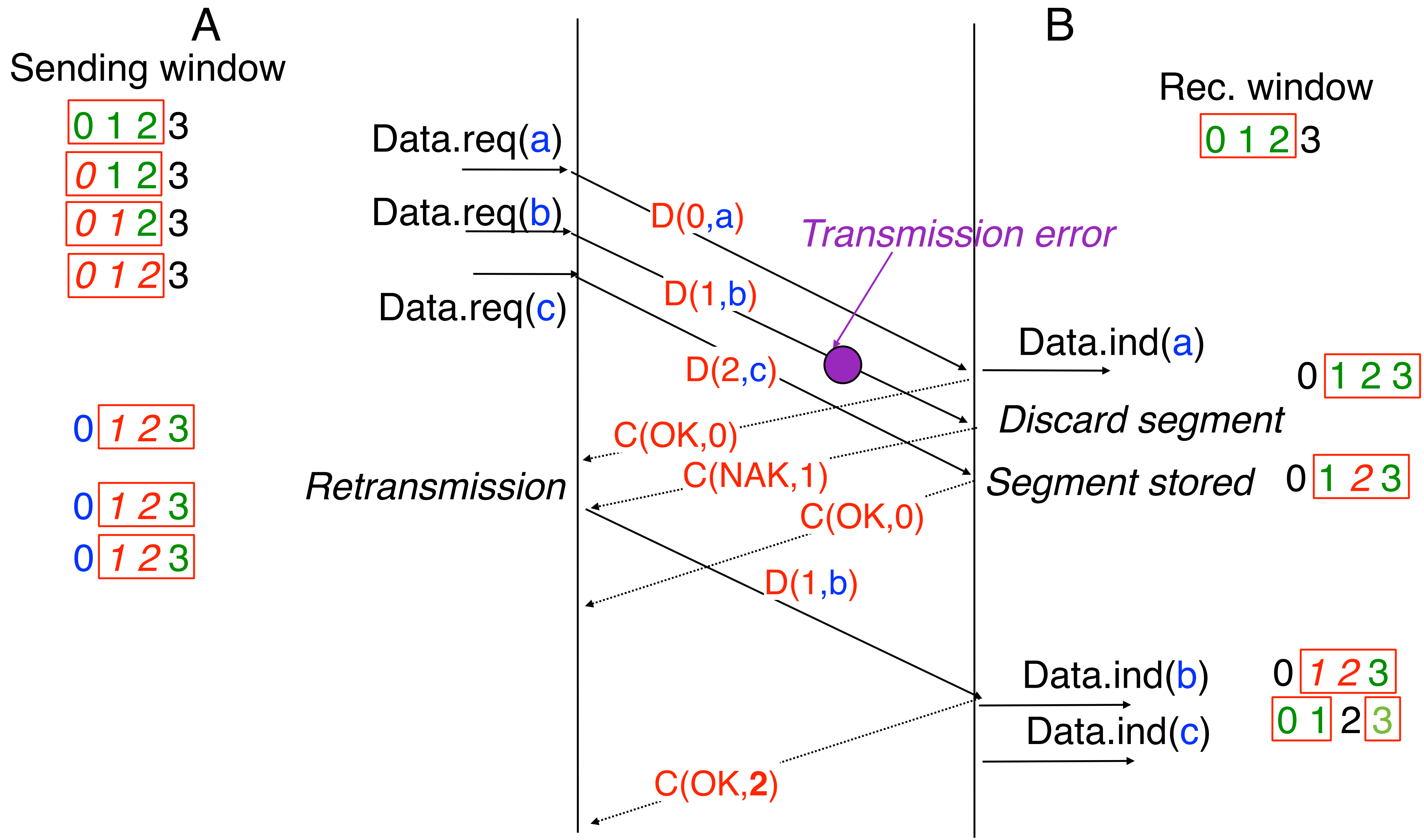
Selective Repeat : Example



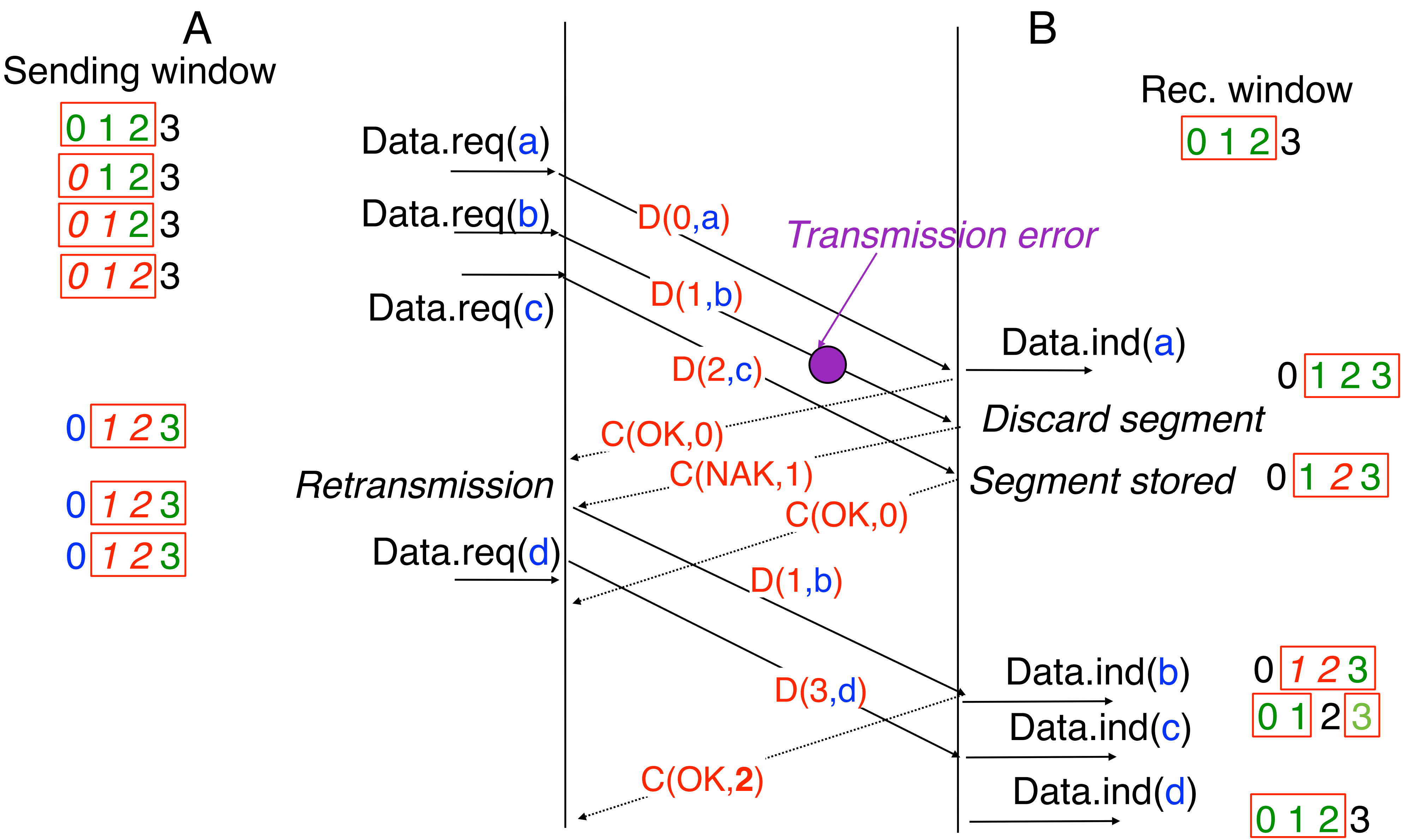
Selective Repeat : Example



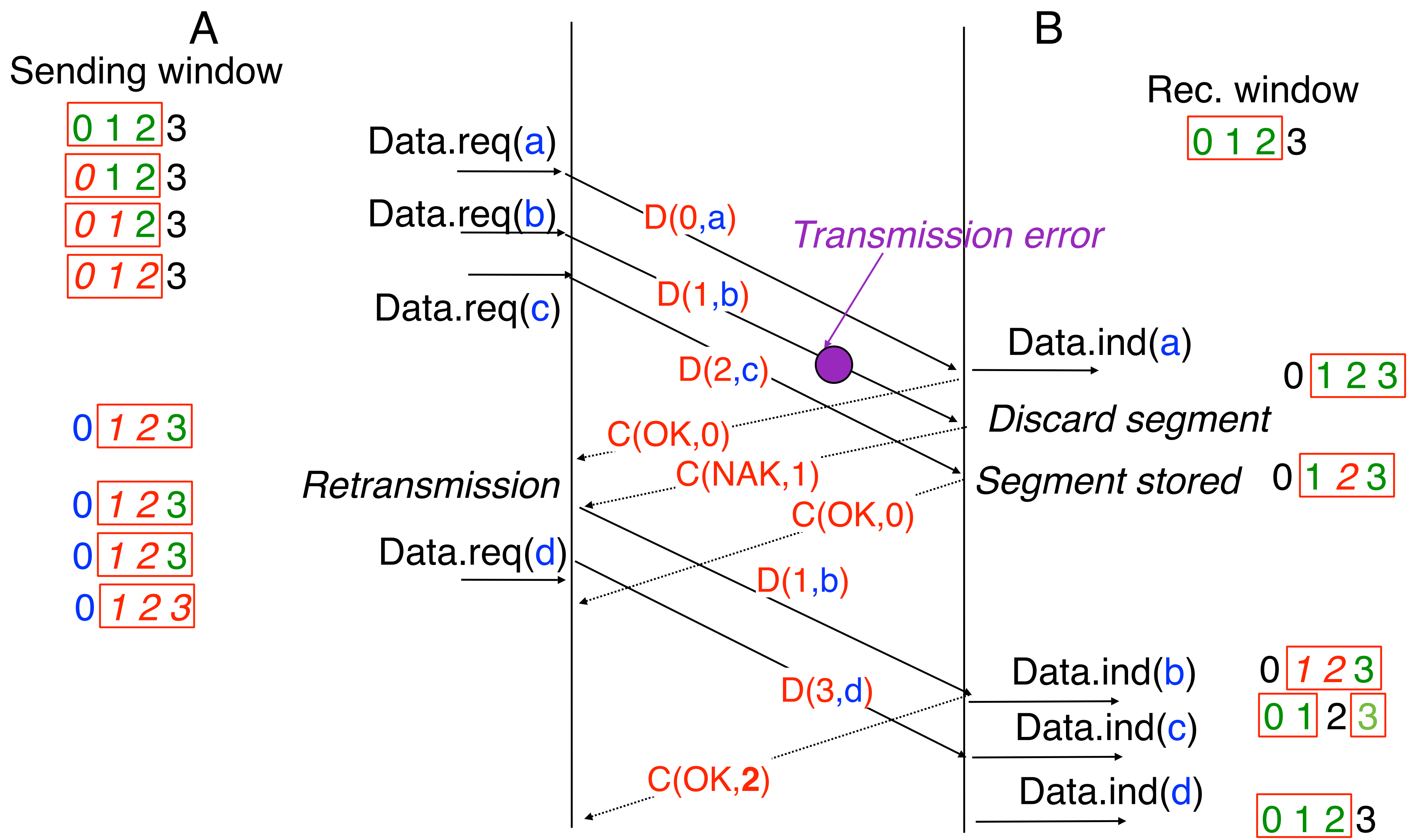
Selective Repeat : Example



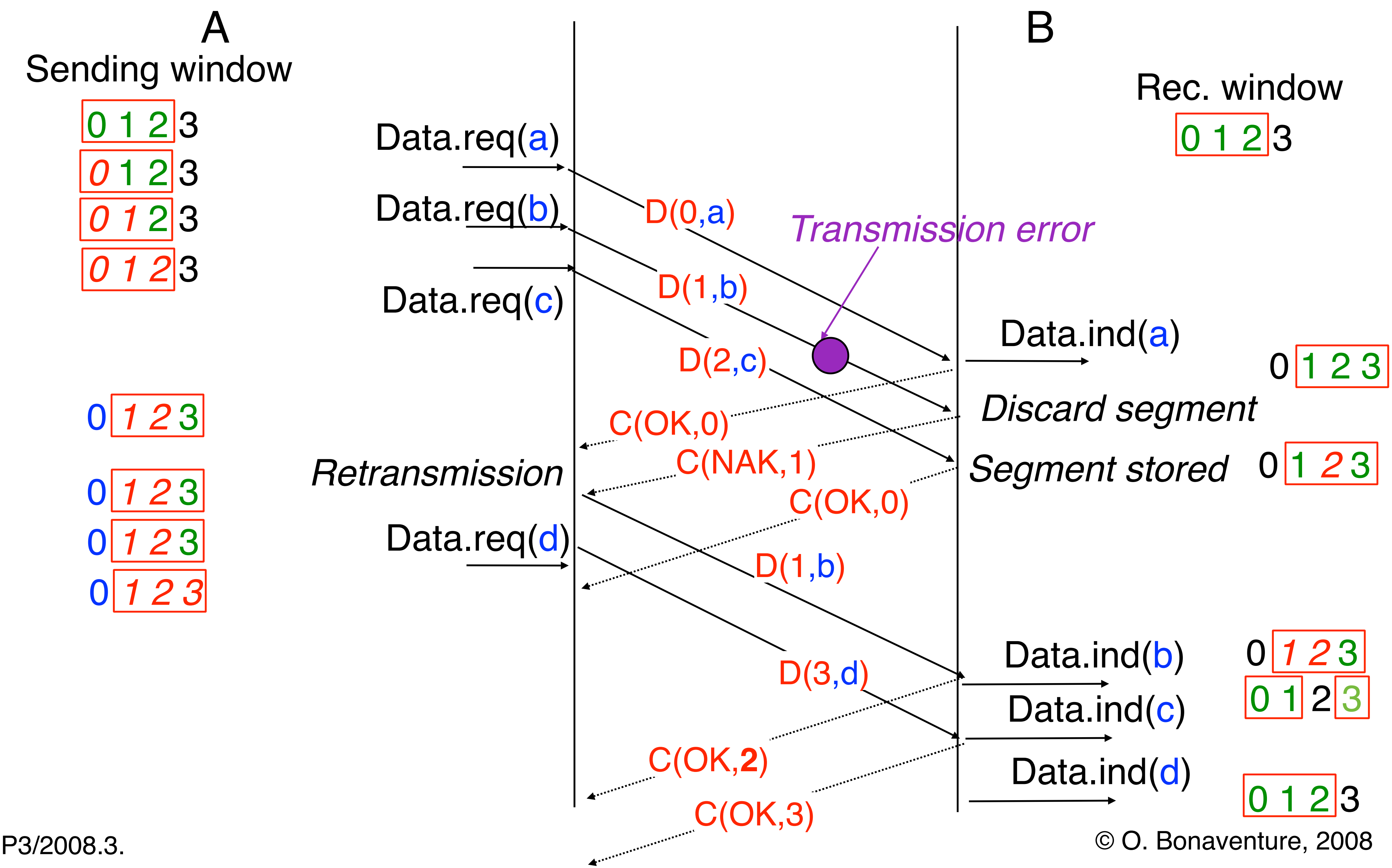
Selective Repeat : Example



Selective Repeat : Example



Selective Repeat : Example



Selective Repeat : Example (2)

A

Sending window

0 1 2 3

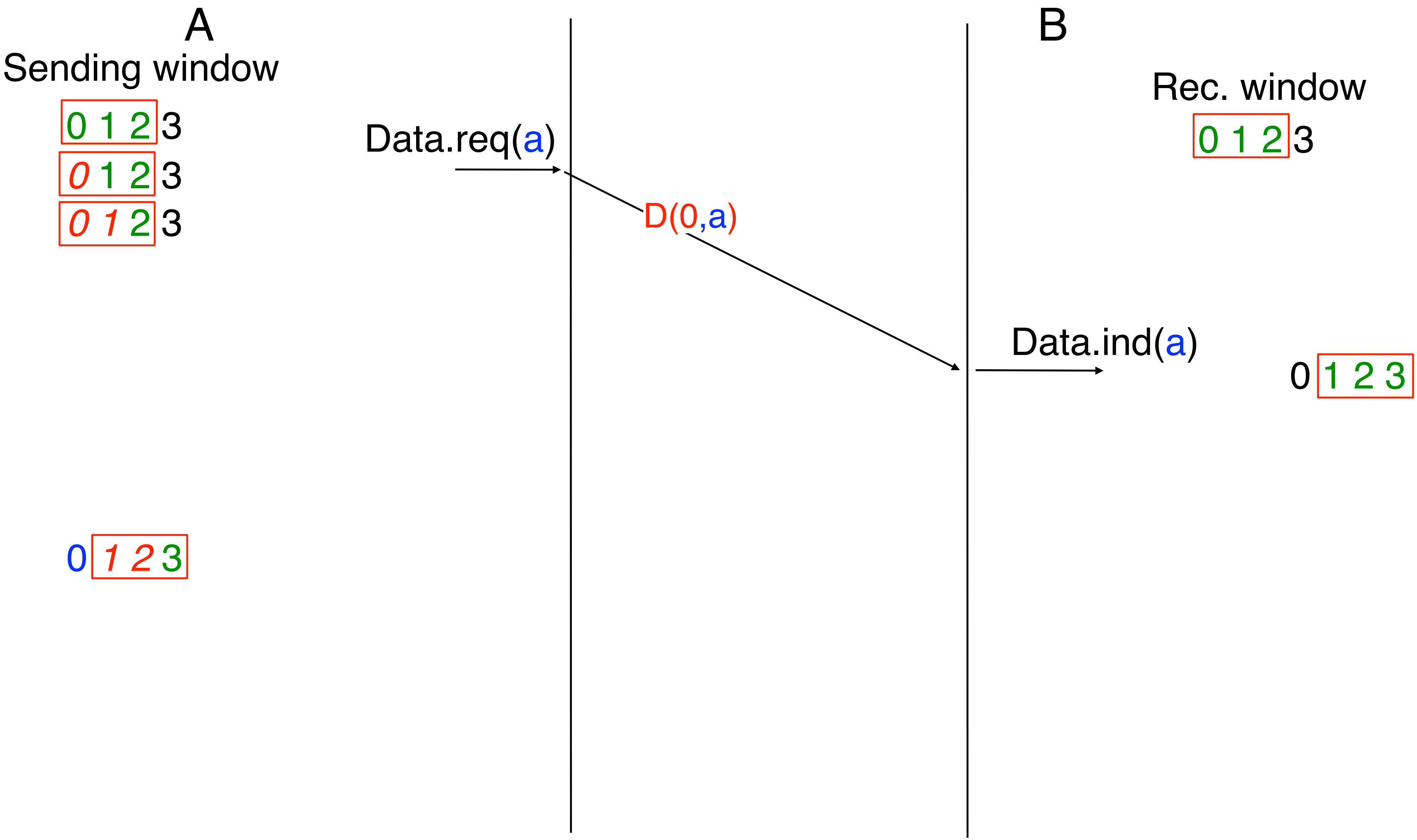
B

Rec. window

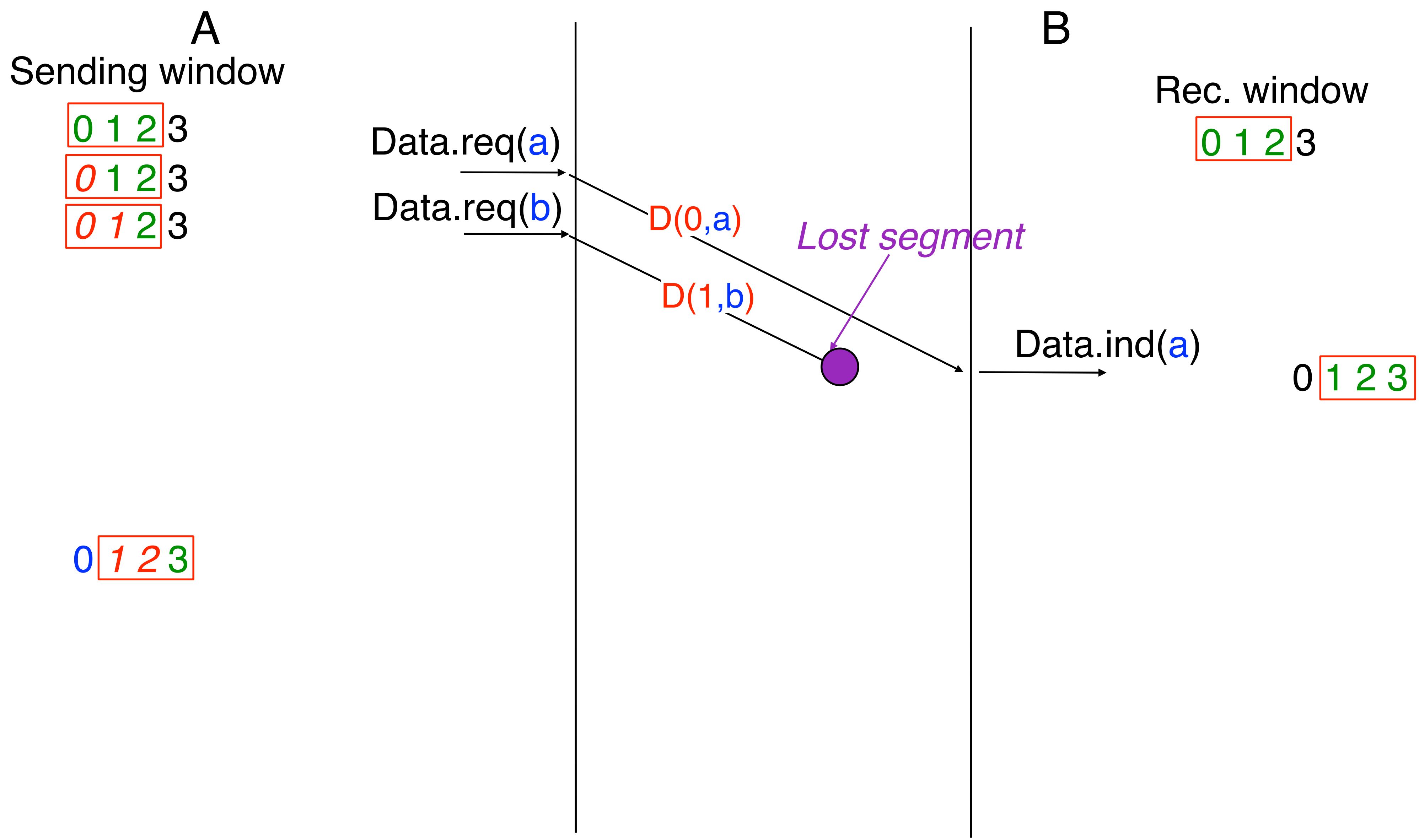
0 1 2 3

0 1 2 3

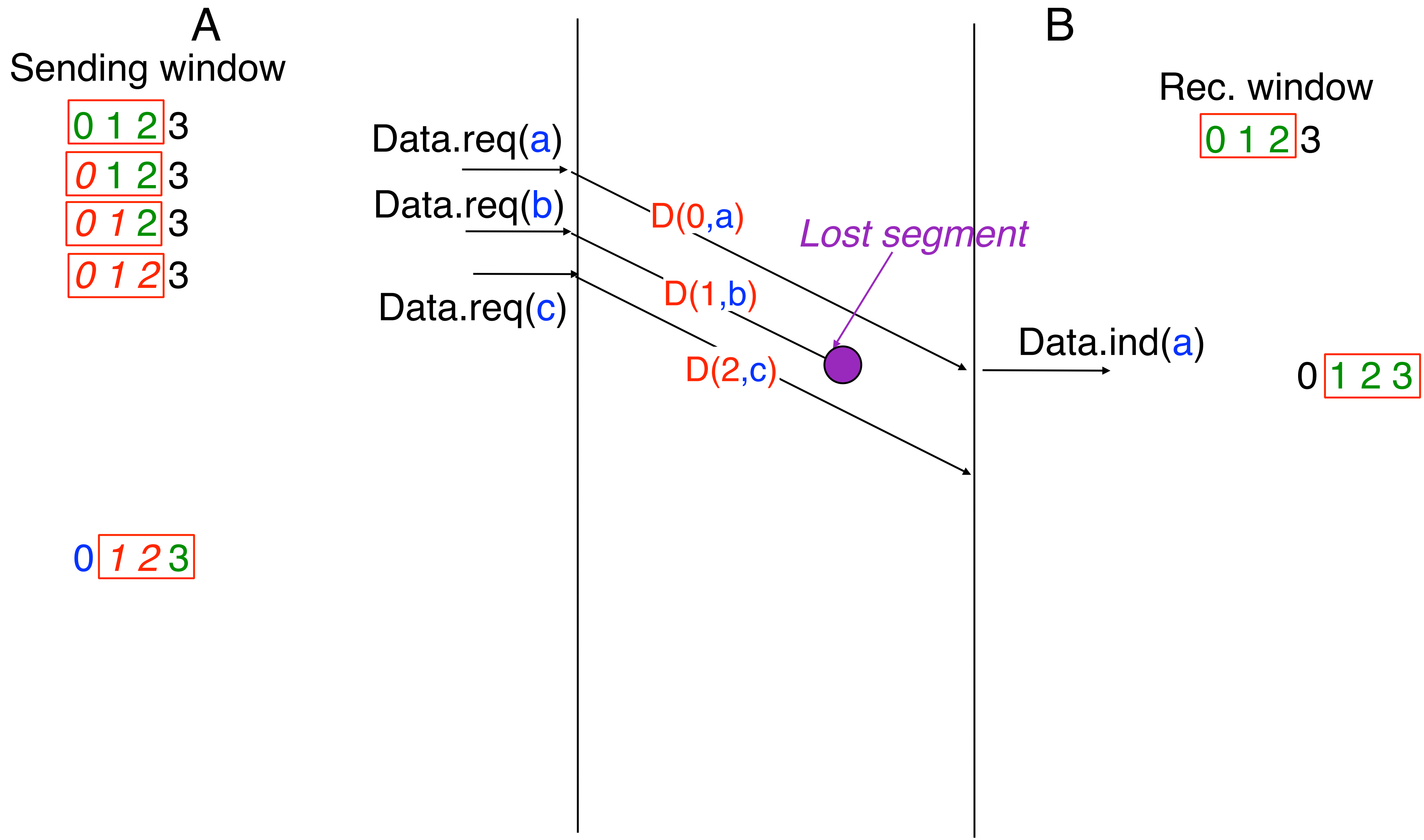
Selective Repeat : Example (2)



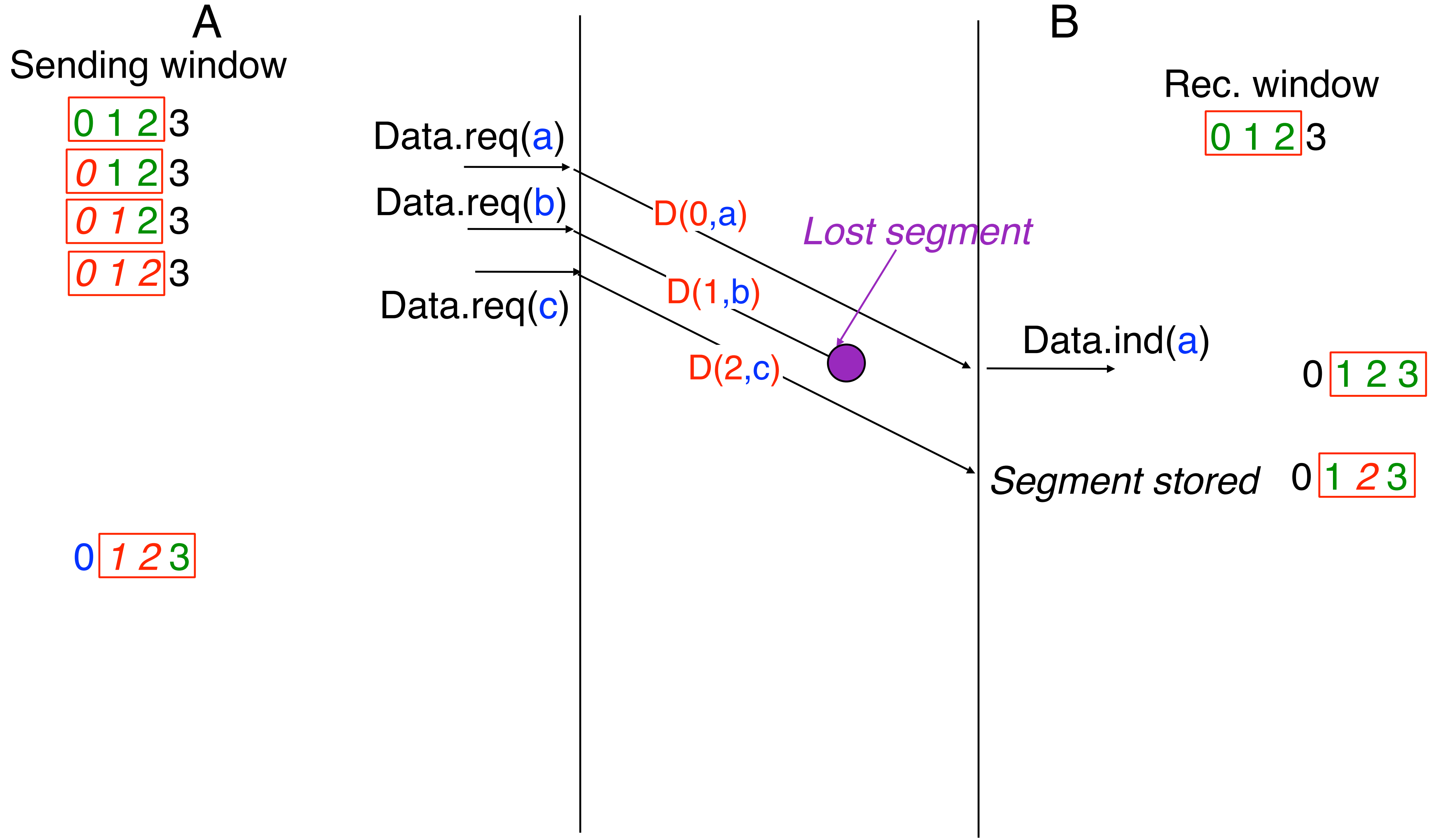
Selective Repeat : Example (2)



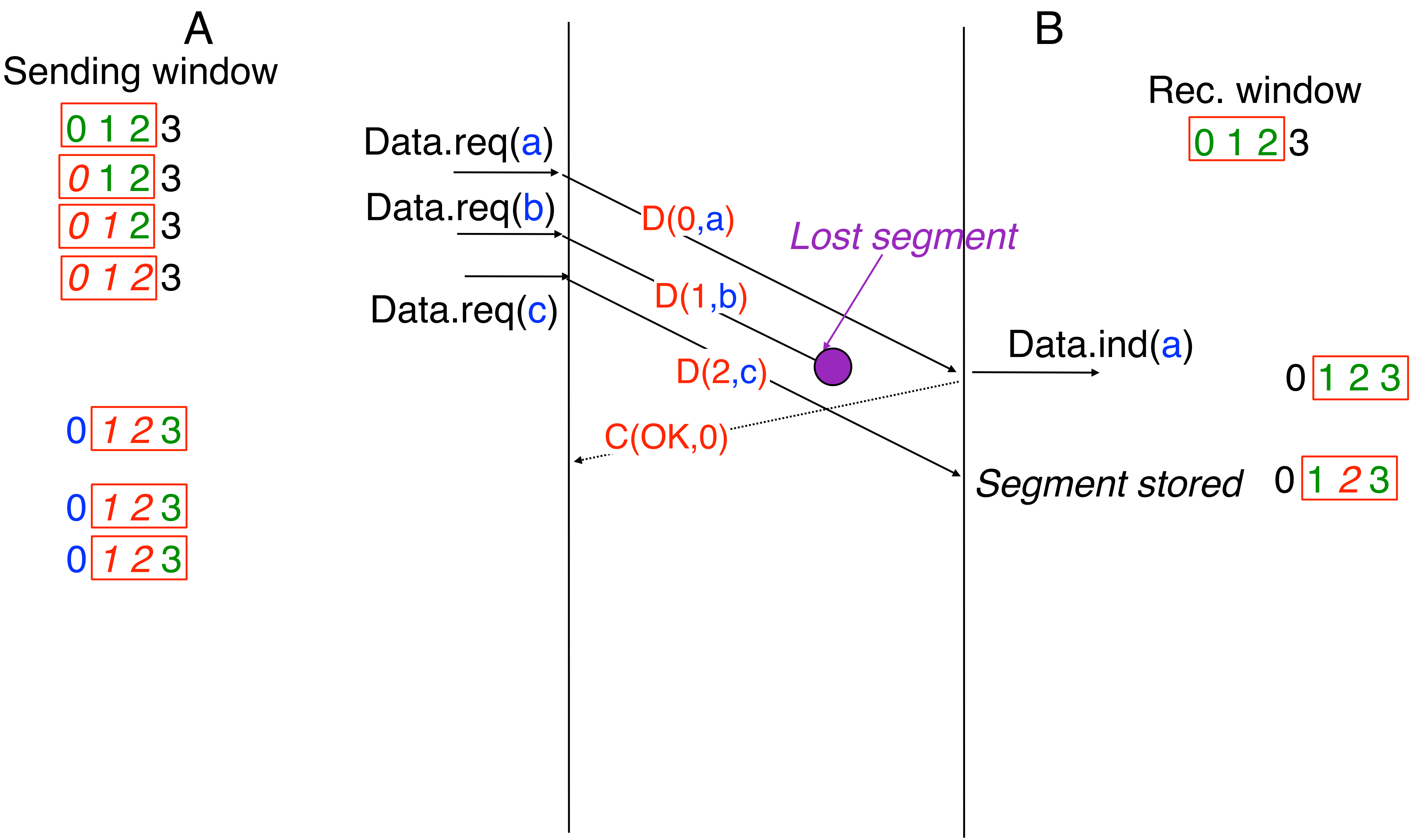
Selective Repeat : Example (2)



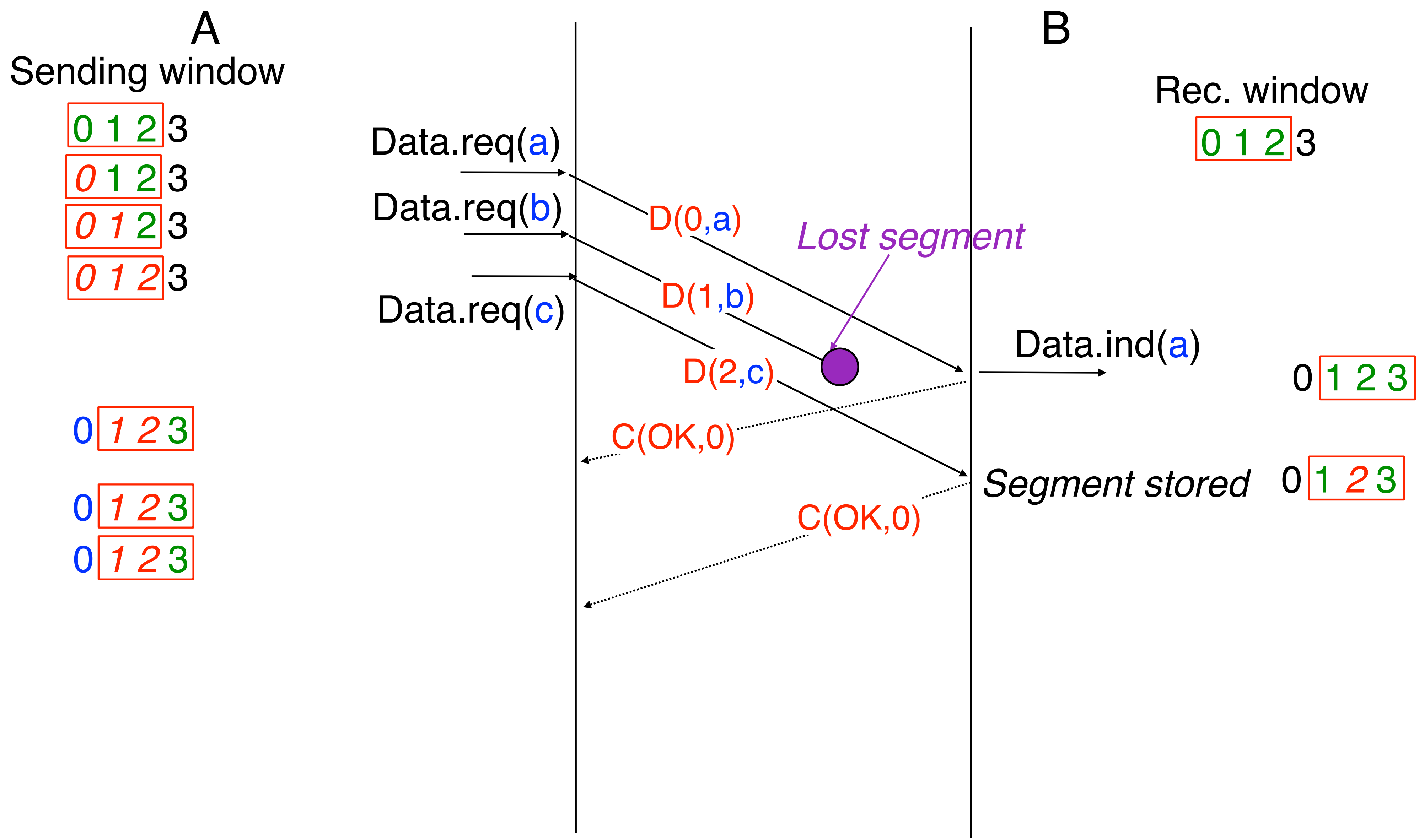
Selective Repeat : Example (2)



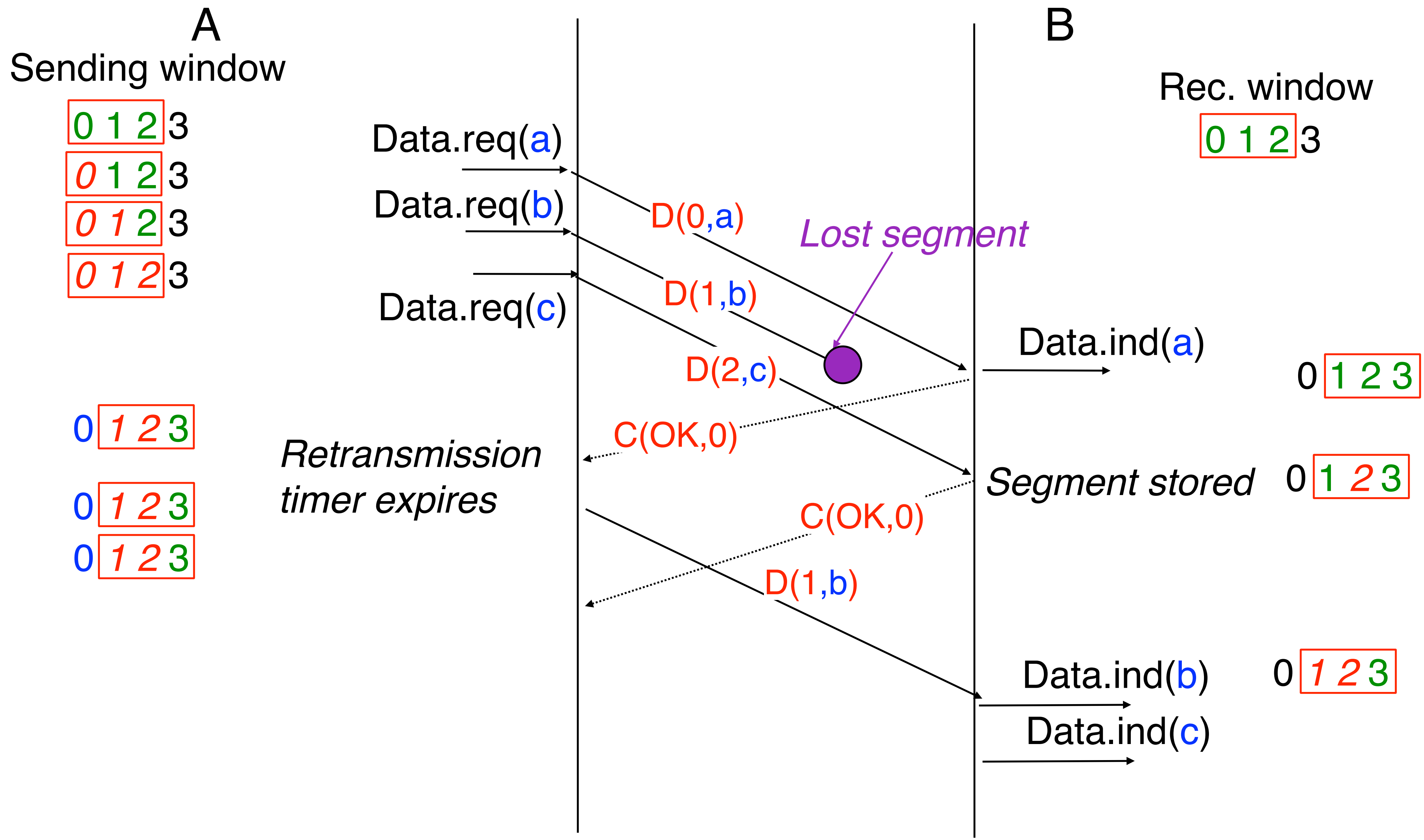
Selective Repeat : Example (2)



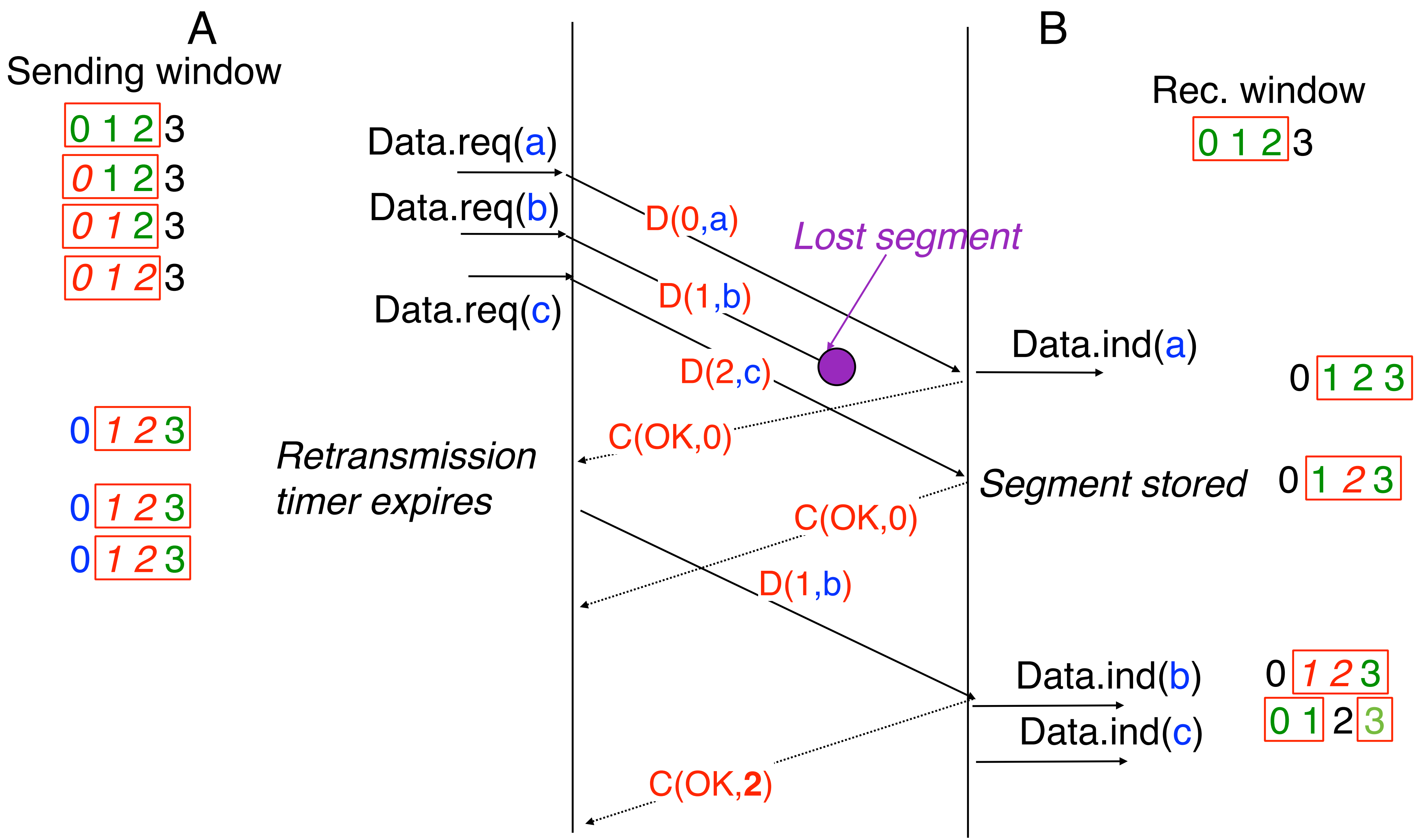
Selective Repeat : Example (2)



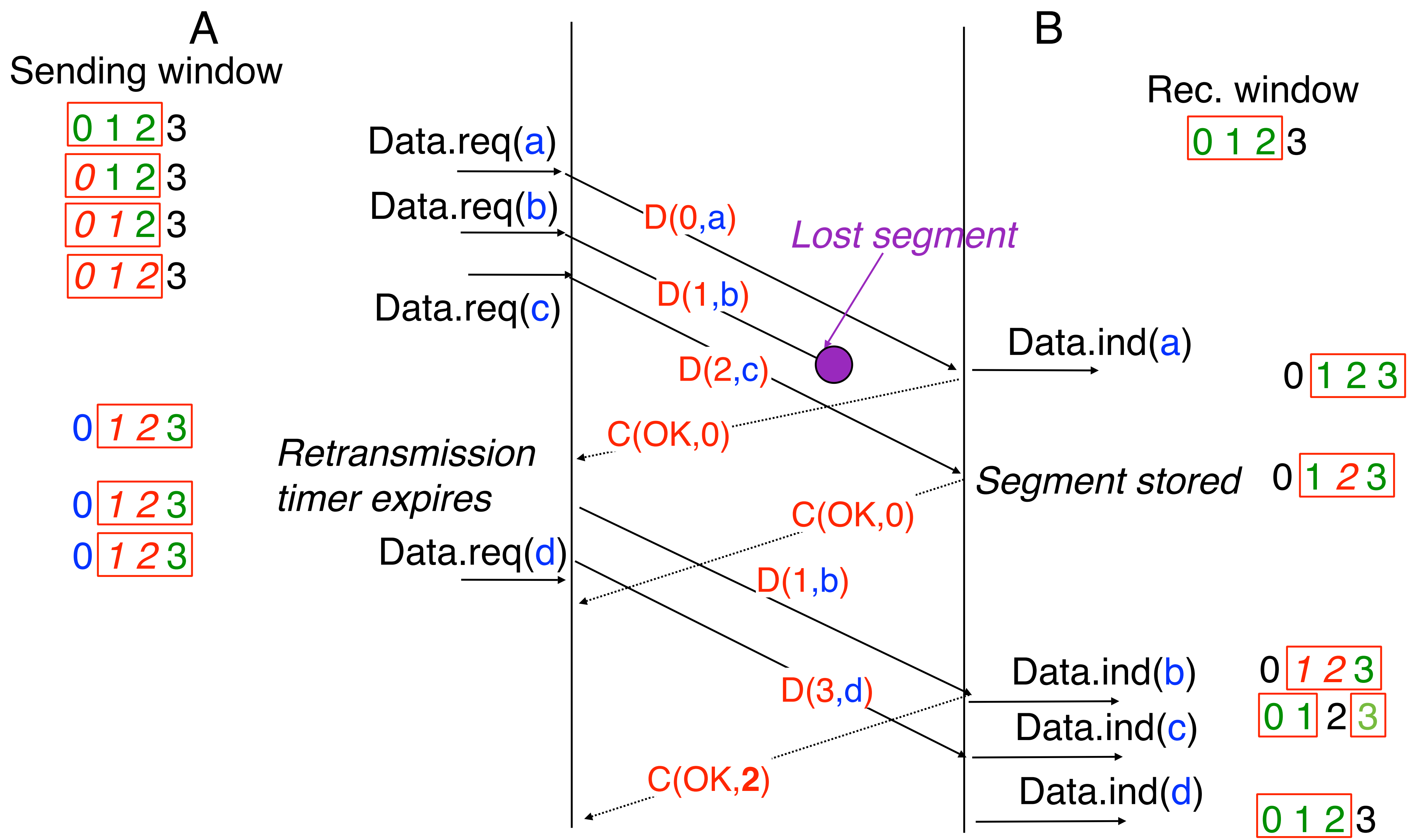
Selective Repeat : Example (2)



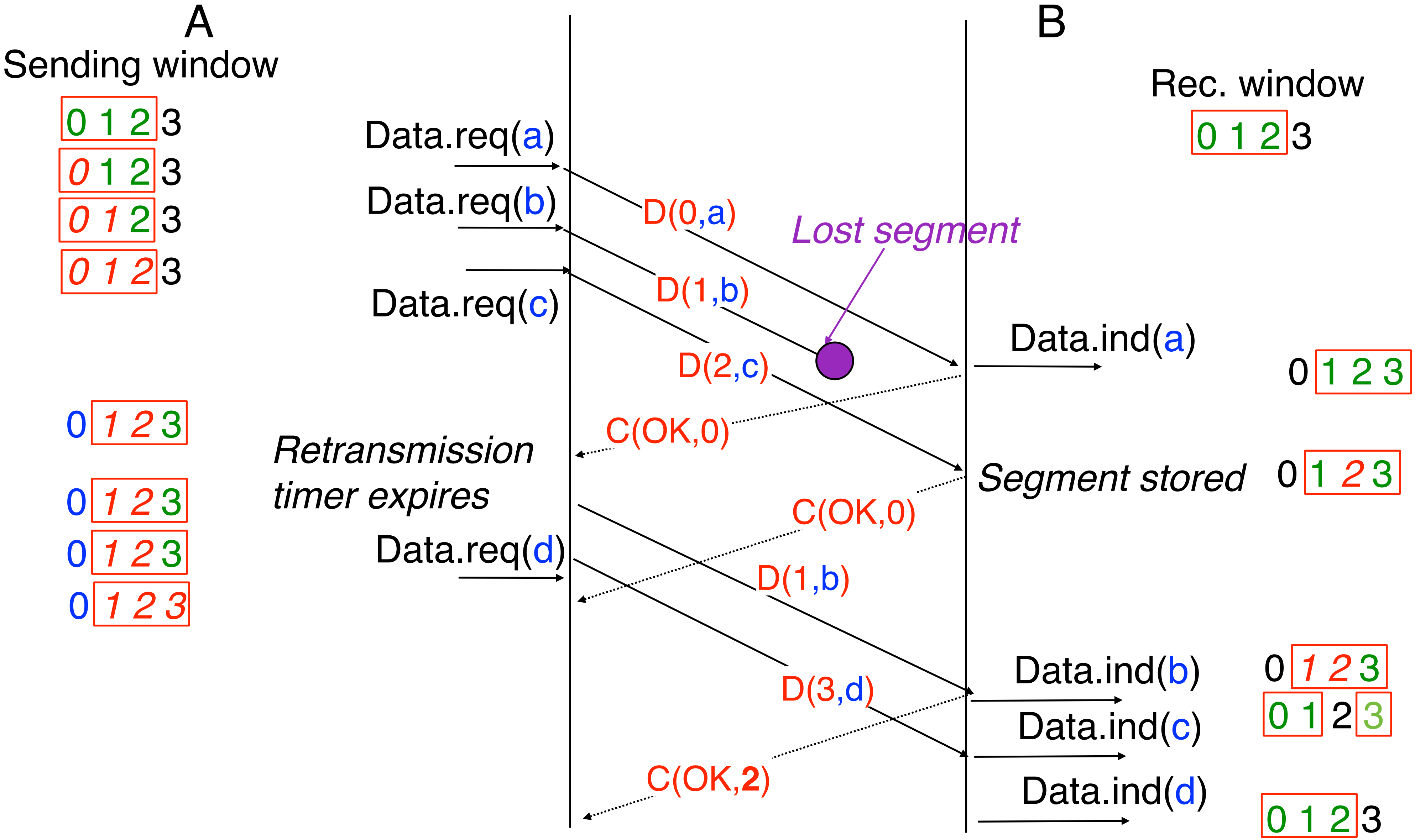
Selective Repeat : Example (2)



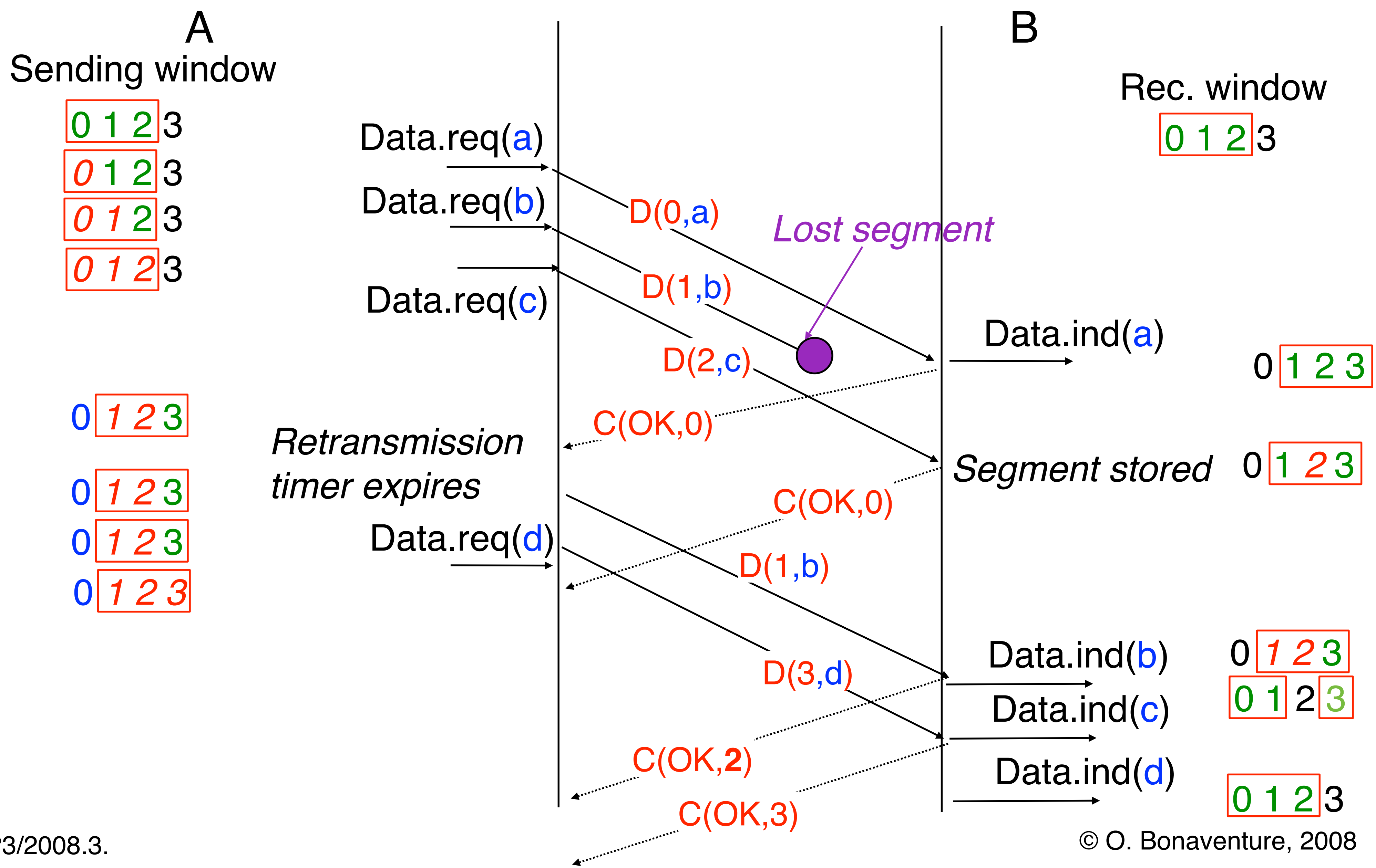
Selective Repeat : Example (2)



Selective Repeat : Example (2)

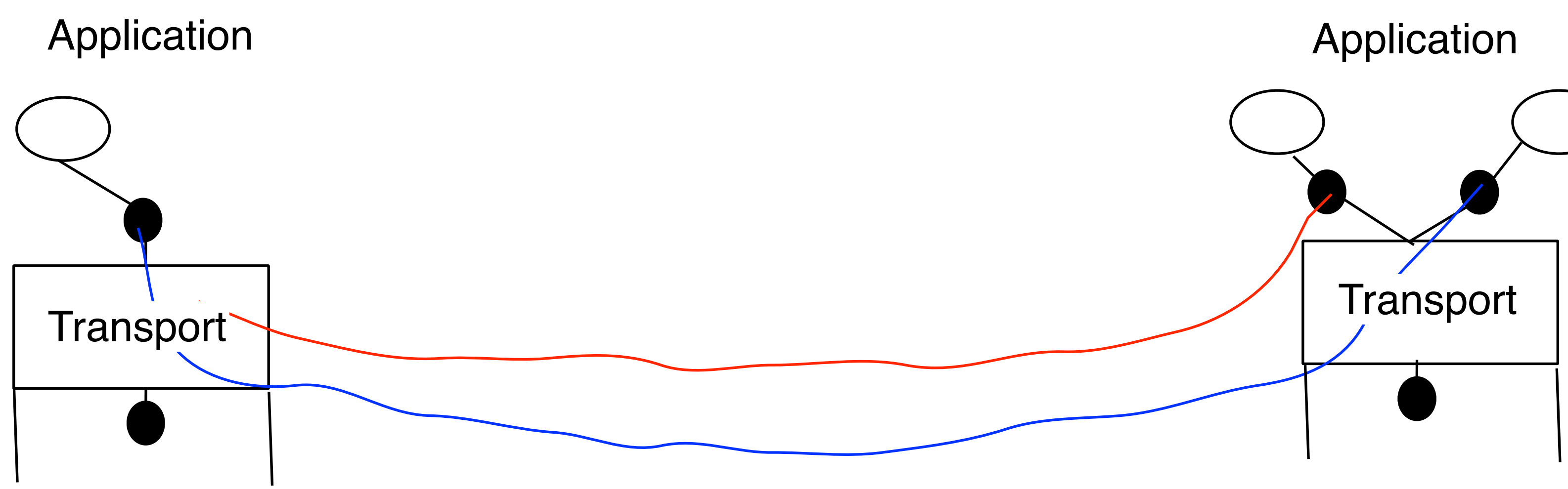


Selective Repeat : Example (2)



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`

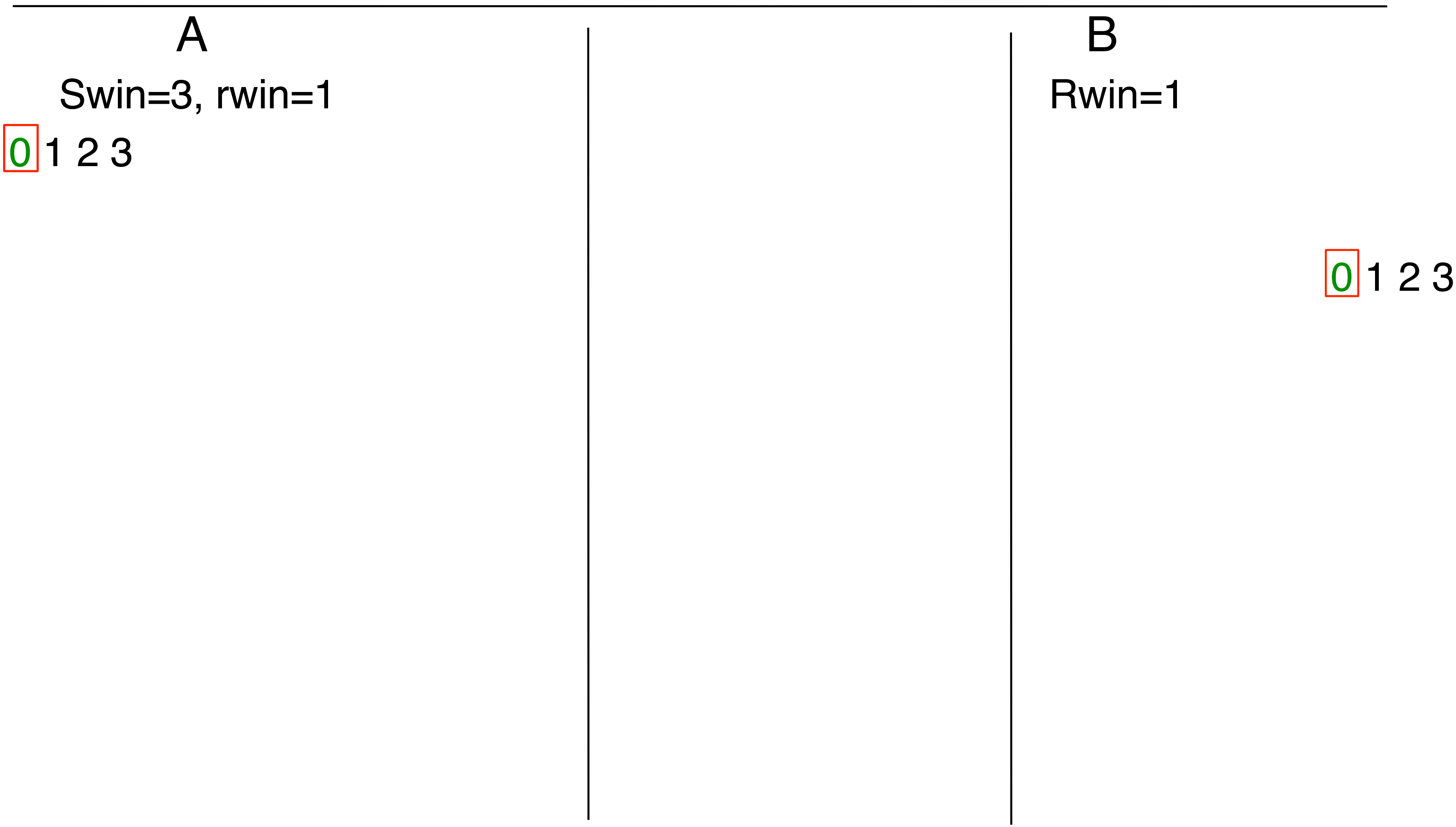
Buffer management (2)

- 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

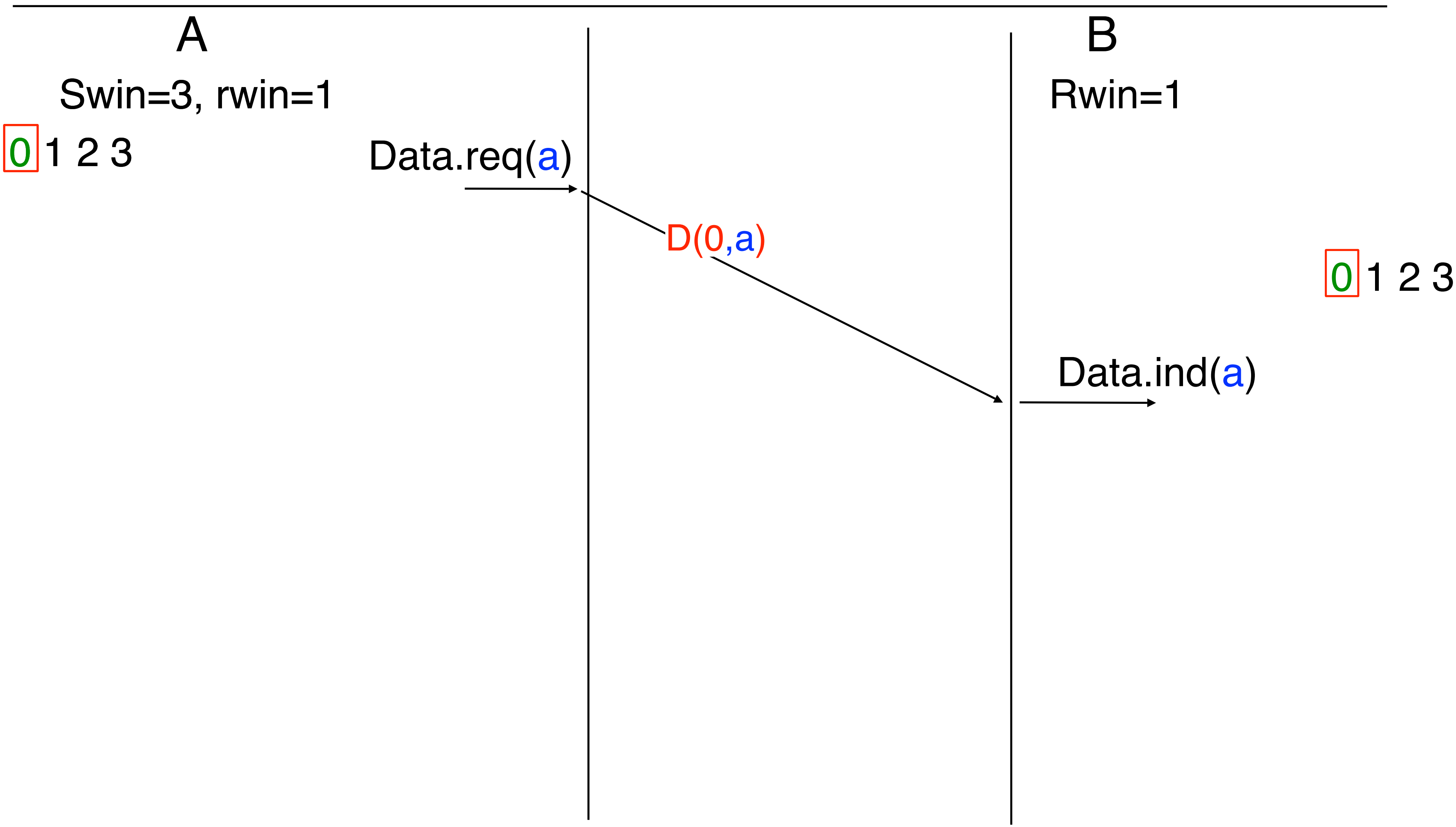
  - New information carried in control segments
    - `win` indicates the current receiving window's size

  - 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`)

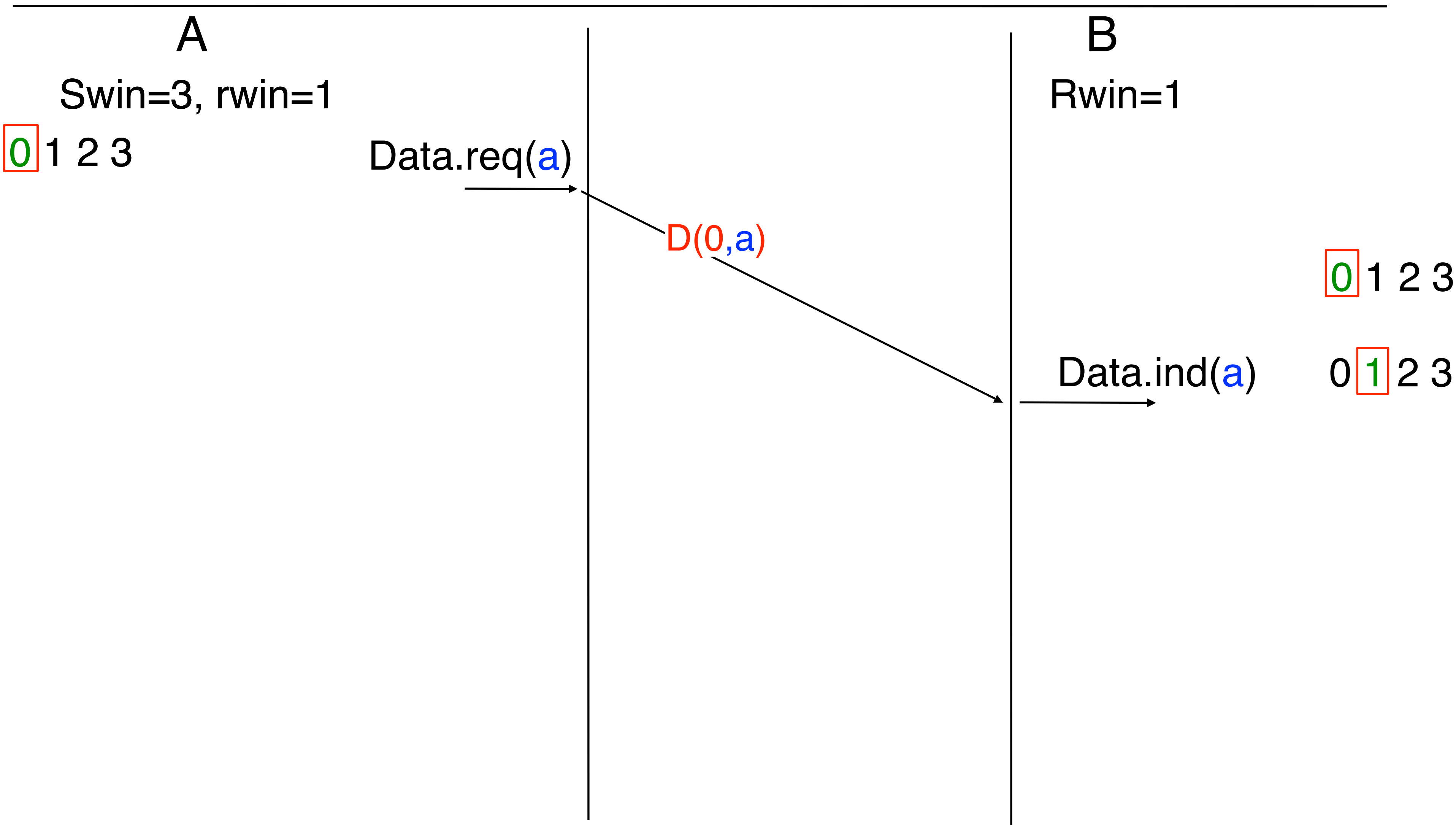
Buffer management (3)



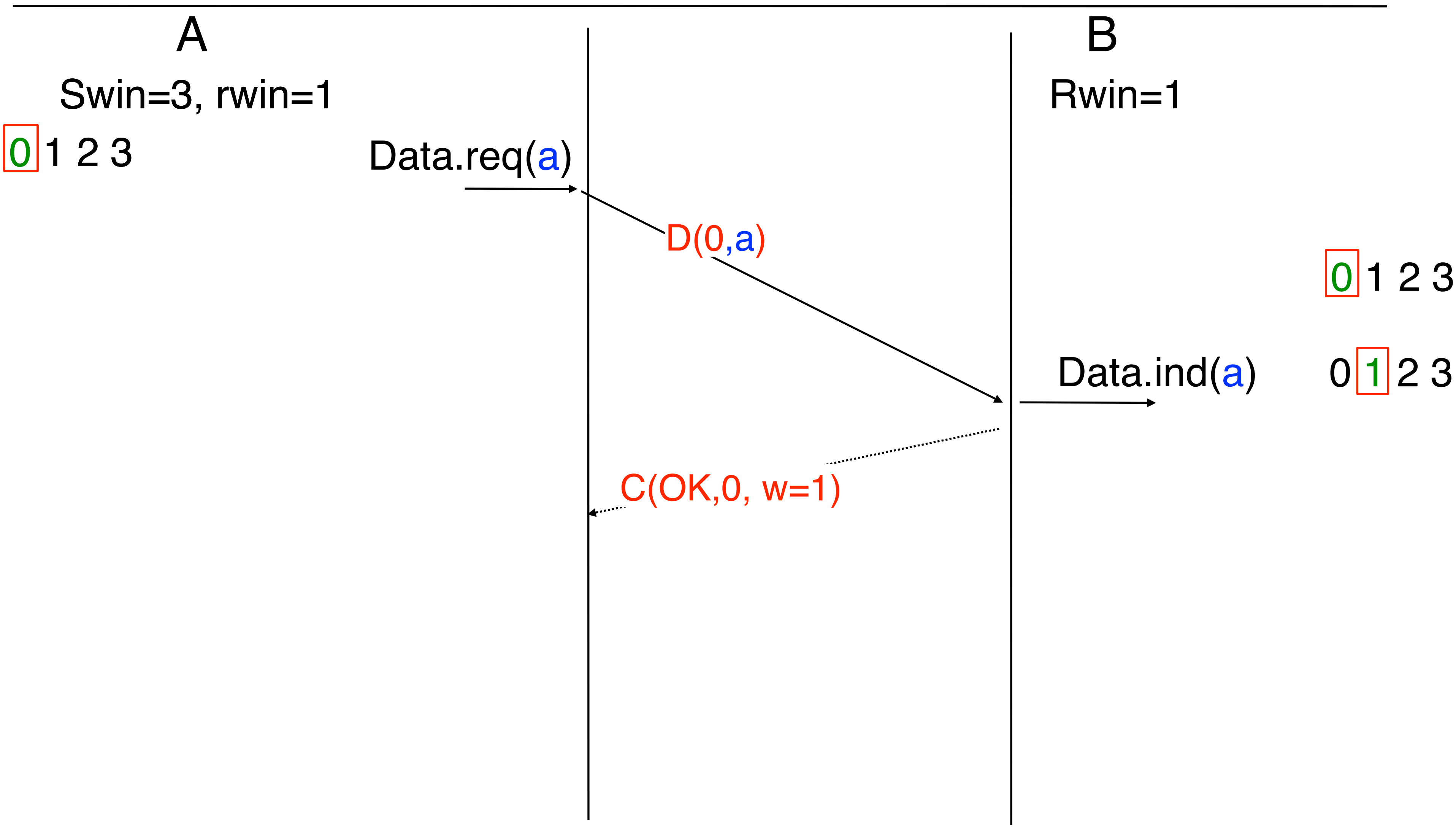
Buffer management (3)



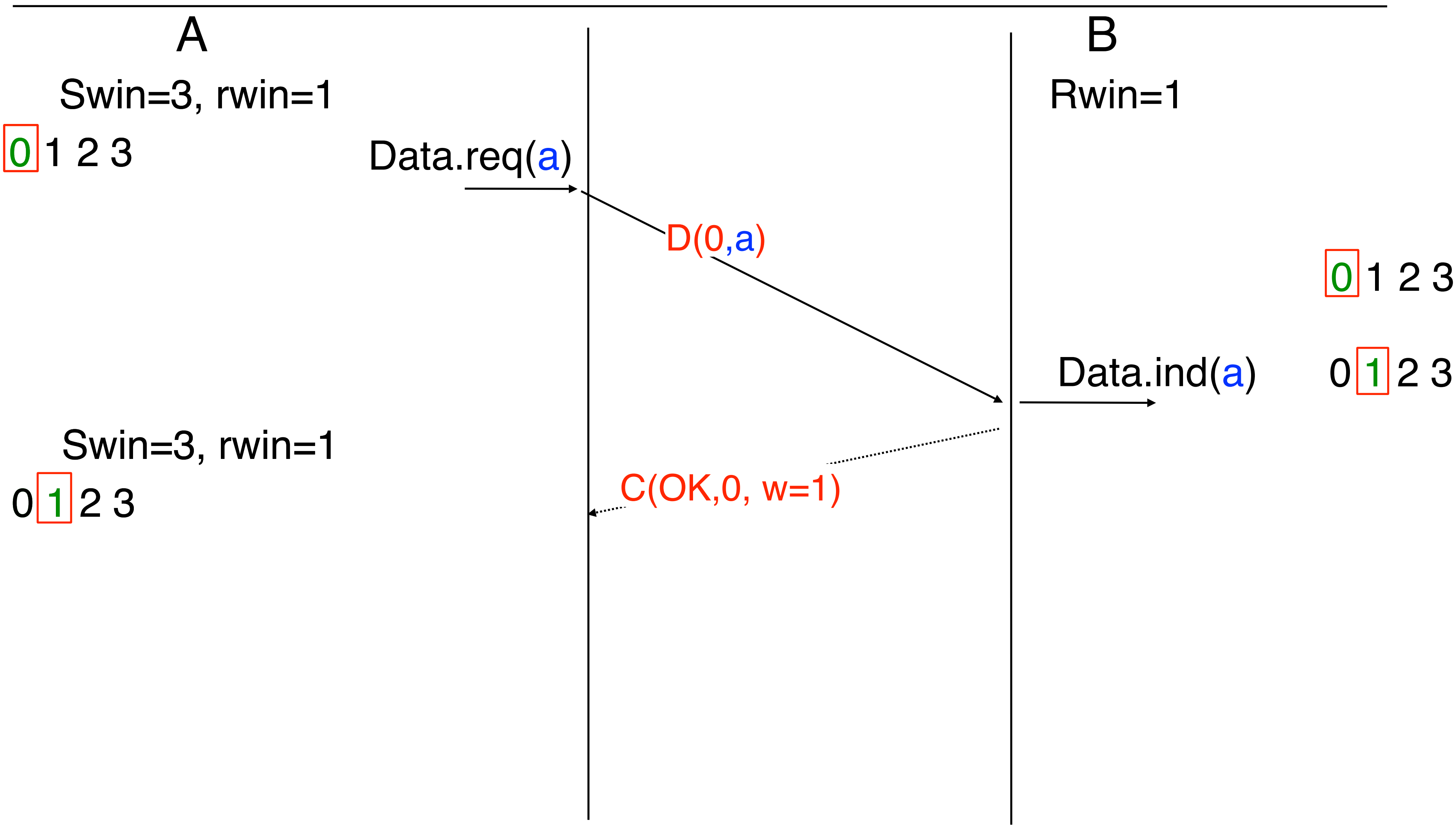
Buffer management (3)



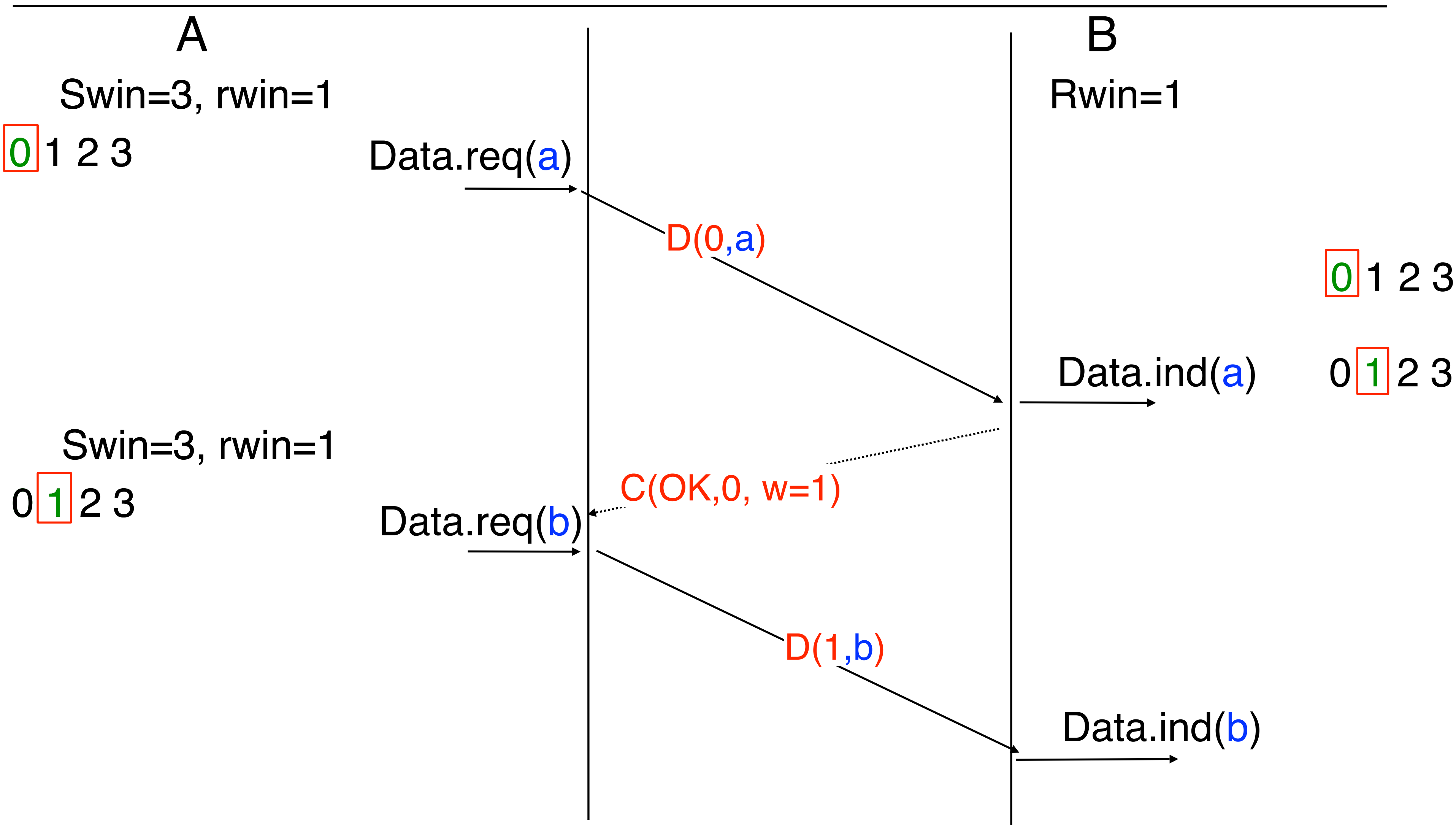
Buffer management (3)



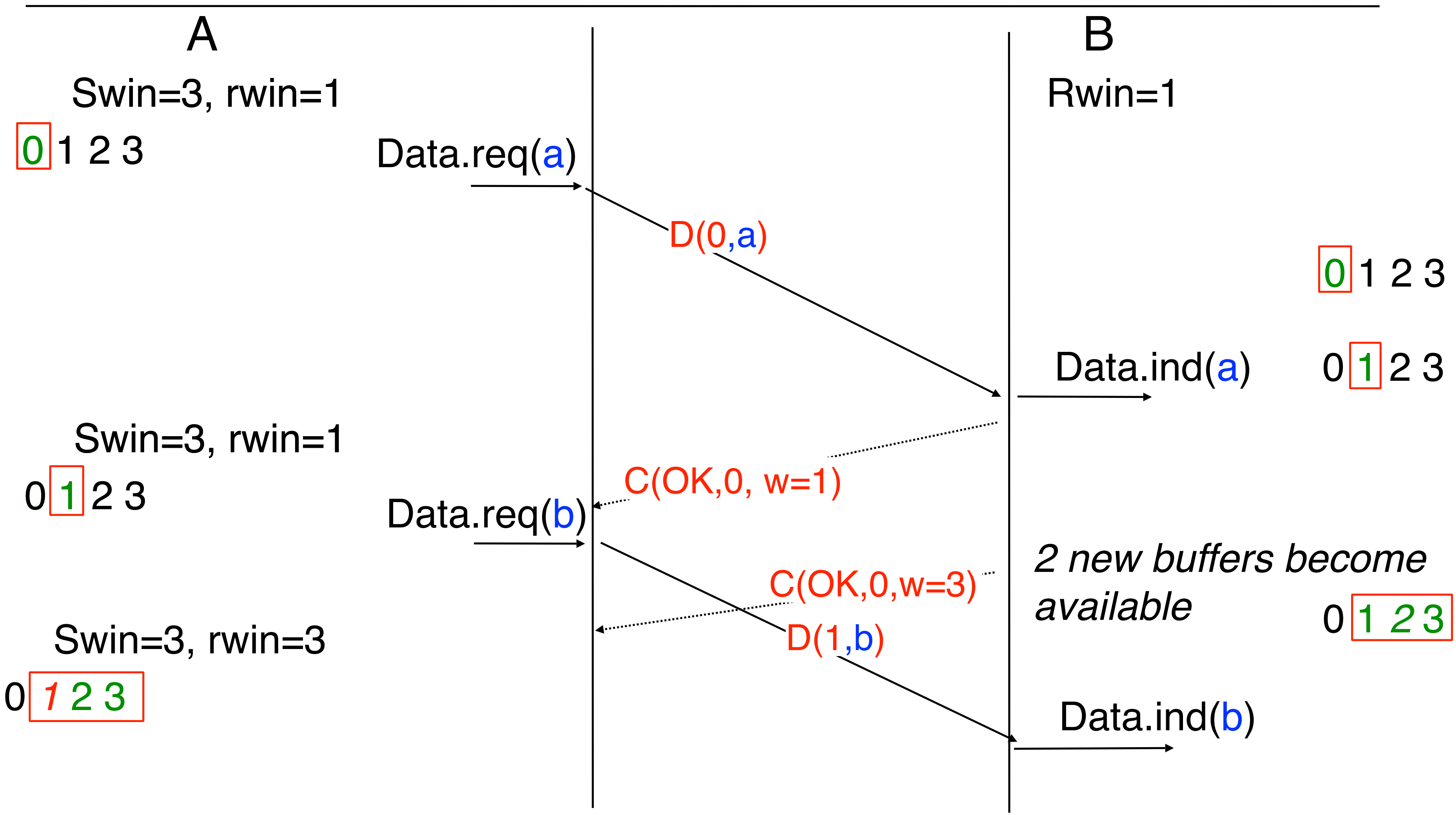
Buffer management (3)



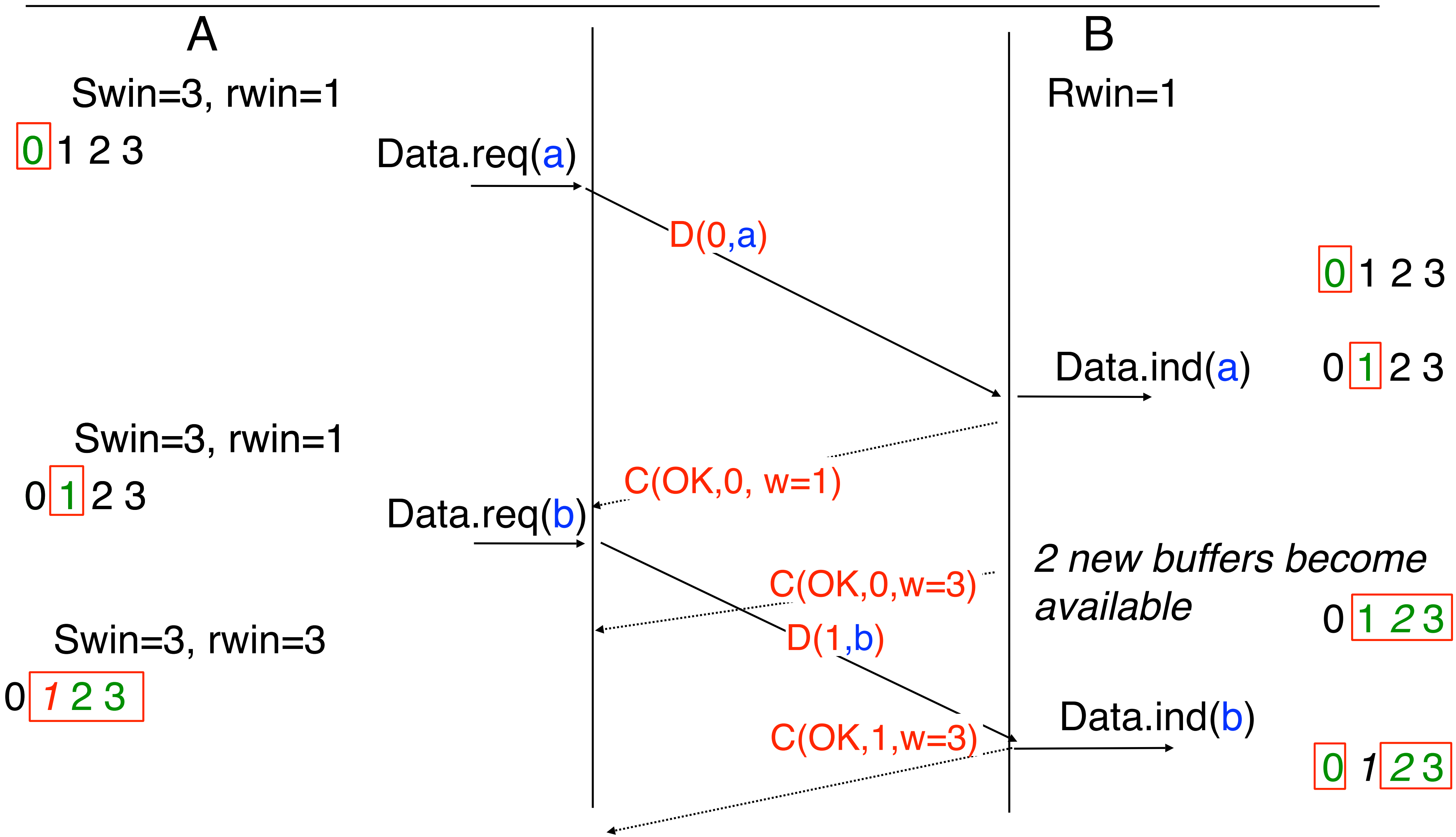
Buffer management (3)



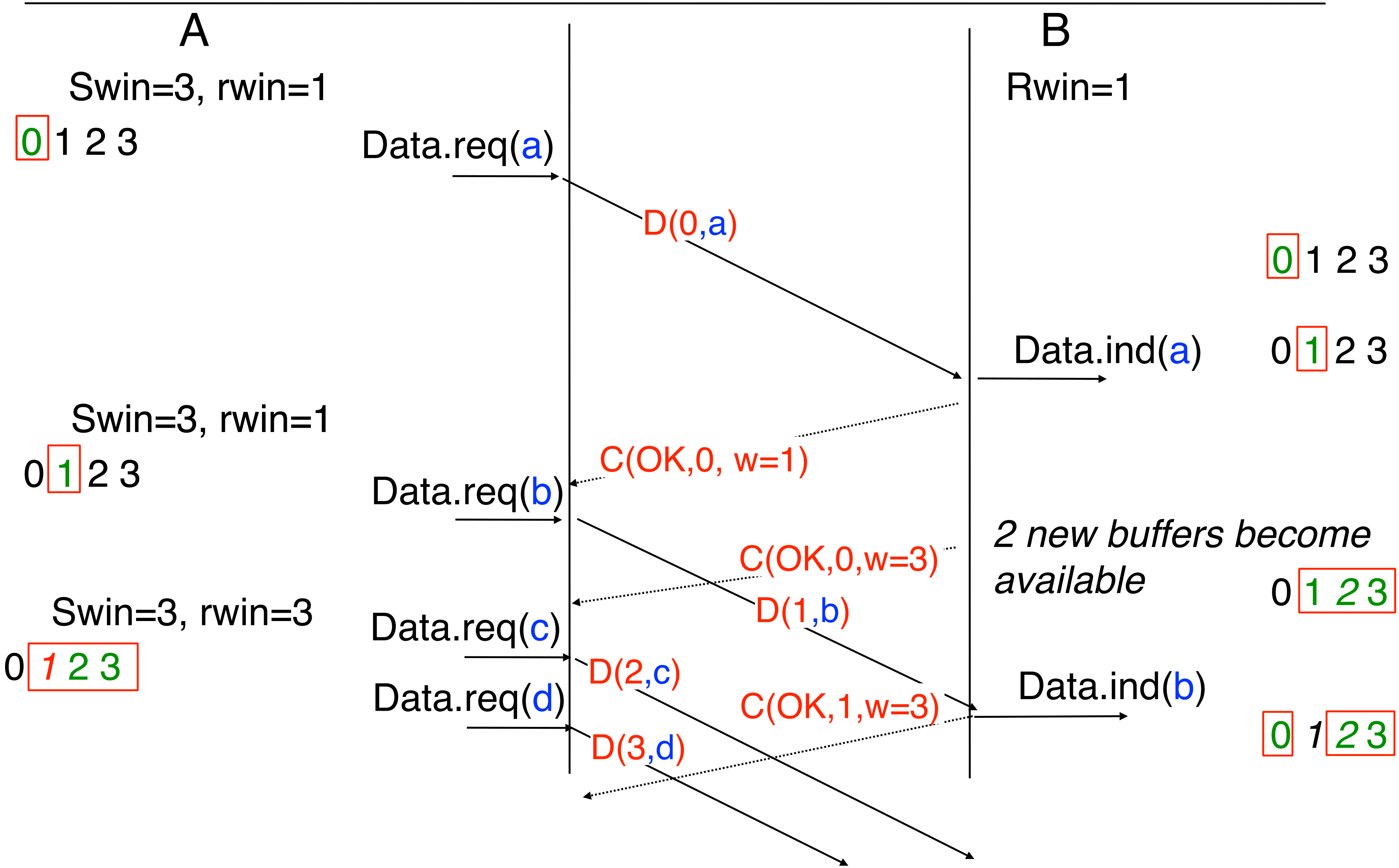
Buffer management (3)



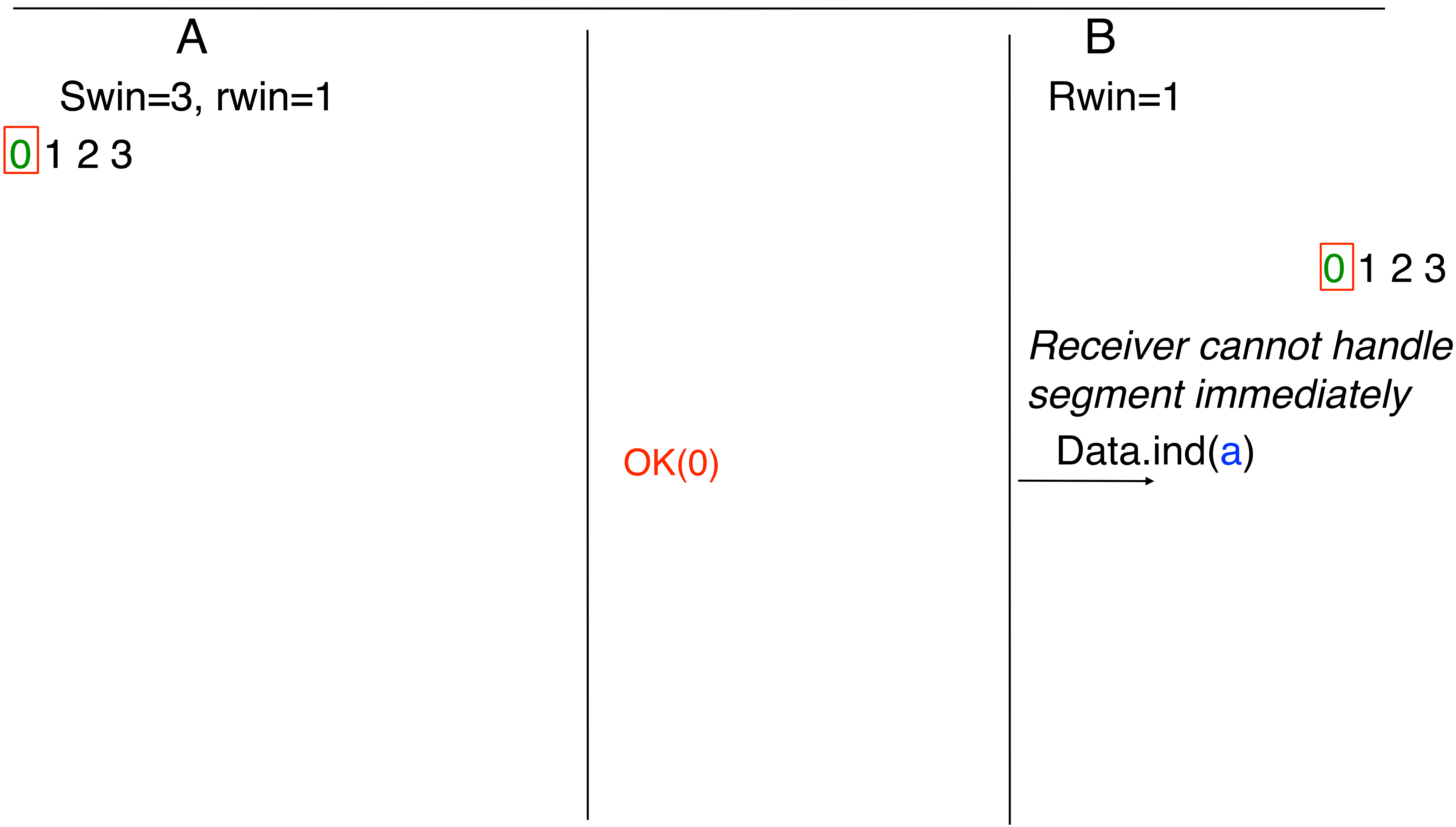
Buffer management (3)



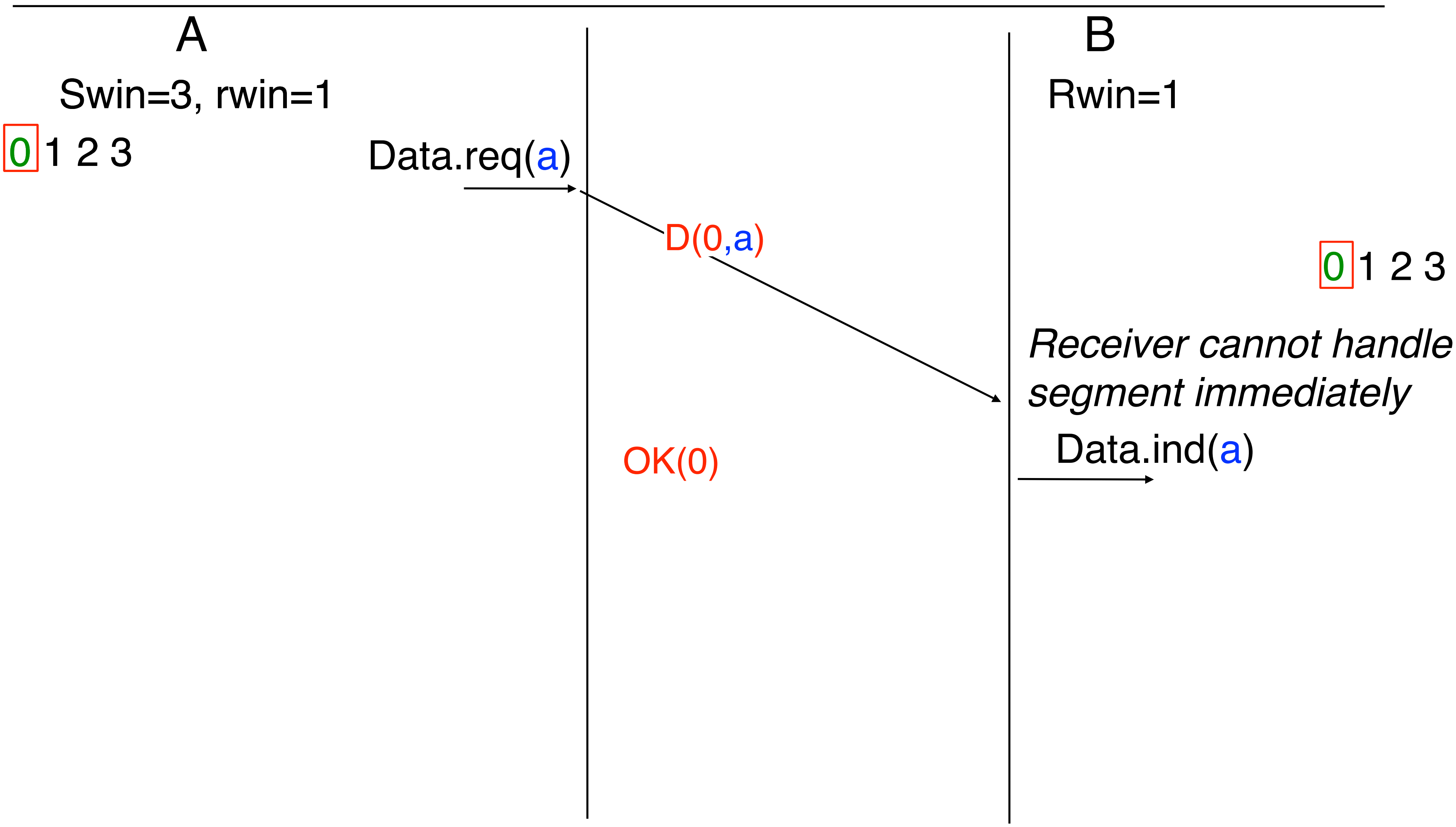
Buffer management (3)



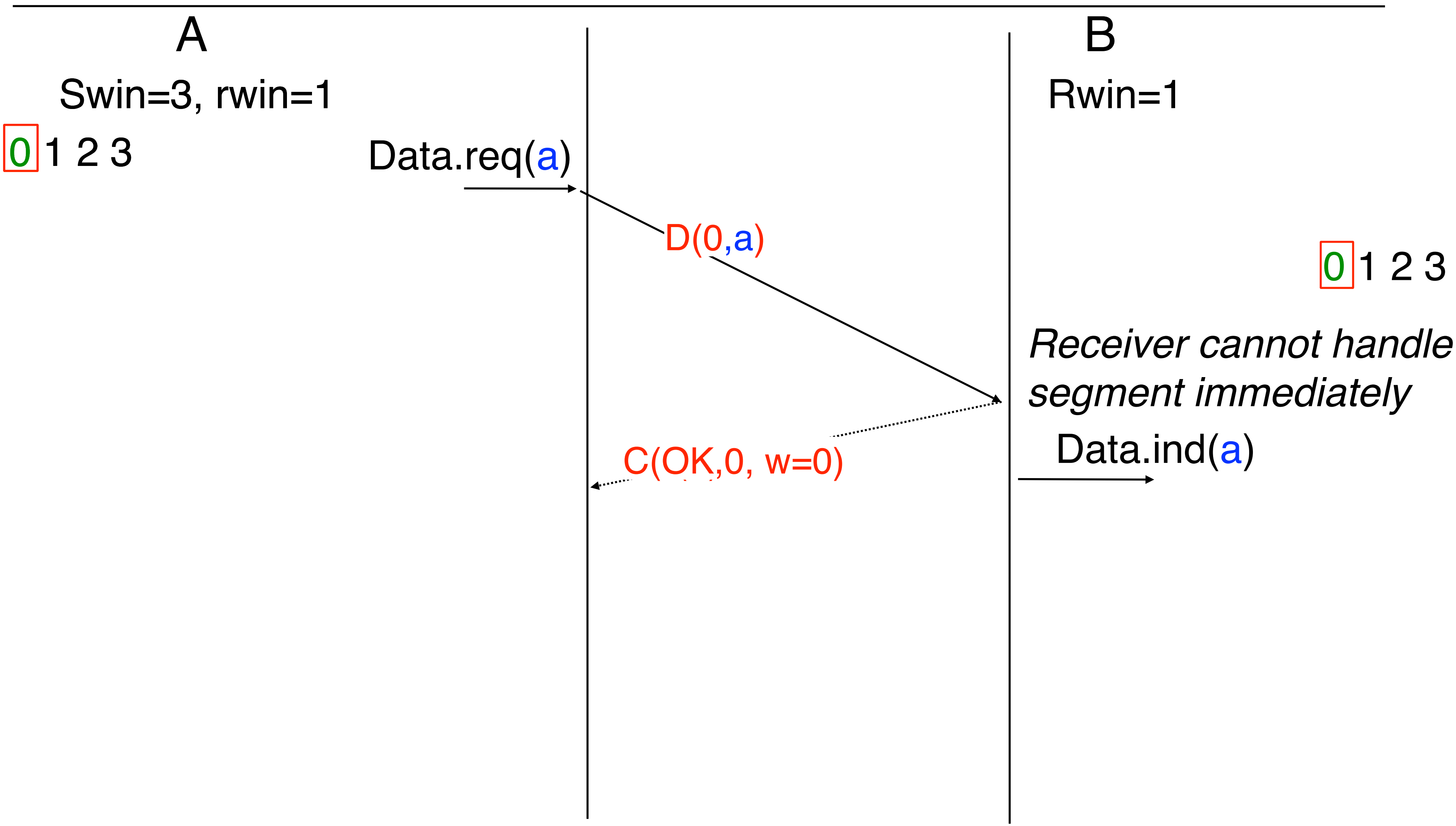
Buffer management (4)



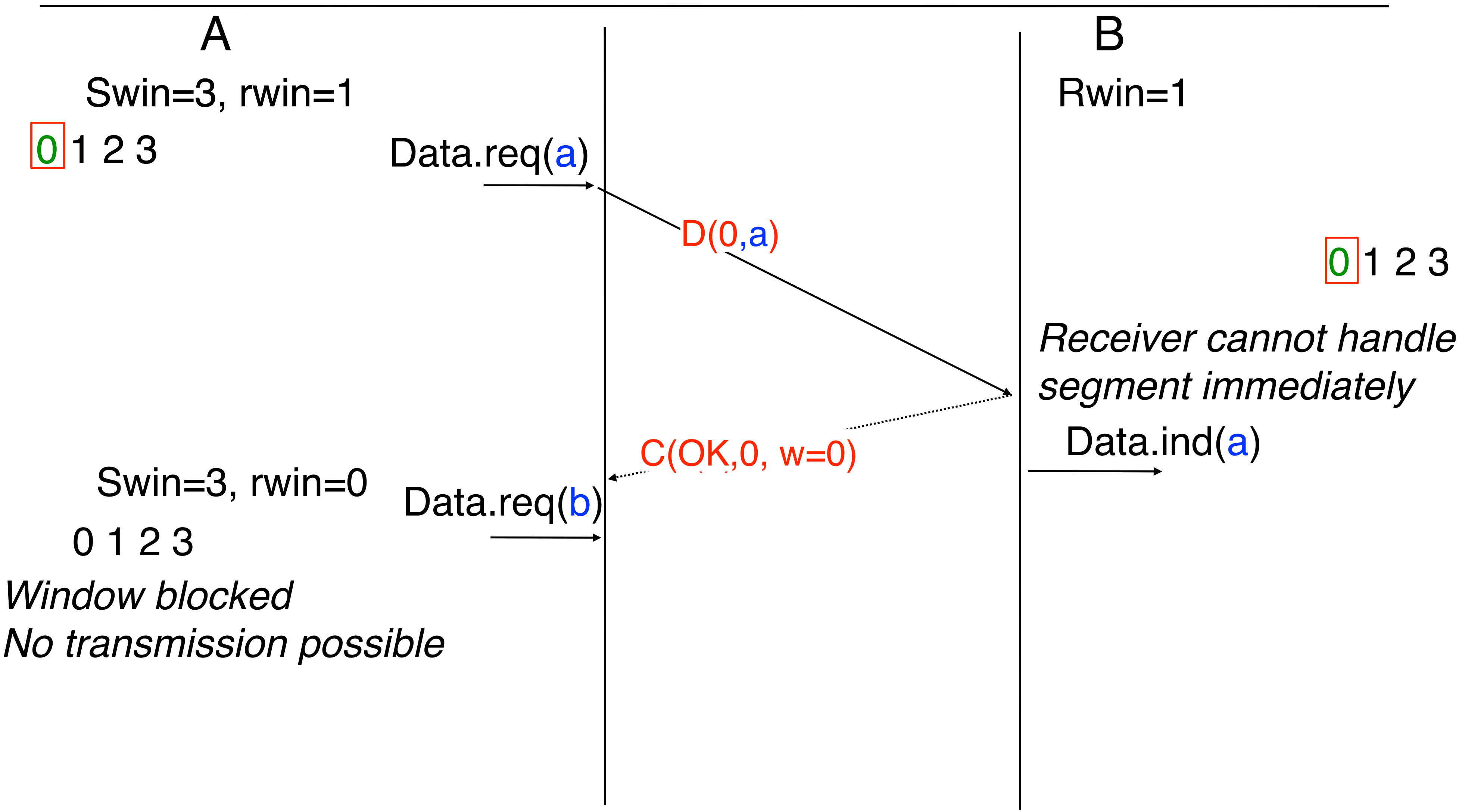
Buffer management (4)



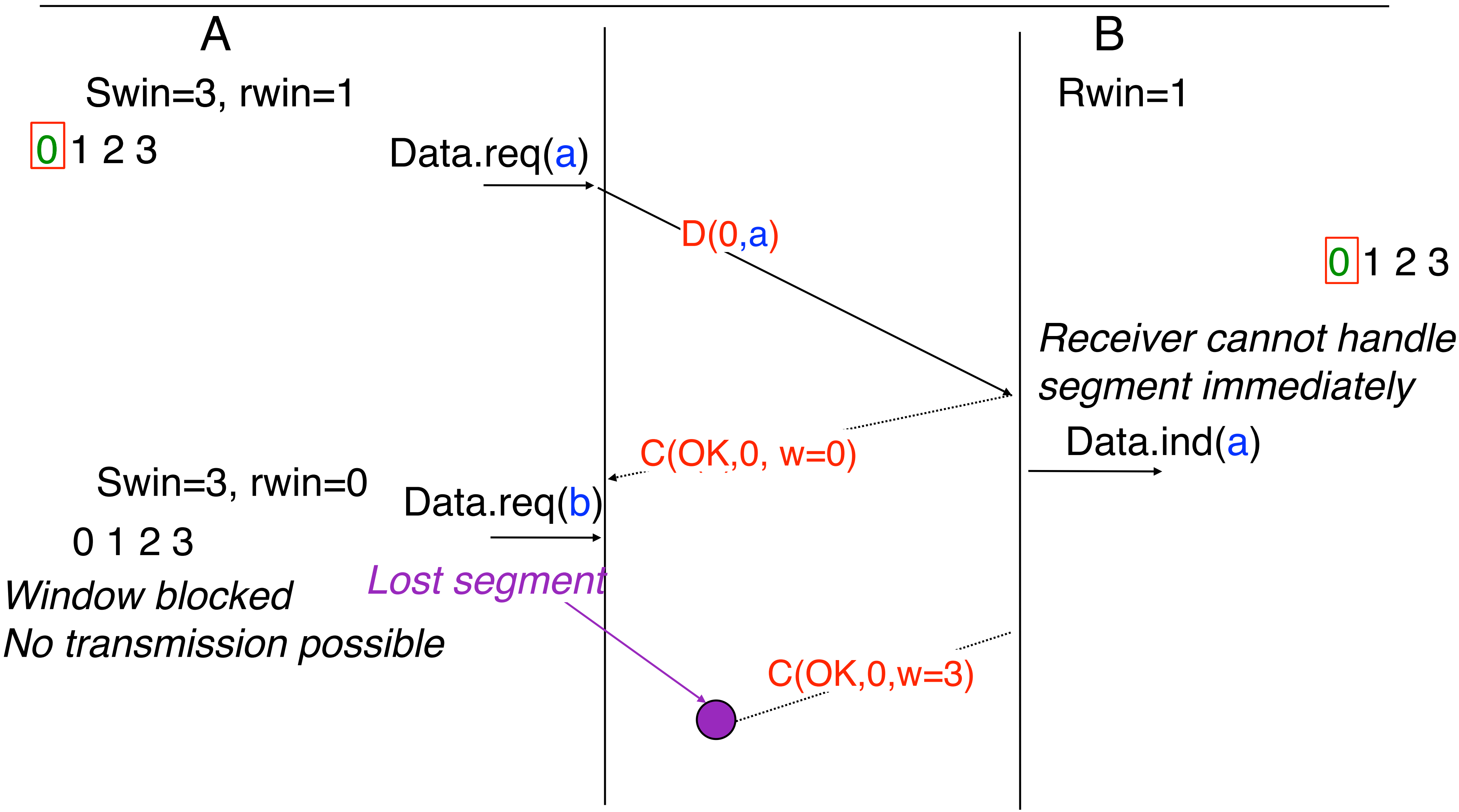
Buffer management (4)



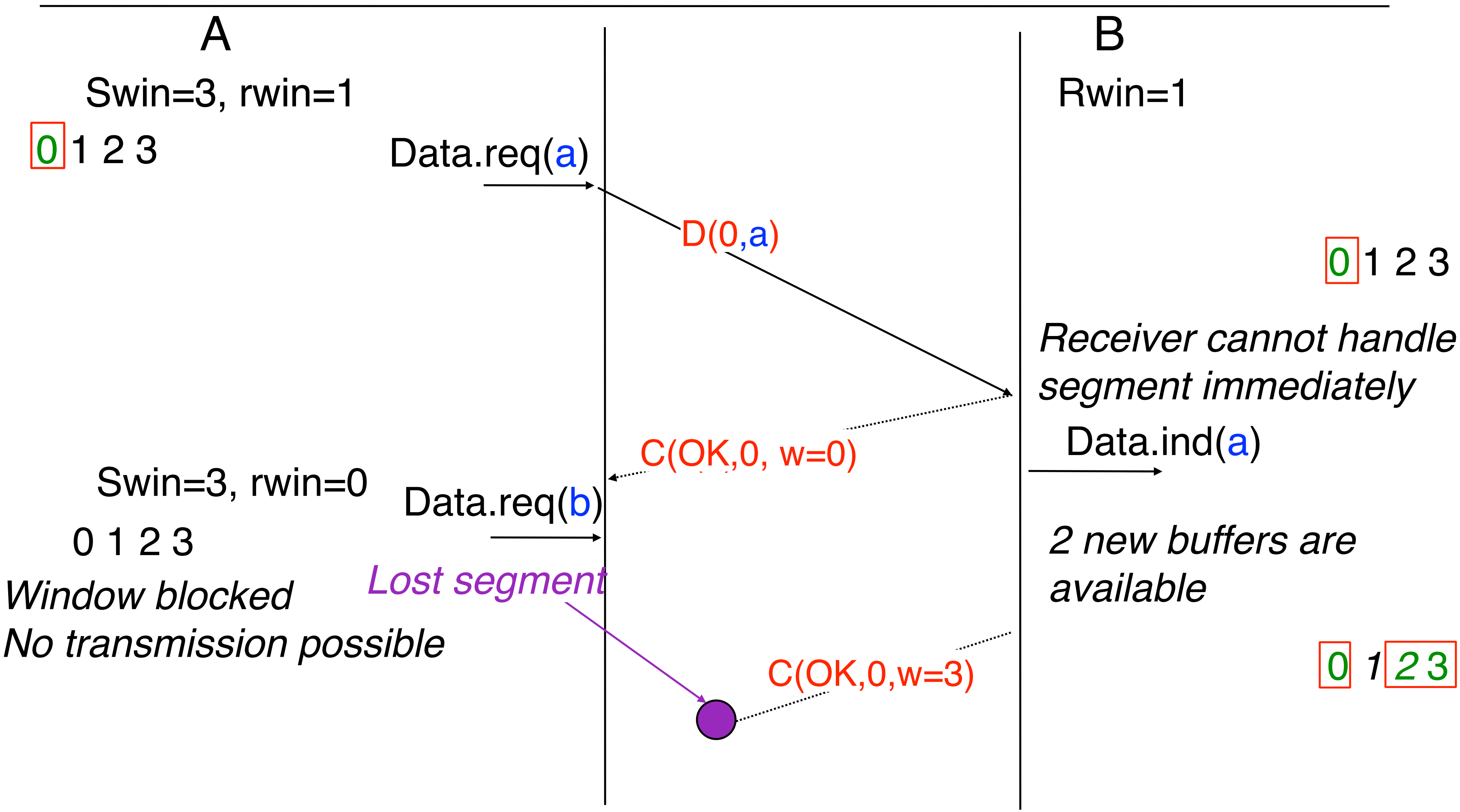
Buffer management (4)



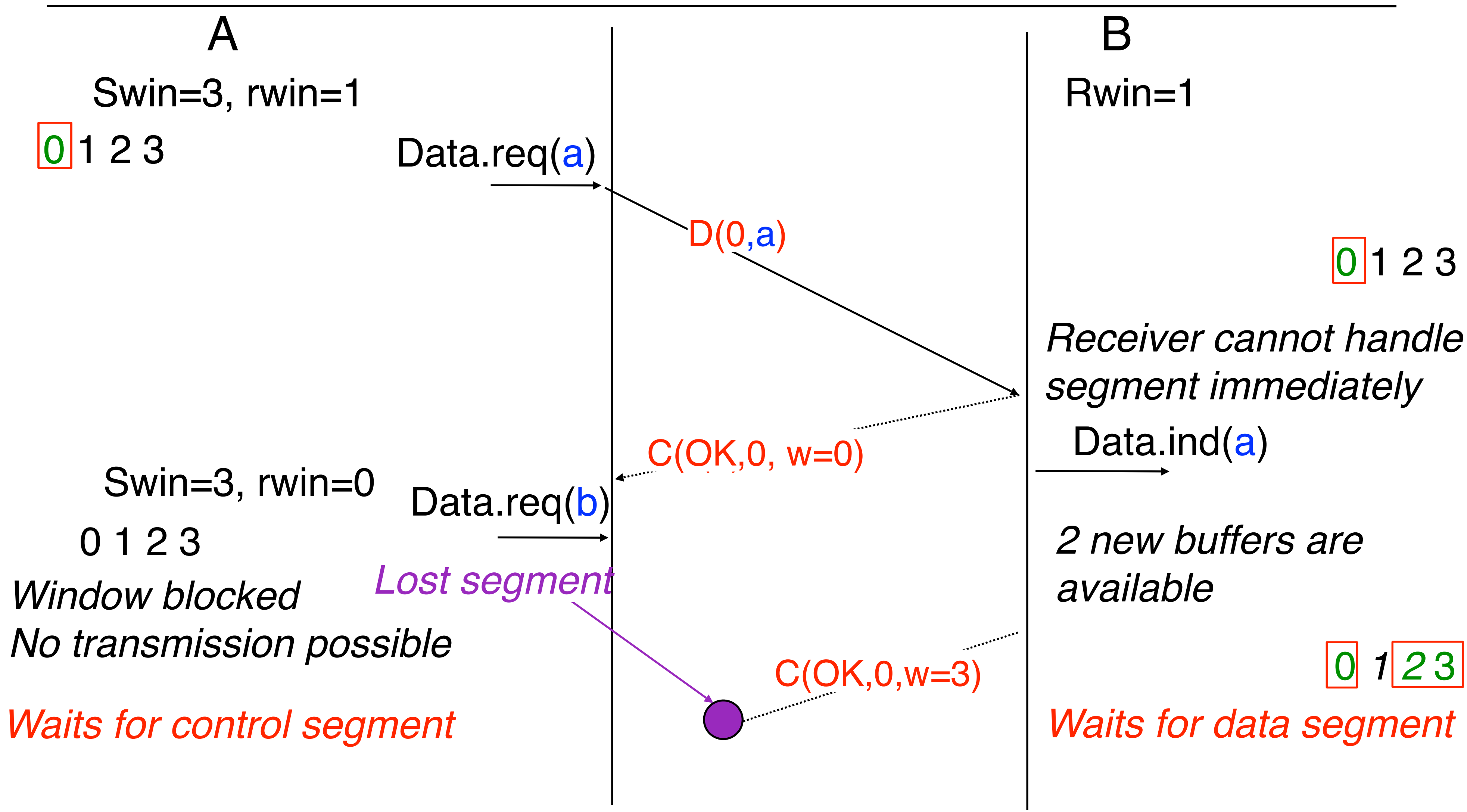
Buffer management (4)



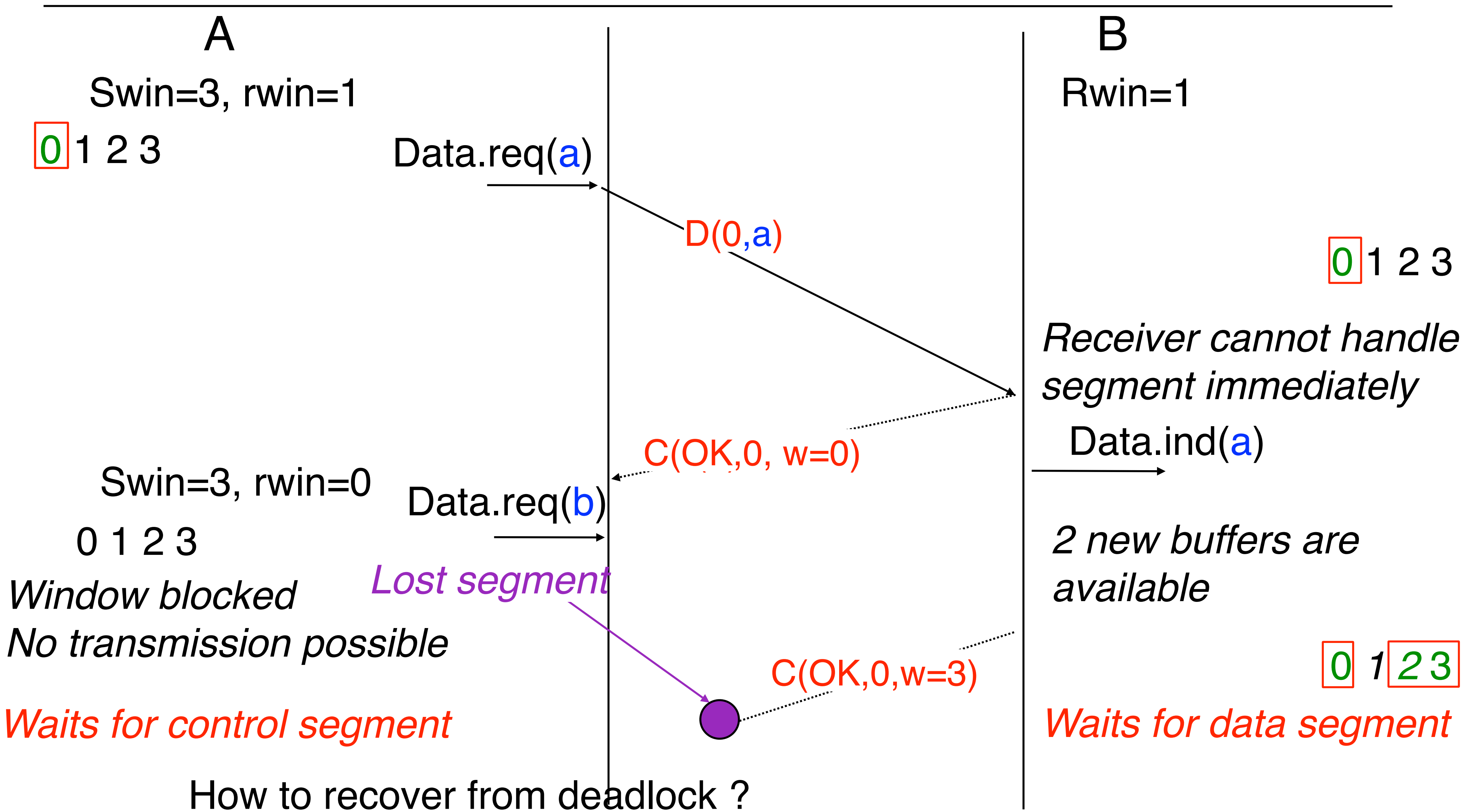
Buffer management (4)



Buffer management (4)



Buffer management (4)



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

Duplication and reordering

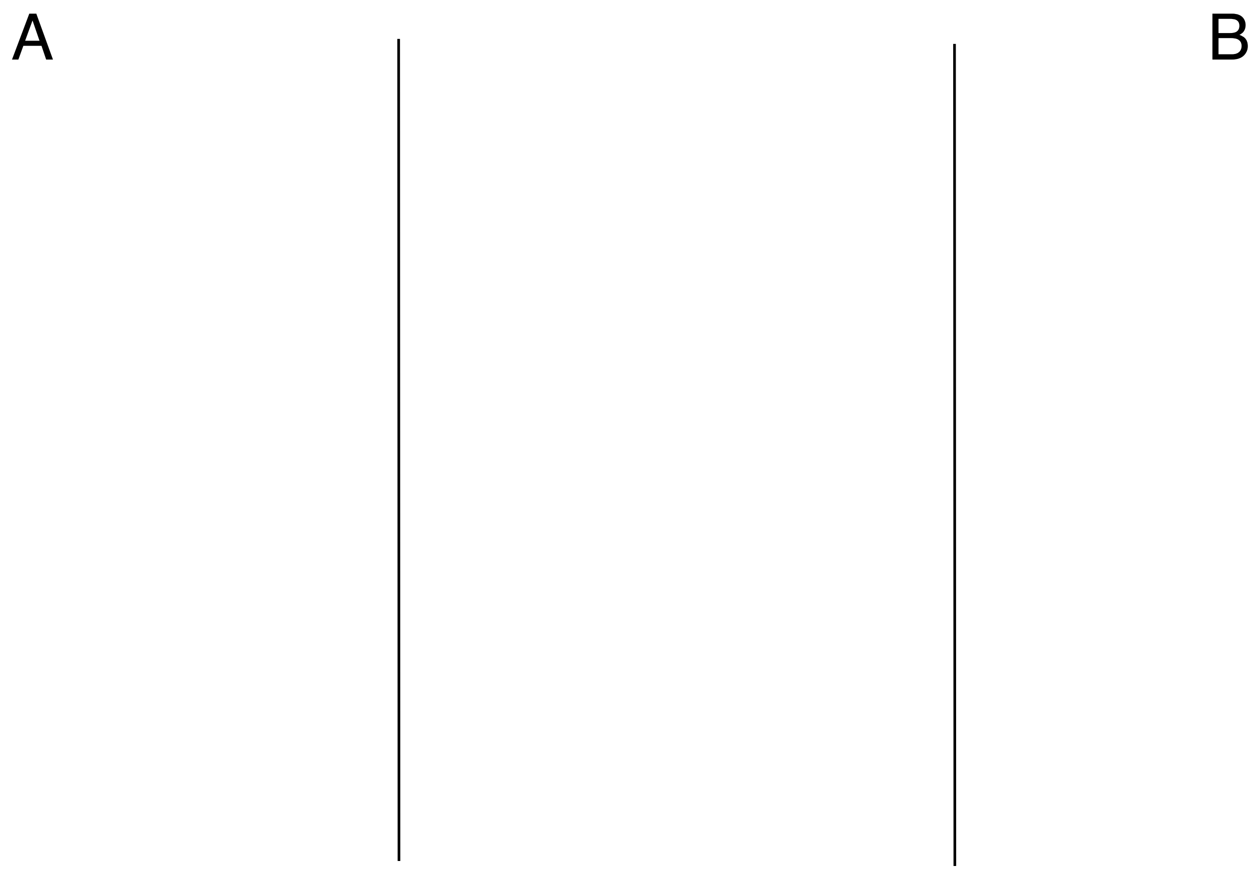
- How can we provide a reliable service in the transport layer ?

- 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)

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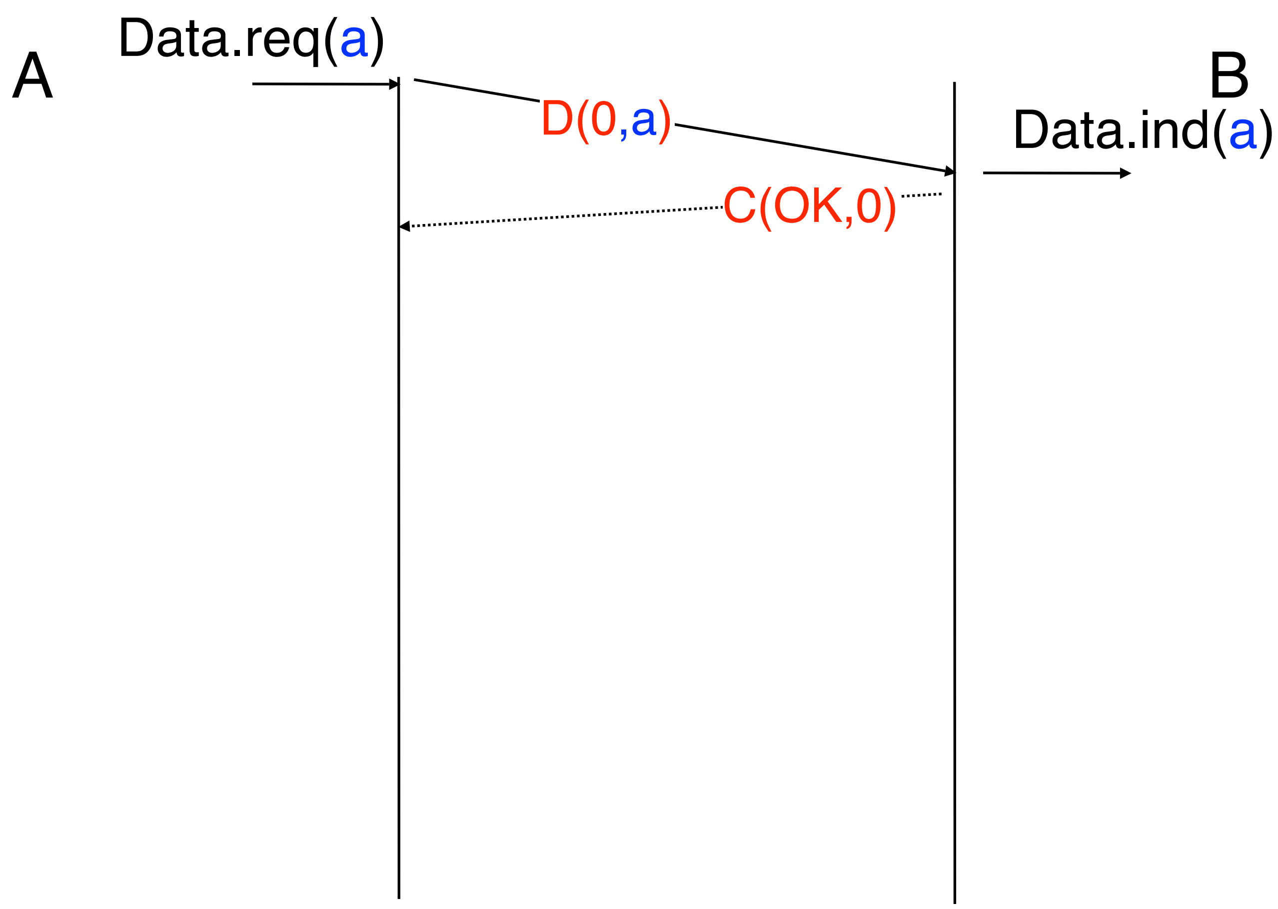
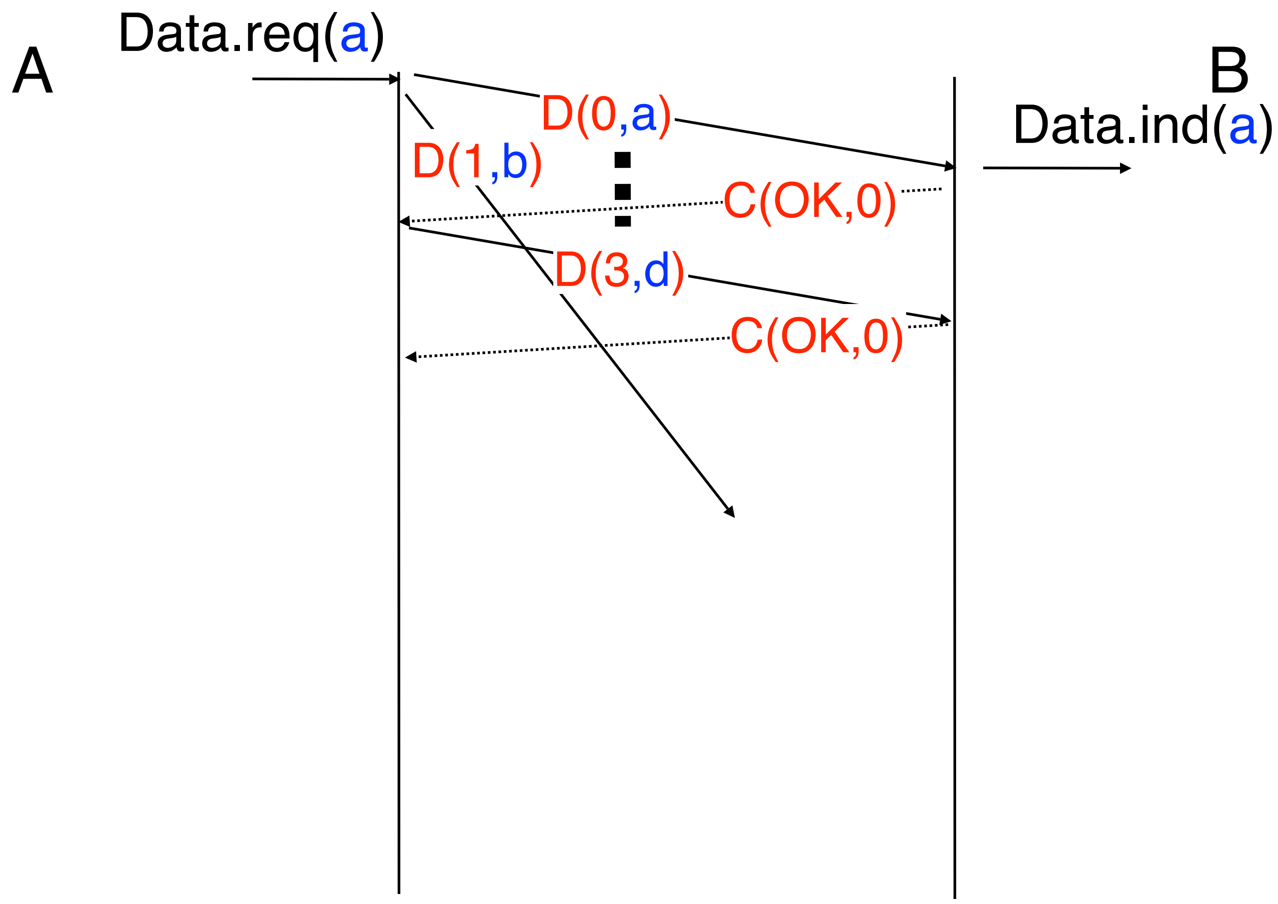


Duplication and reordering (2)

- Problem
  - A late segment could be confused with a valid segment



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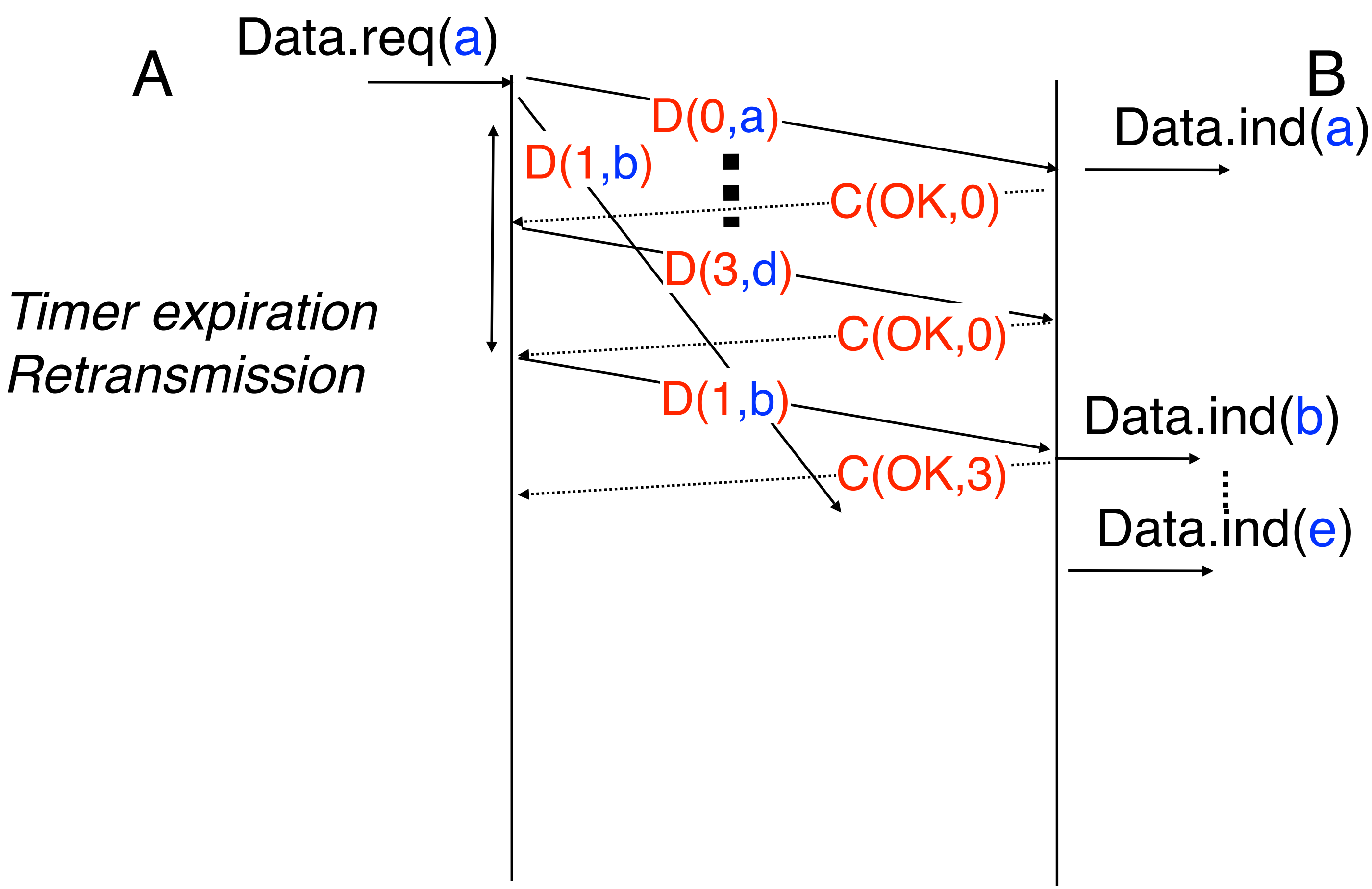

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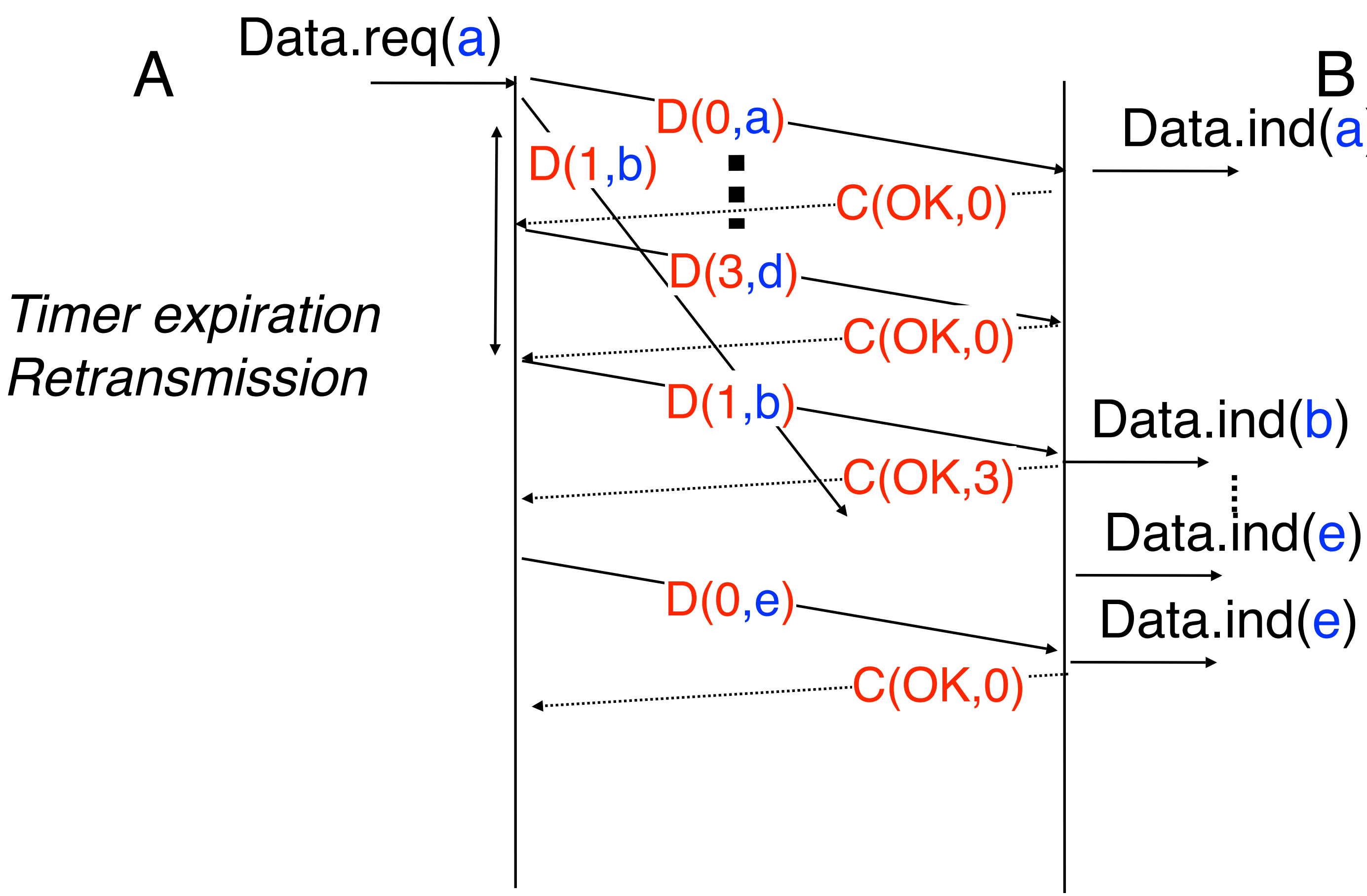

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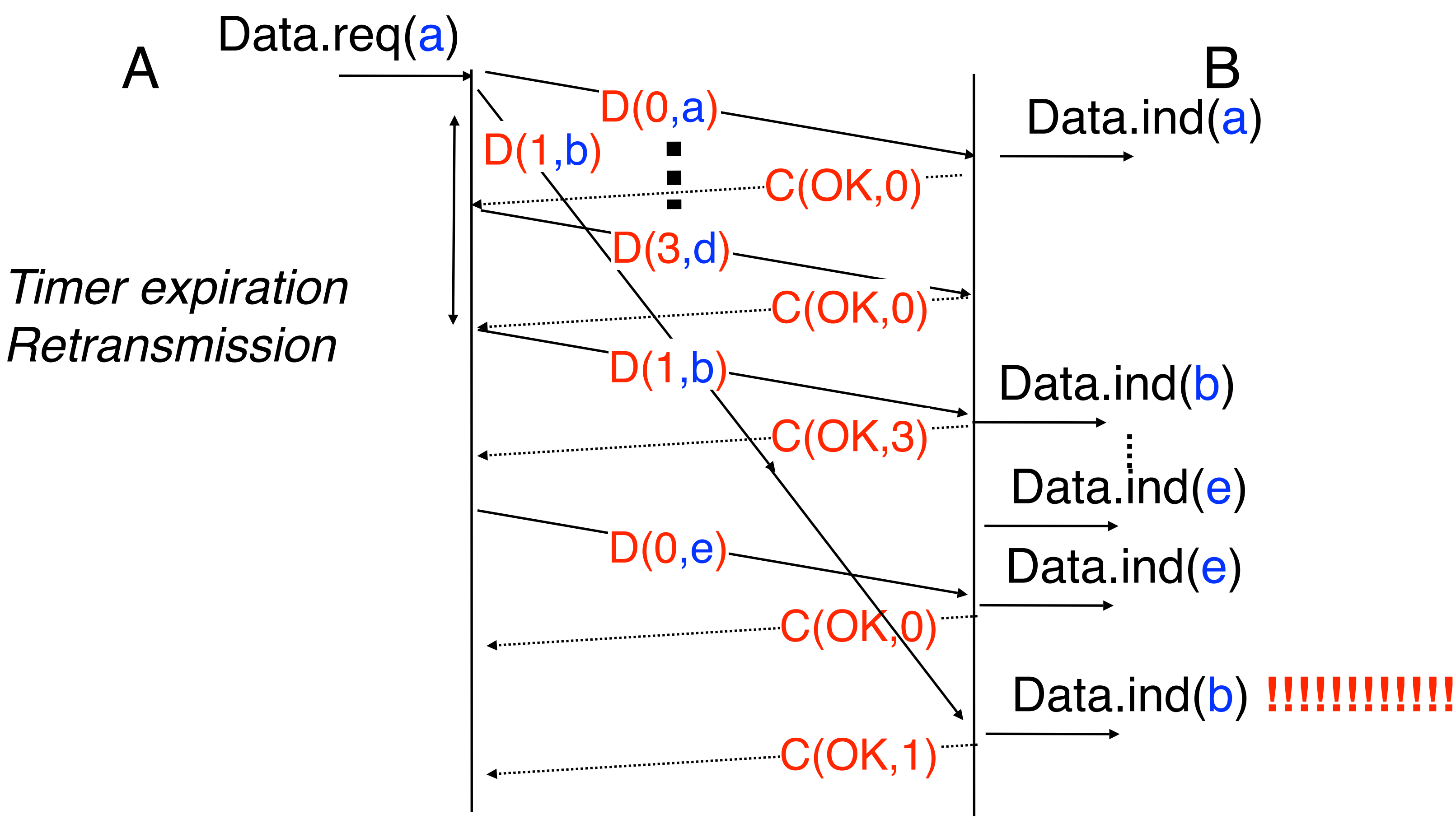


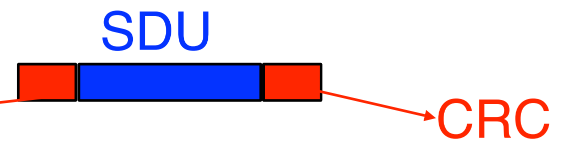
Duplication and reordering (3)

- 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

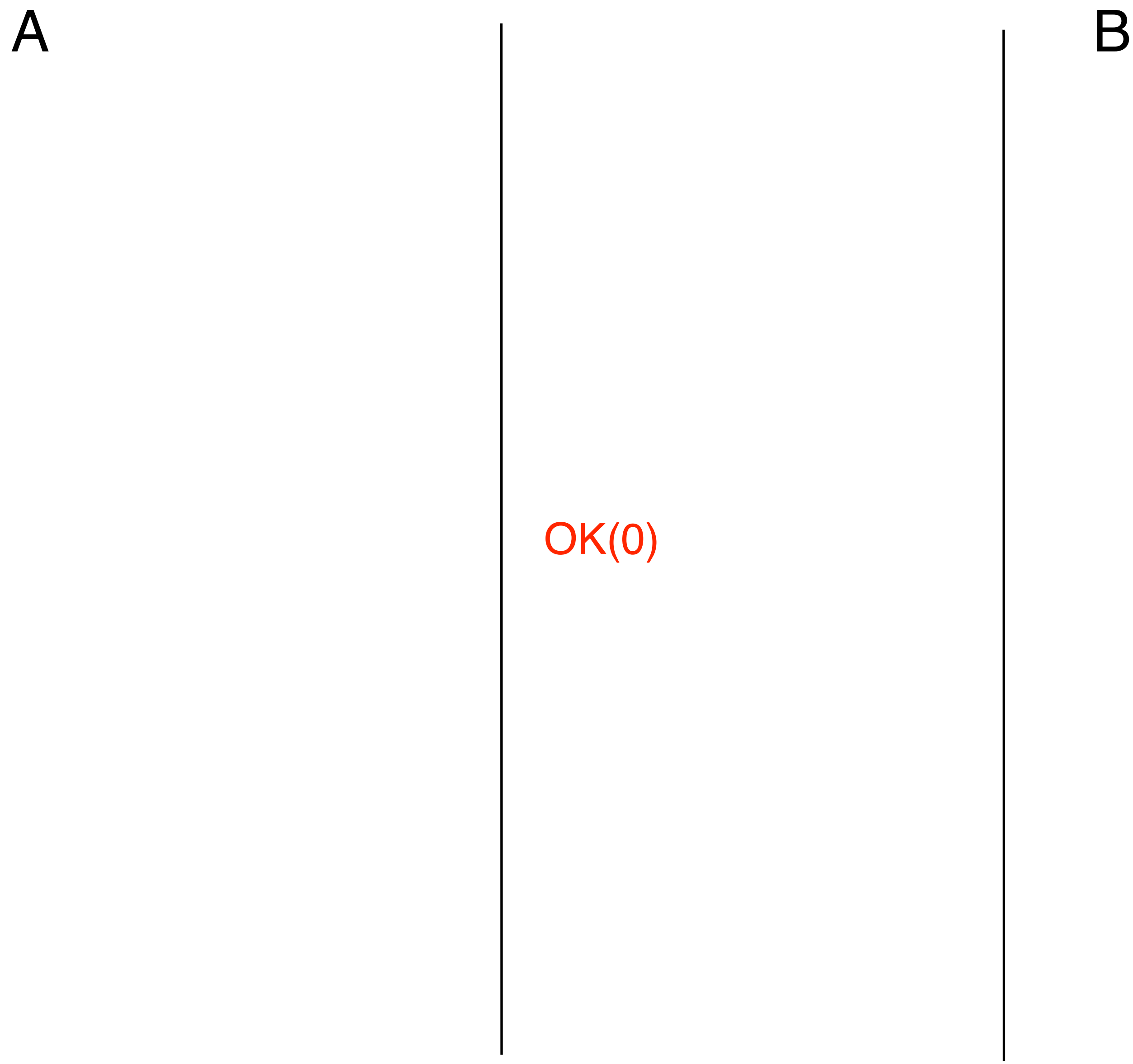
- How can we allow both hosts to transmit data ?

- 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



Seq : segment's sequence number
Ack : sequence number of the last received in-order segment

Bidirectional flow
Example



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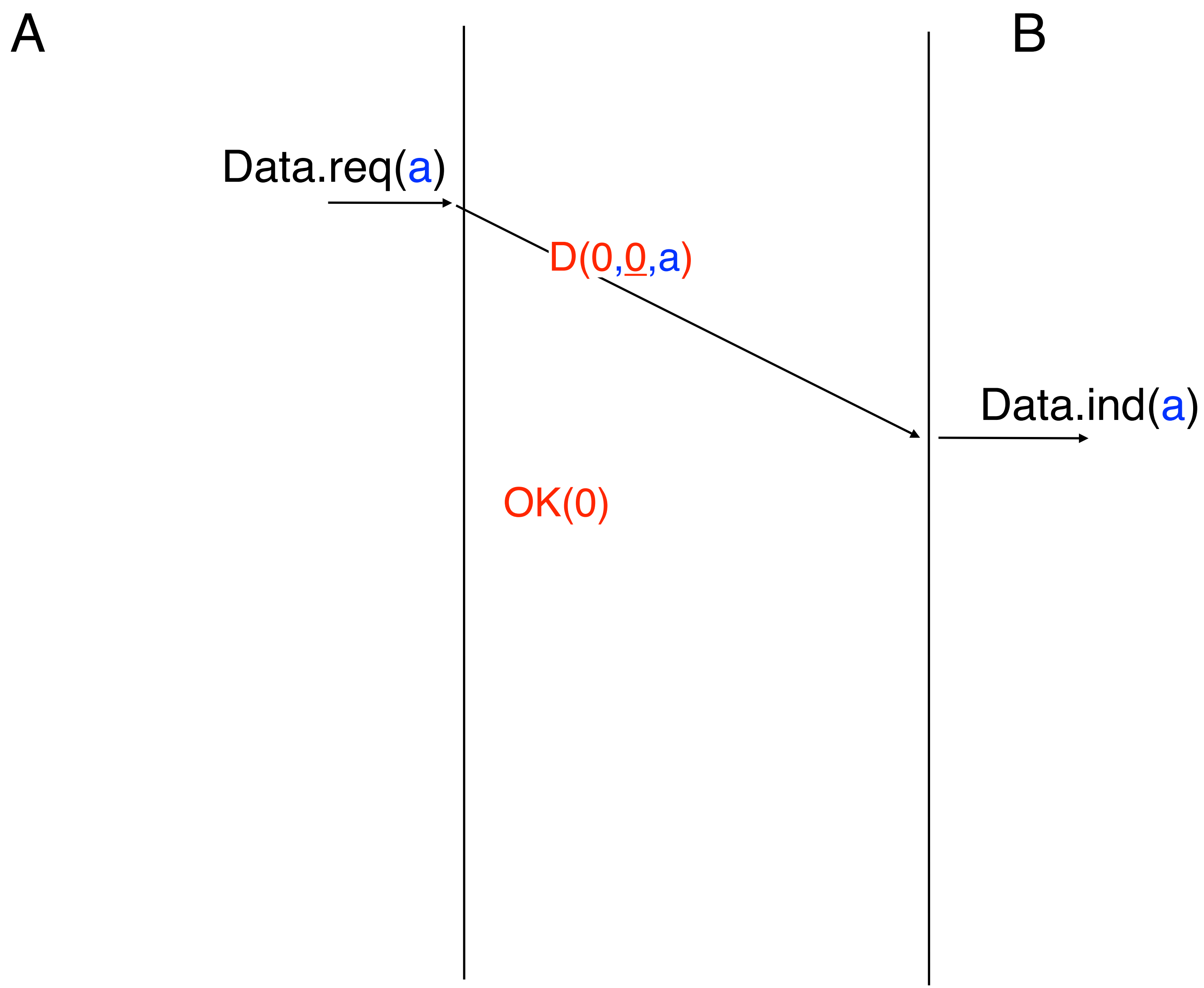

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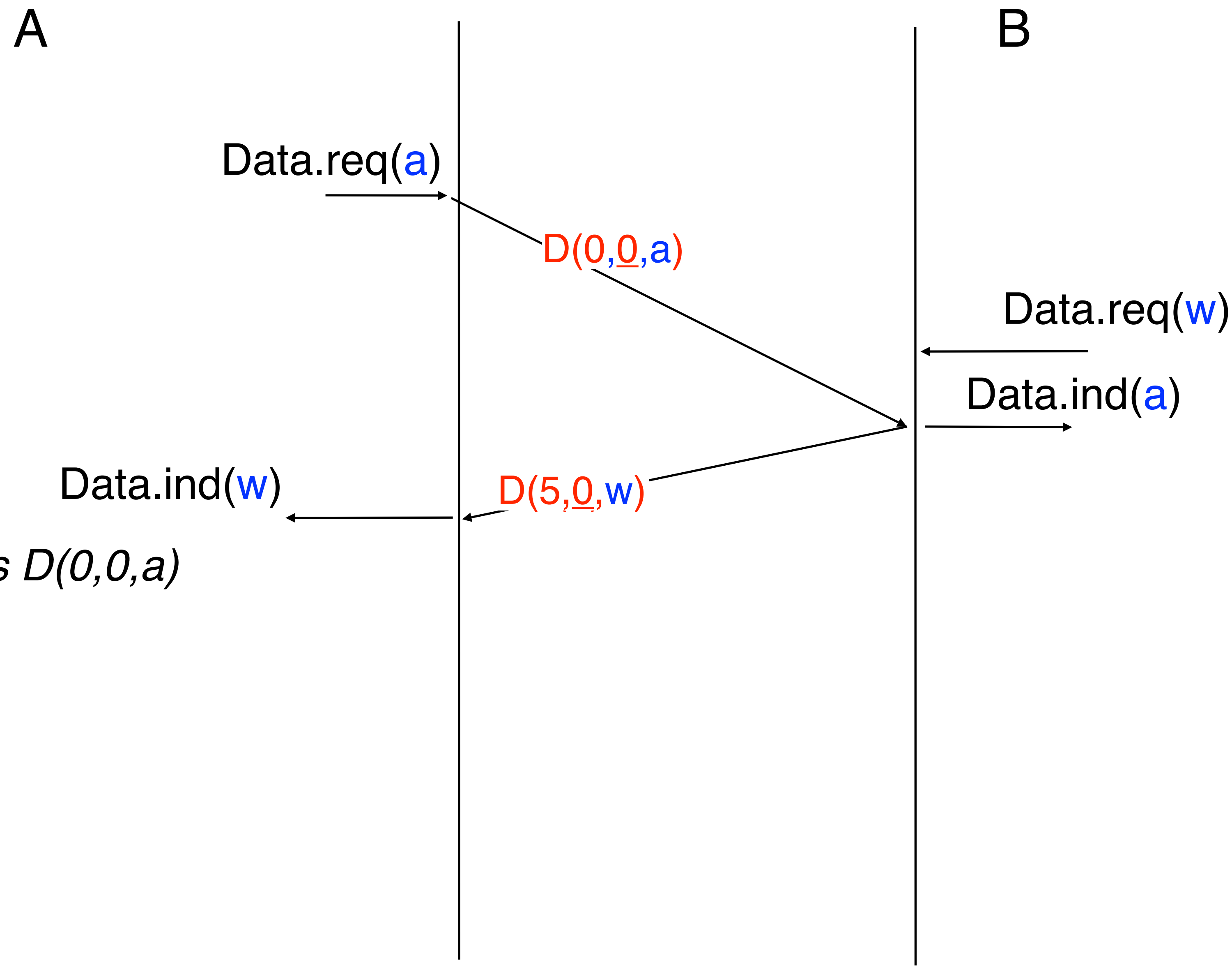
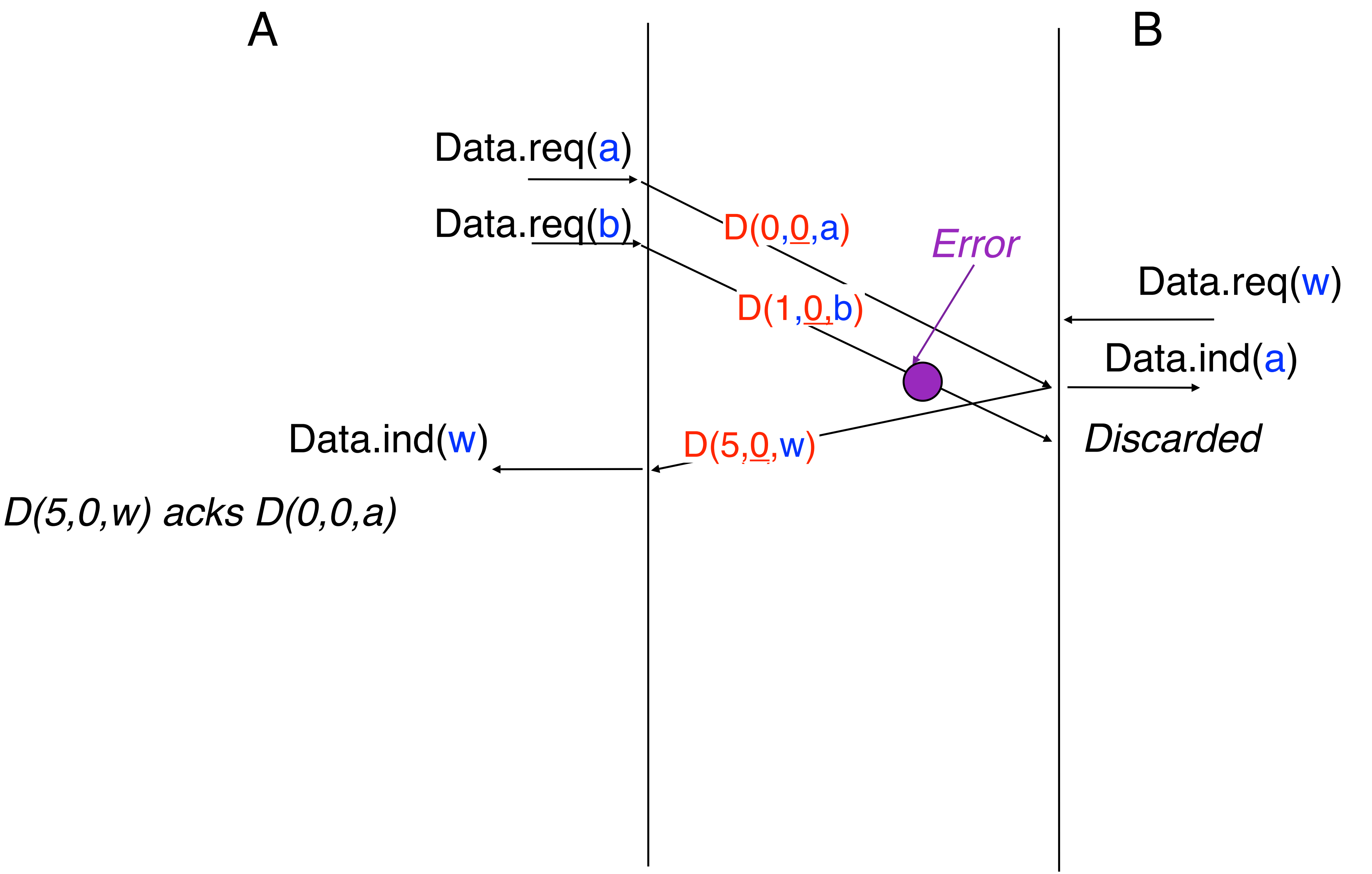


D(5,0,w) acks D(0,0,a)

Bidirectional flow Example



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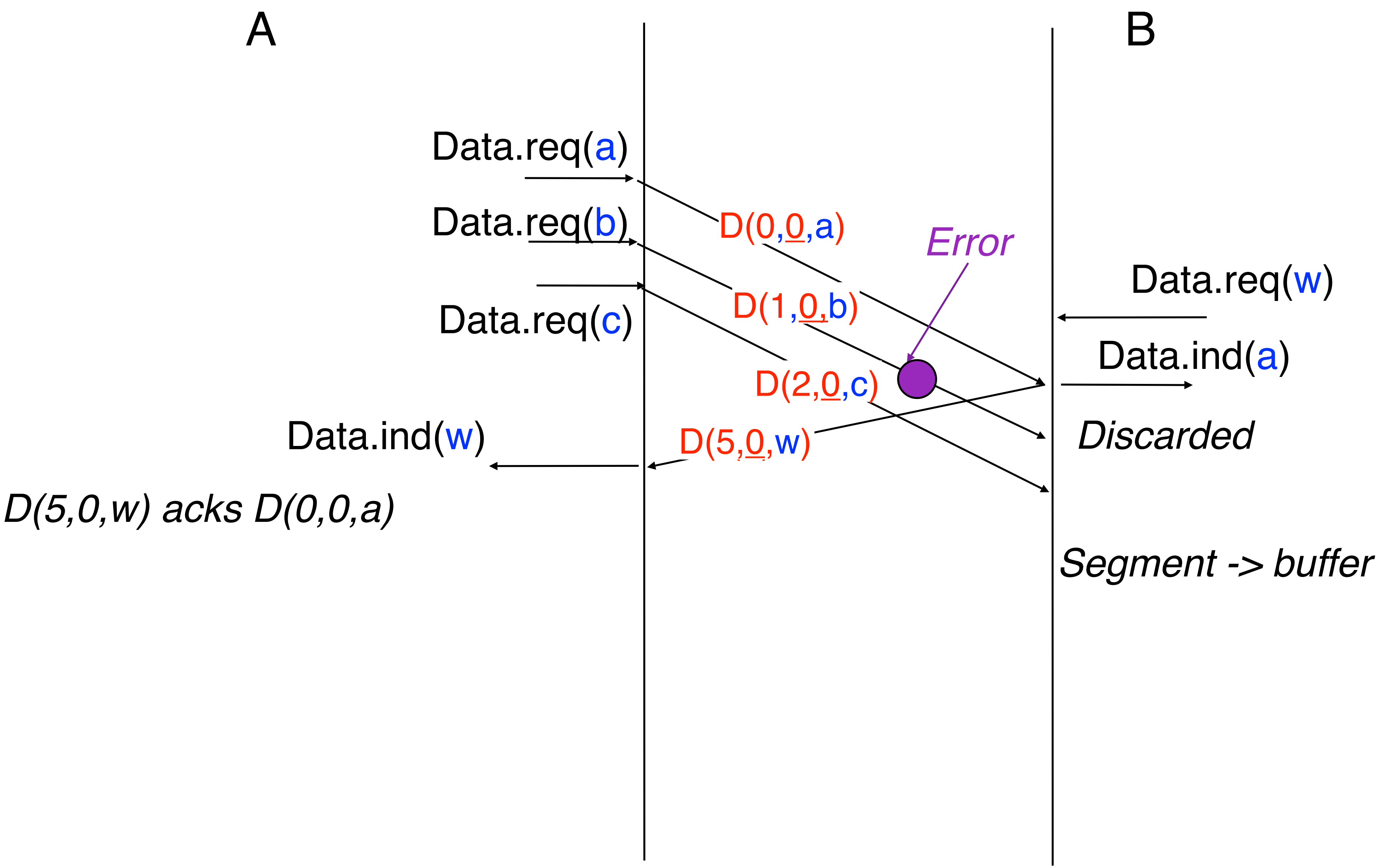

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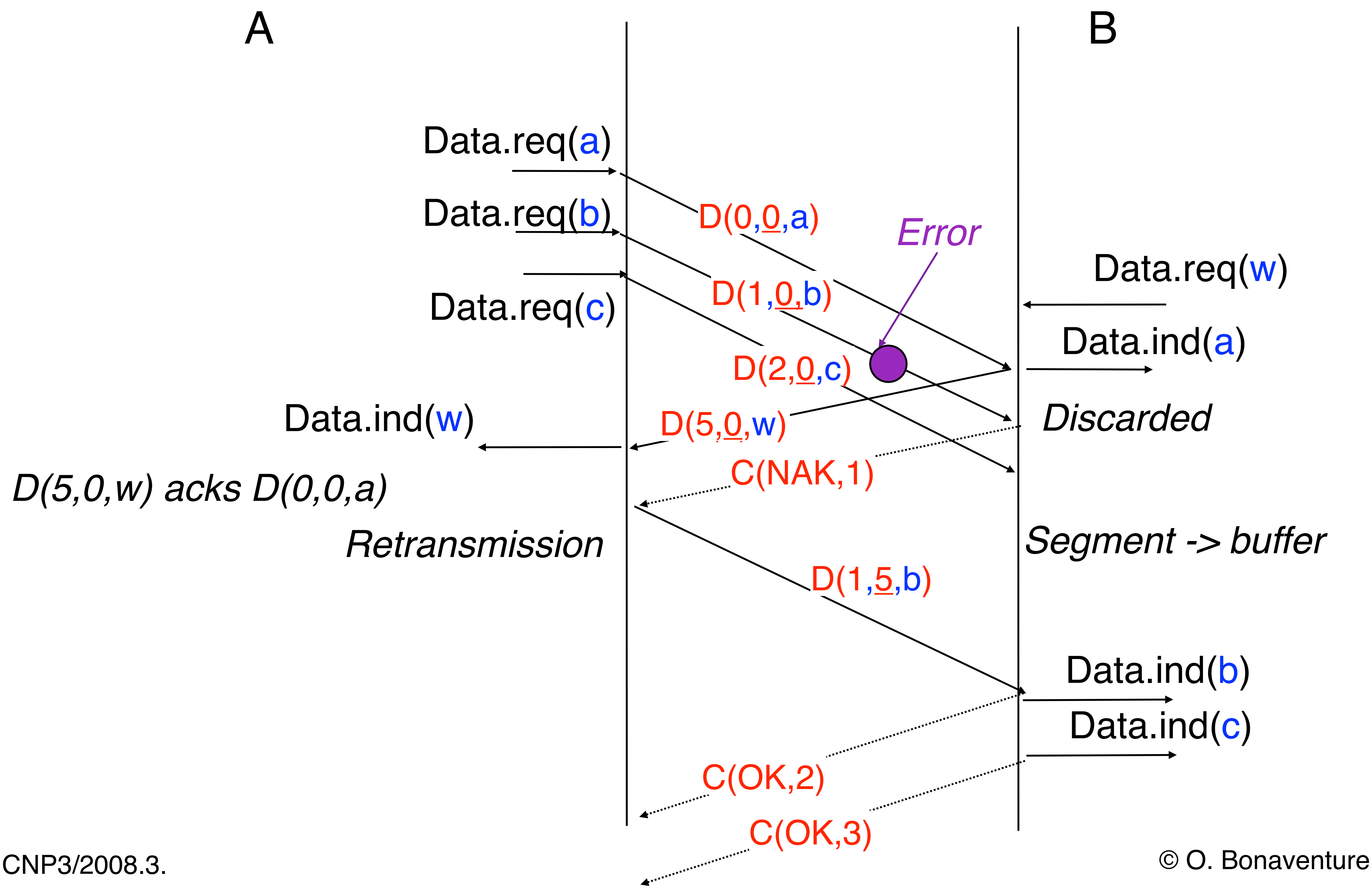
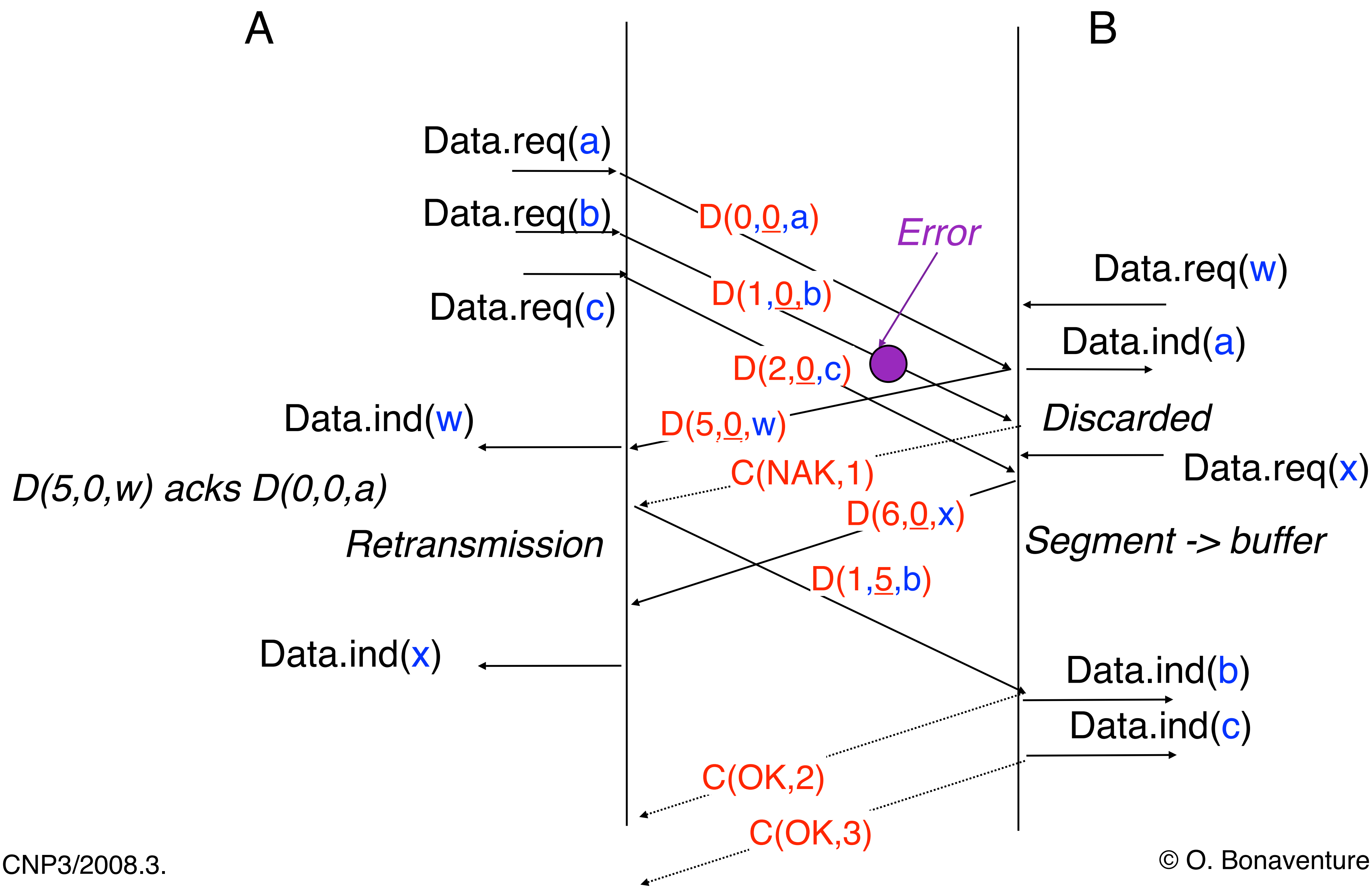
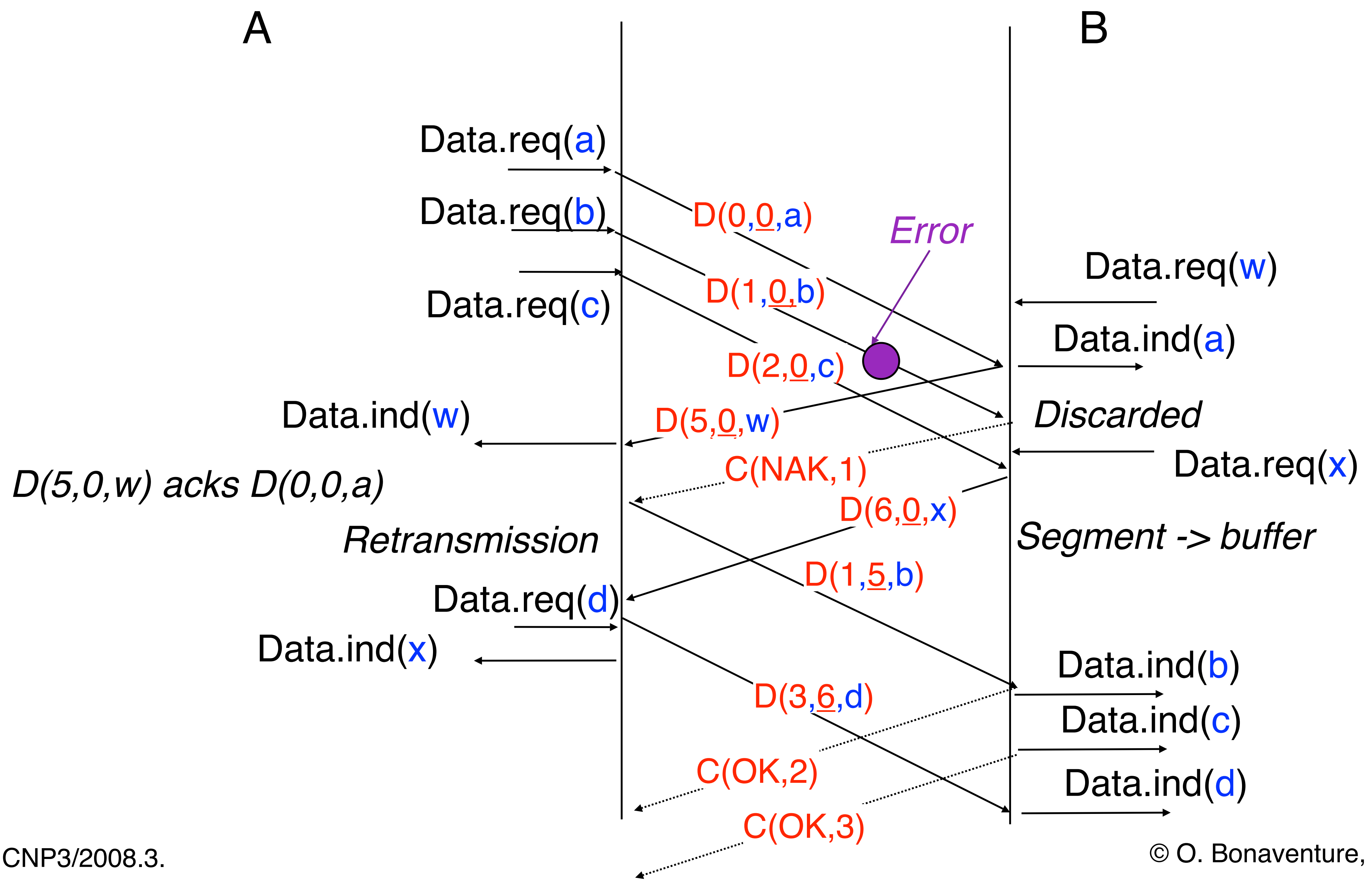


Bidirectional flow
Example



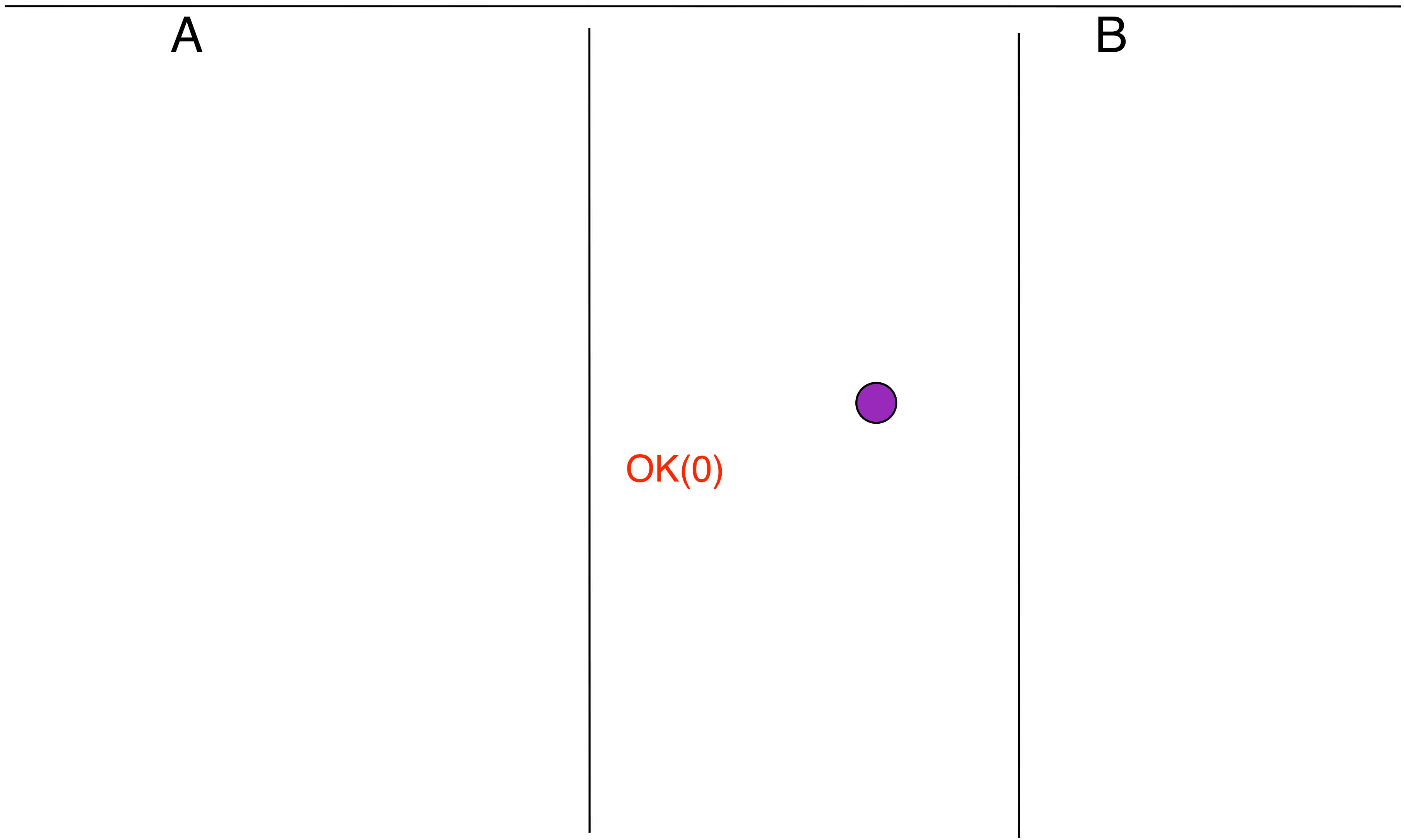
Bidirectional flow Example



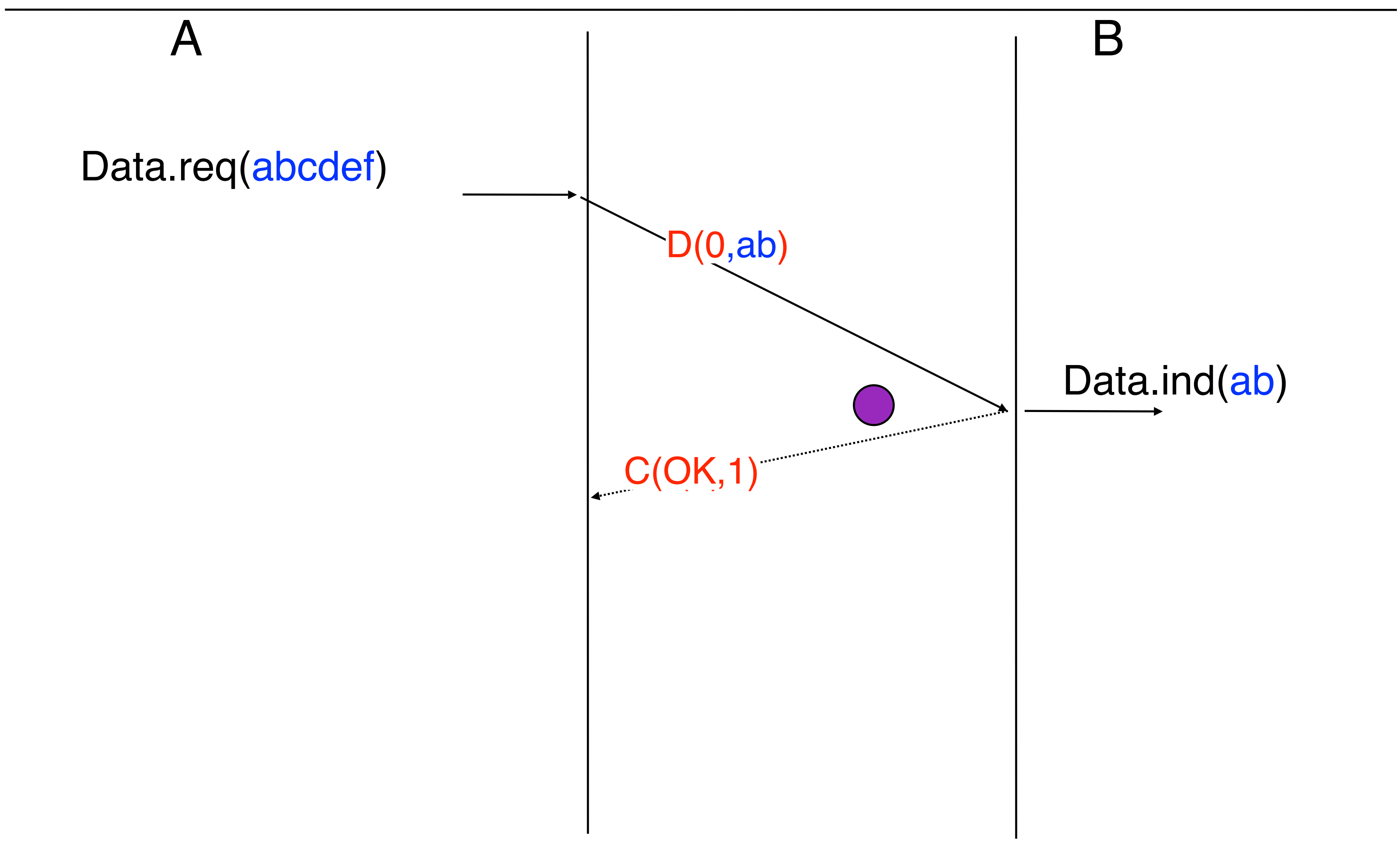
Byte stream service

- 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)



Byte stream service (2)



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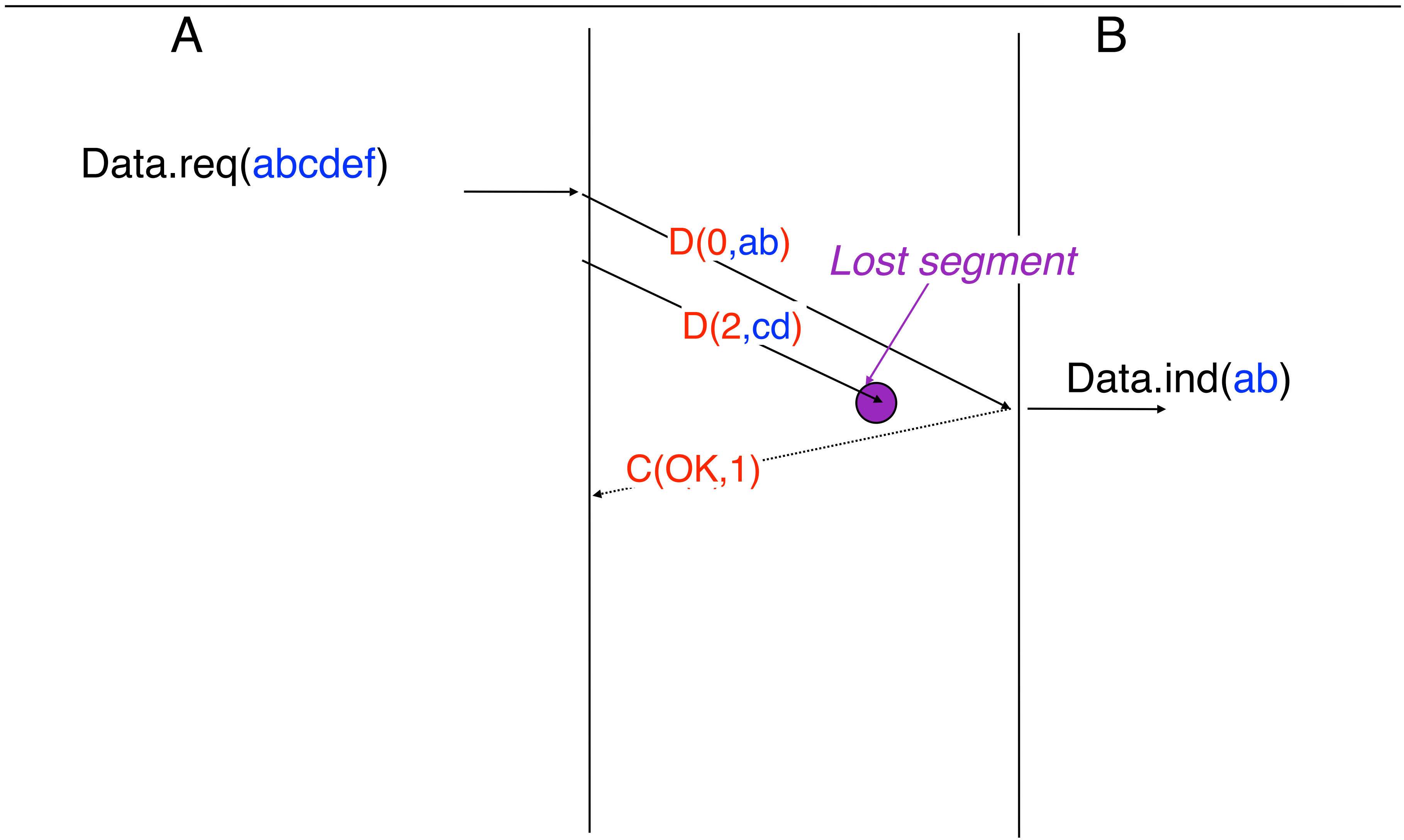

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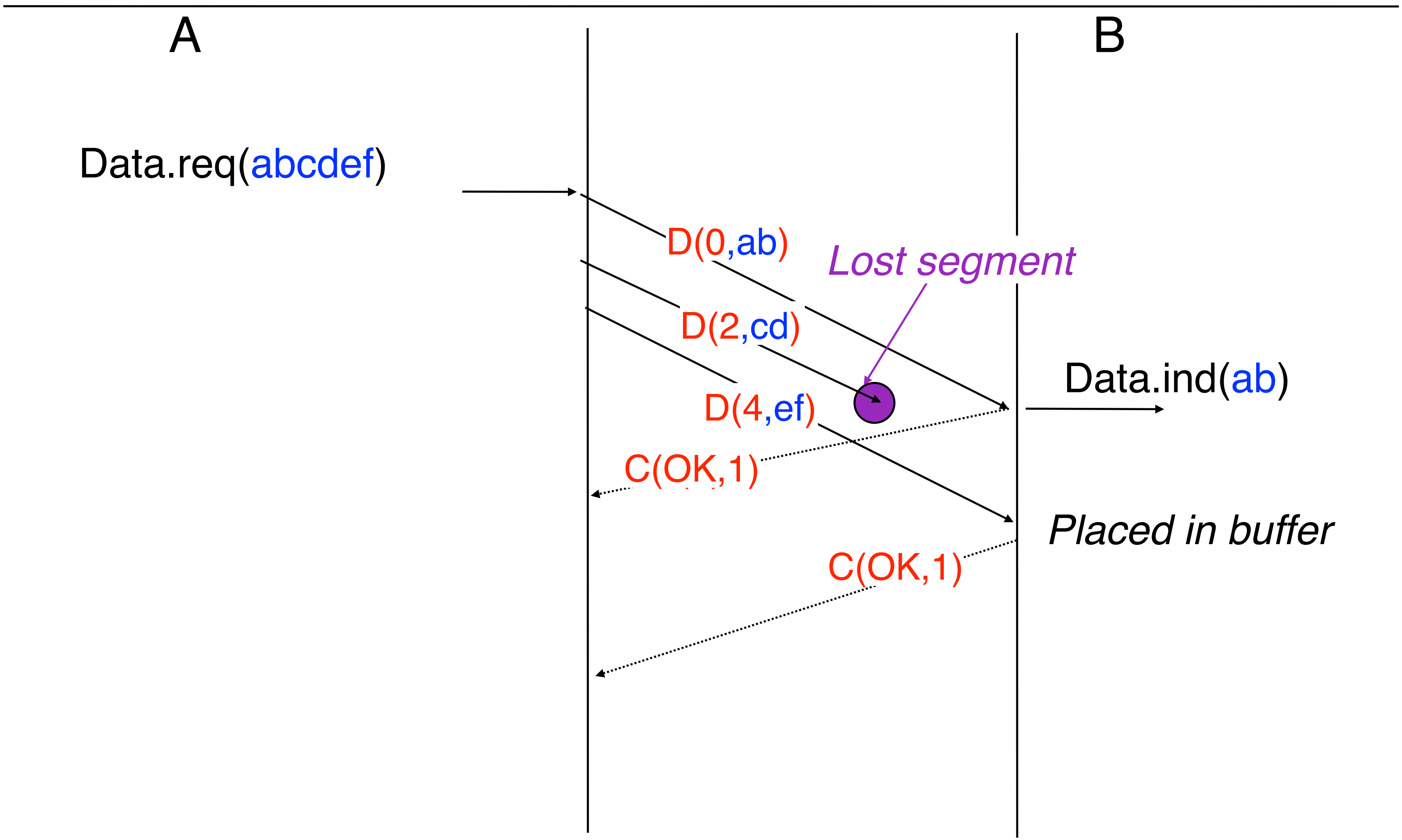

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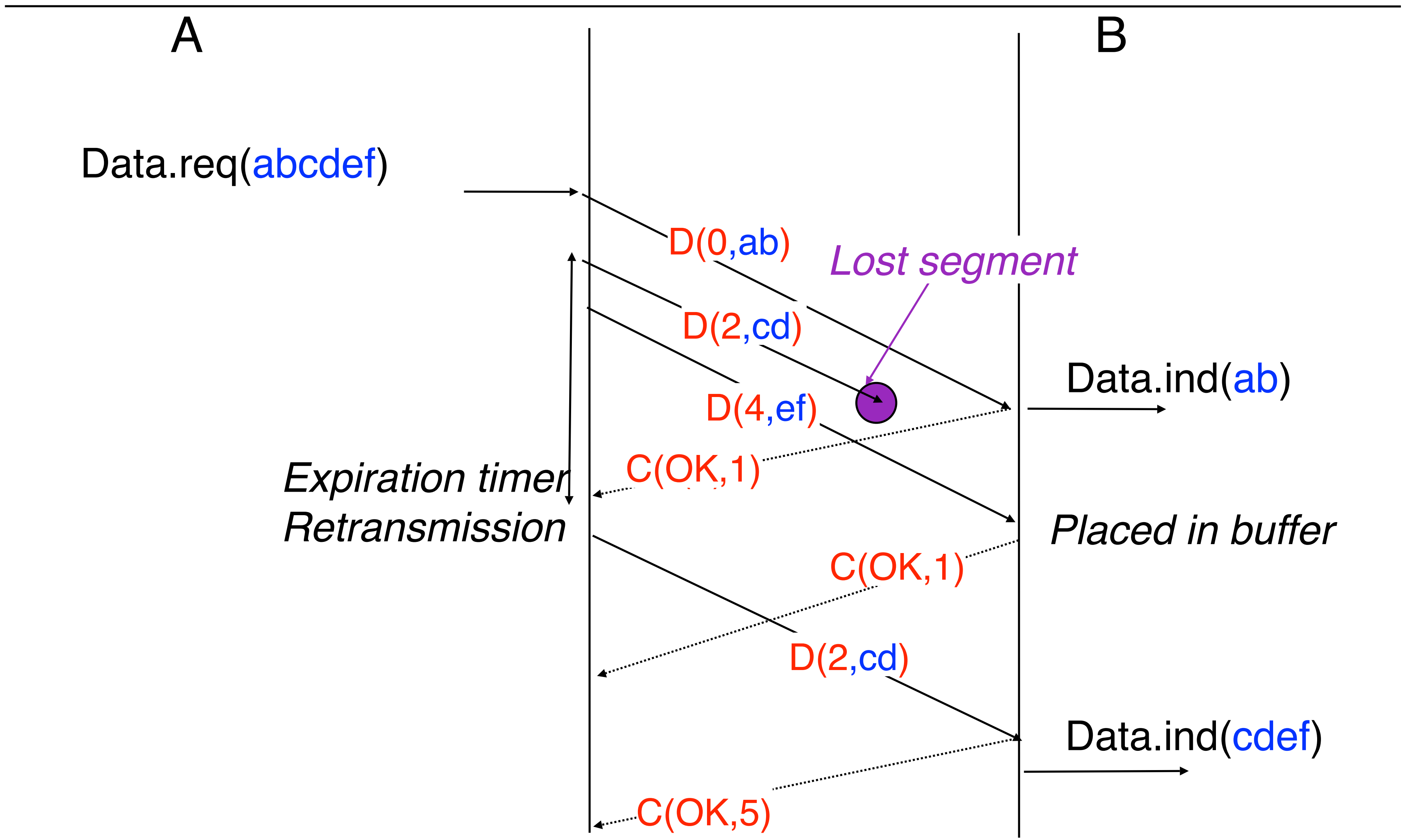

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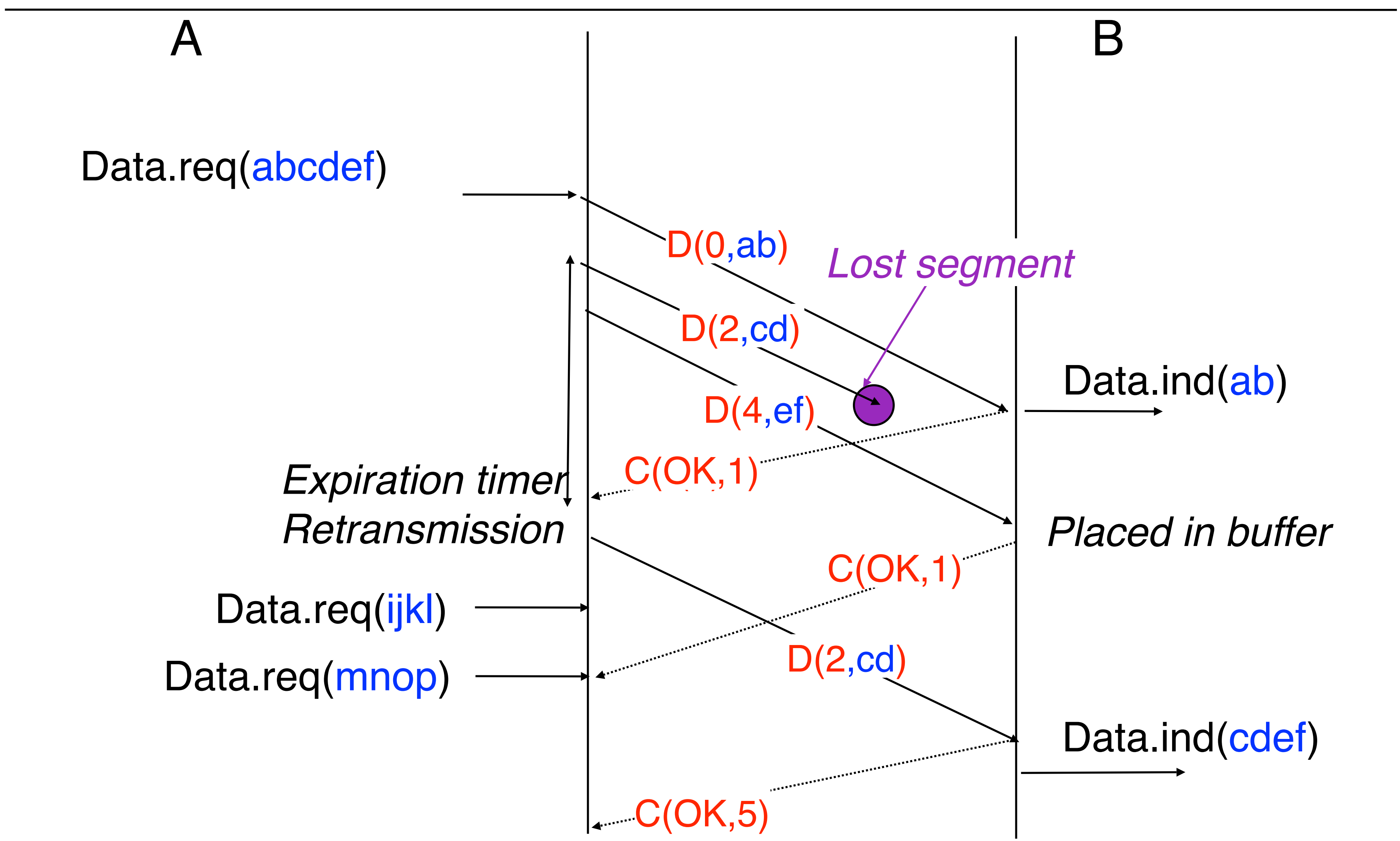

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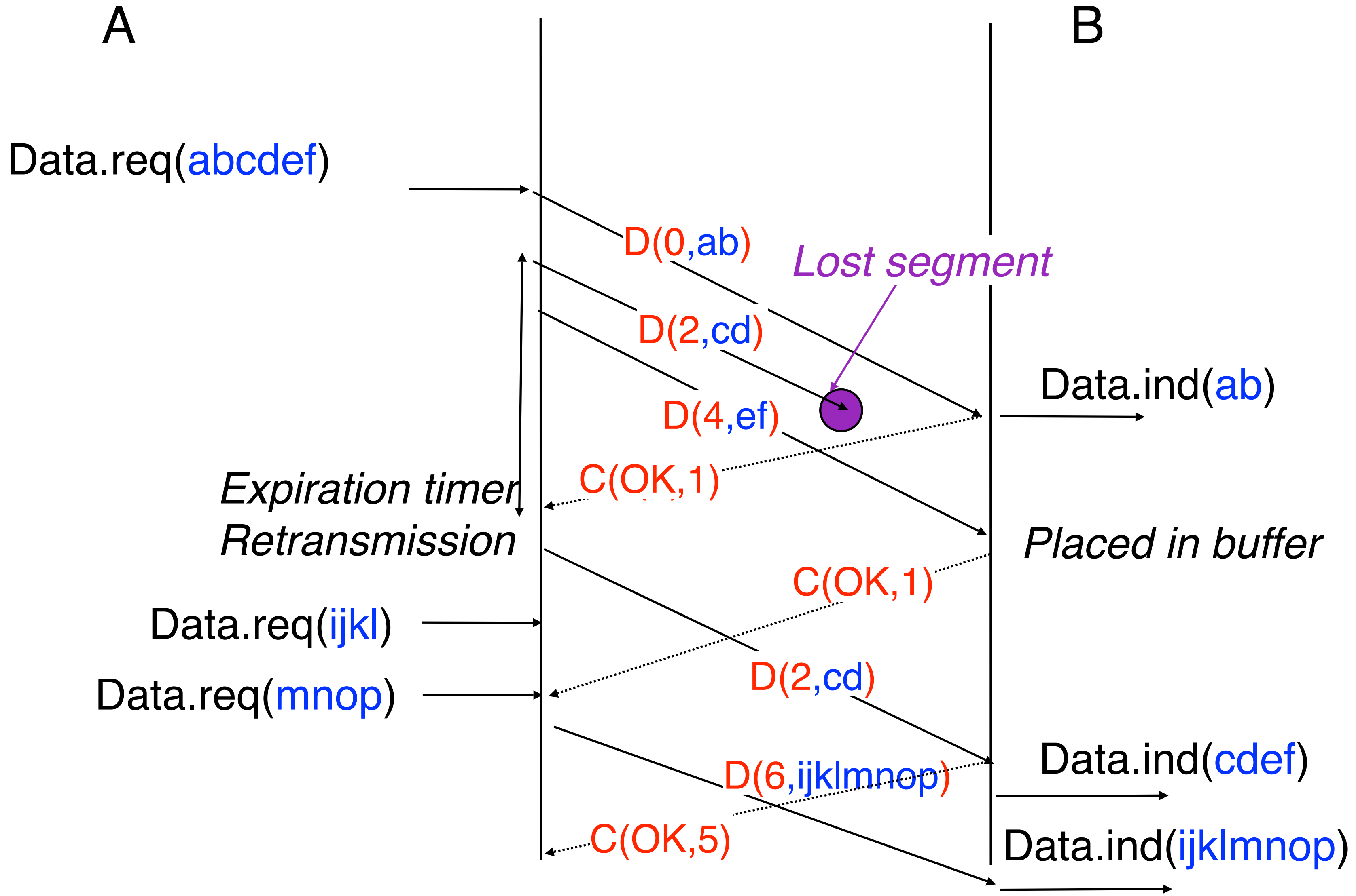

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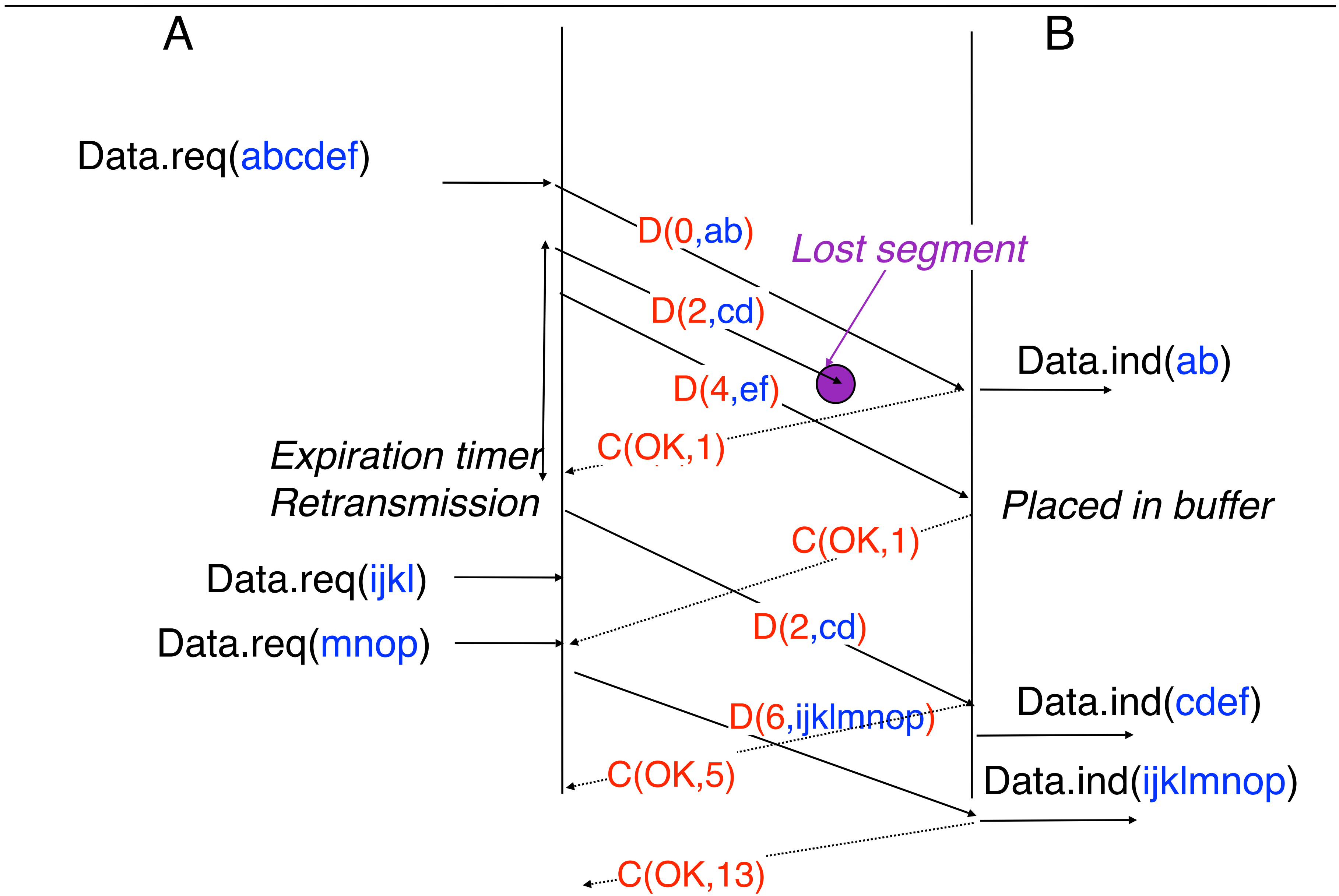


Module 3 : Transport Layer

- 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

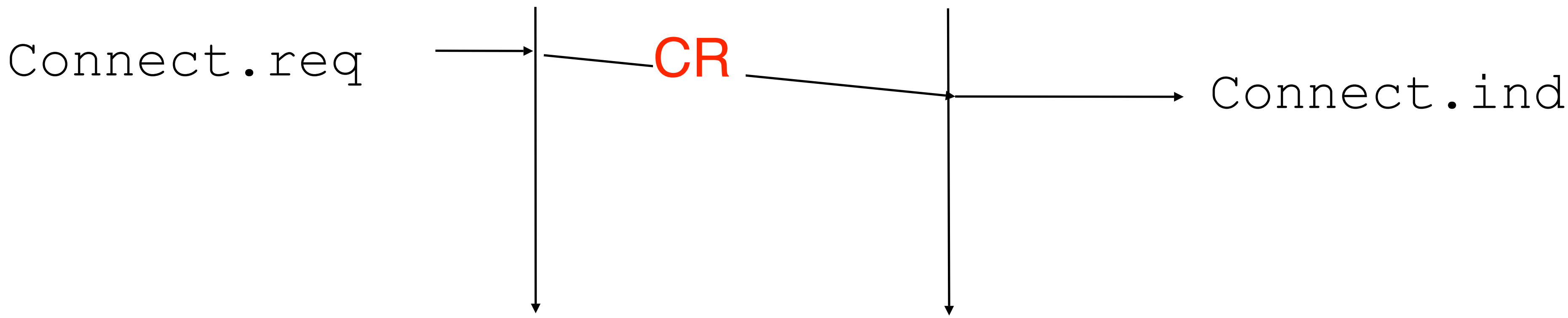
Transport connection establishment

- 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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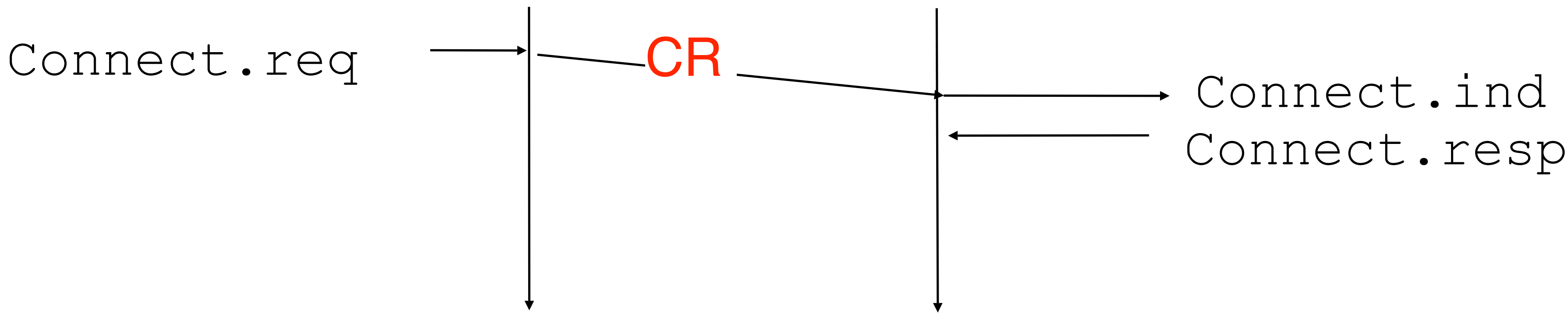

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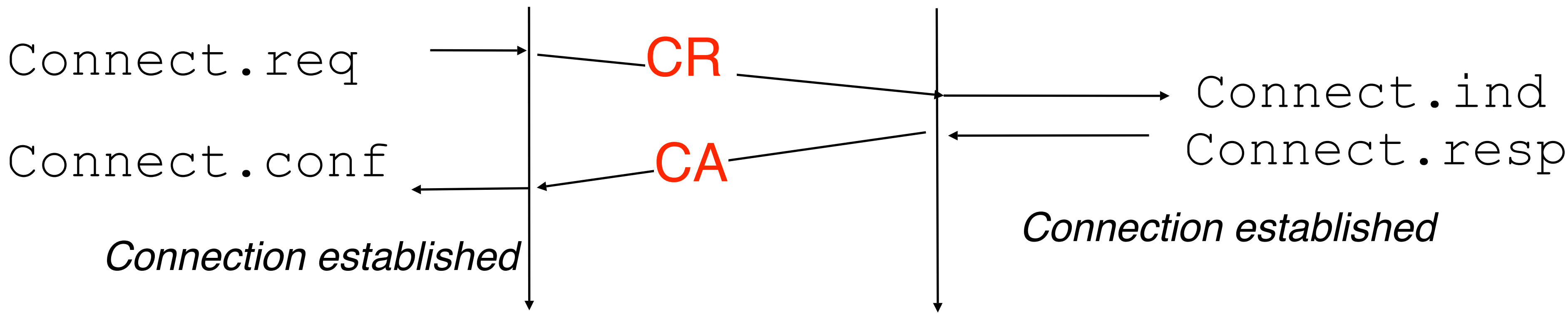

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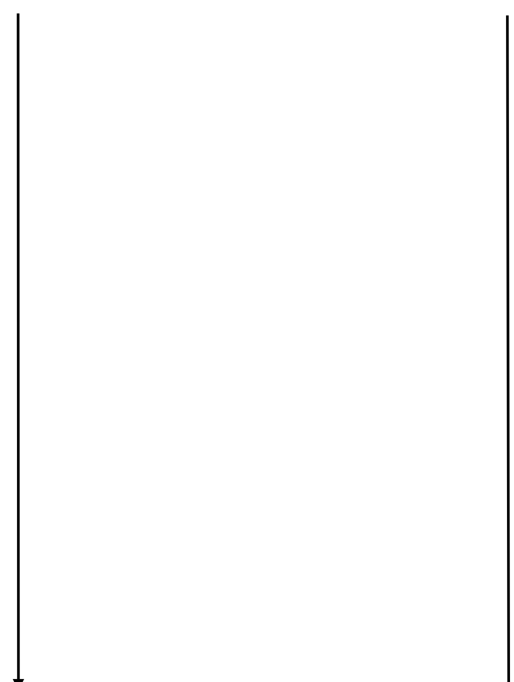
Simple solution (2)

- 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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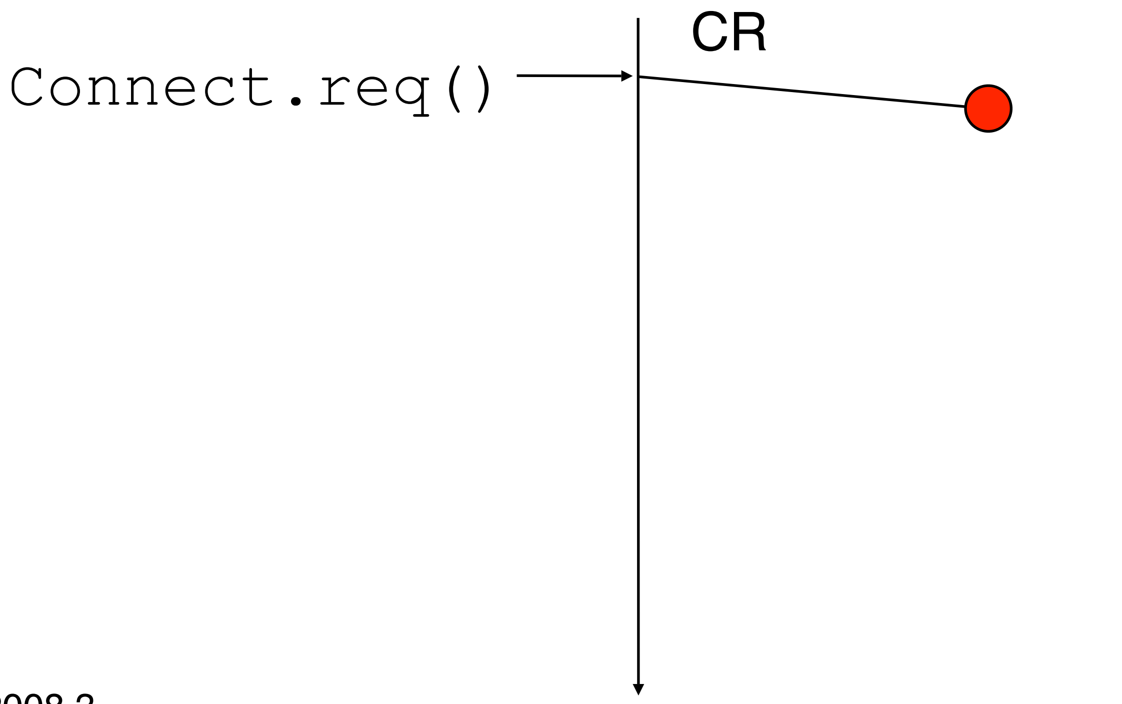

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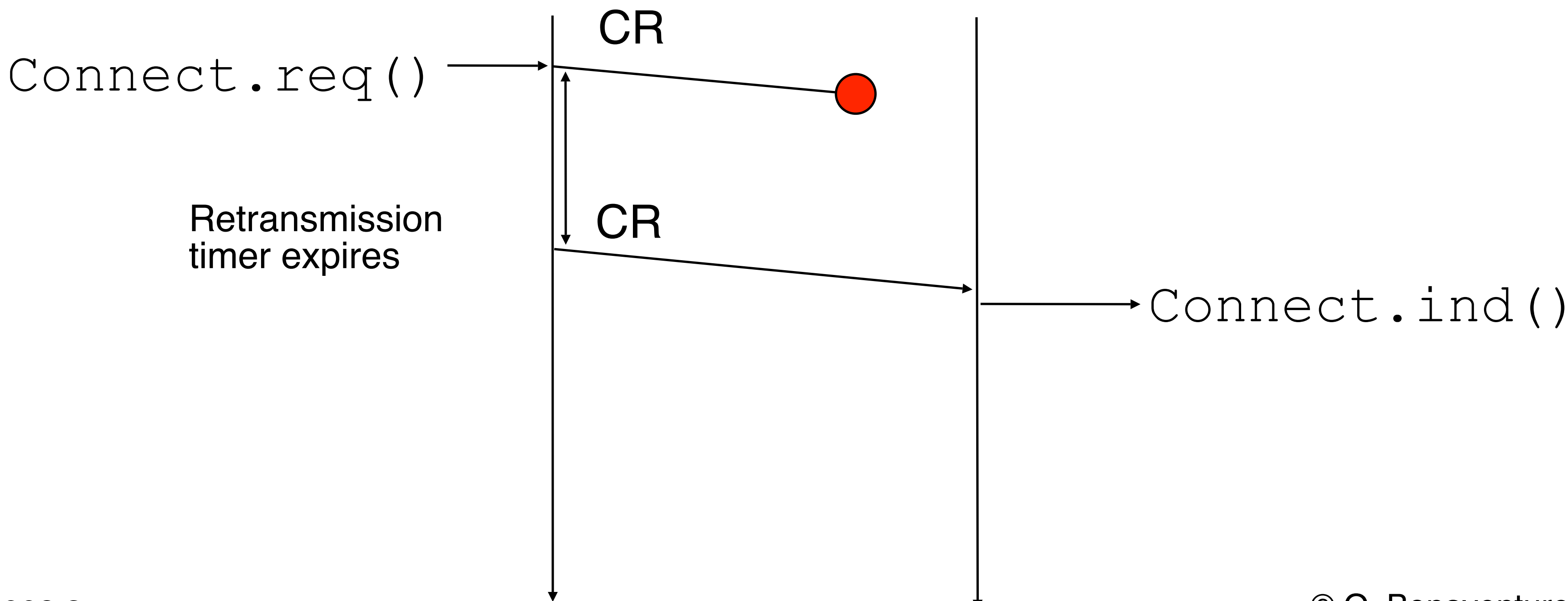

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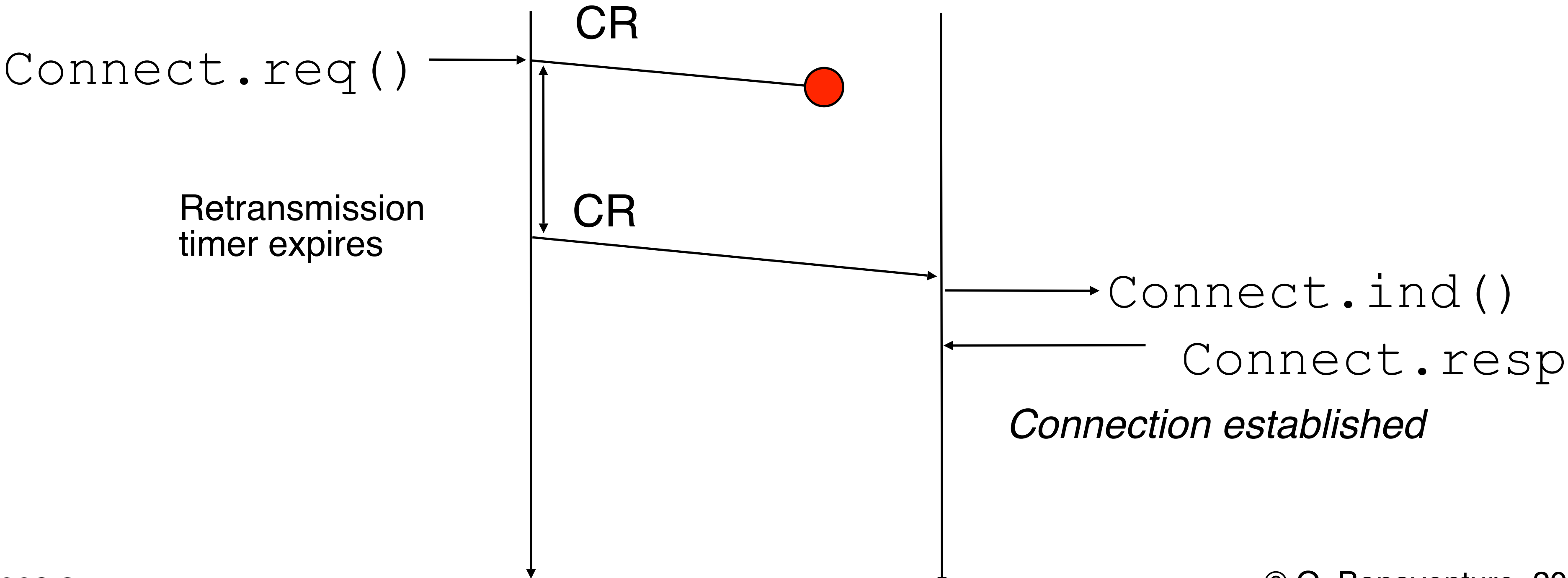

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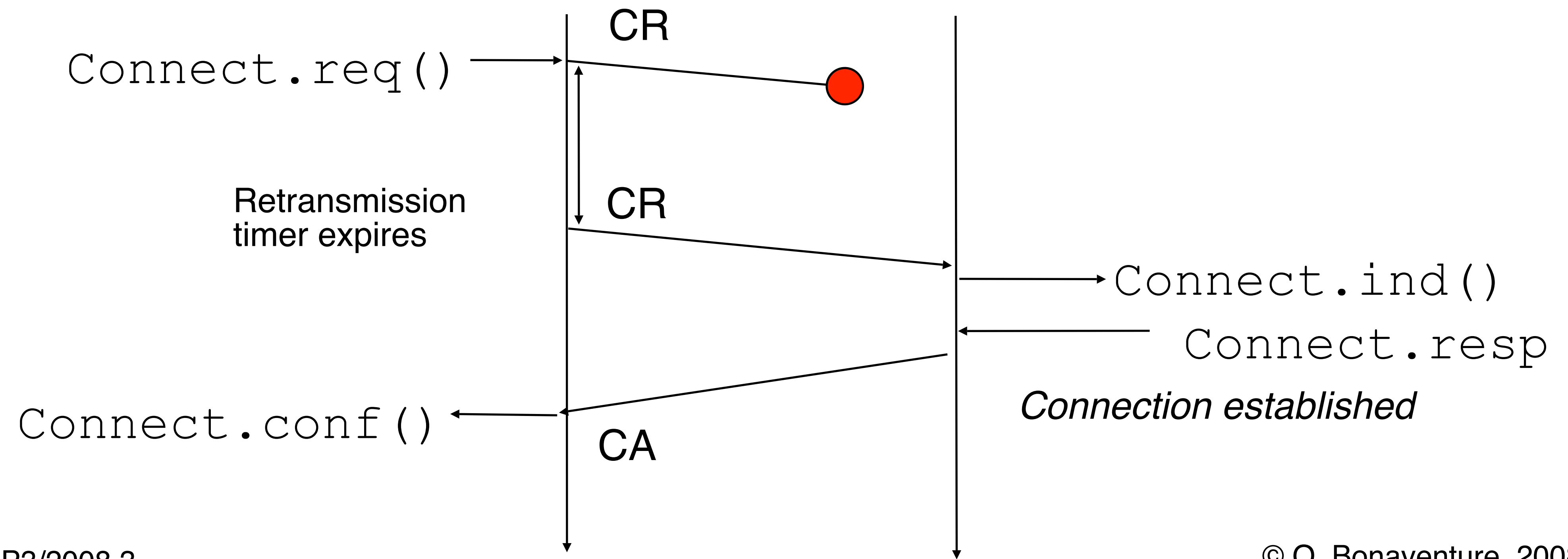

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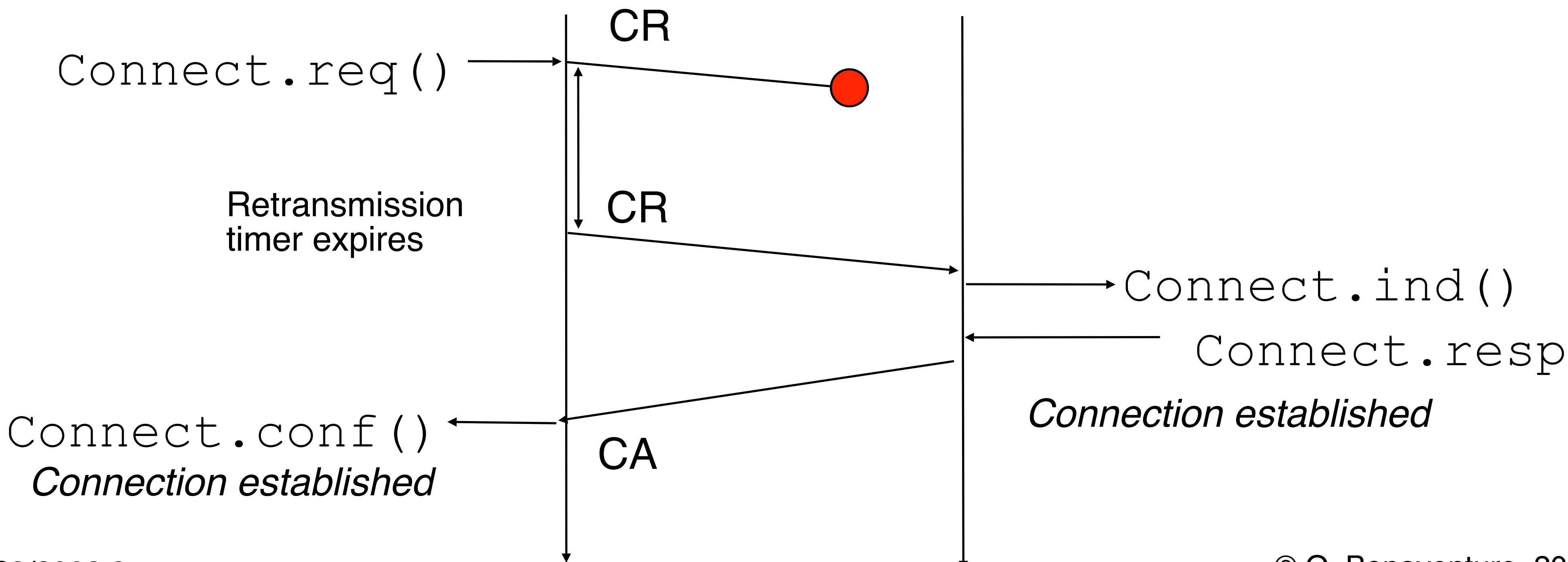
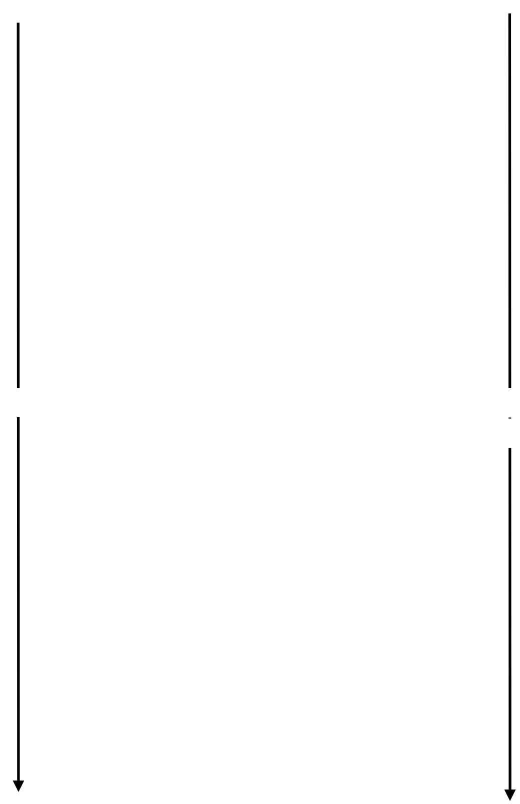


Connection establishment

- 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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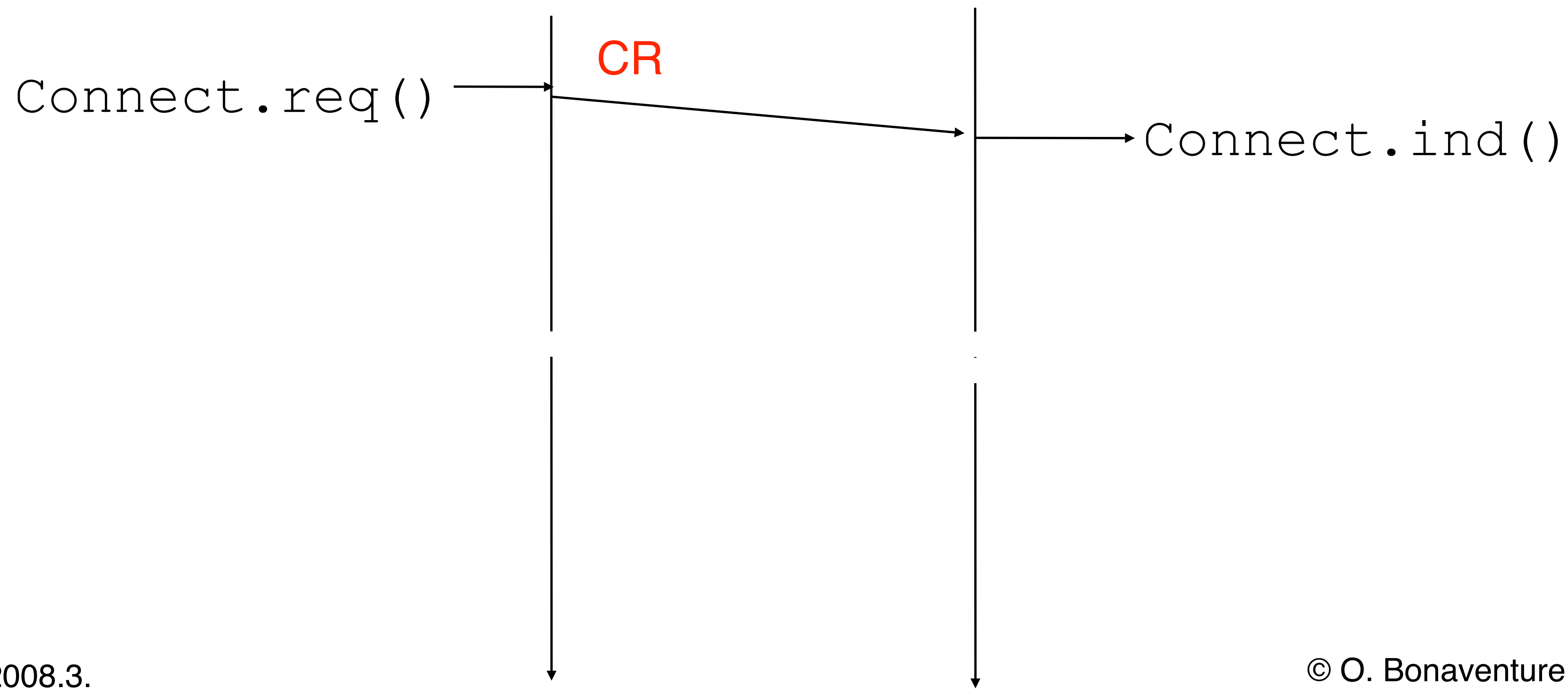

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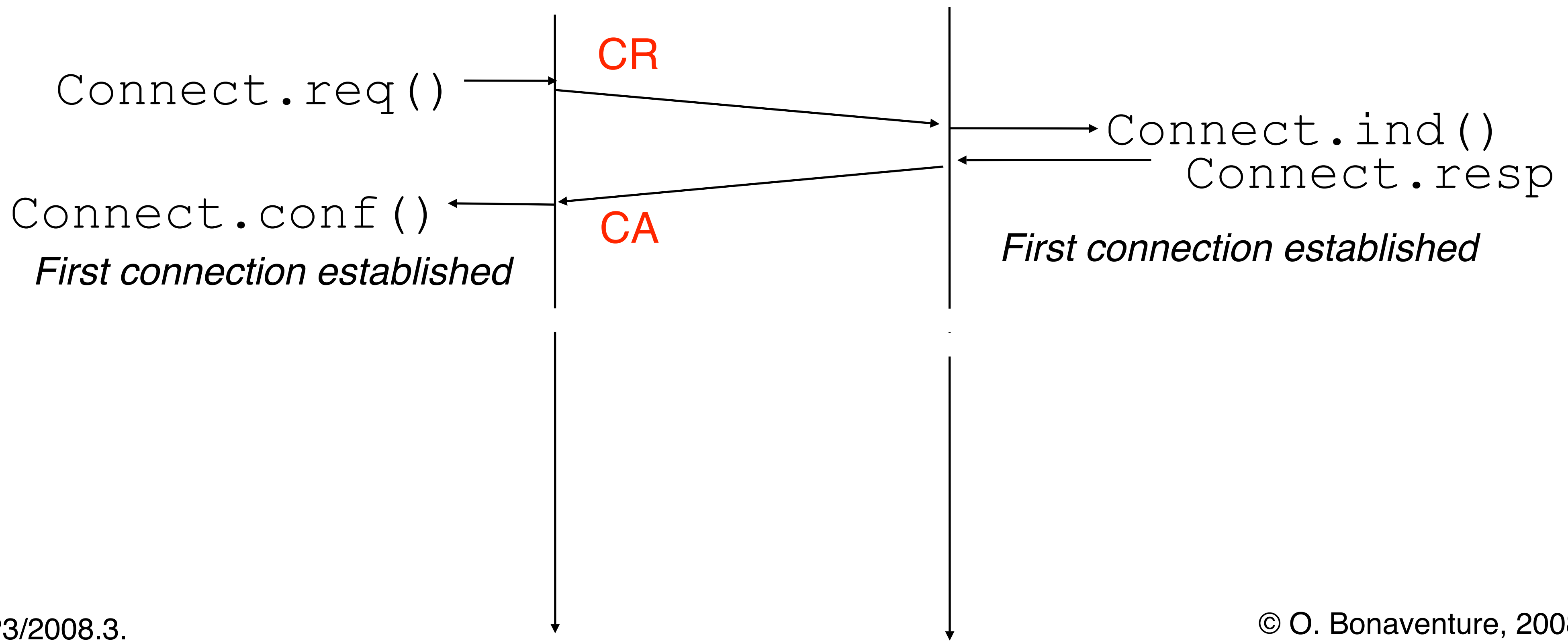

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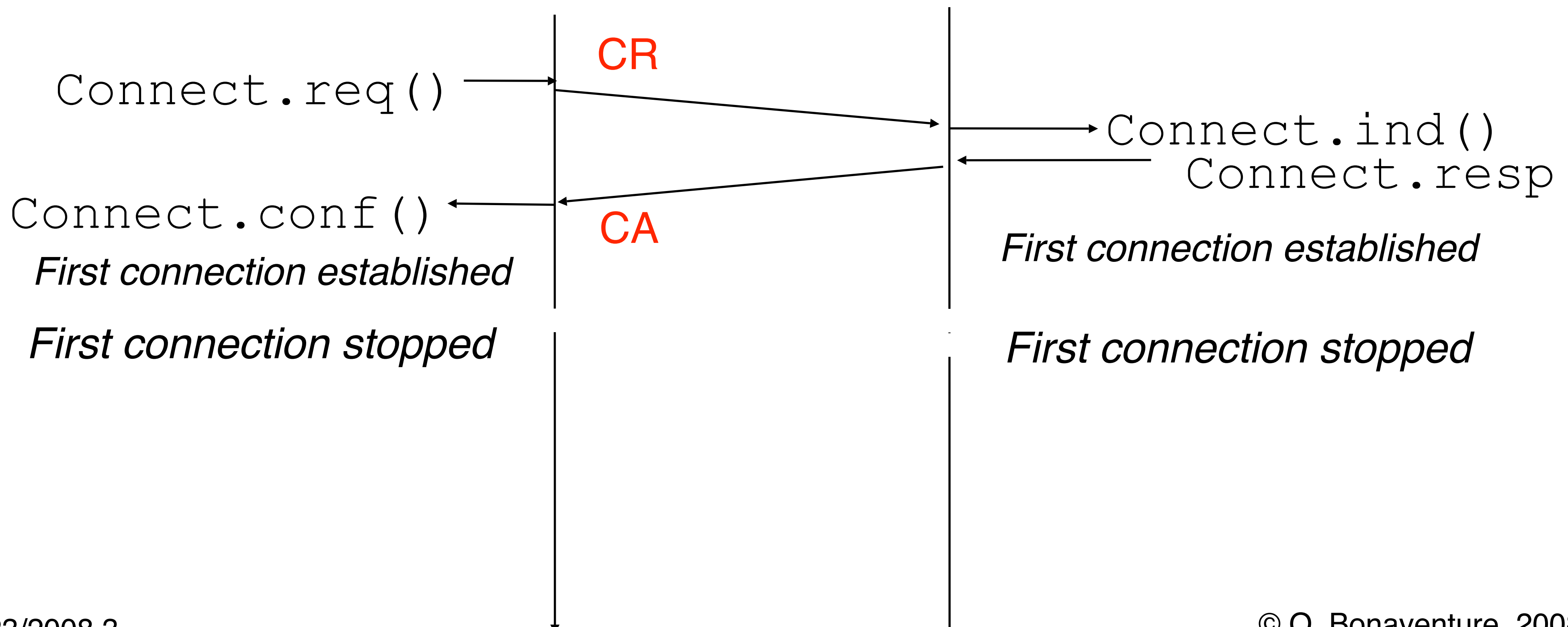

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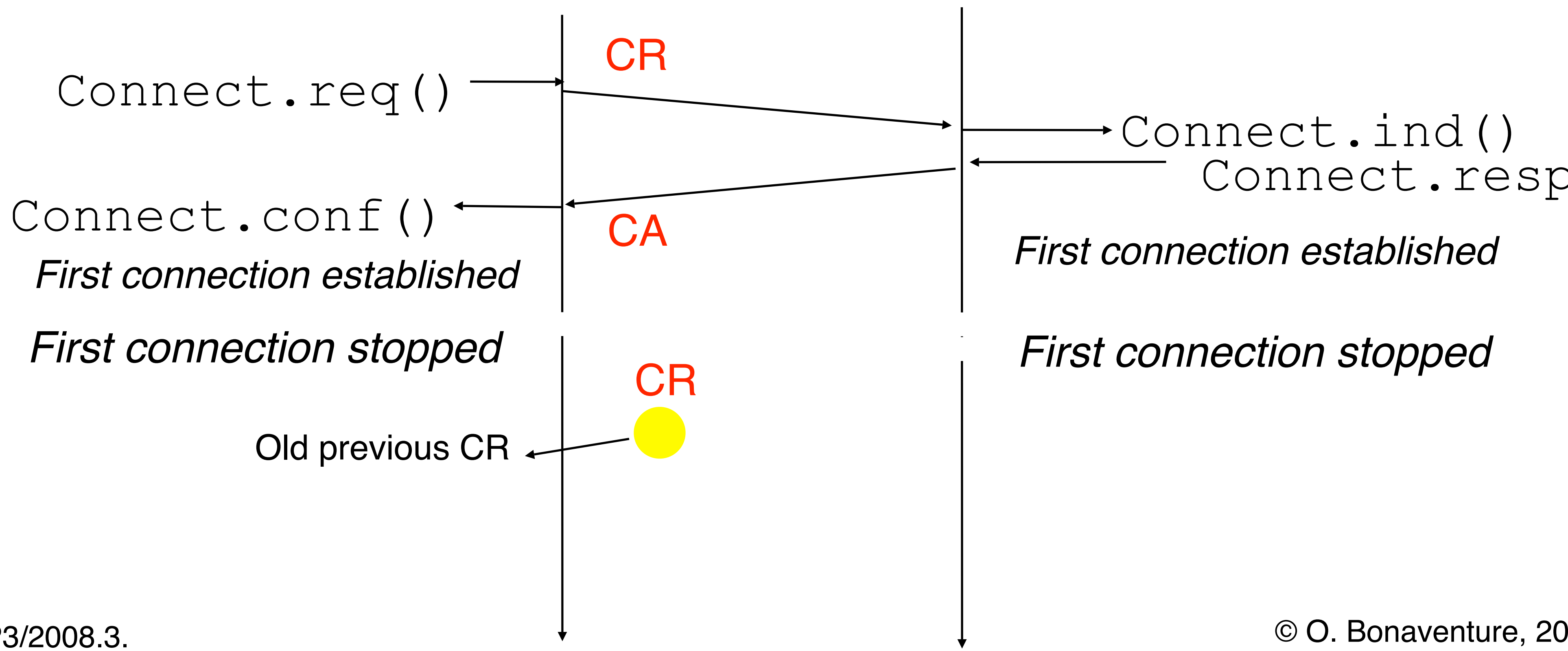

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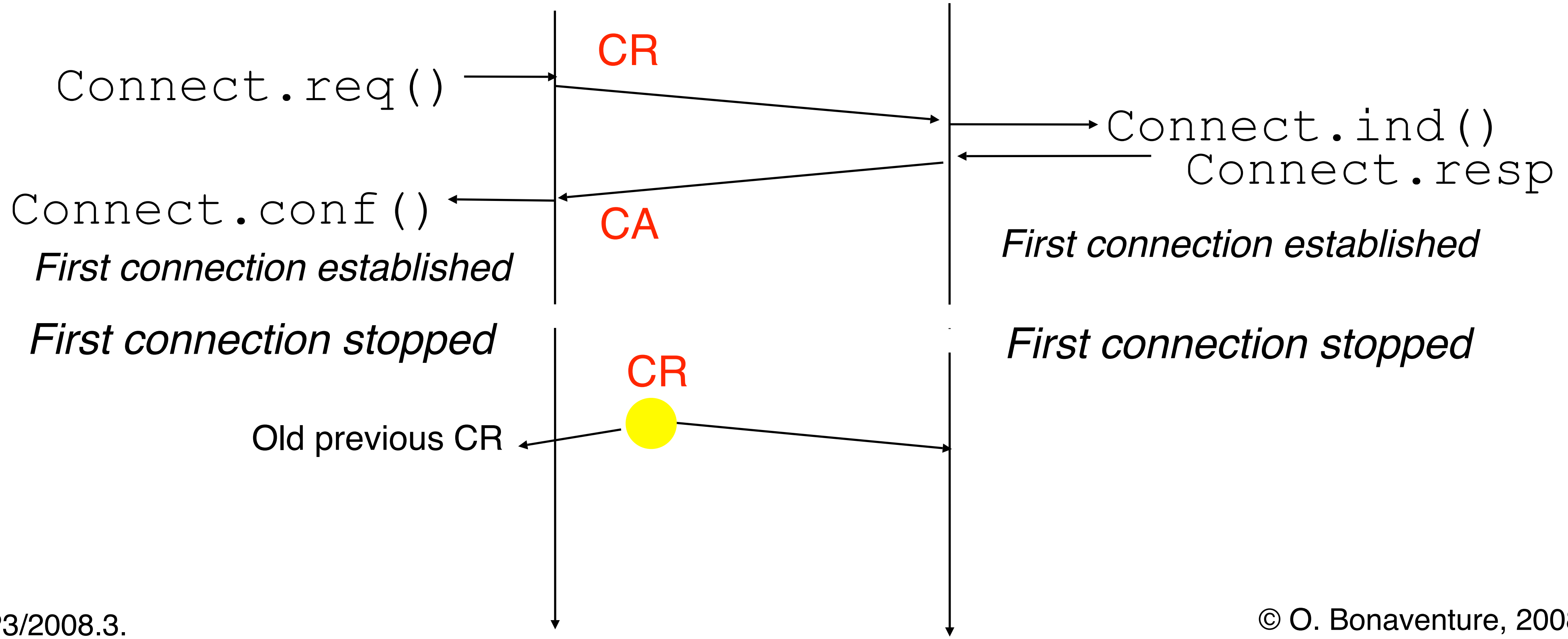

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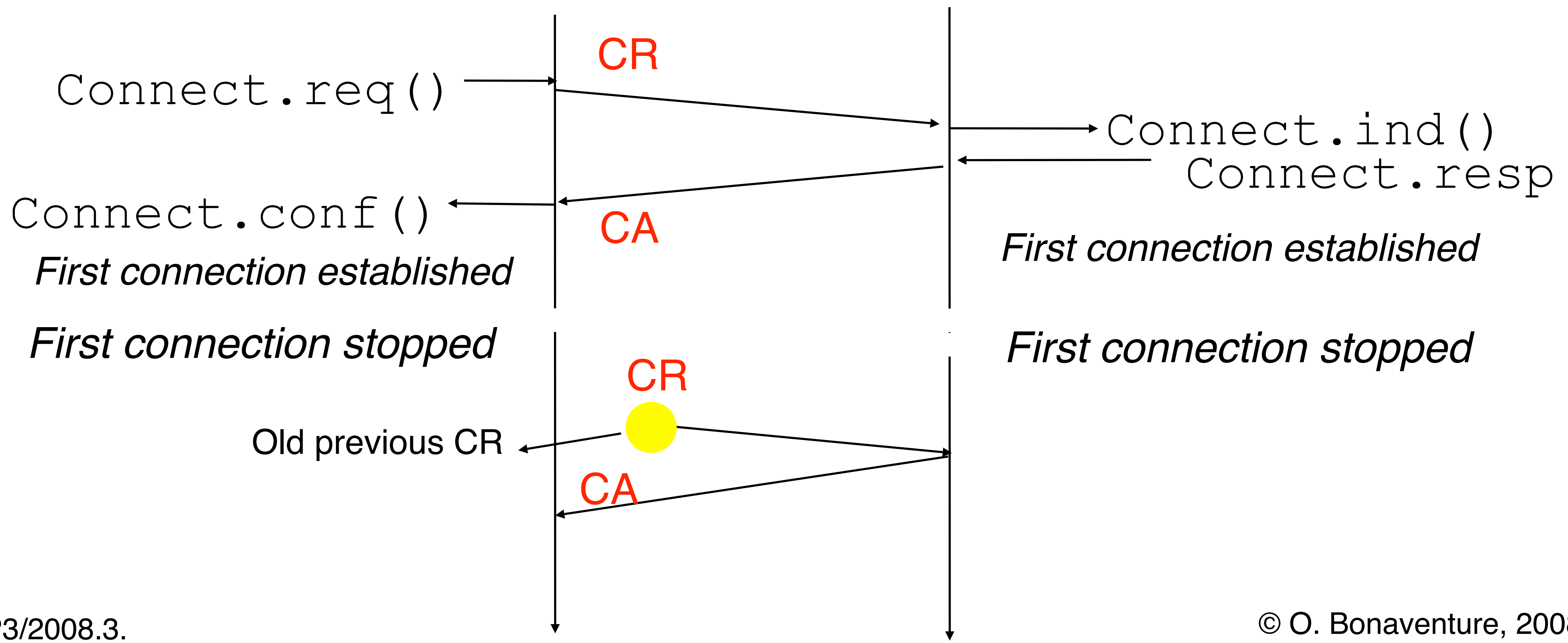

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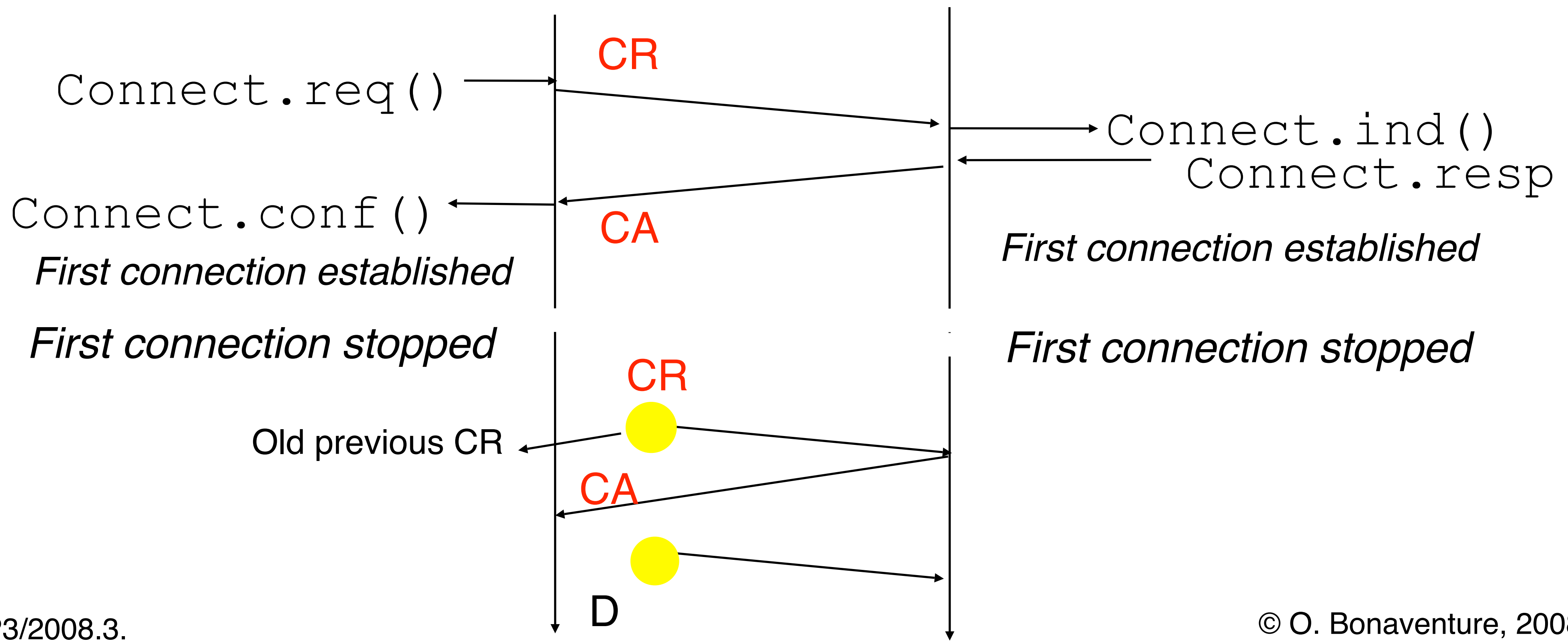

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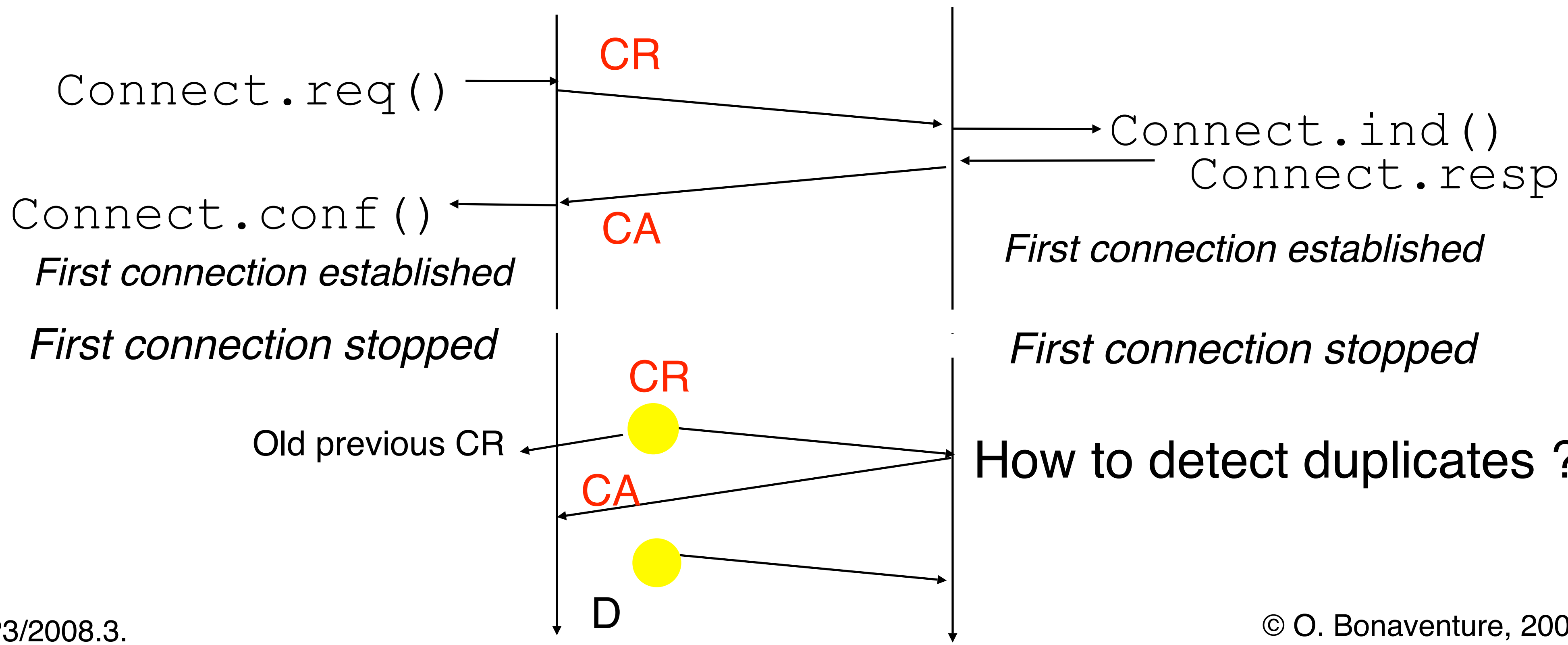

Connection establishment (2)

- 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

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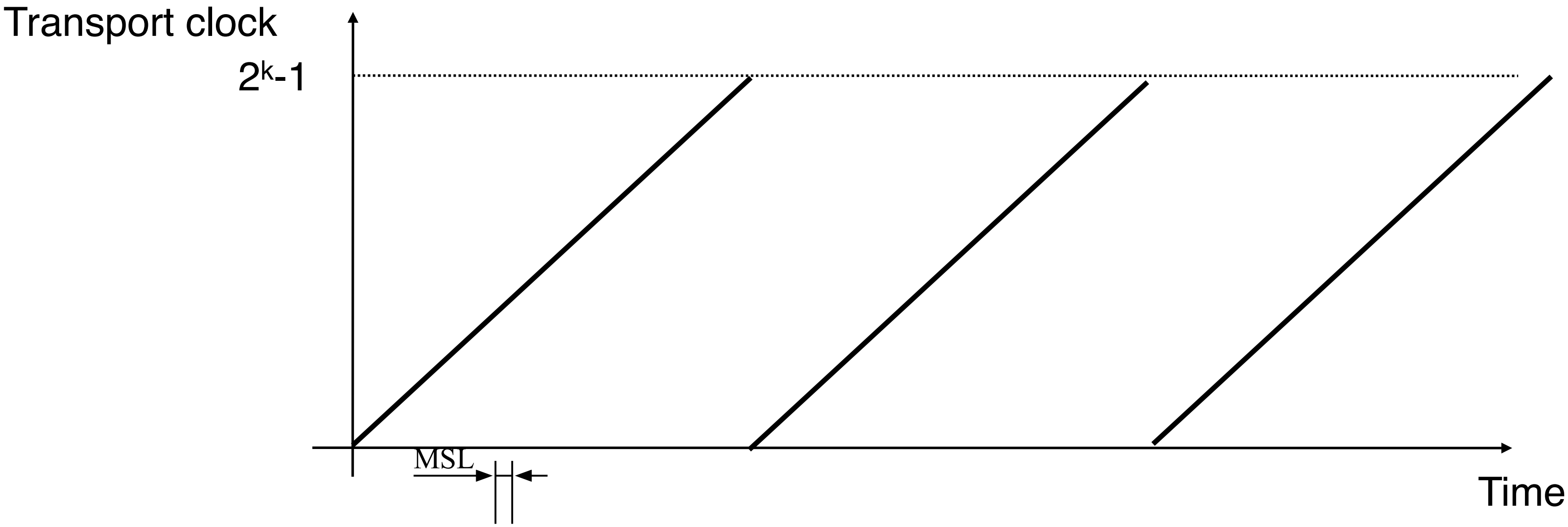
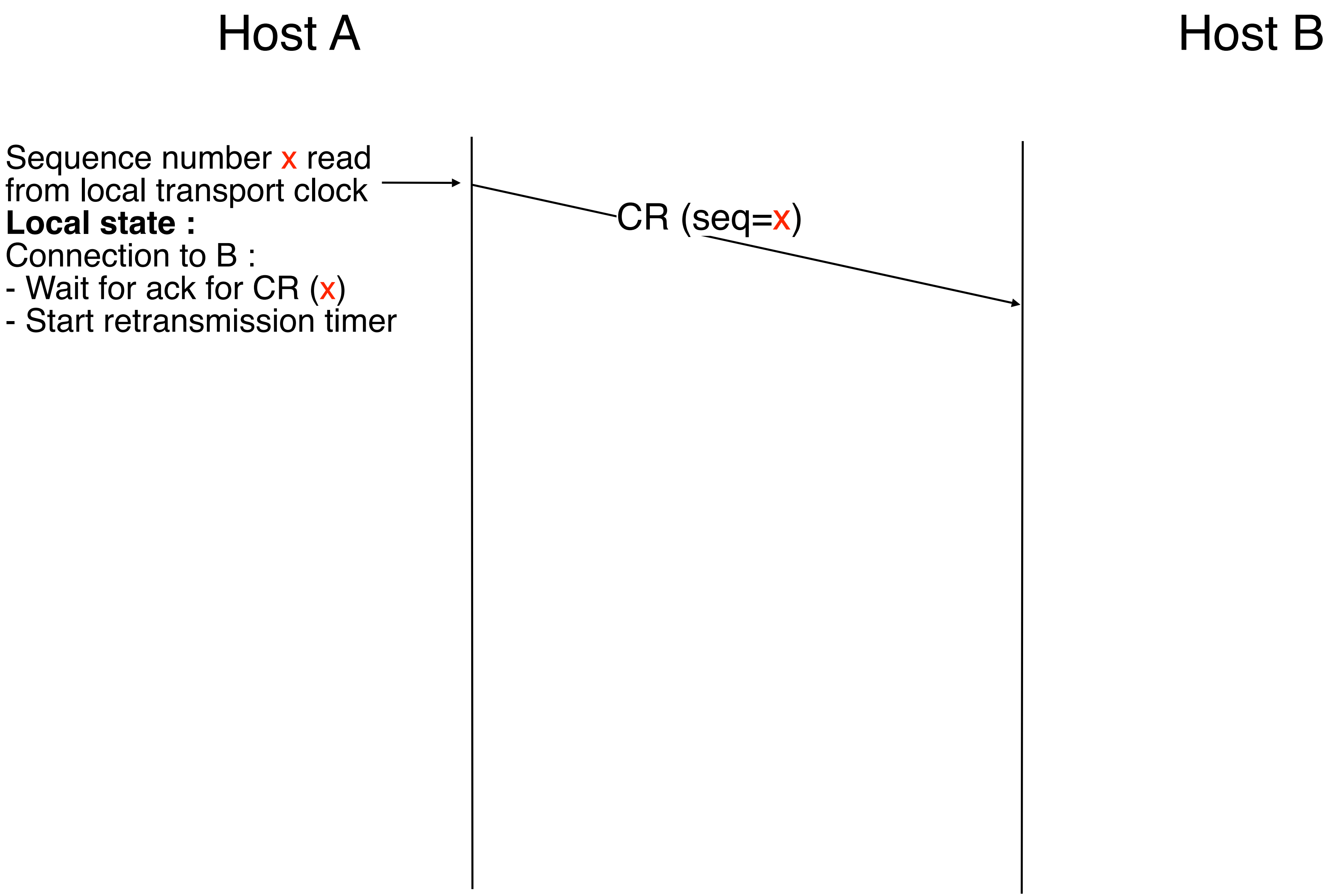


Three way handshake

Host A

Host B

Three way handshake



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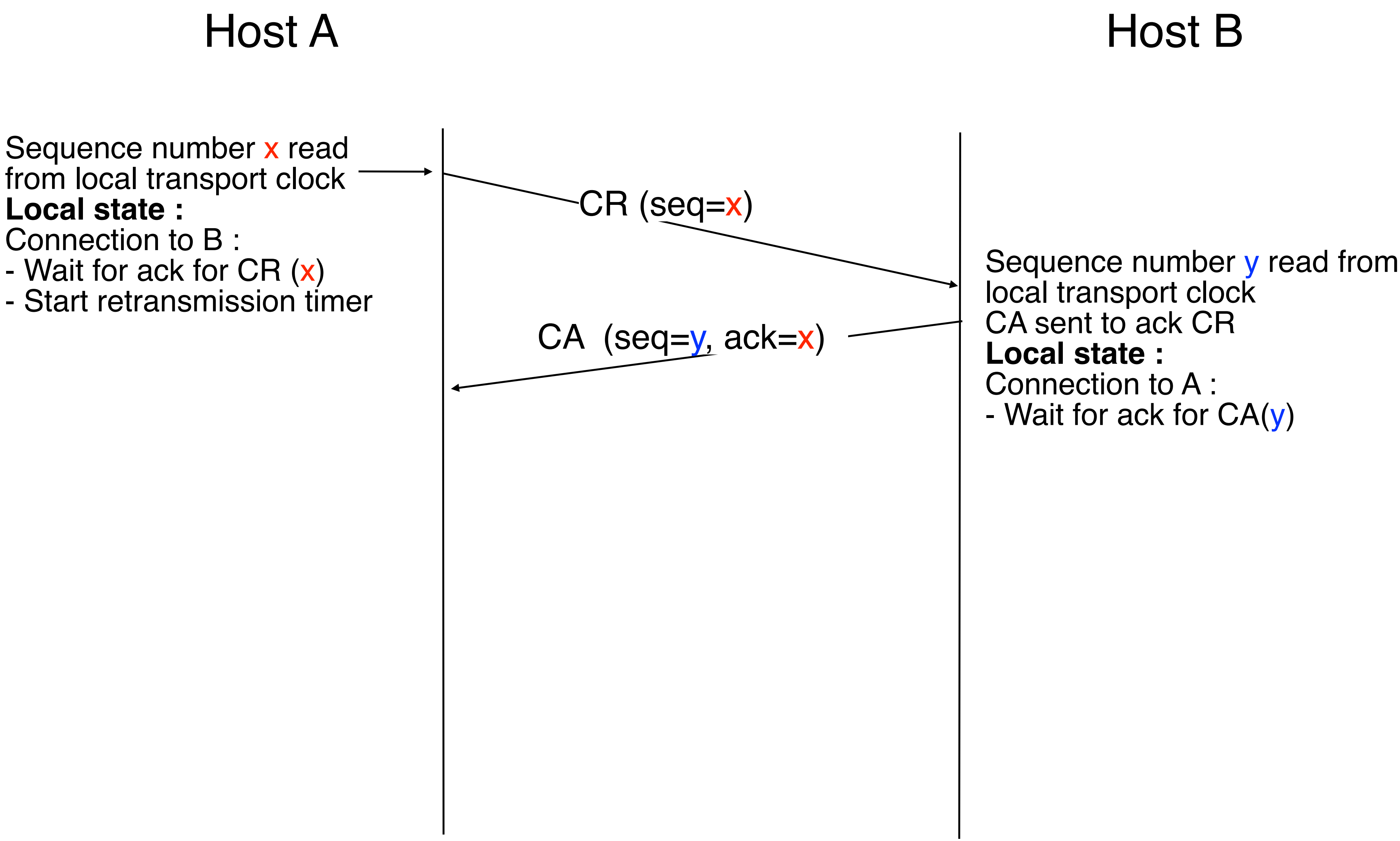
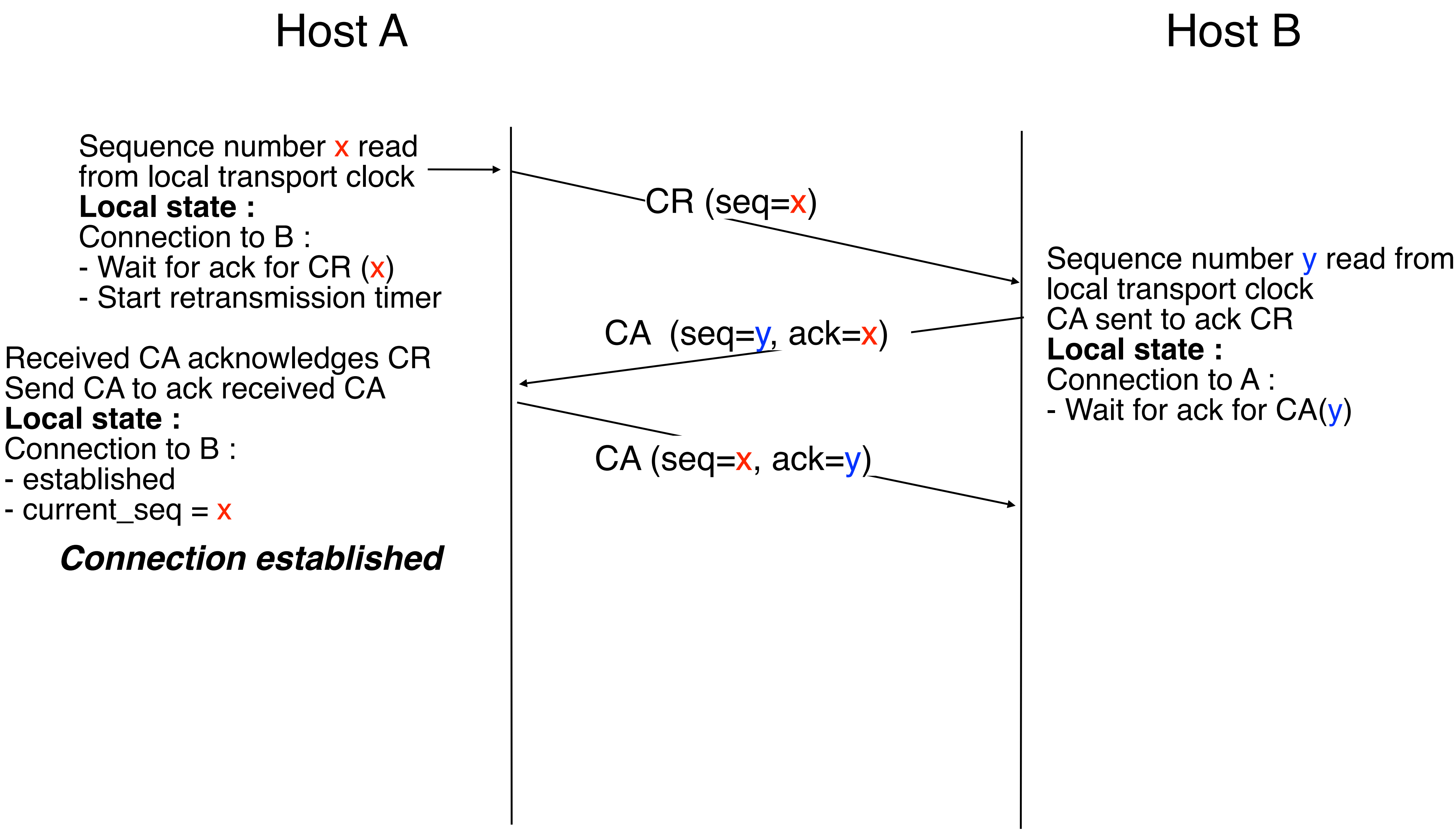


Three way handshake



Three way handshake

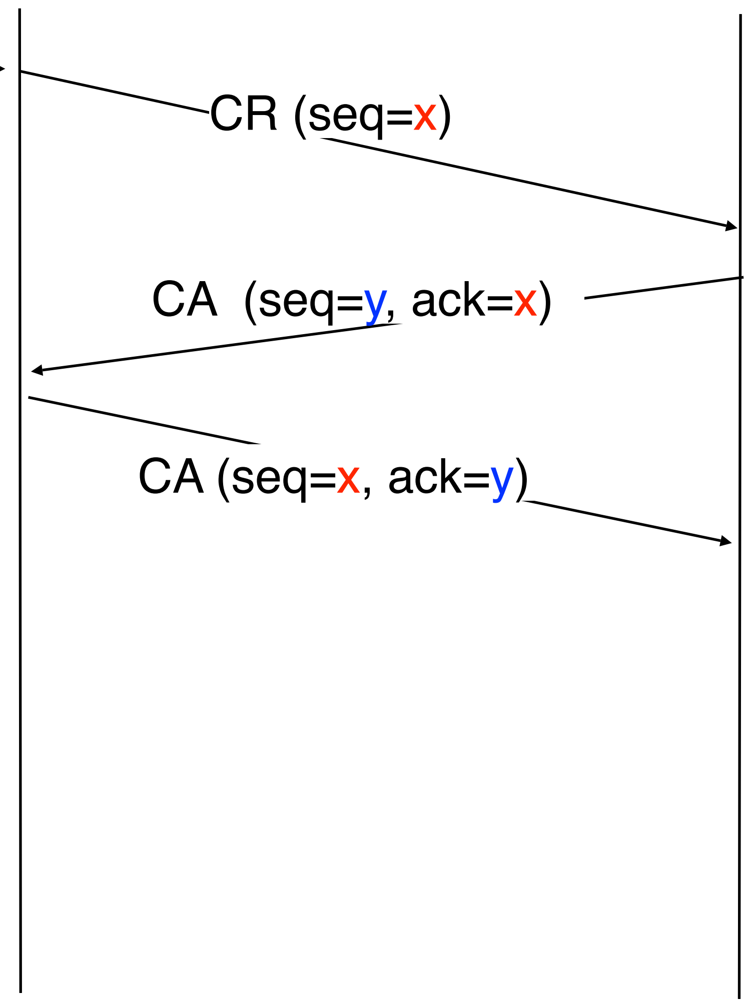
Host A

Host B

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

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

Connection established



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

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

Connection established

Three way handshake

Host A

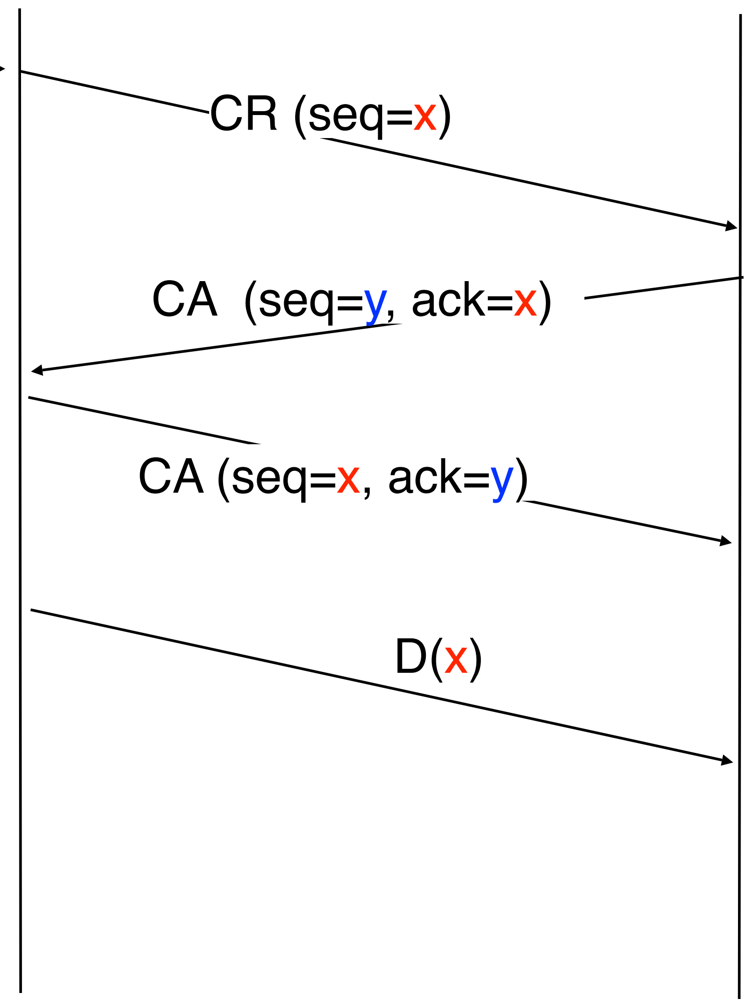
Host B

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

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

Connection established

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

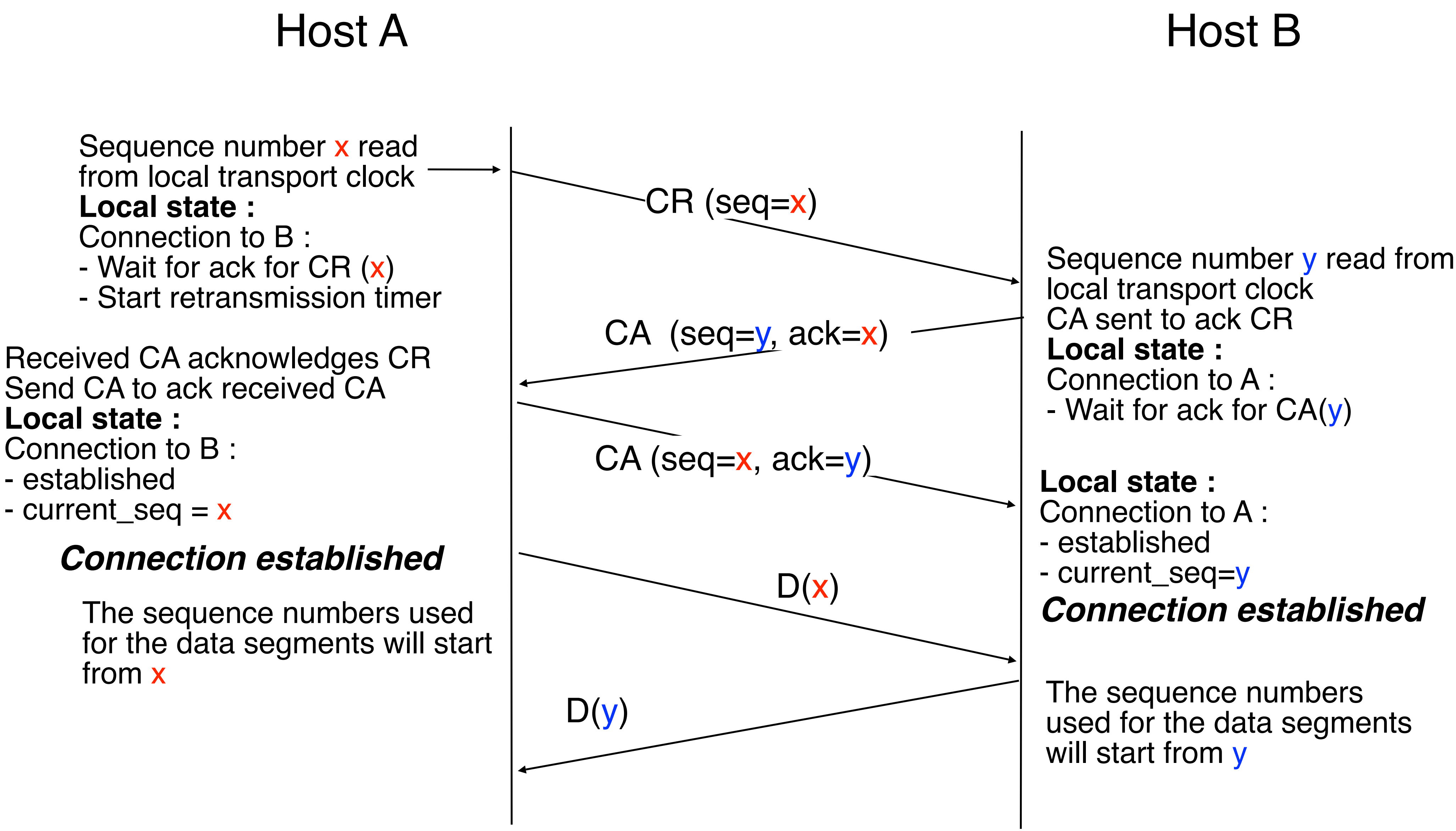


Sequence number y read from local transport clock
CA sent to ack CR
Local state :
Connection to A :
- Wait for ack for CA(y)

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

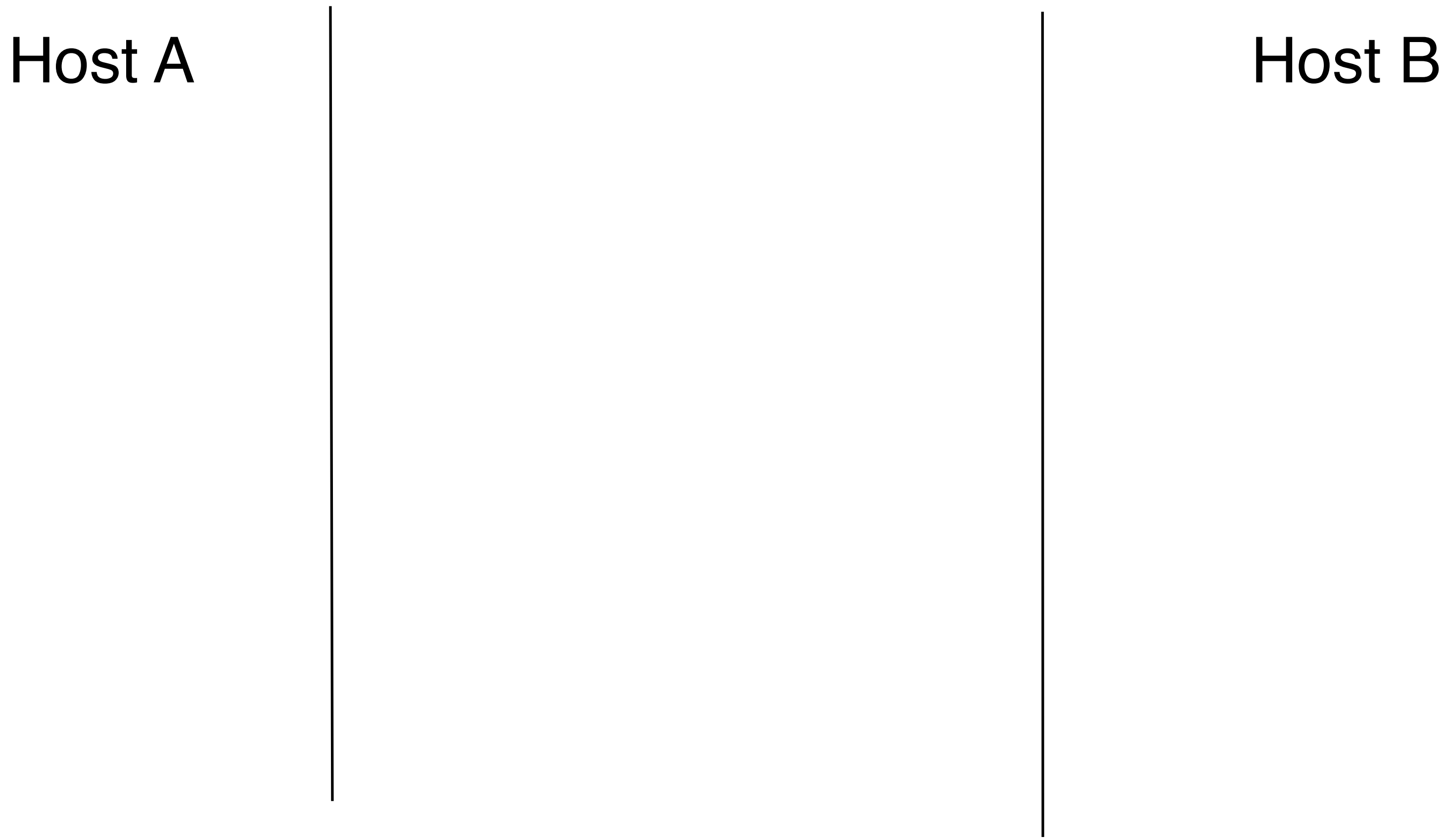
Connection established

Three way handshake



Three way handshake (2)

- What happens with duplicates
  - Duplicate CR



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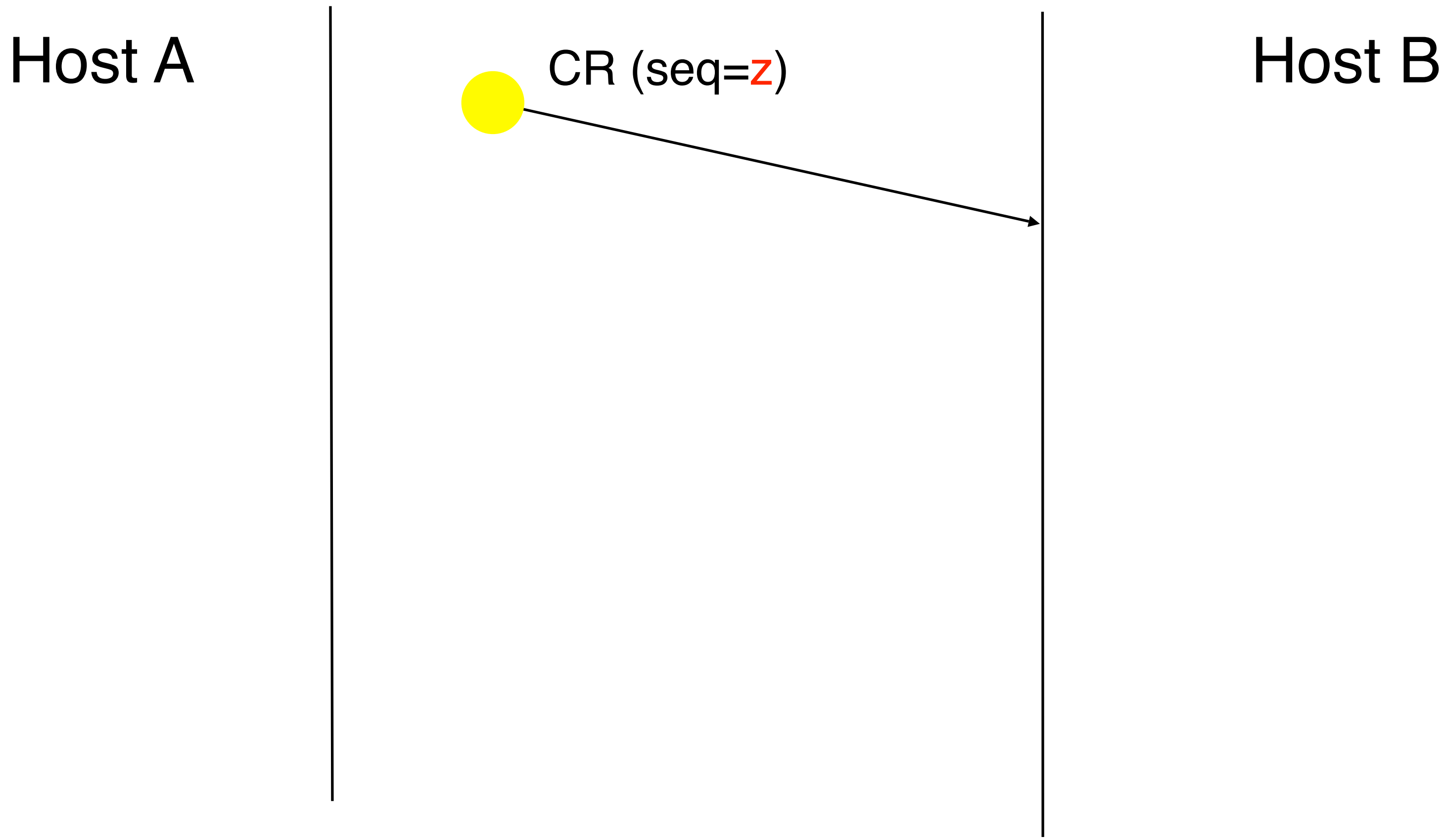

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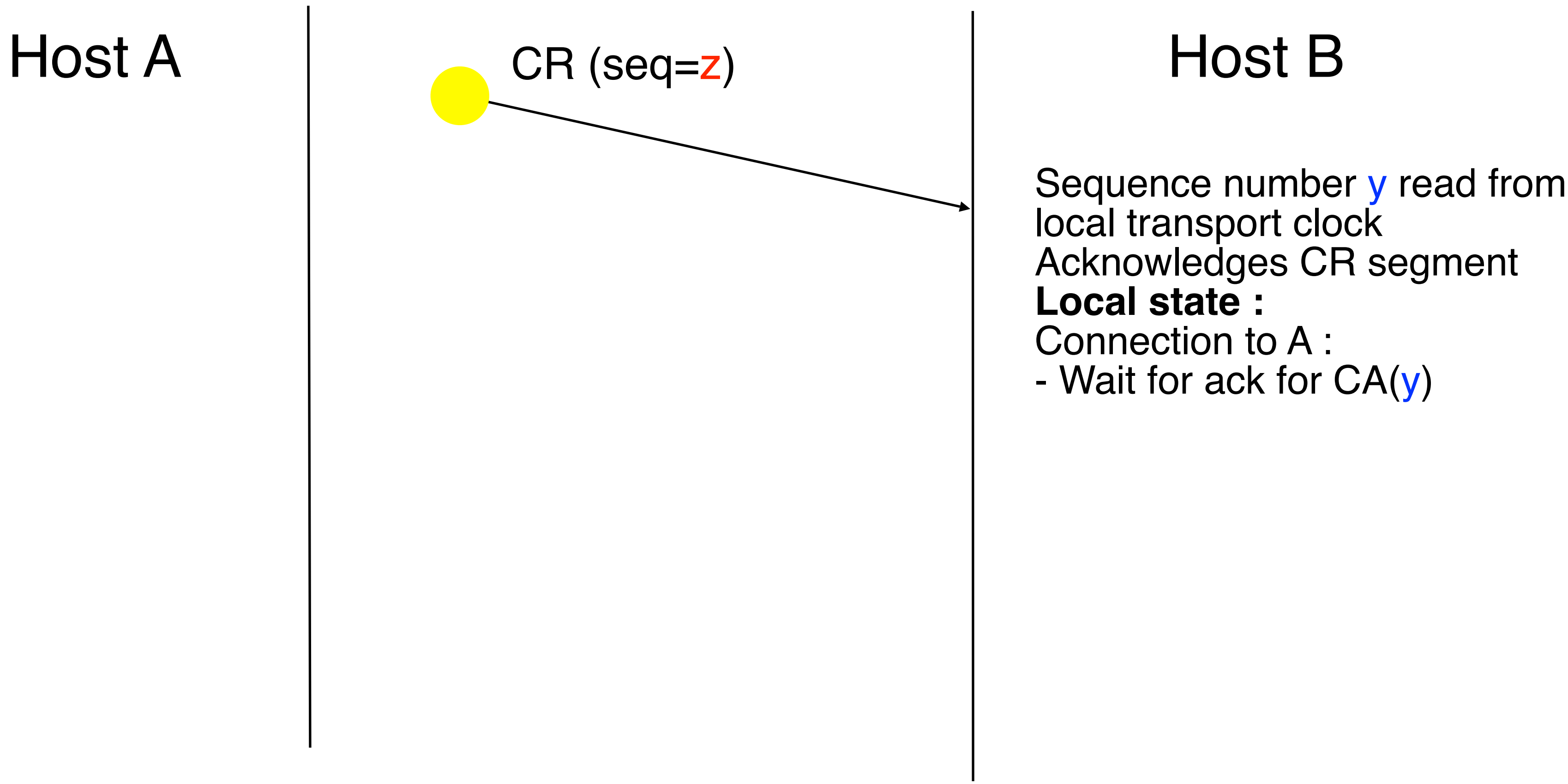

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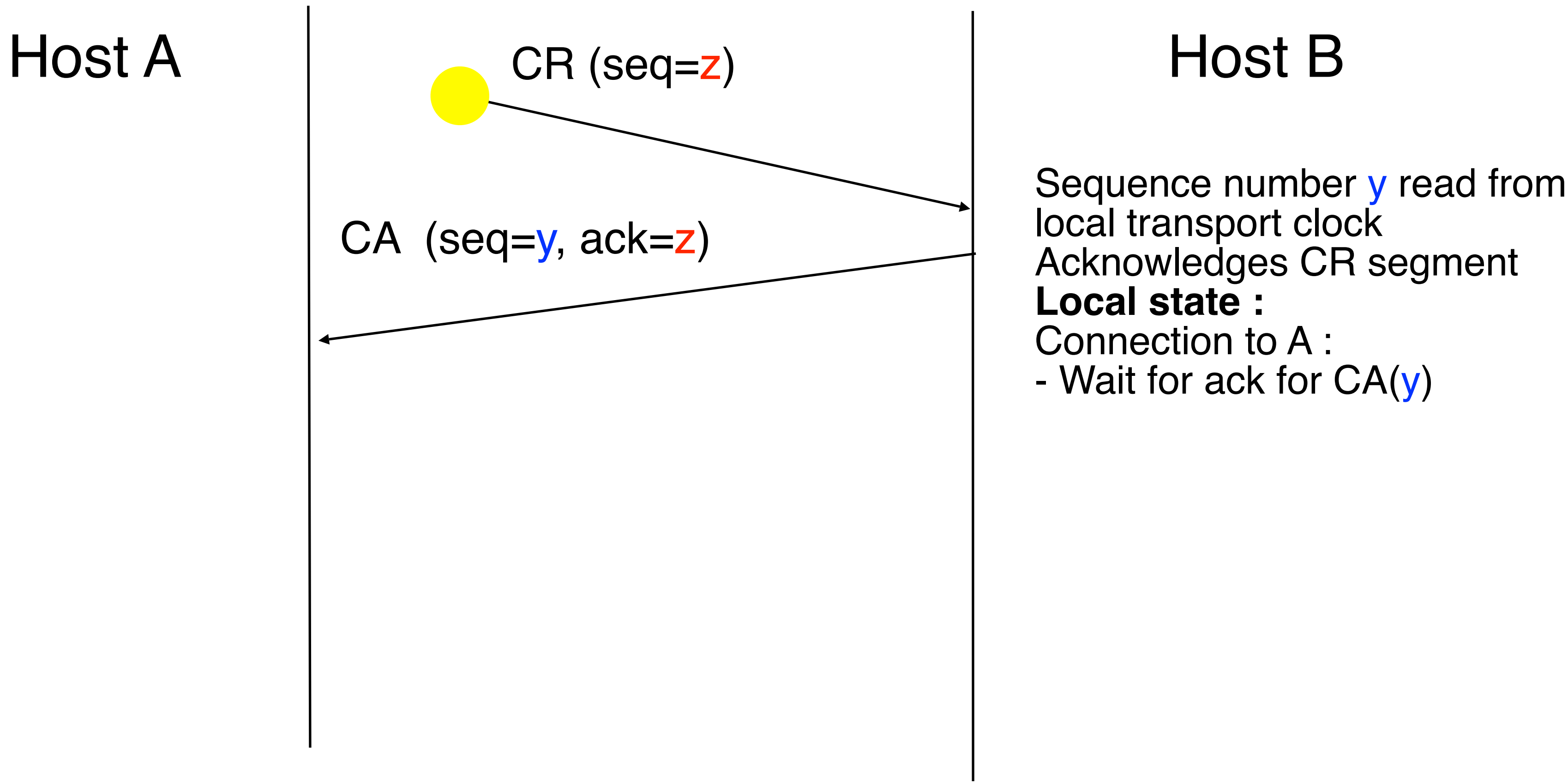

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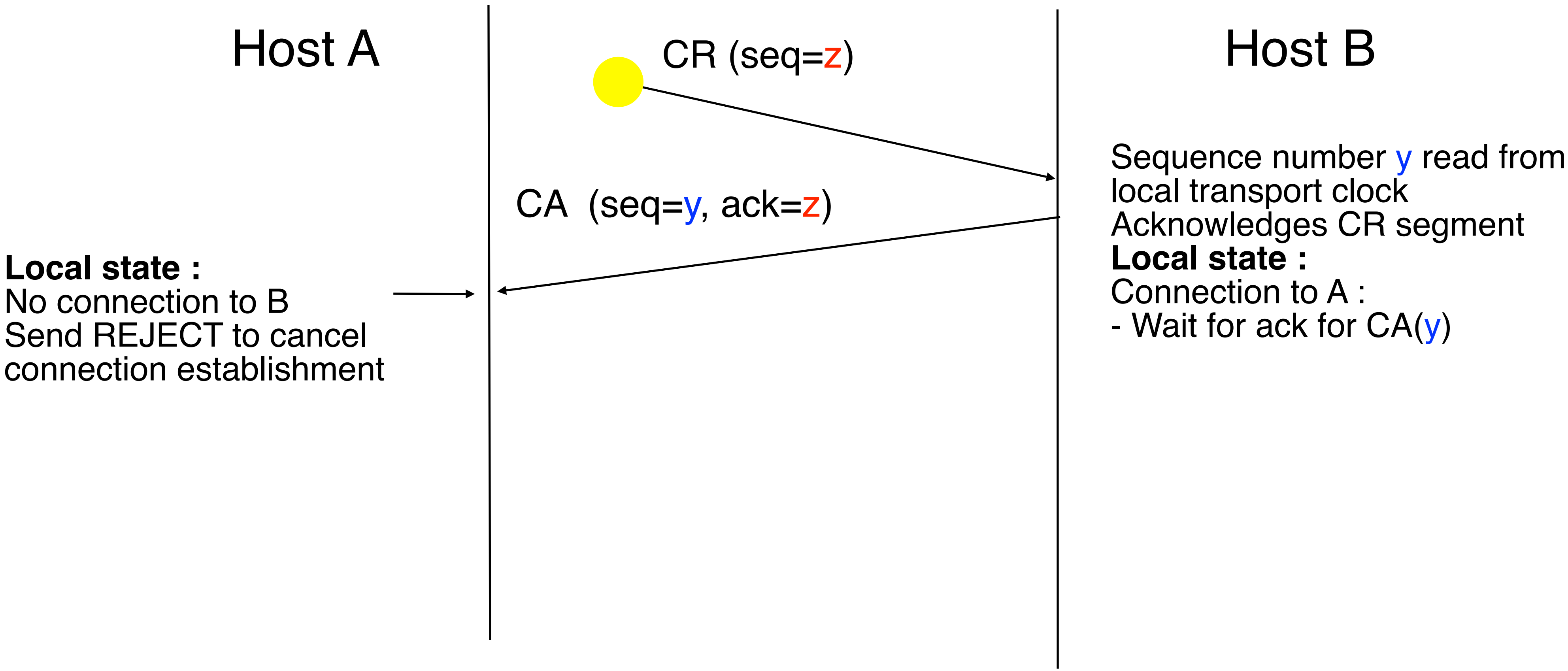

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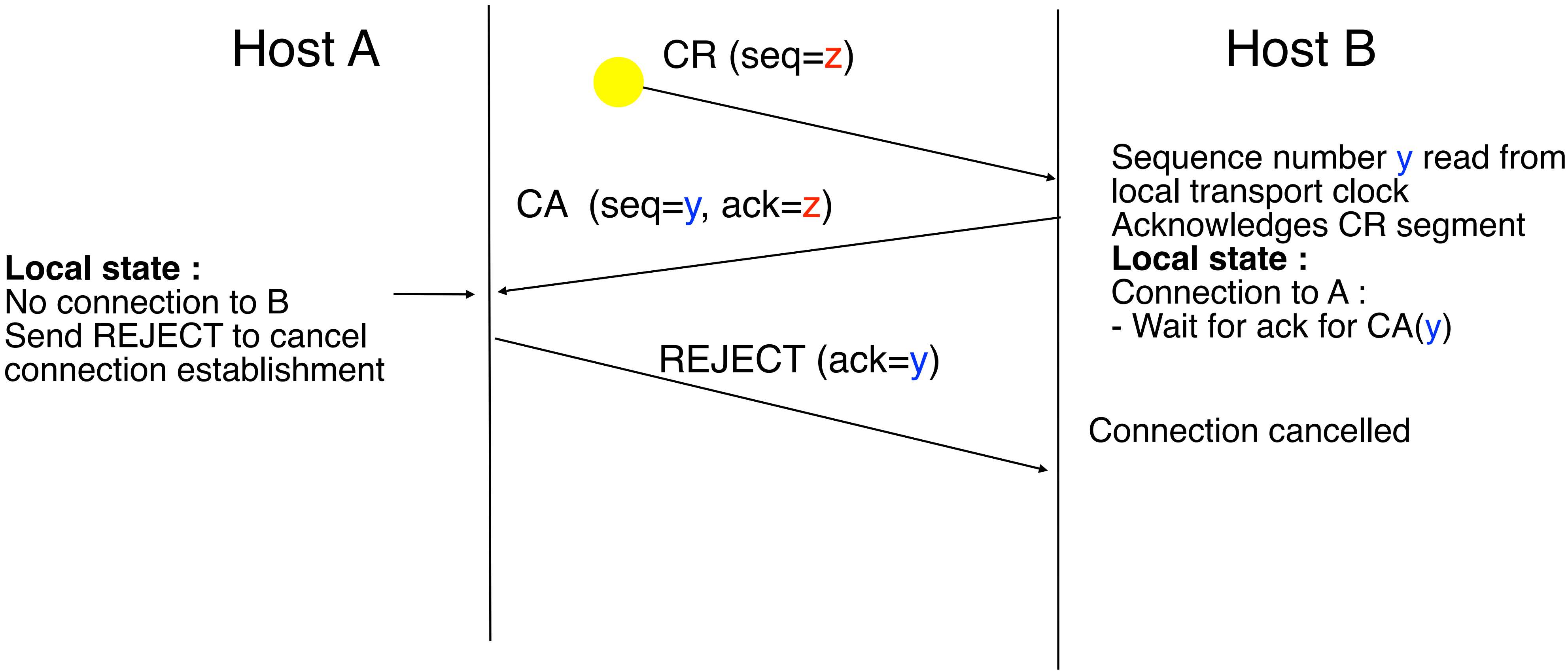


No connection is established

Three way handshake (3)

Host A

Host B

Current state does not contain a CR with seq=x

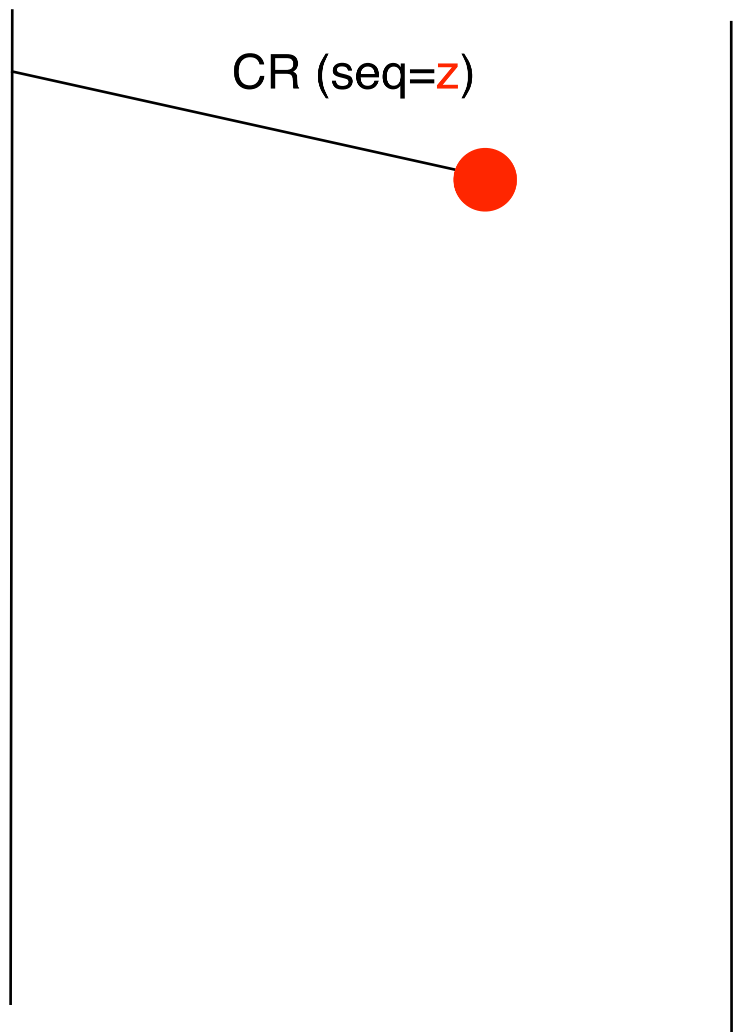
Three way handshake (3)

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

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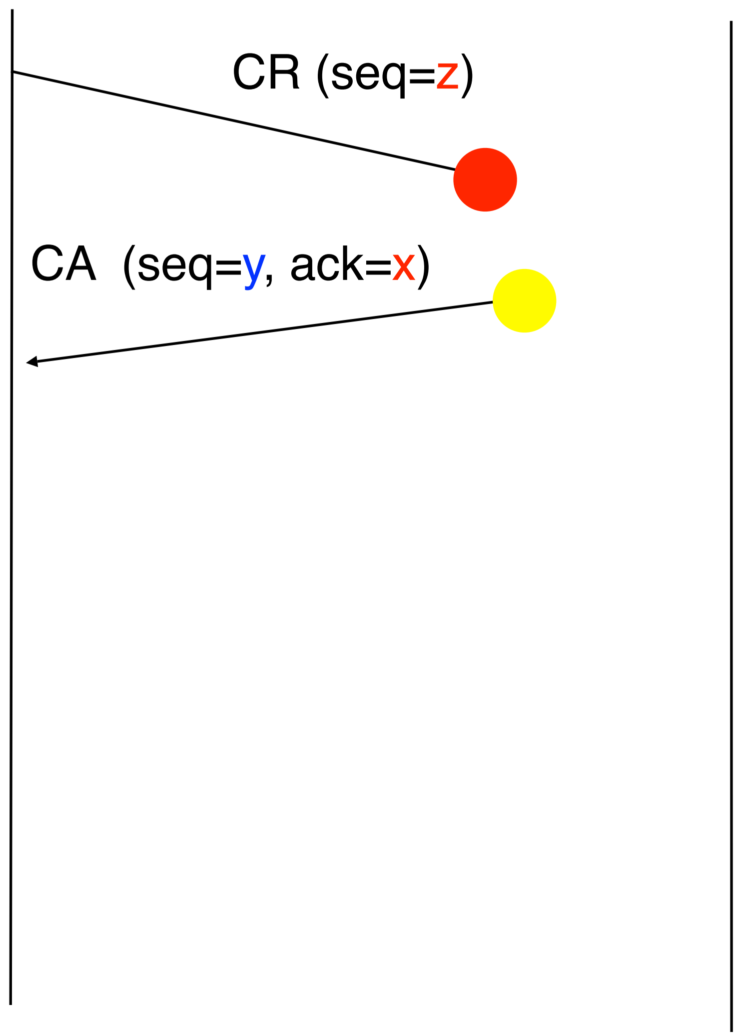


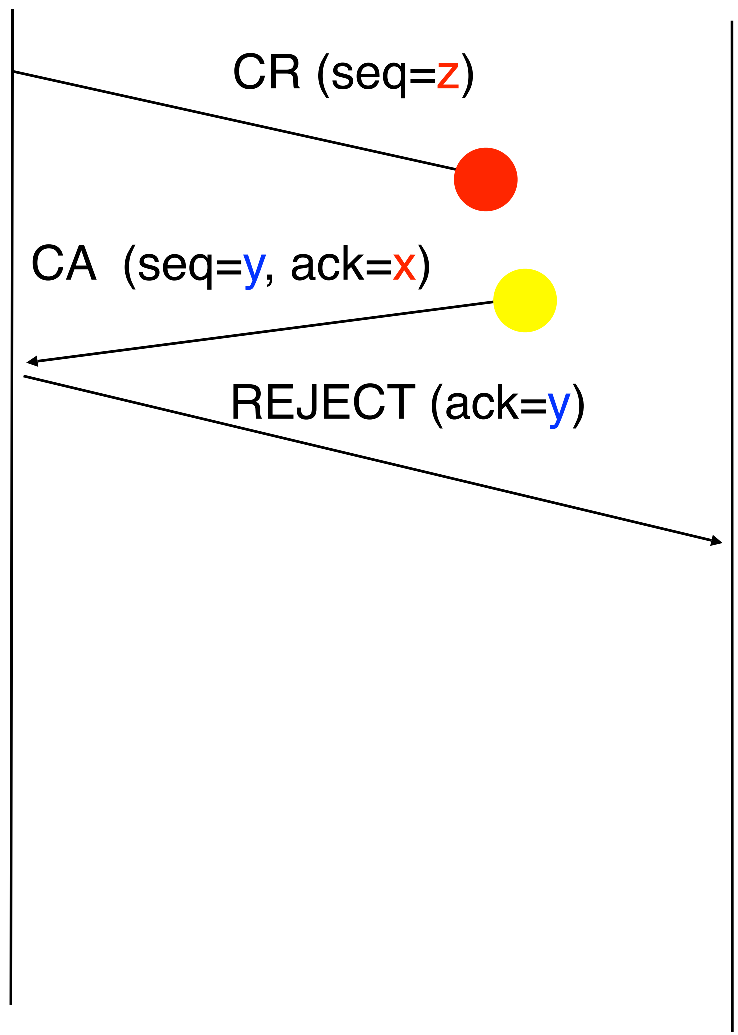
Three way handshake (3)

Host A

Host B

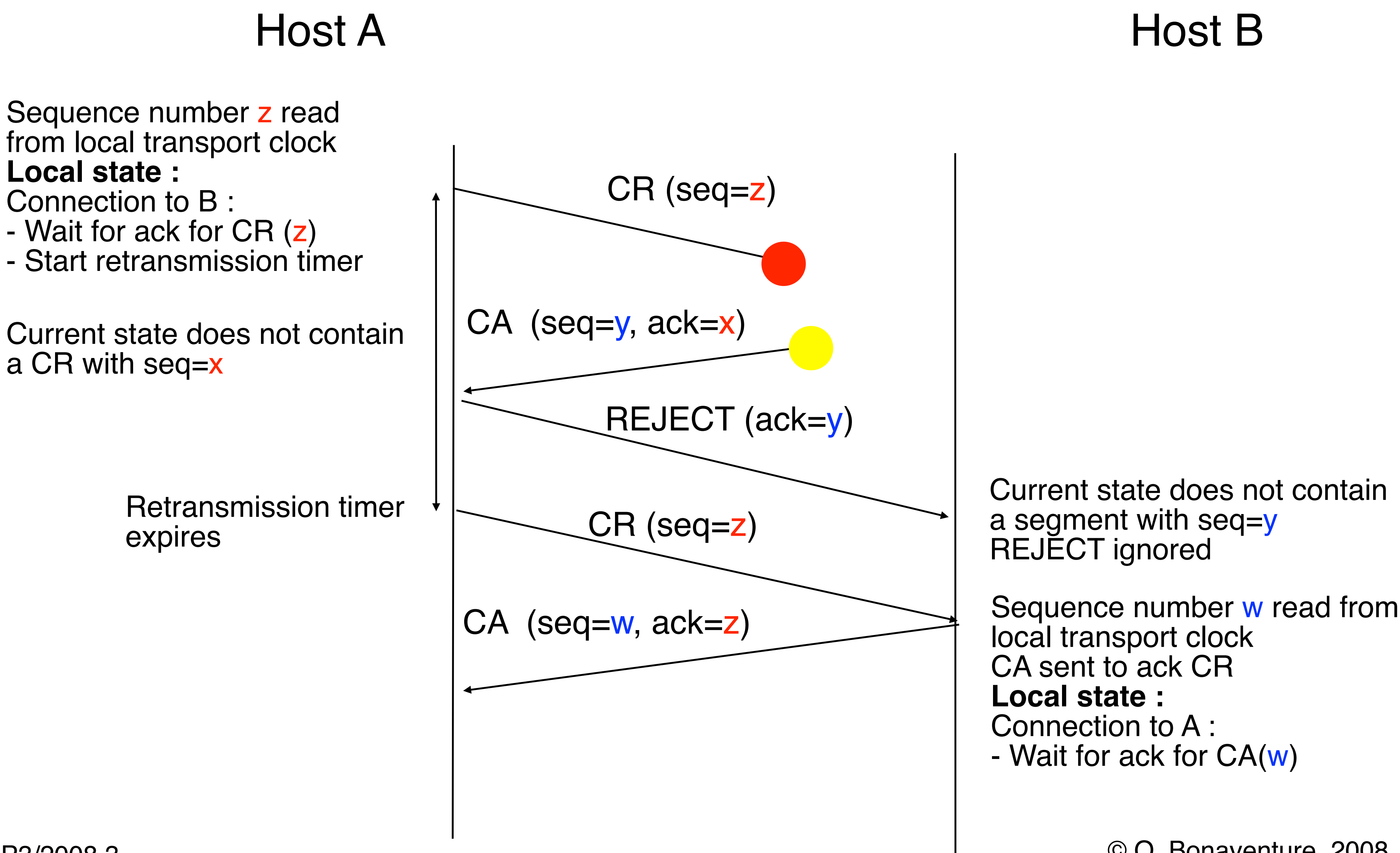
Sequence number z read
from local transport clock
Local state :
Connection to B :
- Wait for ack for CR (z)
- Start retransmission timer

Current state does not contain
a CR with seq=x

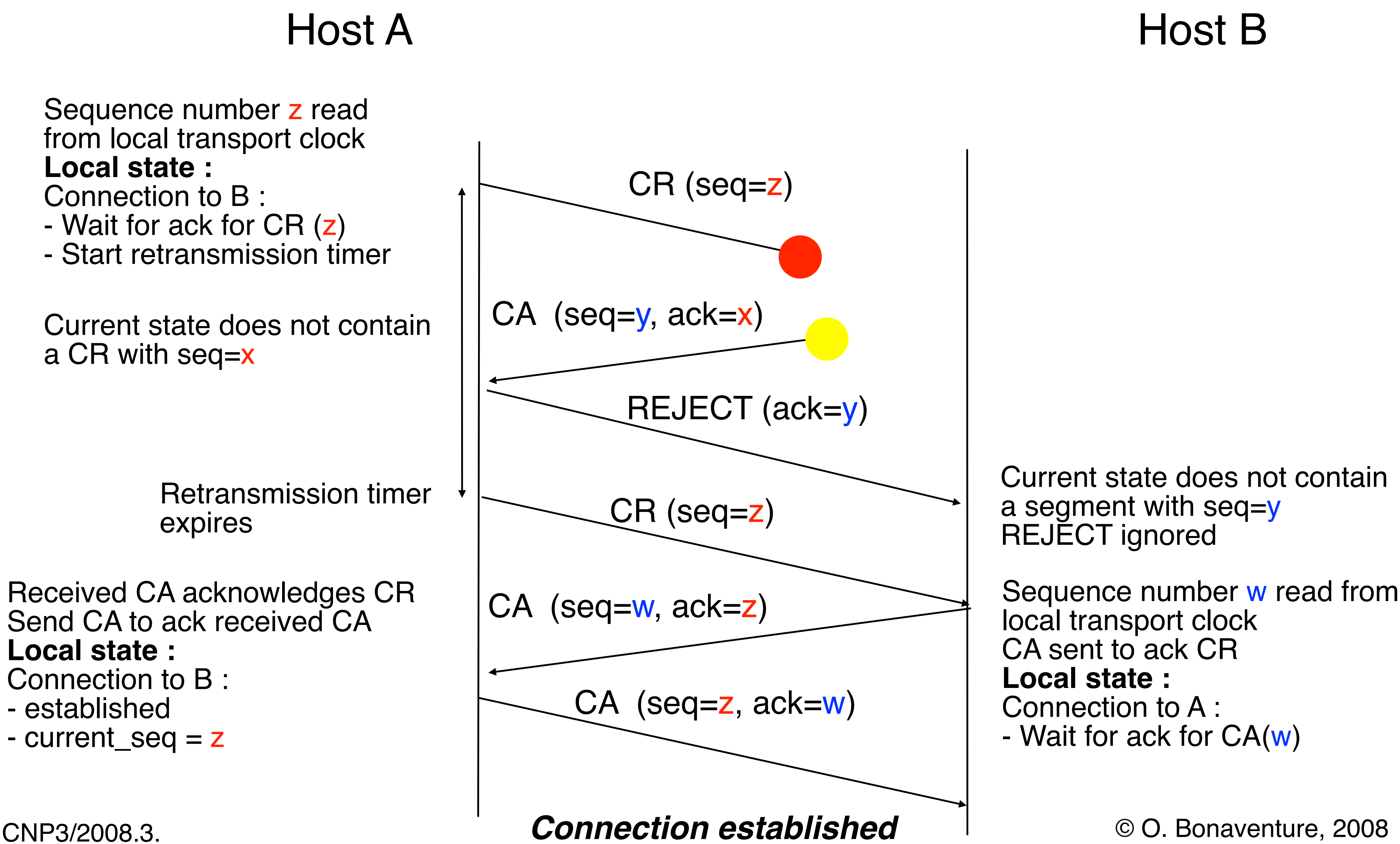


Current state does not contain
a segment with seq=y
REJECT ignored

Three way handshake (3)

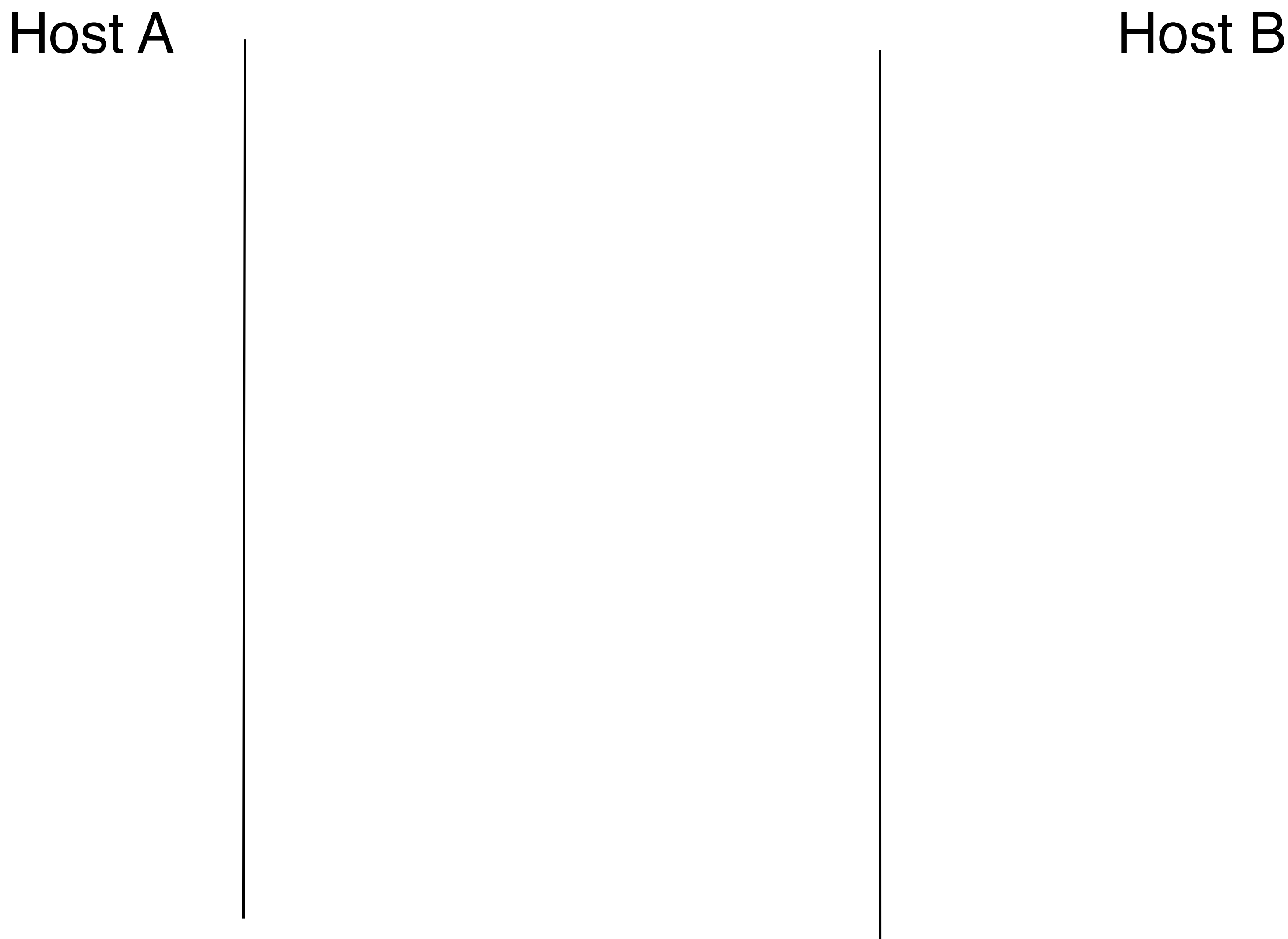


Three way handshake (3)



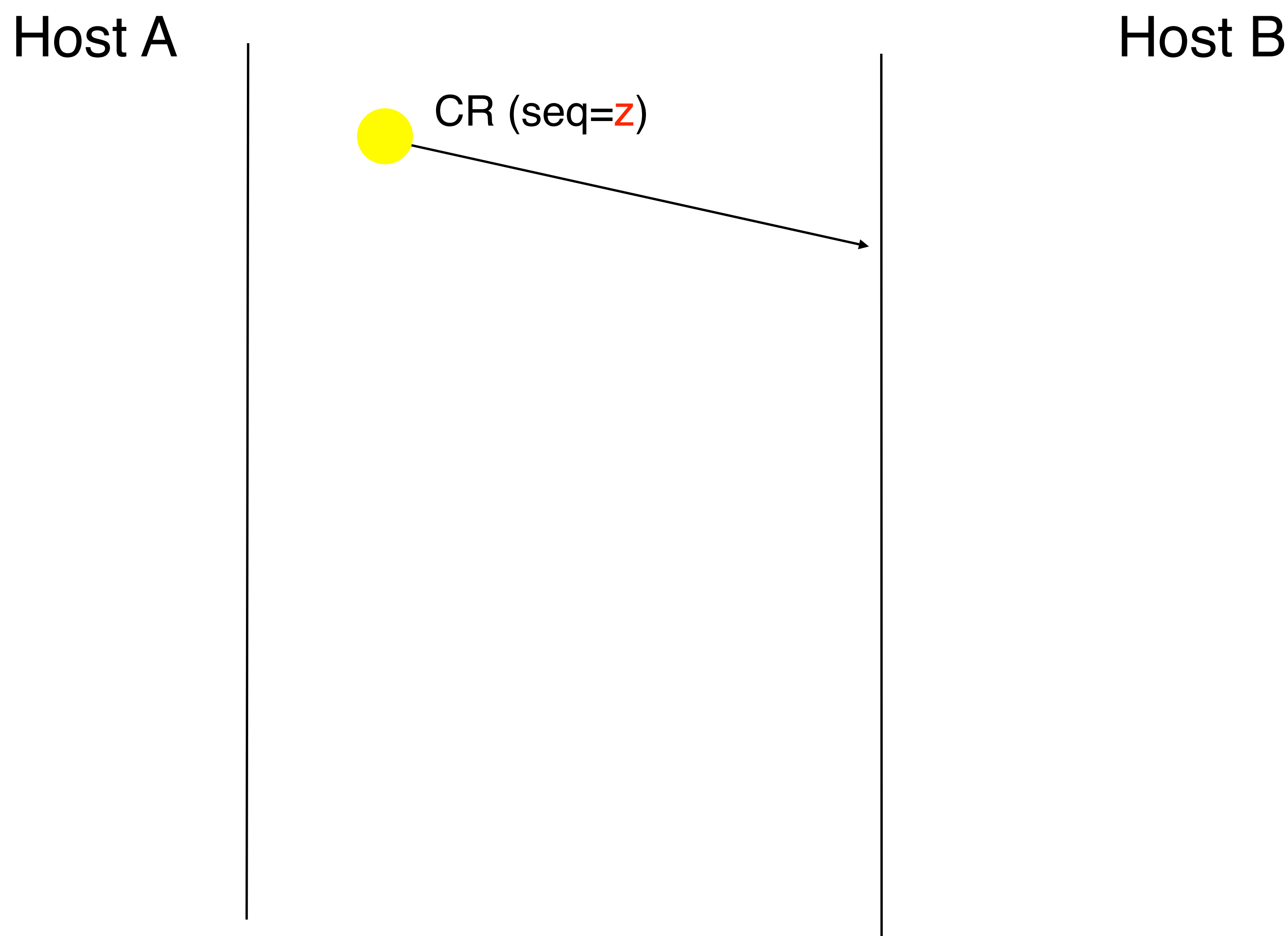
Three way handshake (4)

- Another scenario



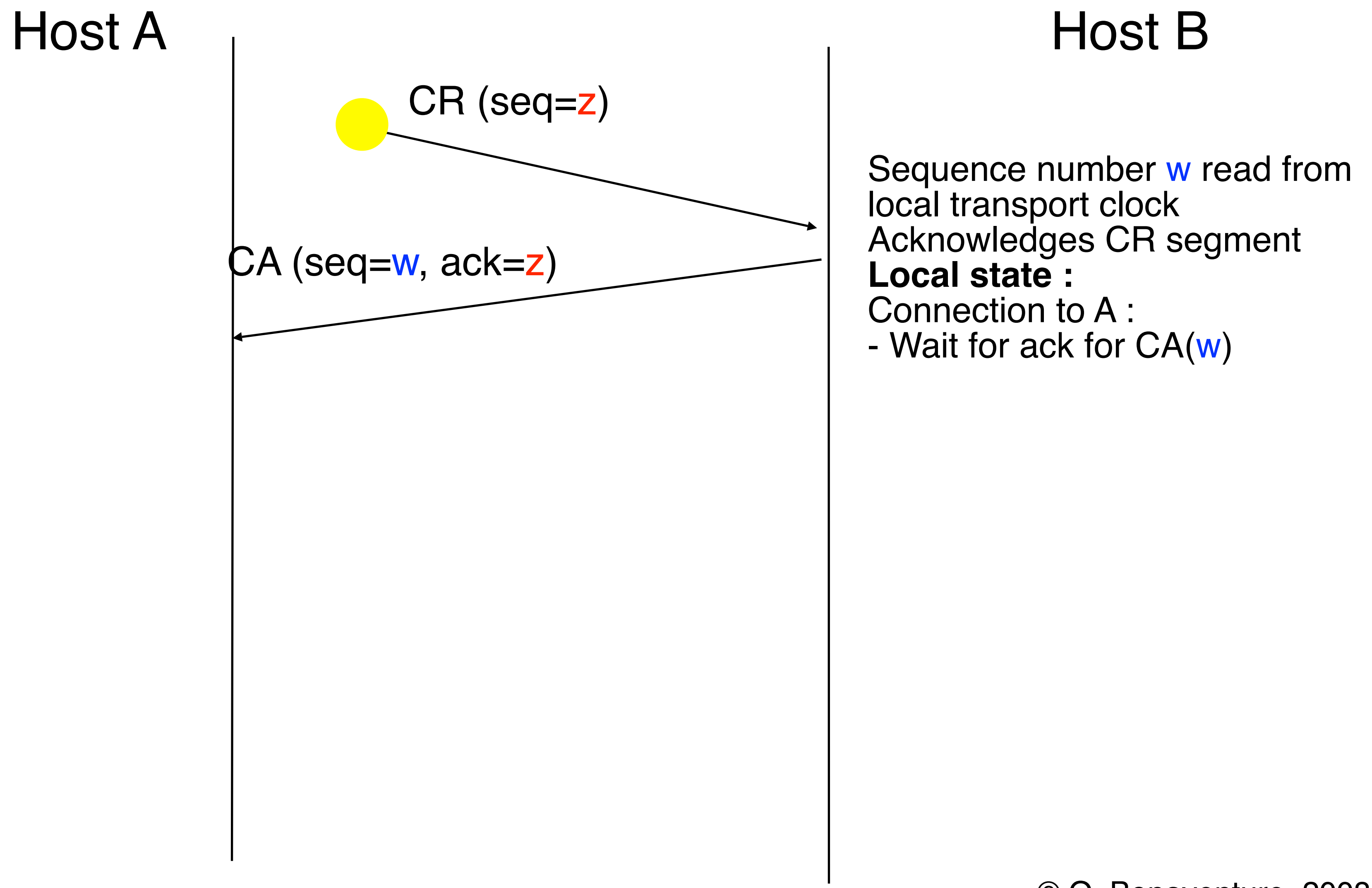
Three way handshake (4)

- Another scenario



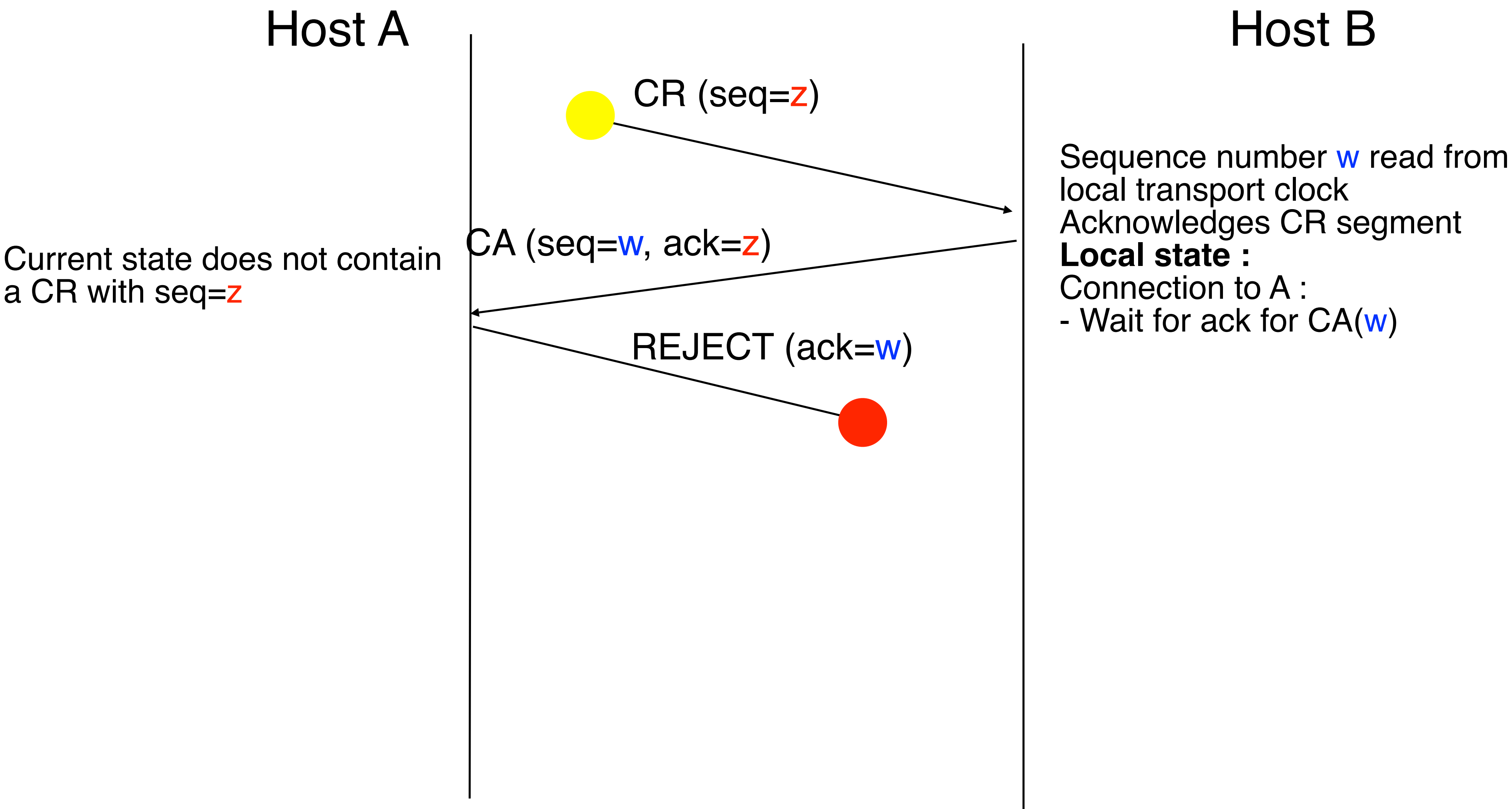
Three way handshake (4)

- Another scenario



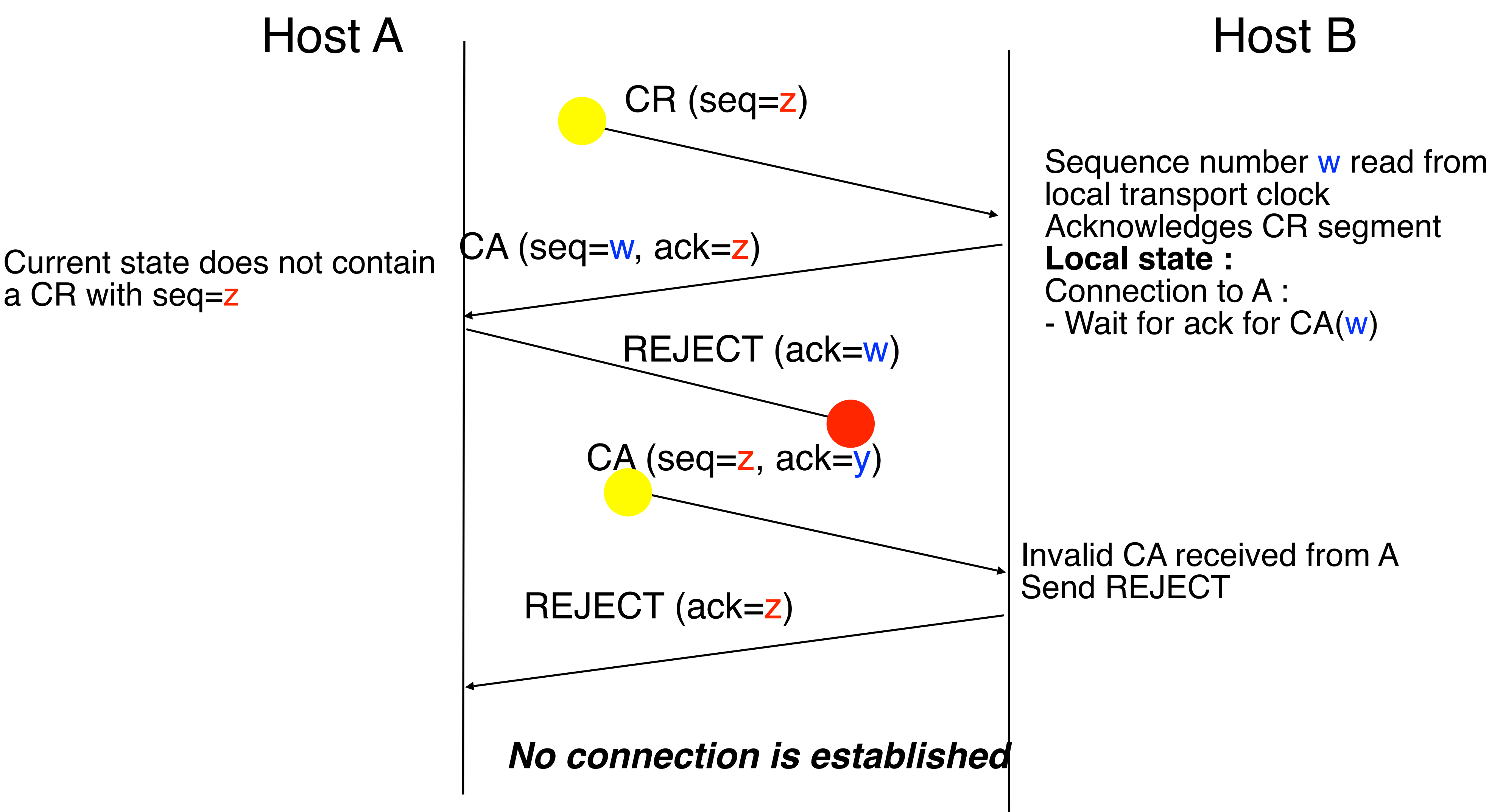
Three way handshake (4)

- Another scenario



Three way handshake (4)

- Another scenario



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

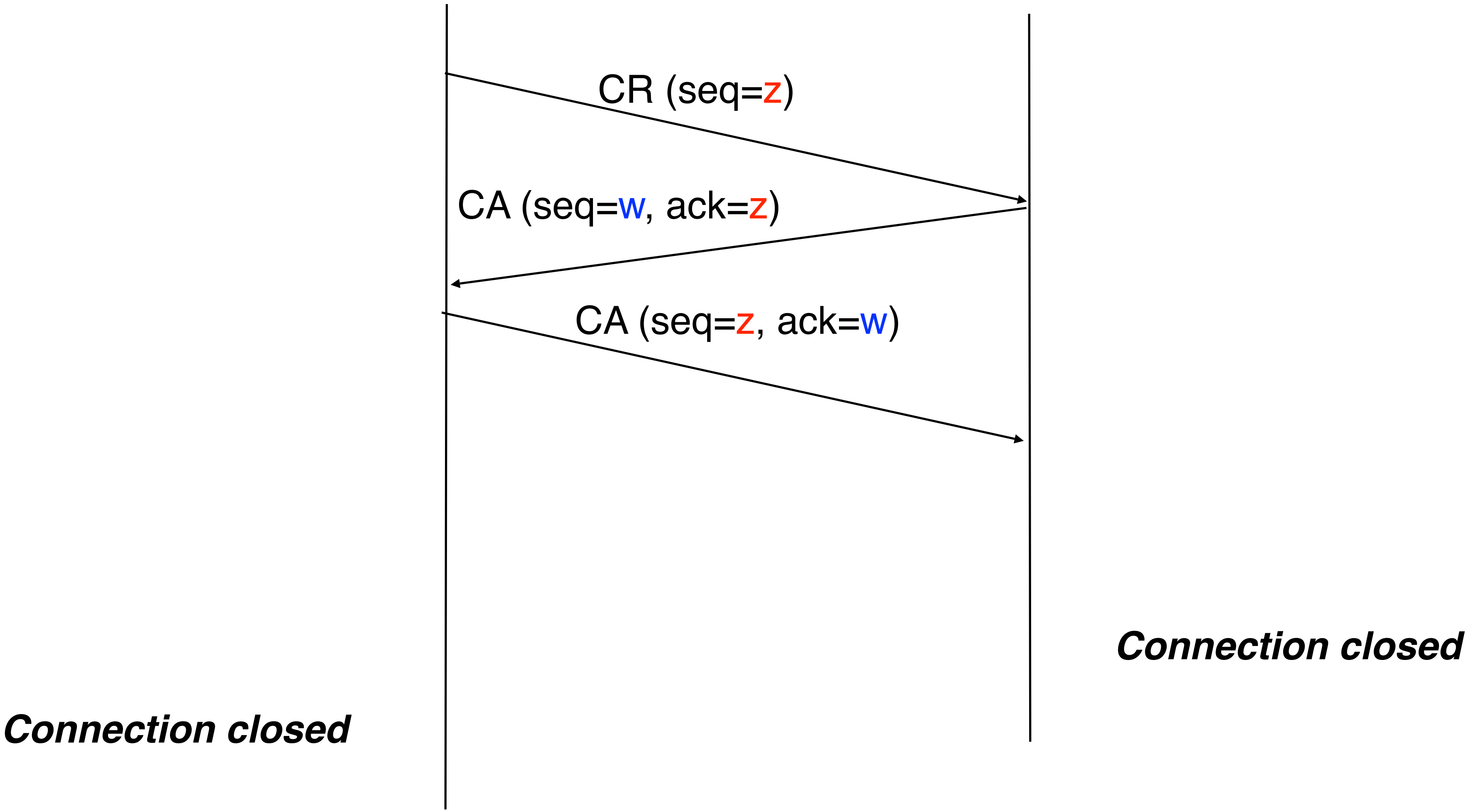
  - Graceful release
    - Each transport entity closes its own direction of data transfer
    - connection will be closed once all data has been correctly delivered

Abrupt release

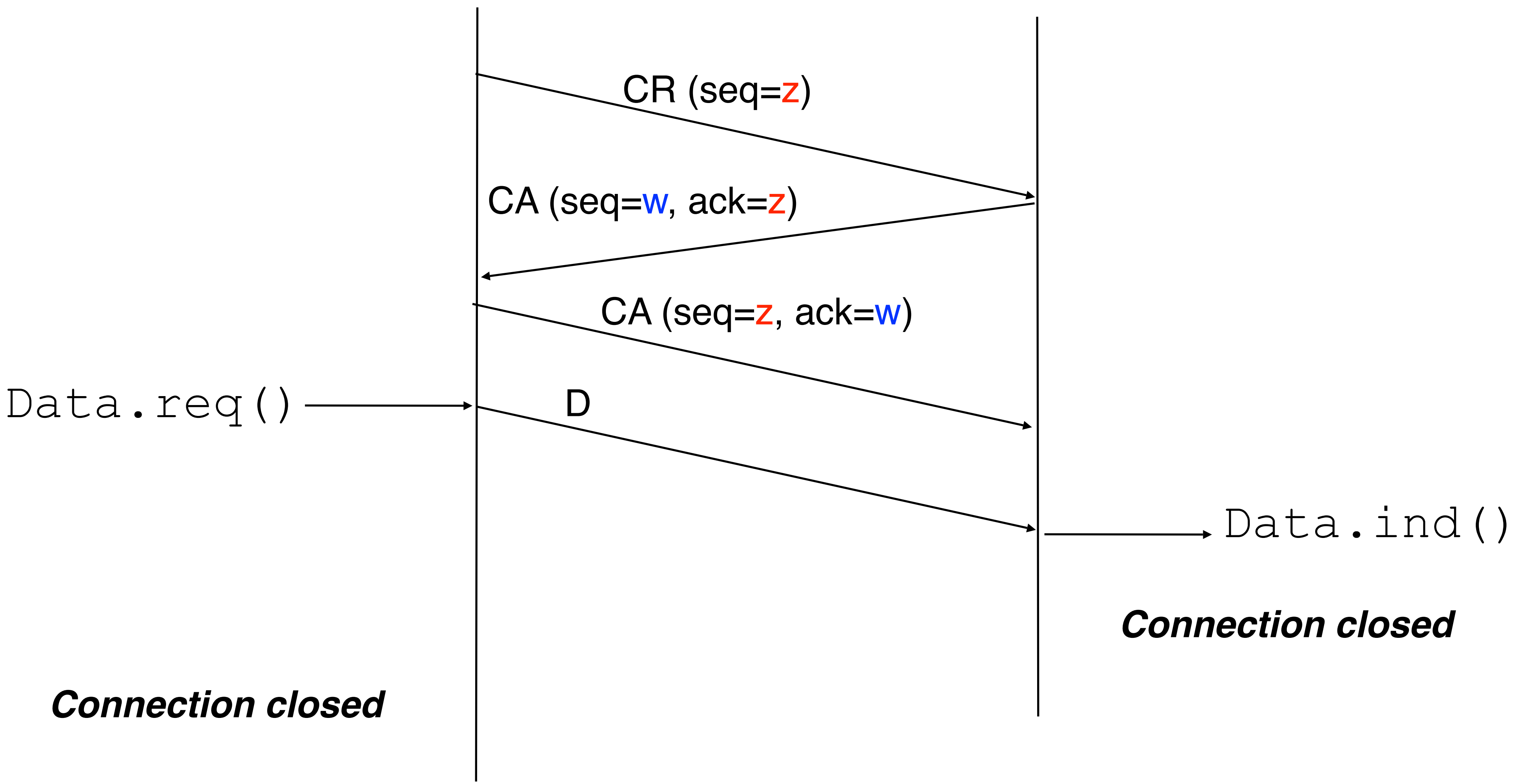
Connection closed

Connection closed

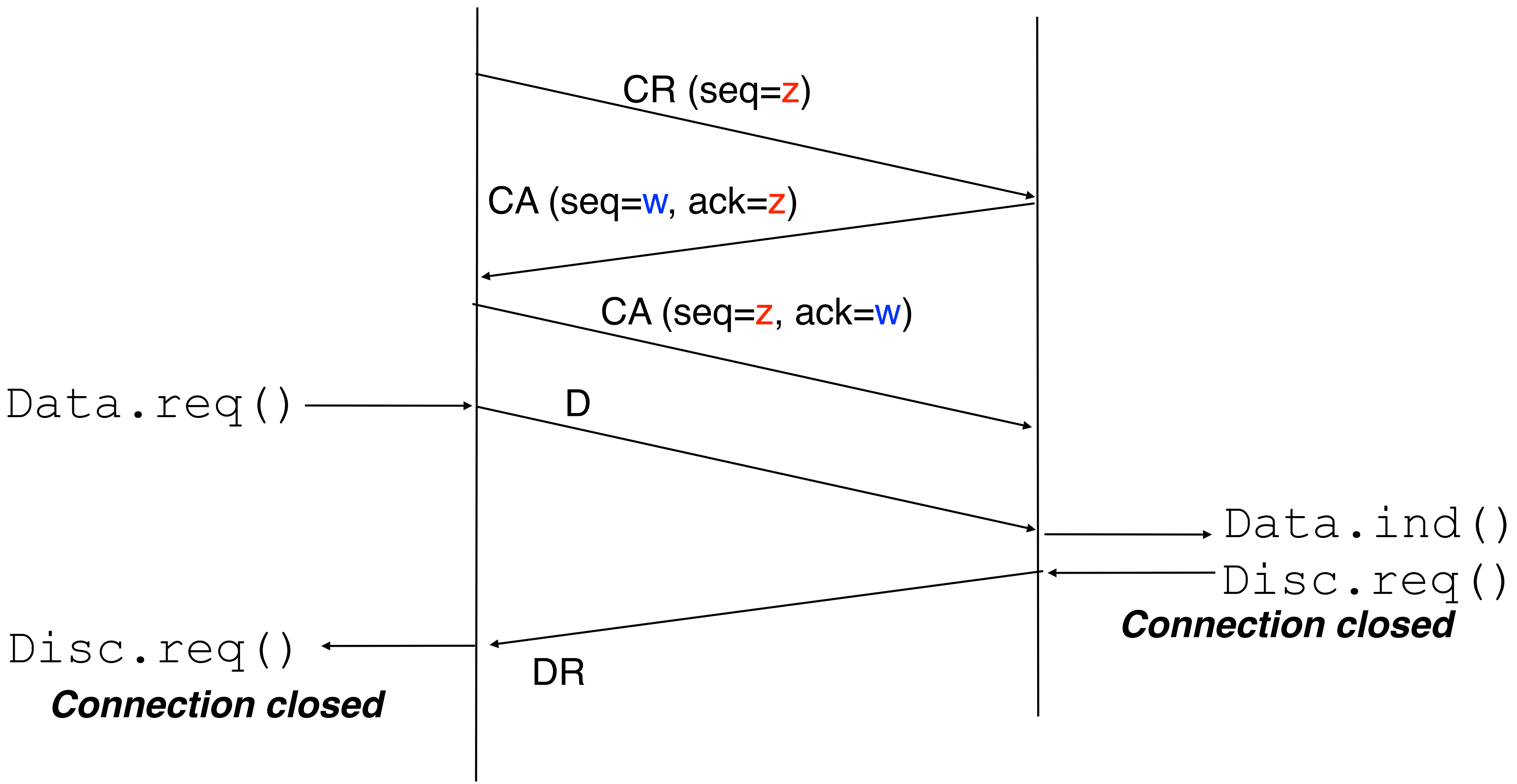
Abrupt release



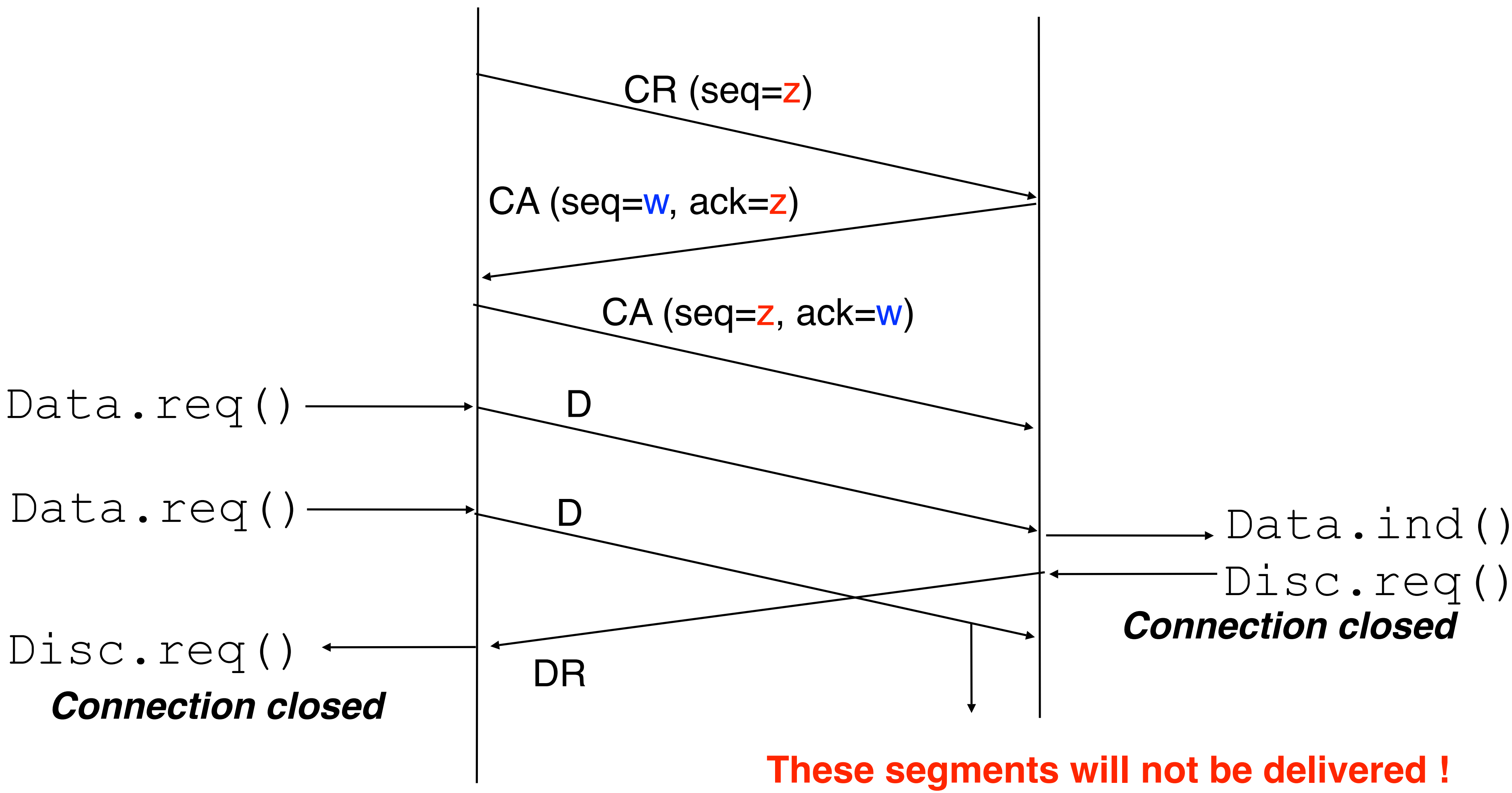
Abrupt release



Abrupt release



Abrupt release



Abrupt release (2)

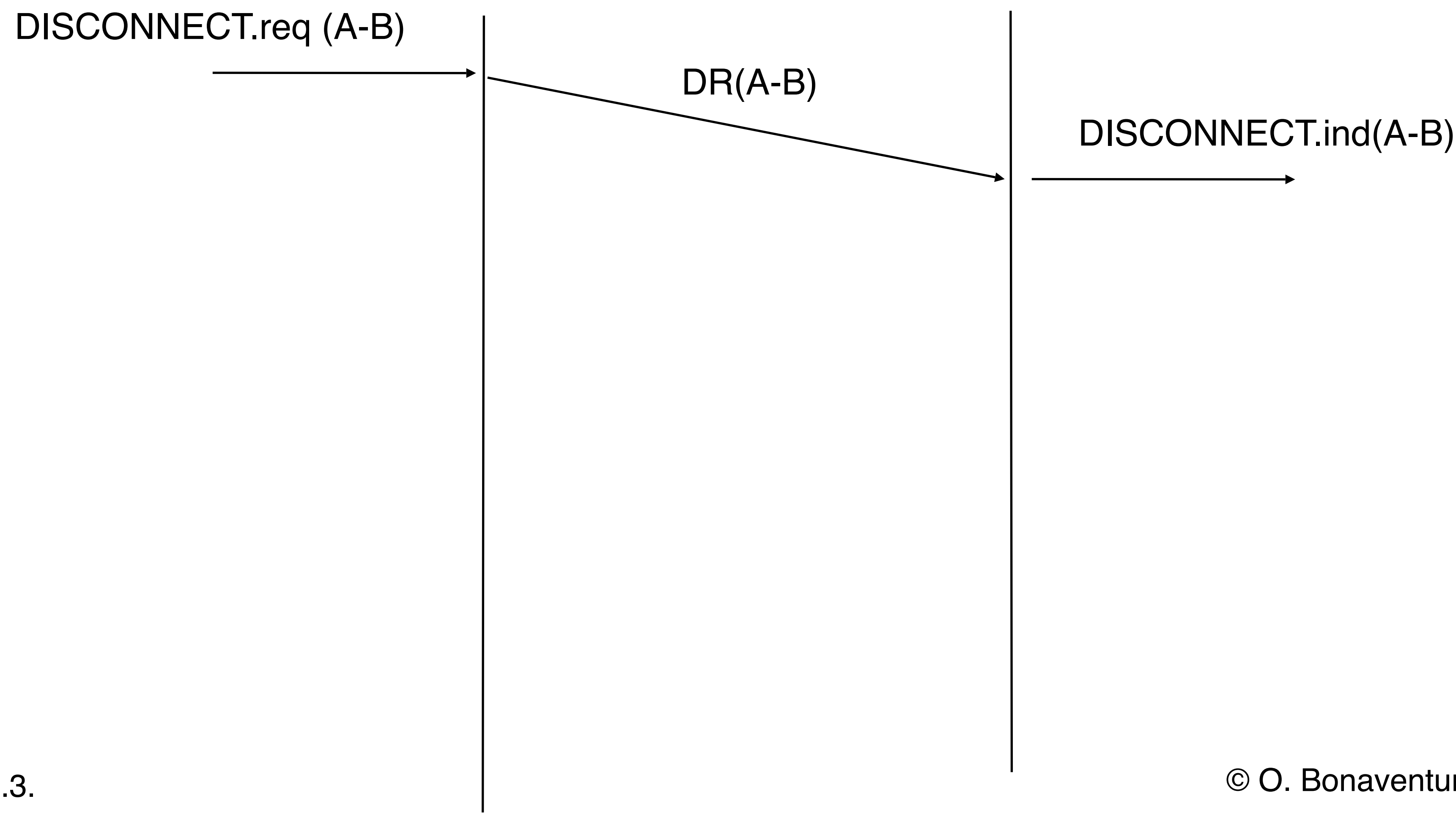
- A transport layer entity may itself be forced to release a transport connection
  - the same data segment has been transmitted multiple times without receiving an acknowledgement
  - the network layer reports that the destination host is not reachable anymore
  - the transport layer entity does not 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
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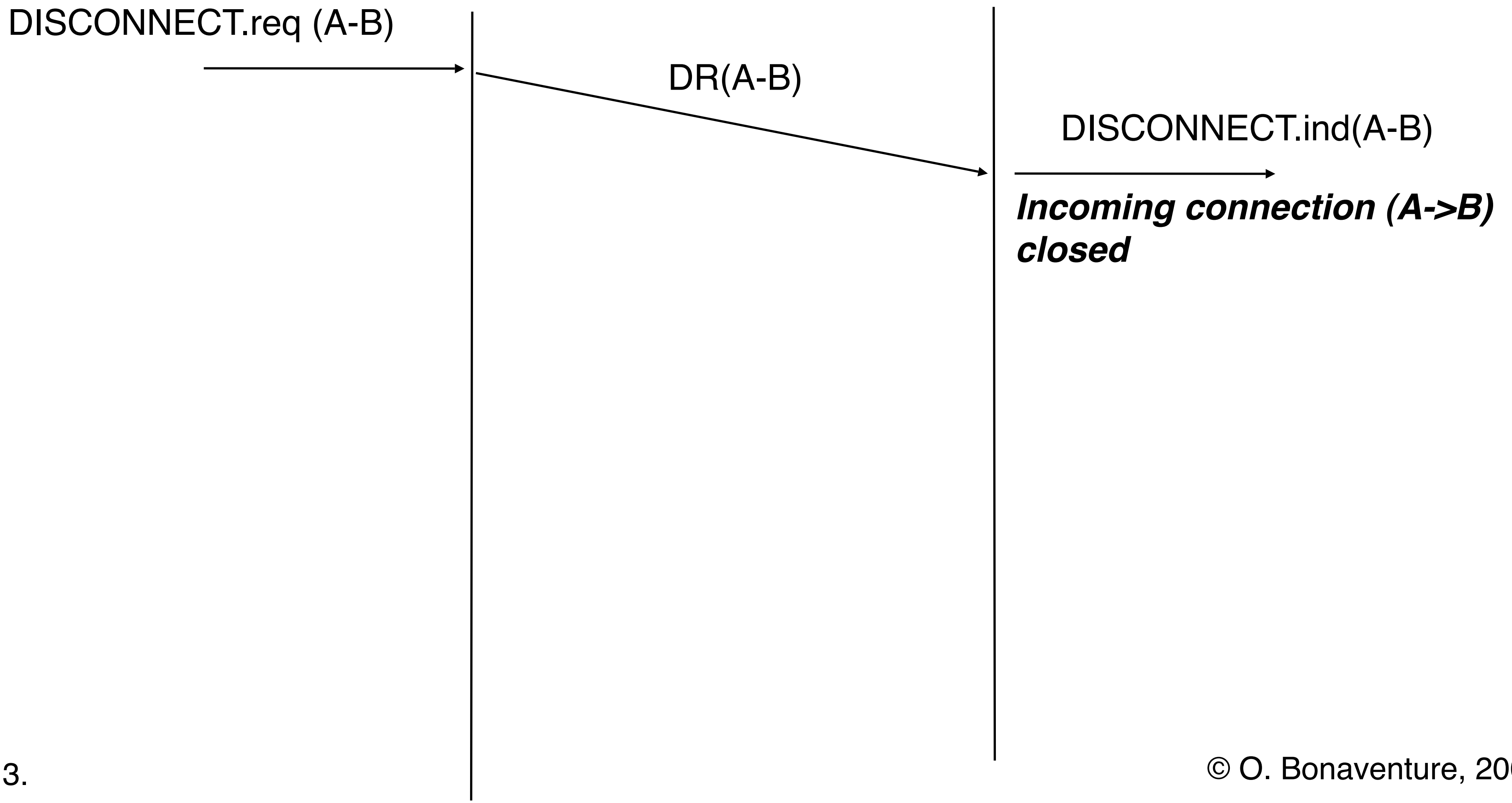

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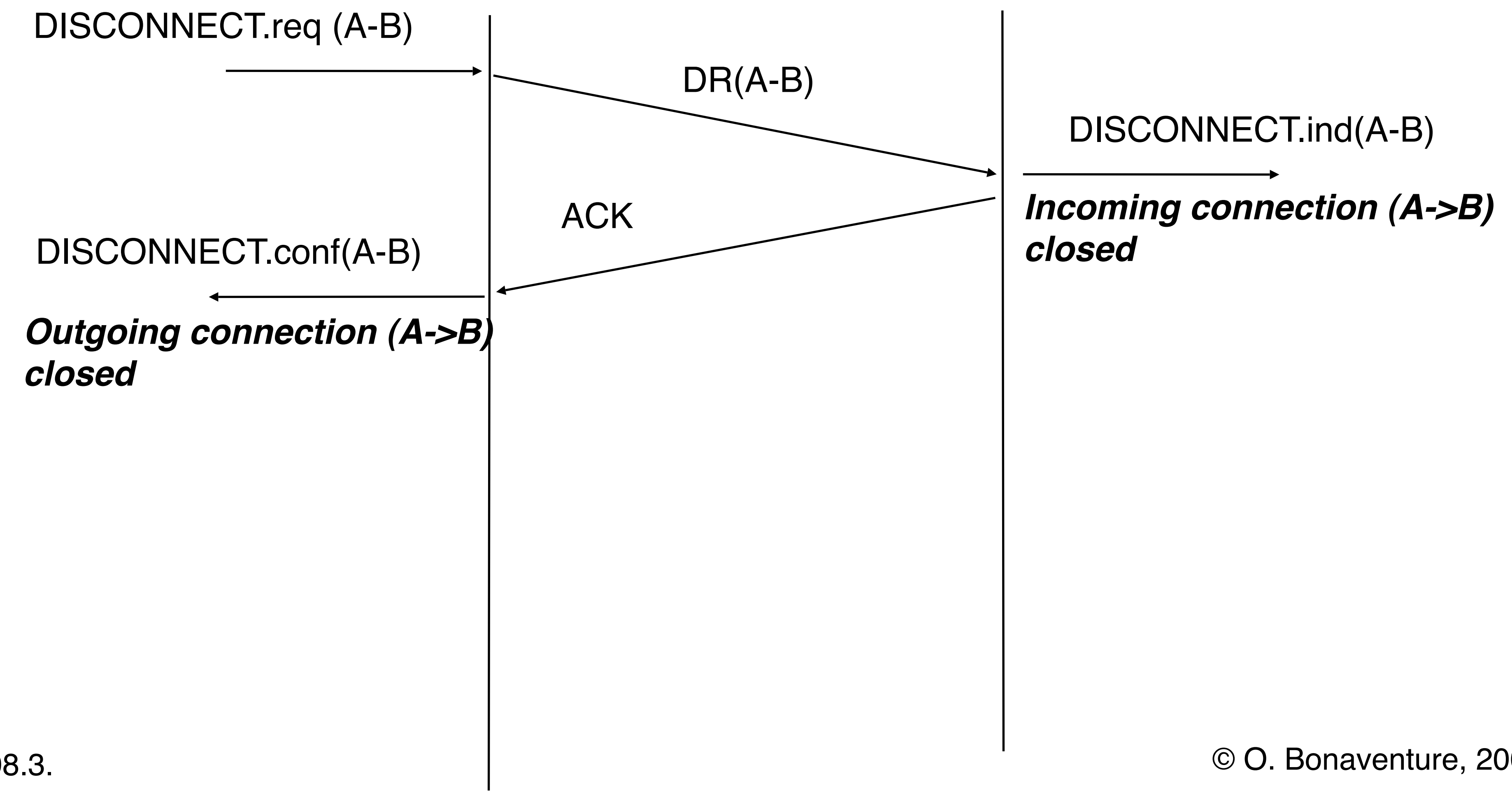

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- Principle
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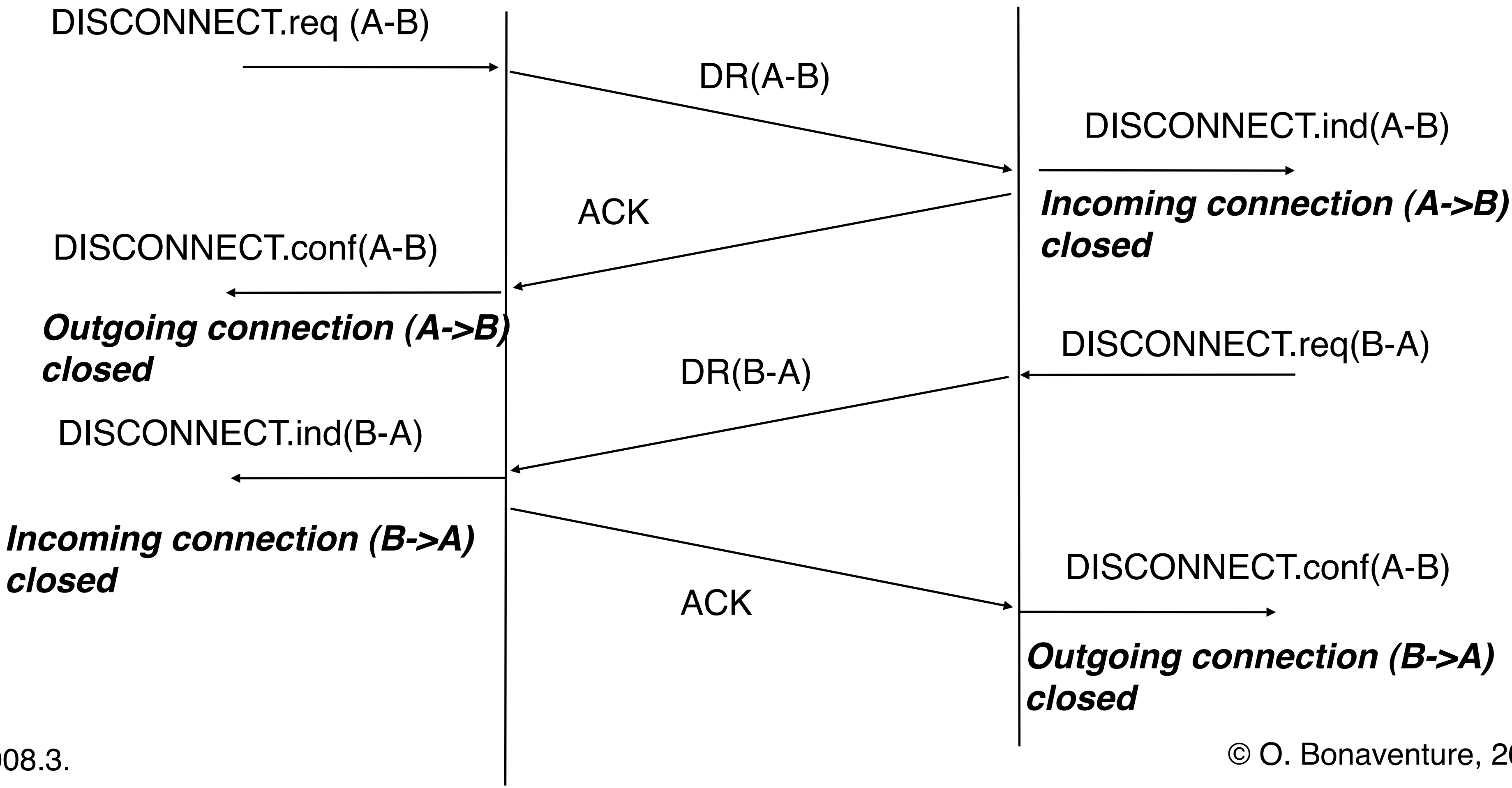


Reliability of the transport layer

- 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

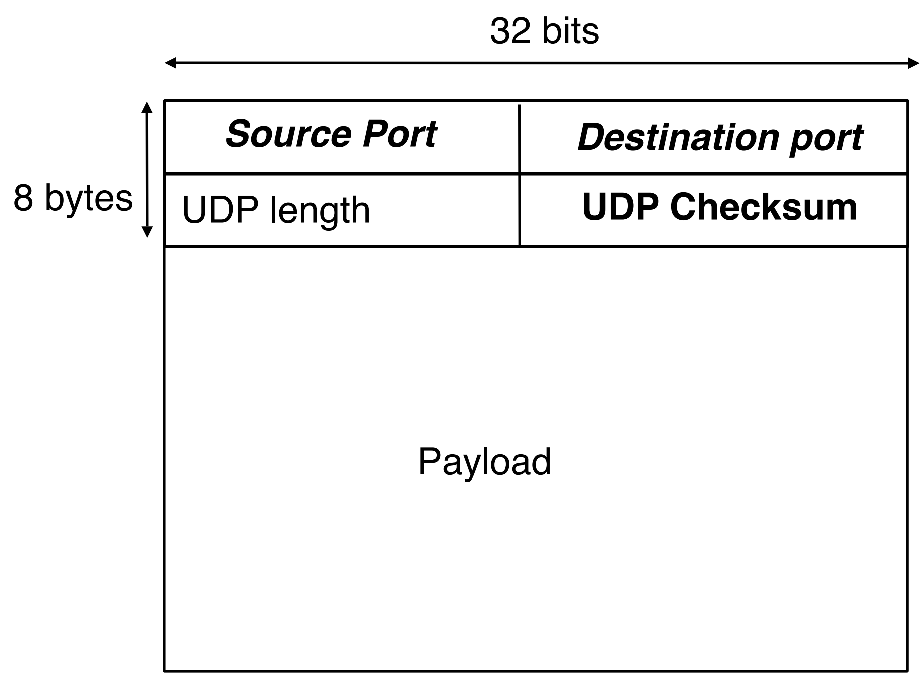
- User Datagram Protocol (UDP)
  - The simplest transport protocol
- Goal
  - Allow applications to exchange small SDUs by relying on the IP service
    - on most operating systems, sending raw IP packets requires special privileges while any application can use directly the transport service
- Constraint
  - 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

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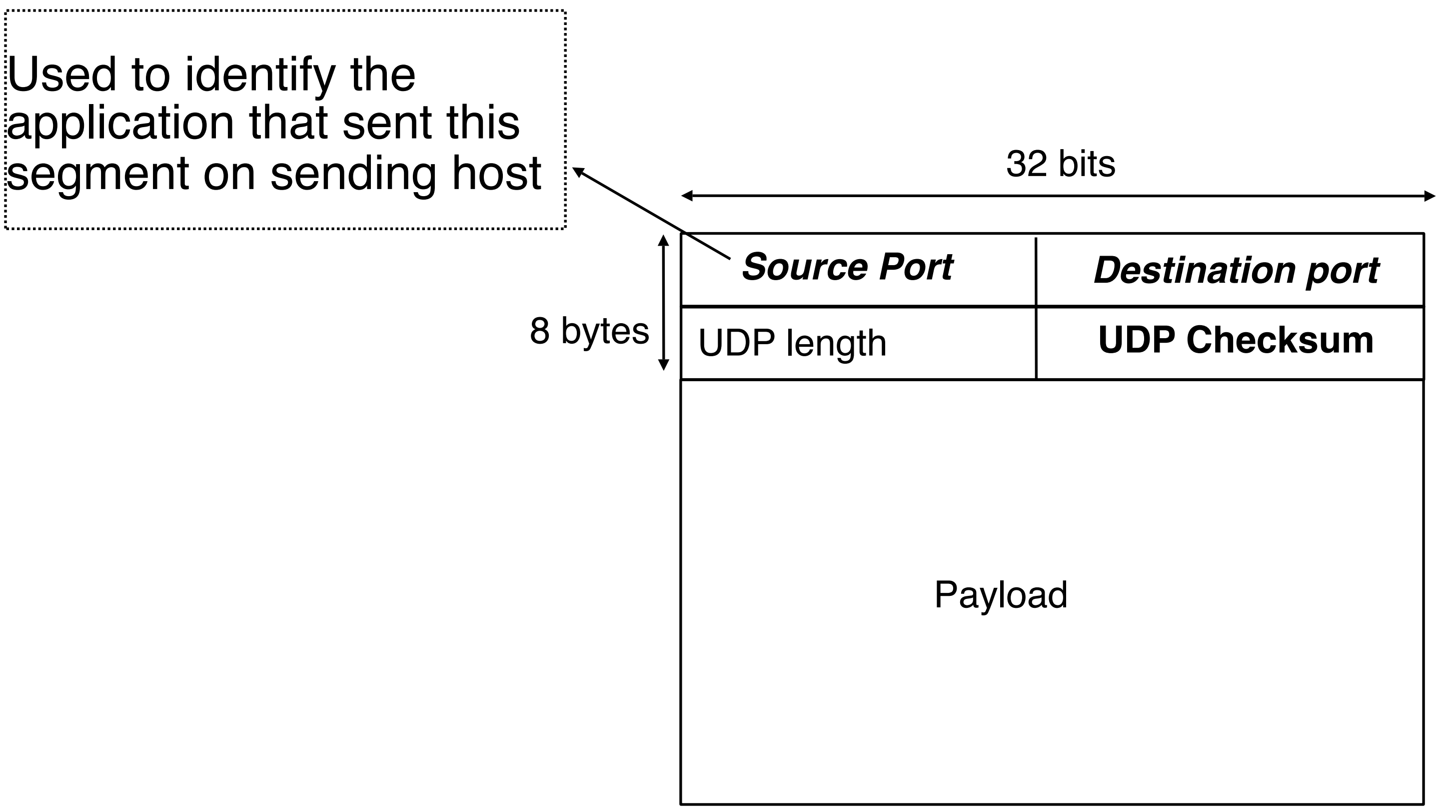

UDP protocol

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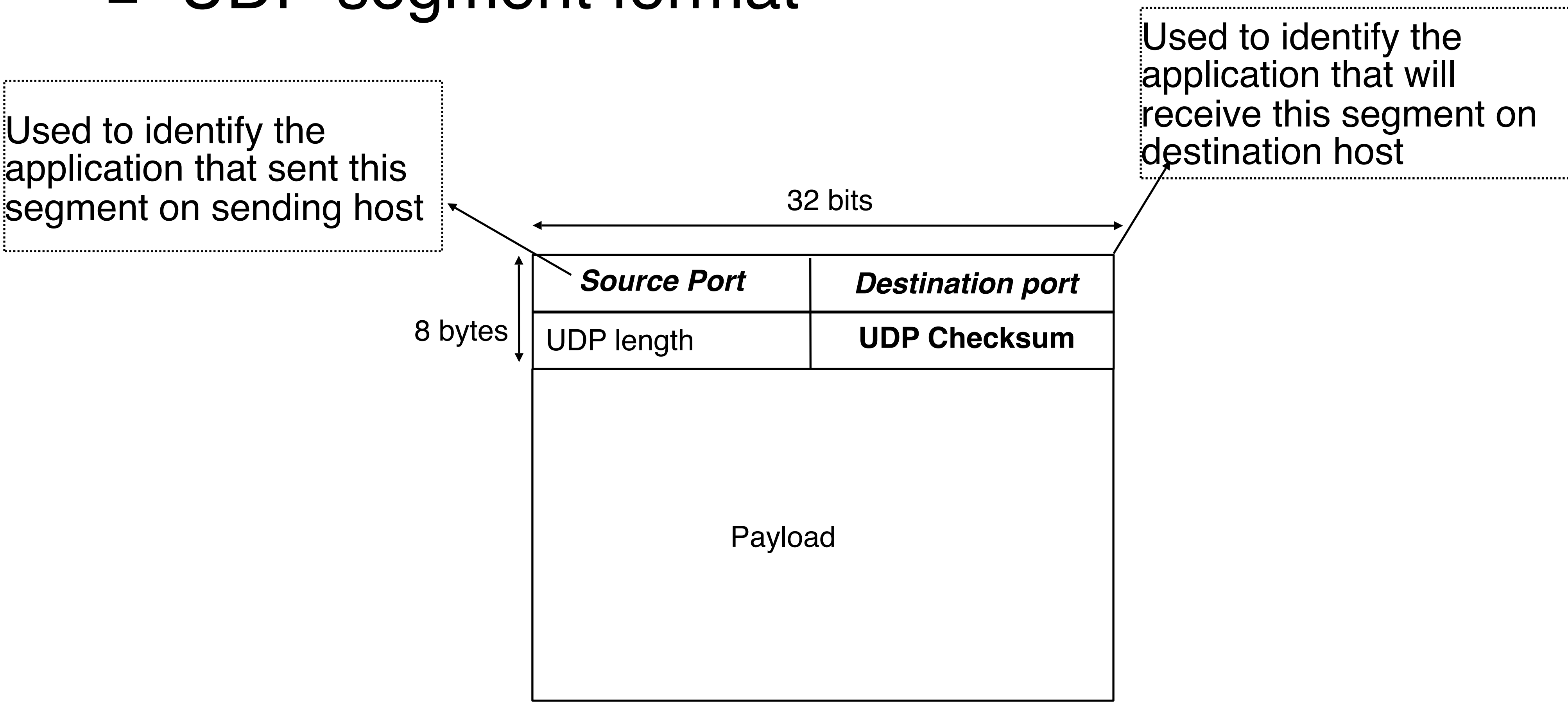

UDP protocol

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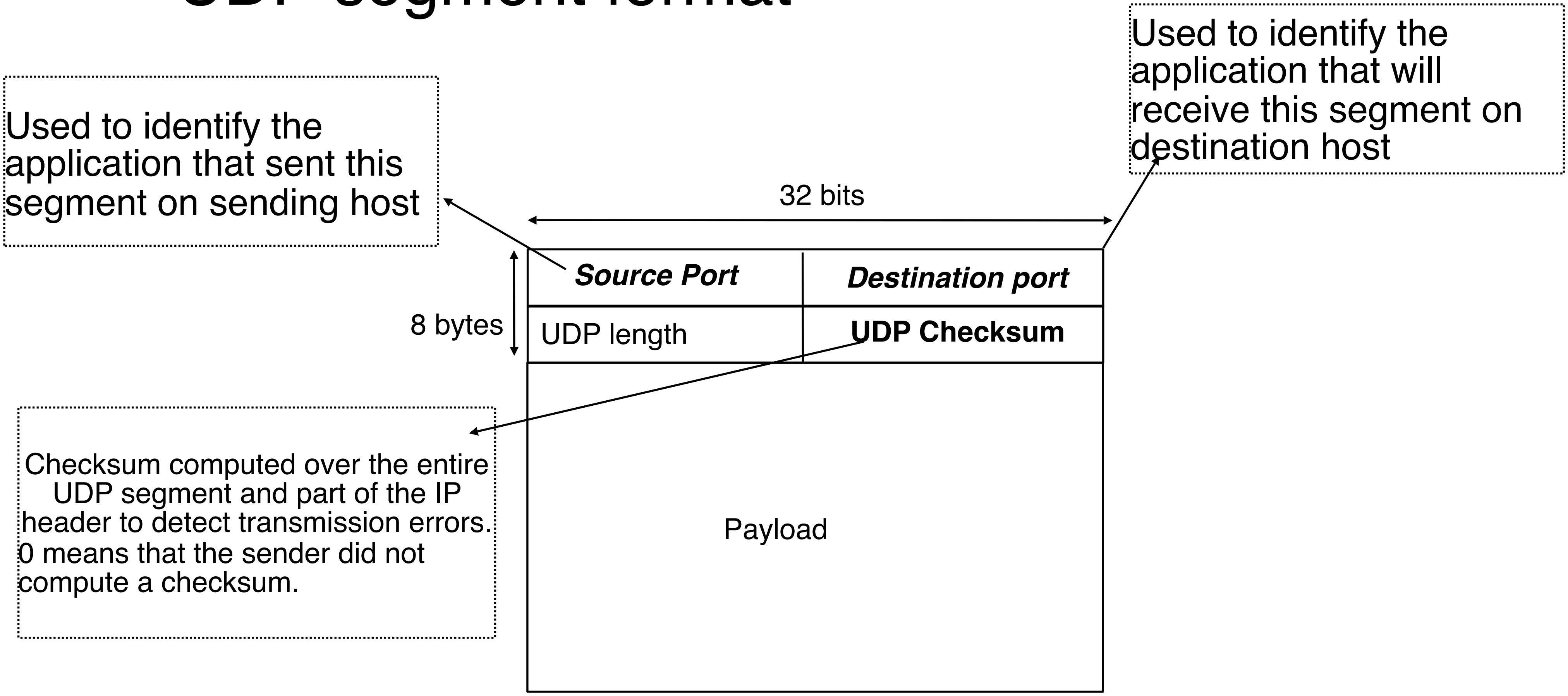

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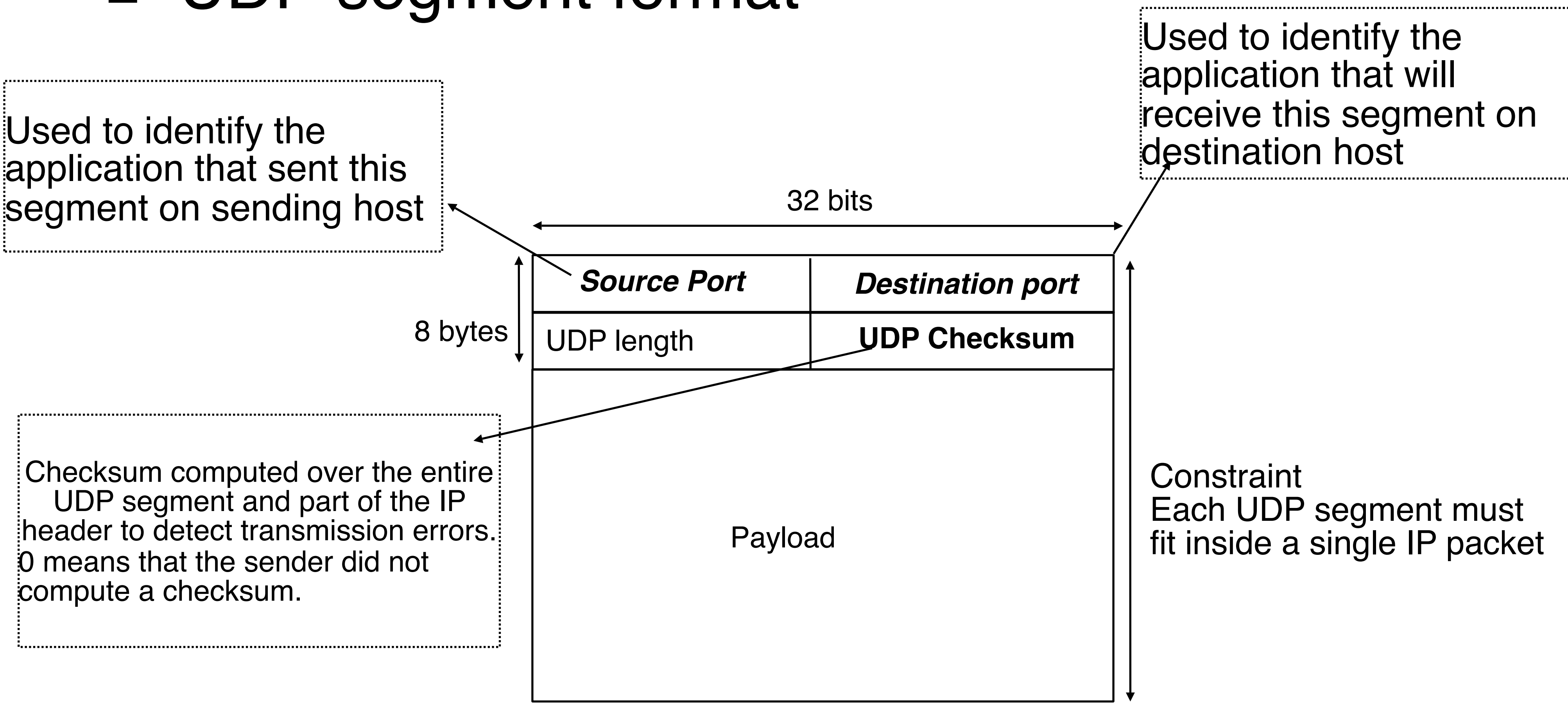
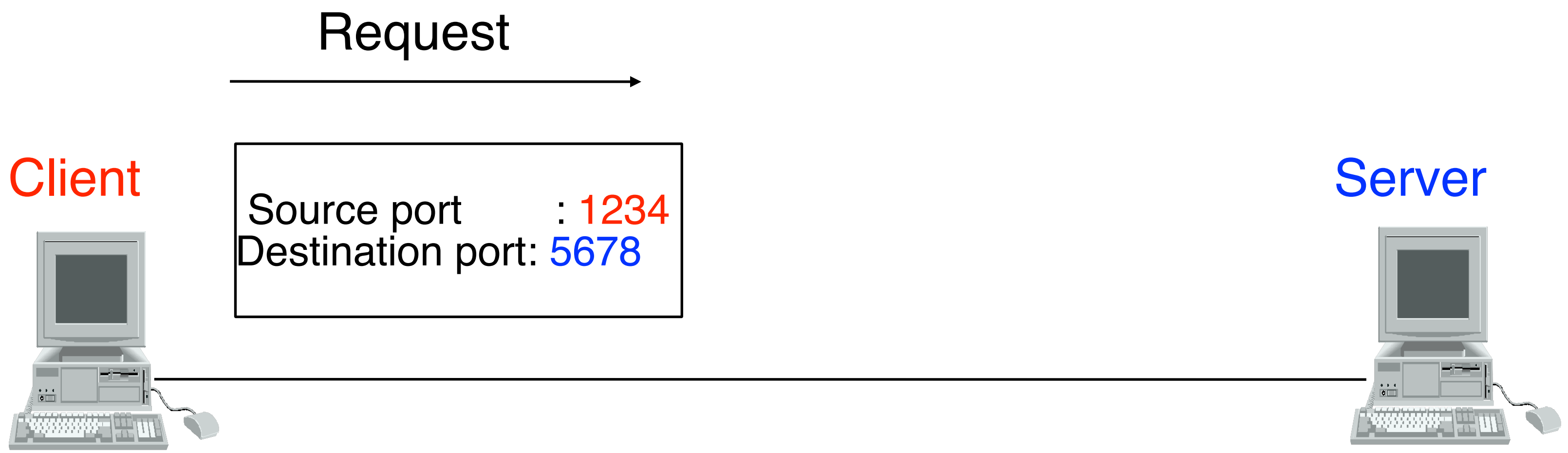


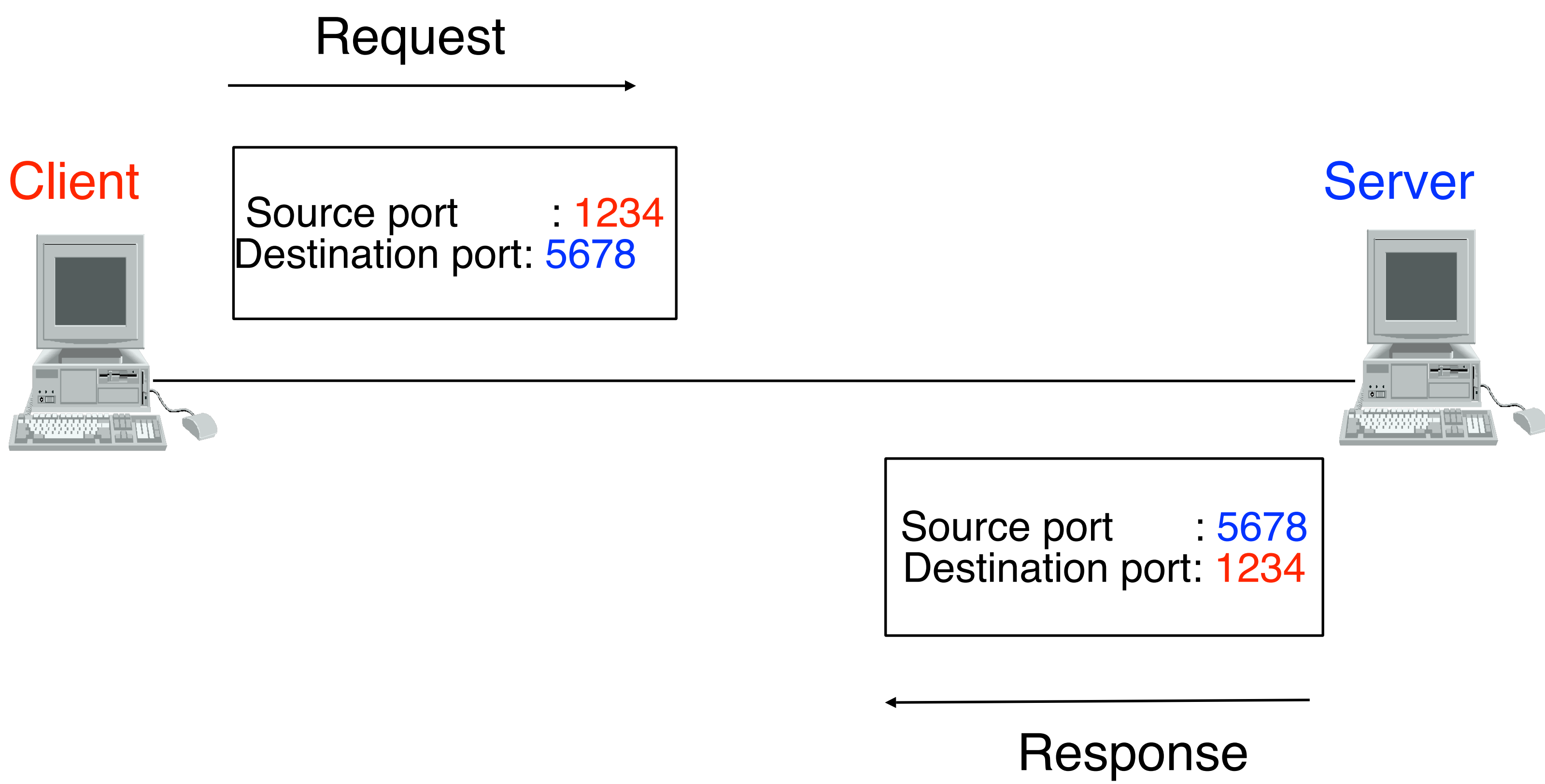
UDP Protocol (2)

- 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

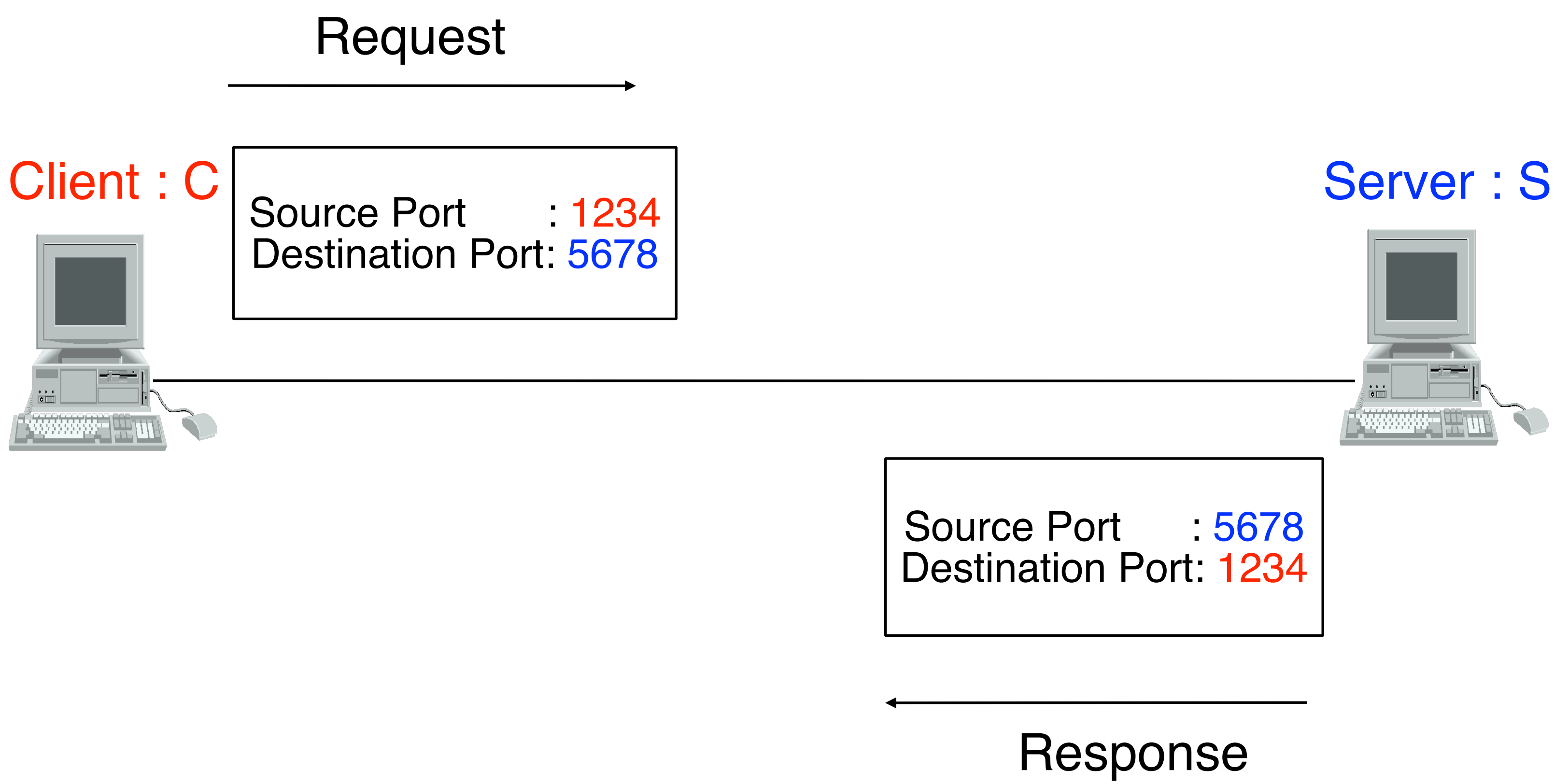
- Transmission Control Protocol
- Provides a reliable byte stream service
- Characteristics of the TCP service
  - TCP connections
  - Data transfer is reliable
    - no loss
    - no errors
    - no duplications
  - Data transfer is bidirectional
  - TCP relies on the IP service
  - TCP only supports 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



Established TCP connections on client

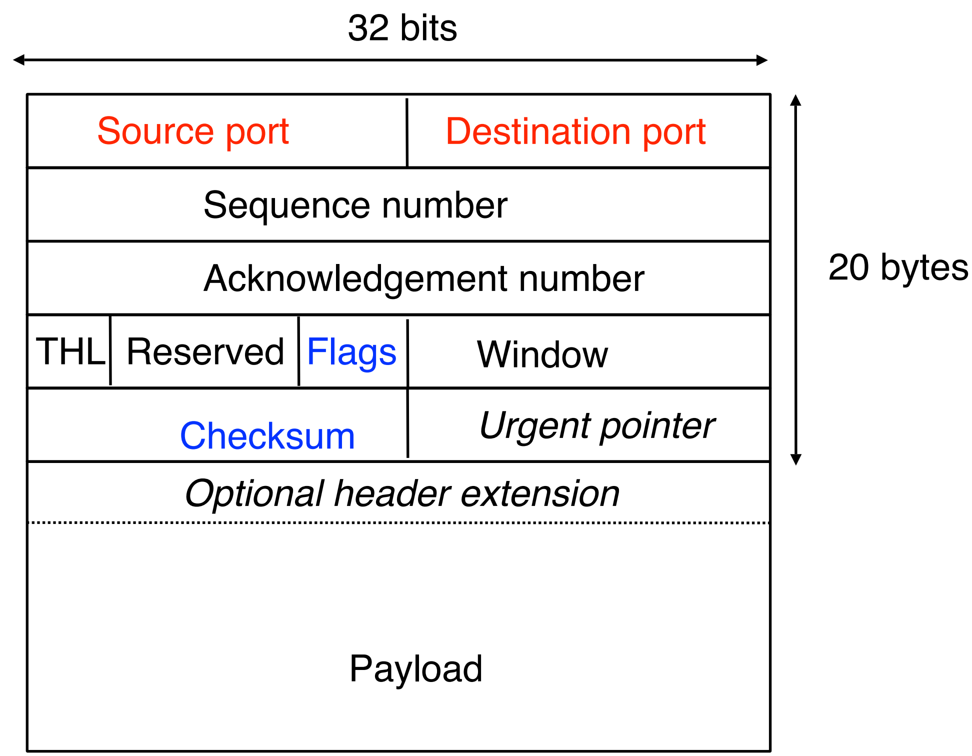
Local IP	Remote IP	Local Port	Remote Port
C	S	1234	5678

Established TCP connections on server

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

TCP protocol

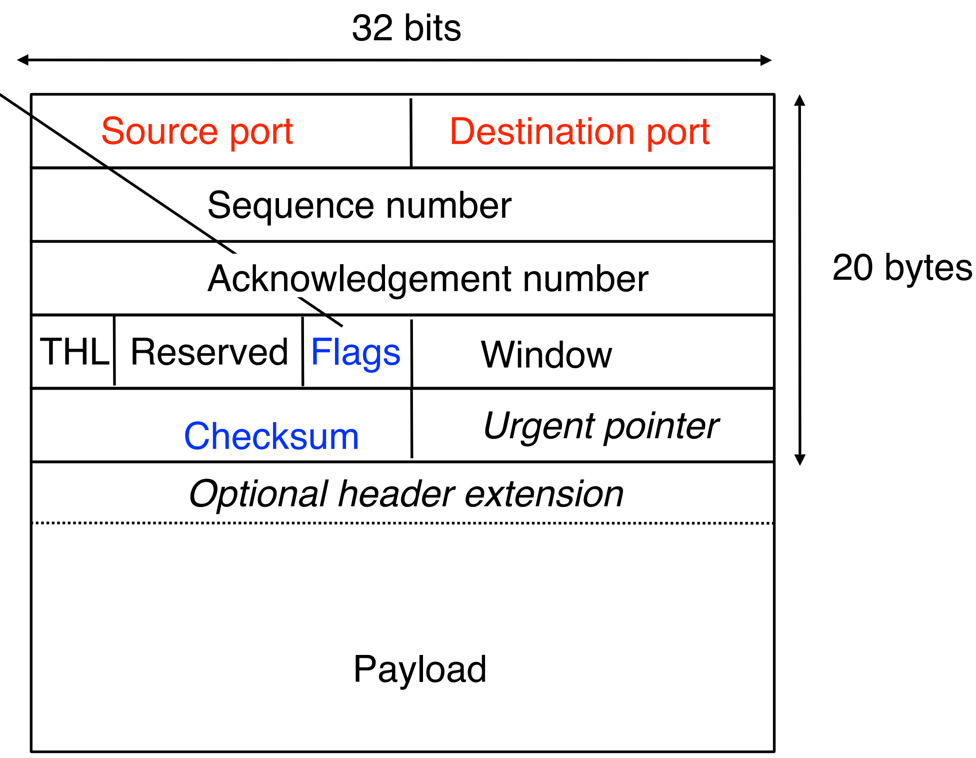
- Single segment format



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

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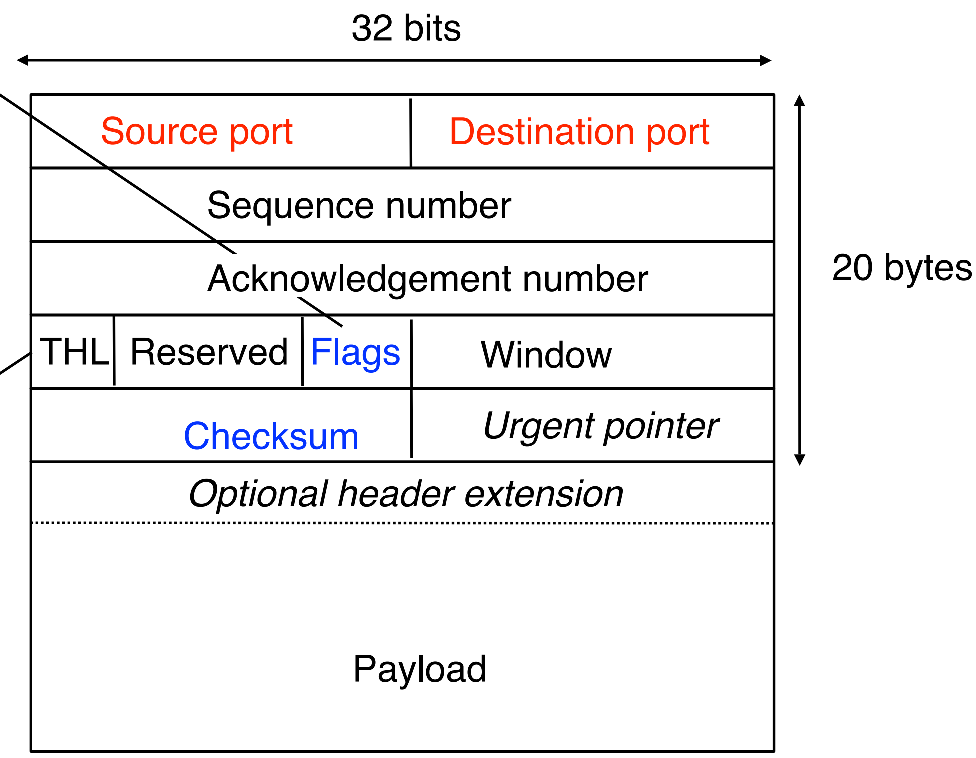
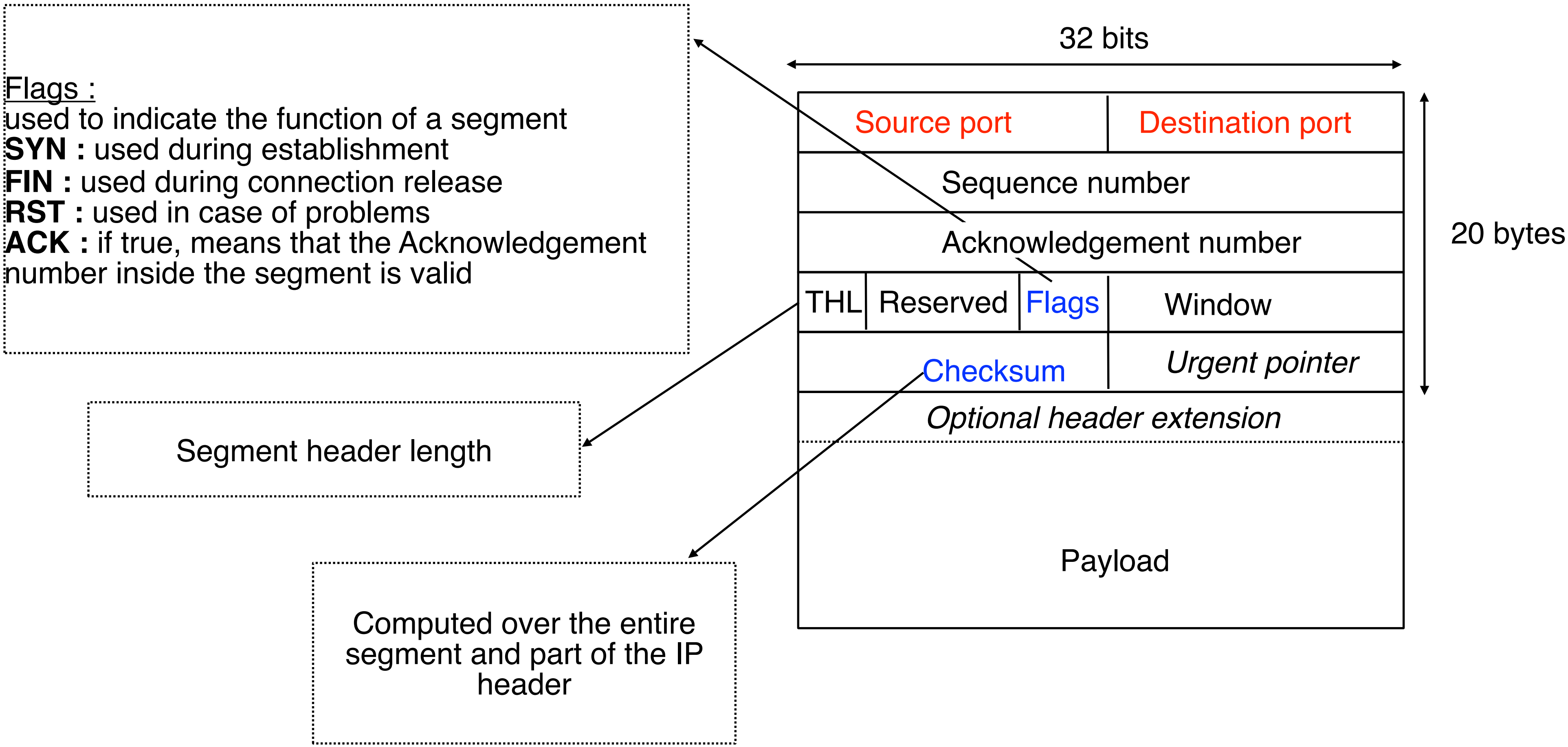
Segment header length



TCP protocol

- Single segment format

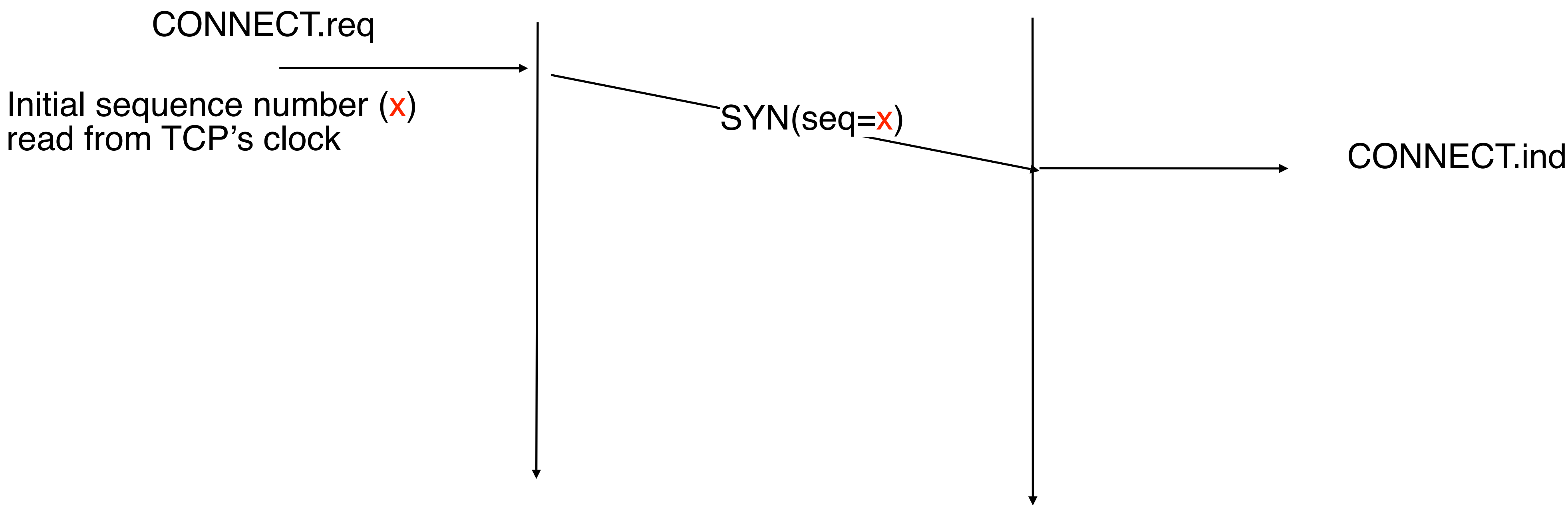


TCP connection establishment

- Three-way handshake

TCP connection establishment

- Three-way handshake



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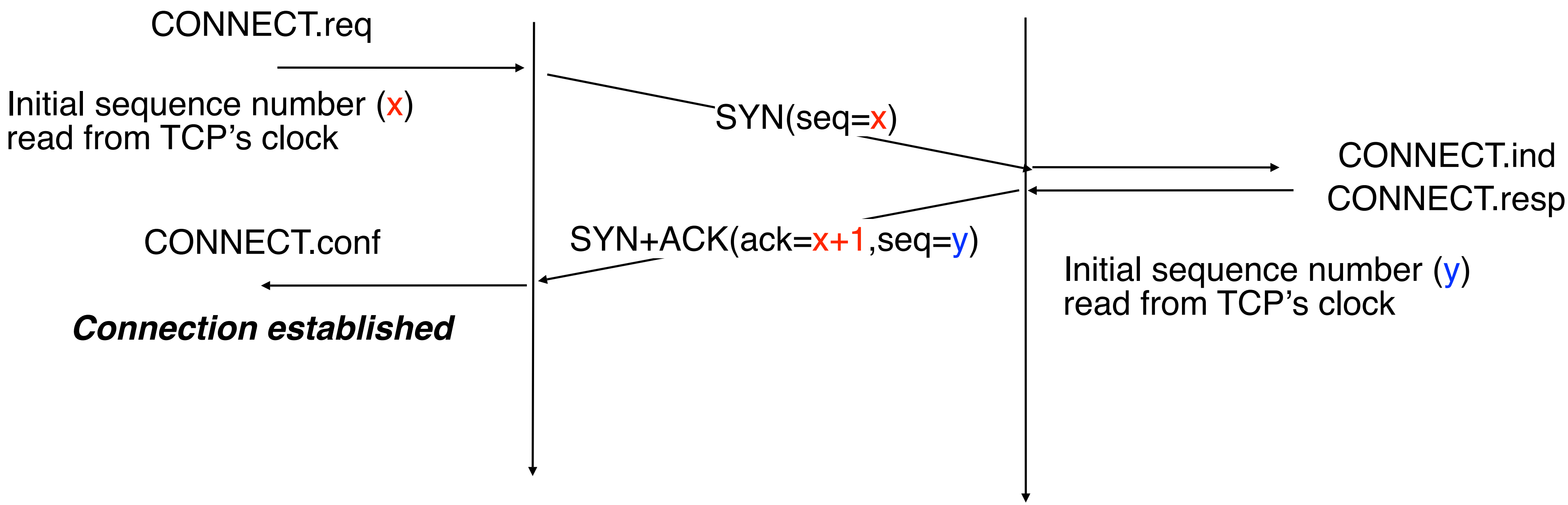

TCP connection establishment

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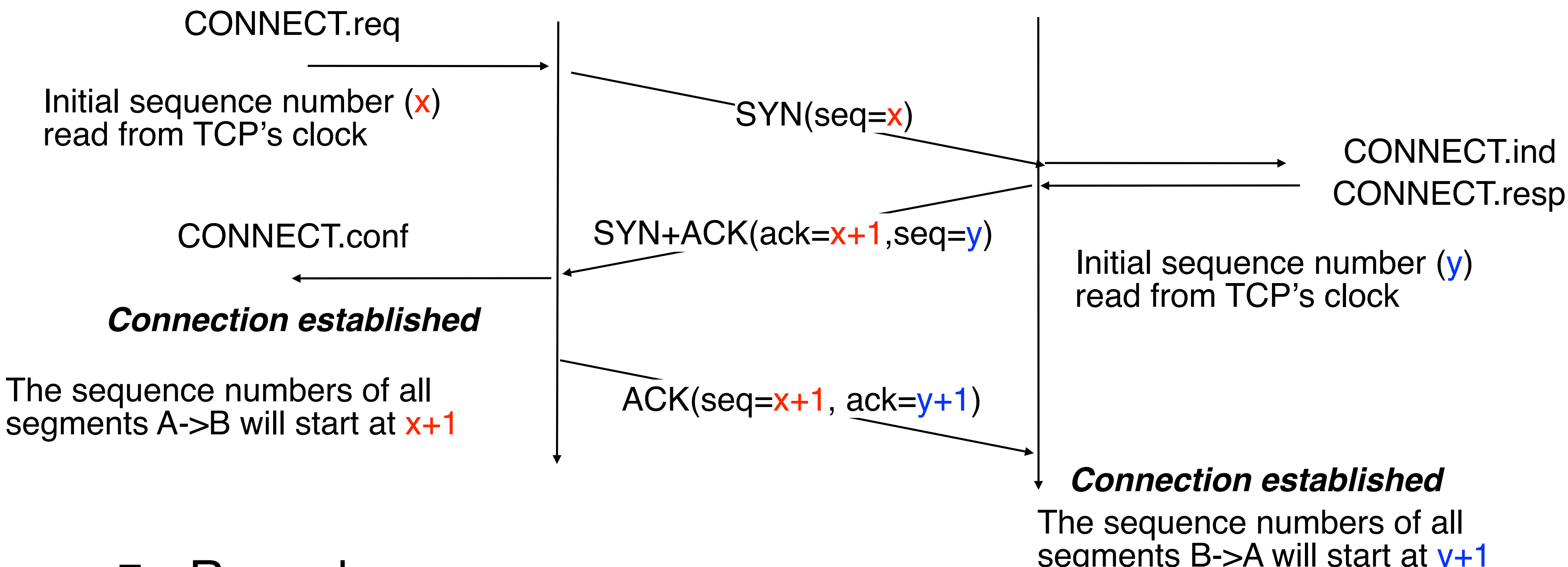

- Remarks
  - Setting the SYN flag in a segment consumes one sequence number
  - The ACK flag is set only when the acknowledgement field contains a valid value
  - The default recommendation for the TCP clock is to be incremented by 1 at least after 4 microseconds and after each TCP connection establishment

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
  - During the opening of a connection, it is possible to negotiate the utilisation of TCP extensions
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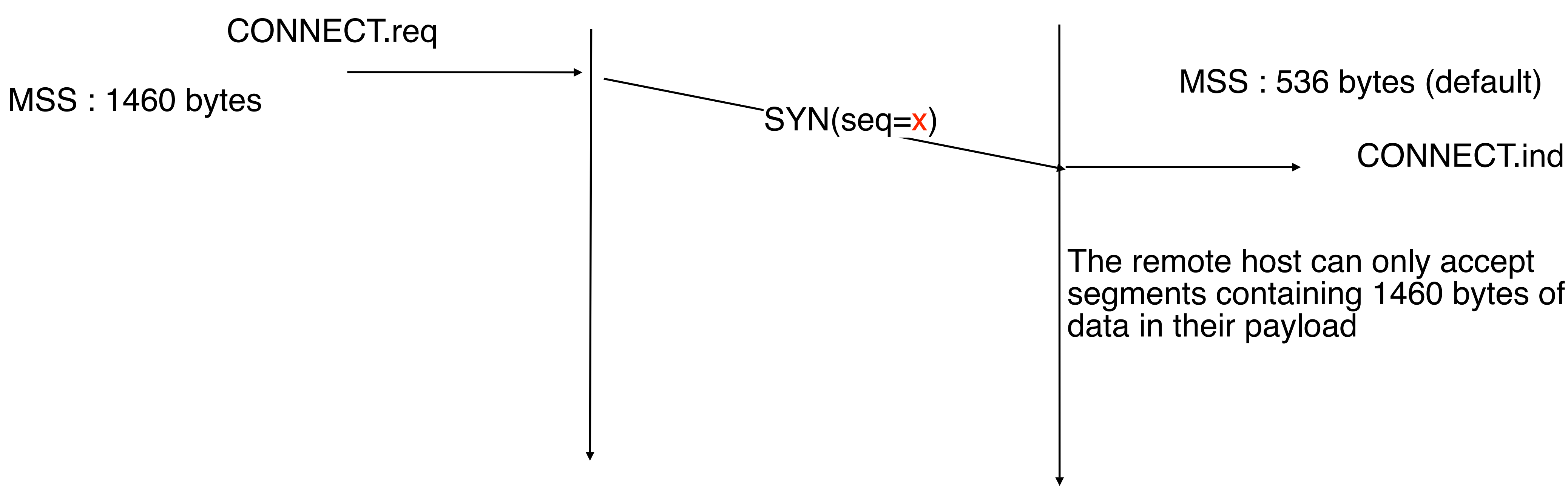

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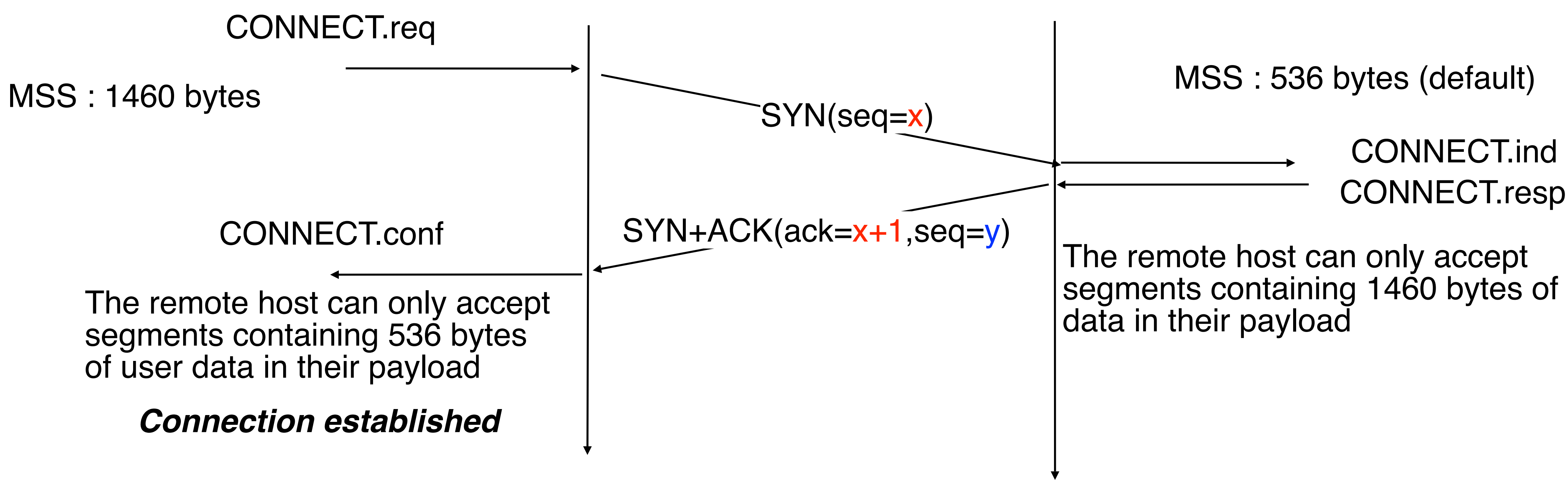

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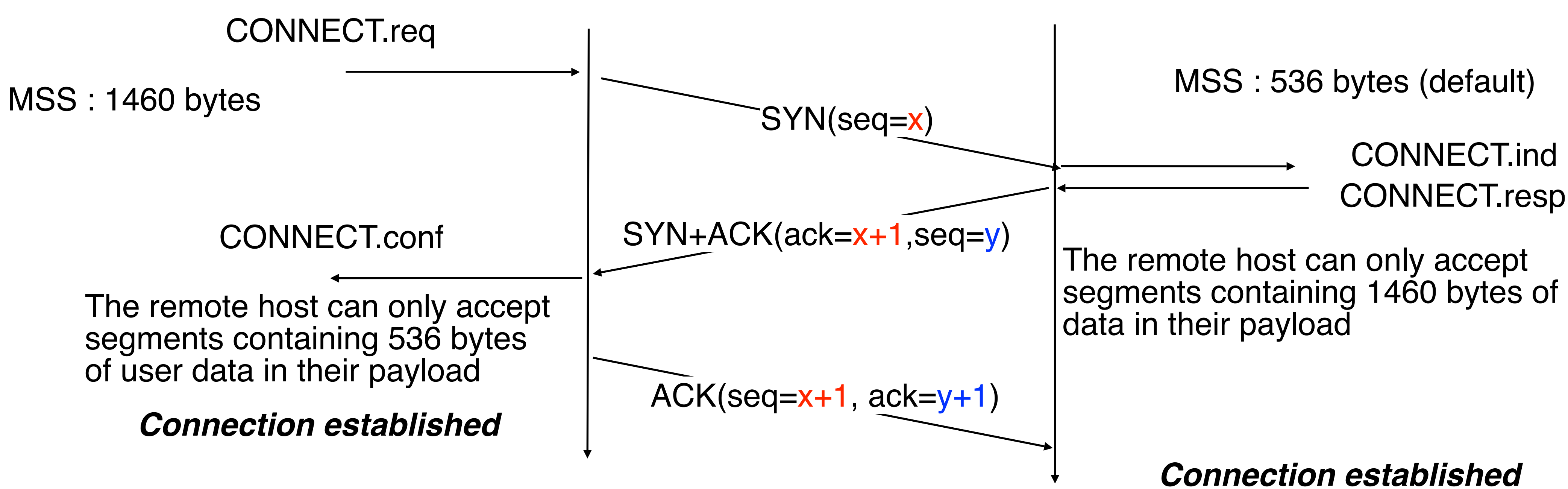

TCP connection establishment (3)

- Rejection of connection establishment

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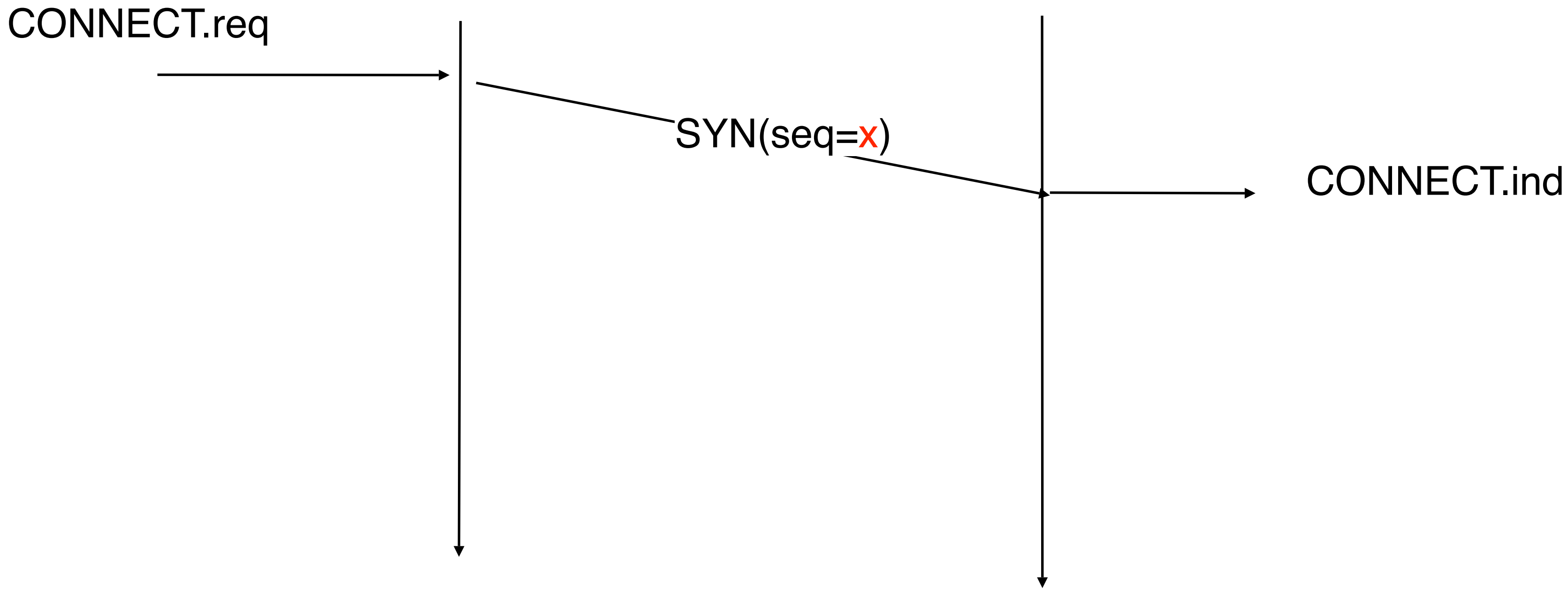

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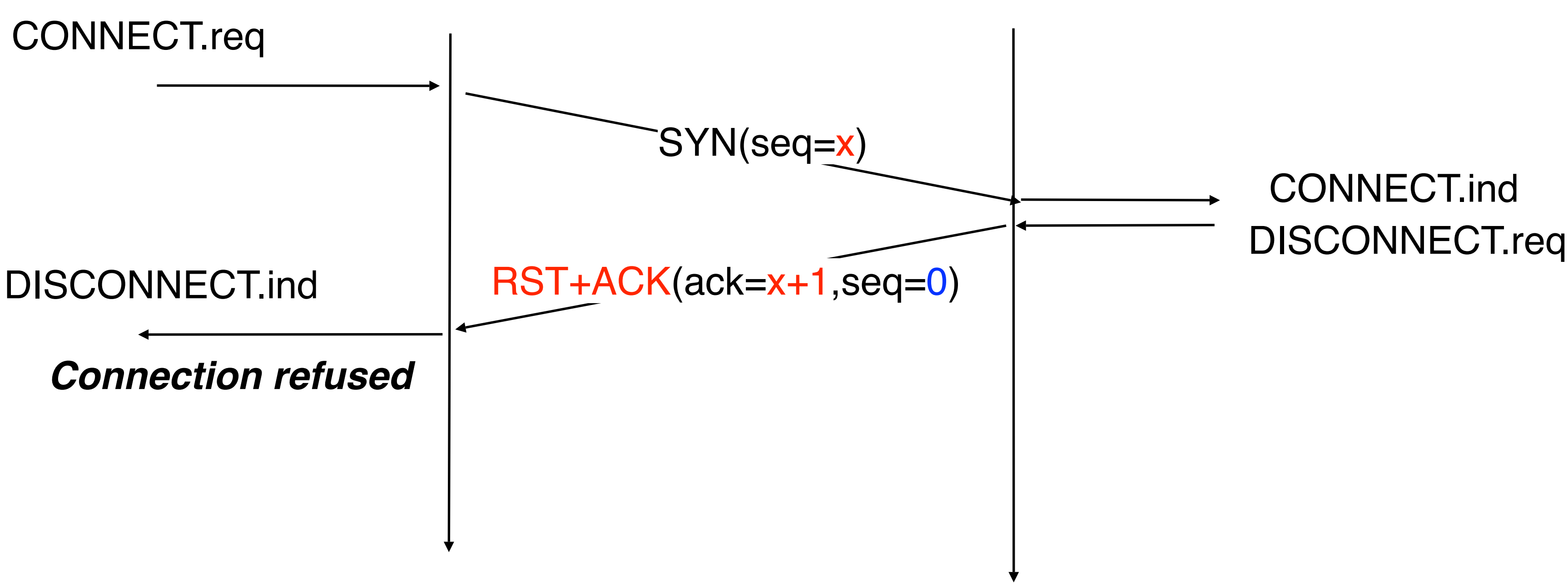

TCP connection establishment (3)

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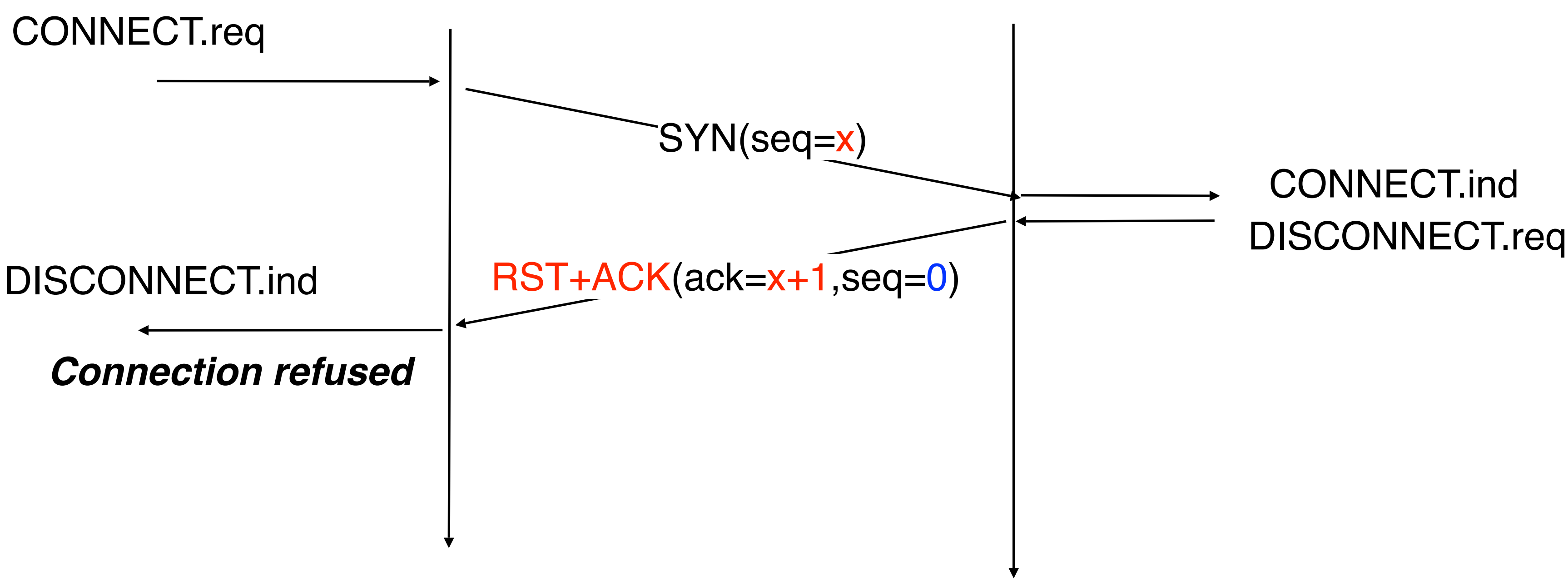
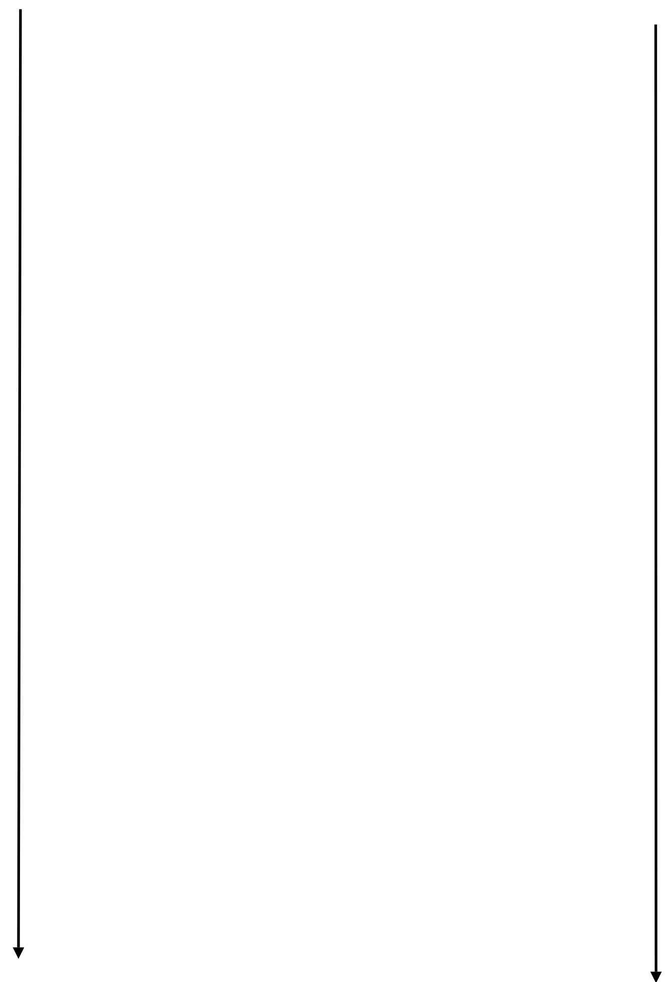


A TCP entity should never send a RST segment upon reception of another RST segment

TCP connection establishment (4)

- Simultaneous establishment



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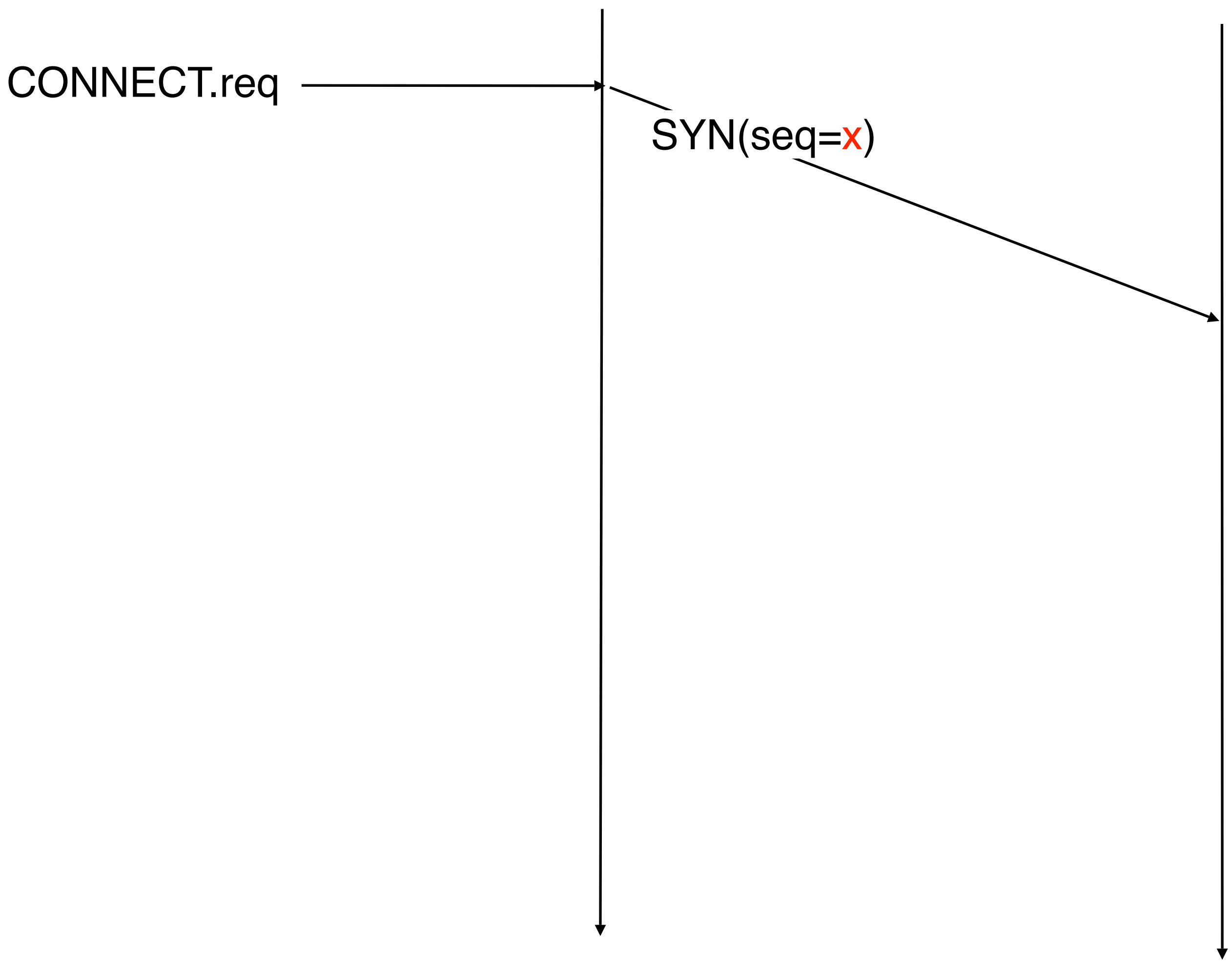

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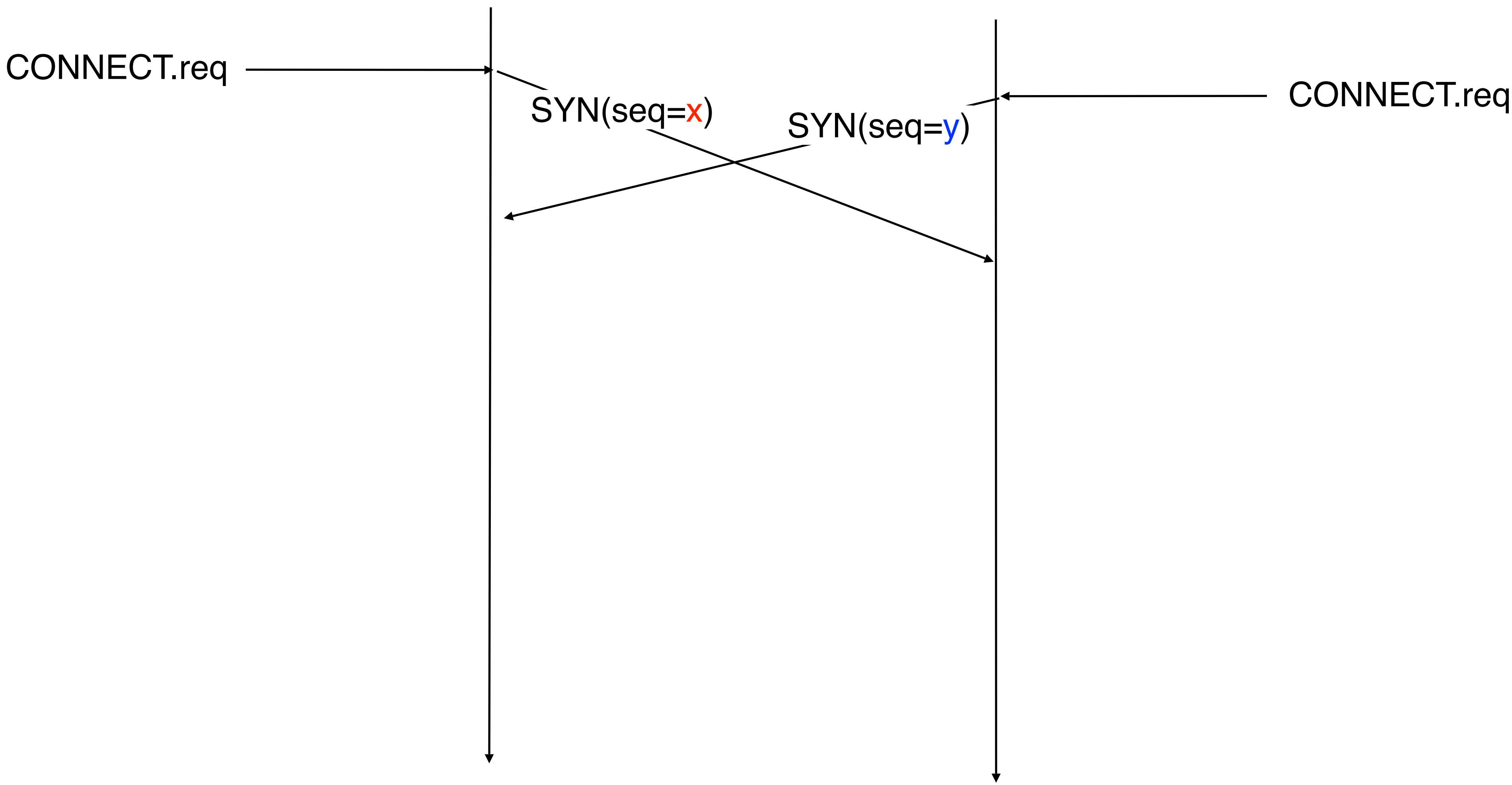

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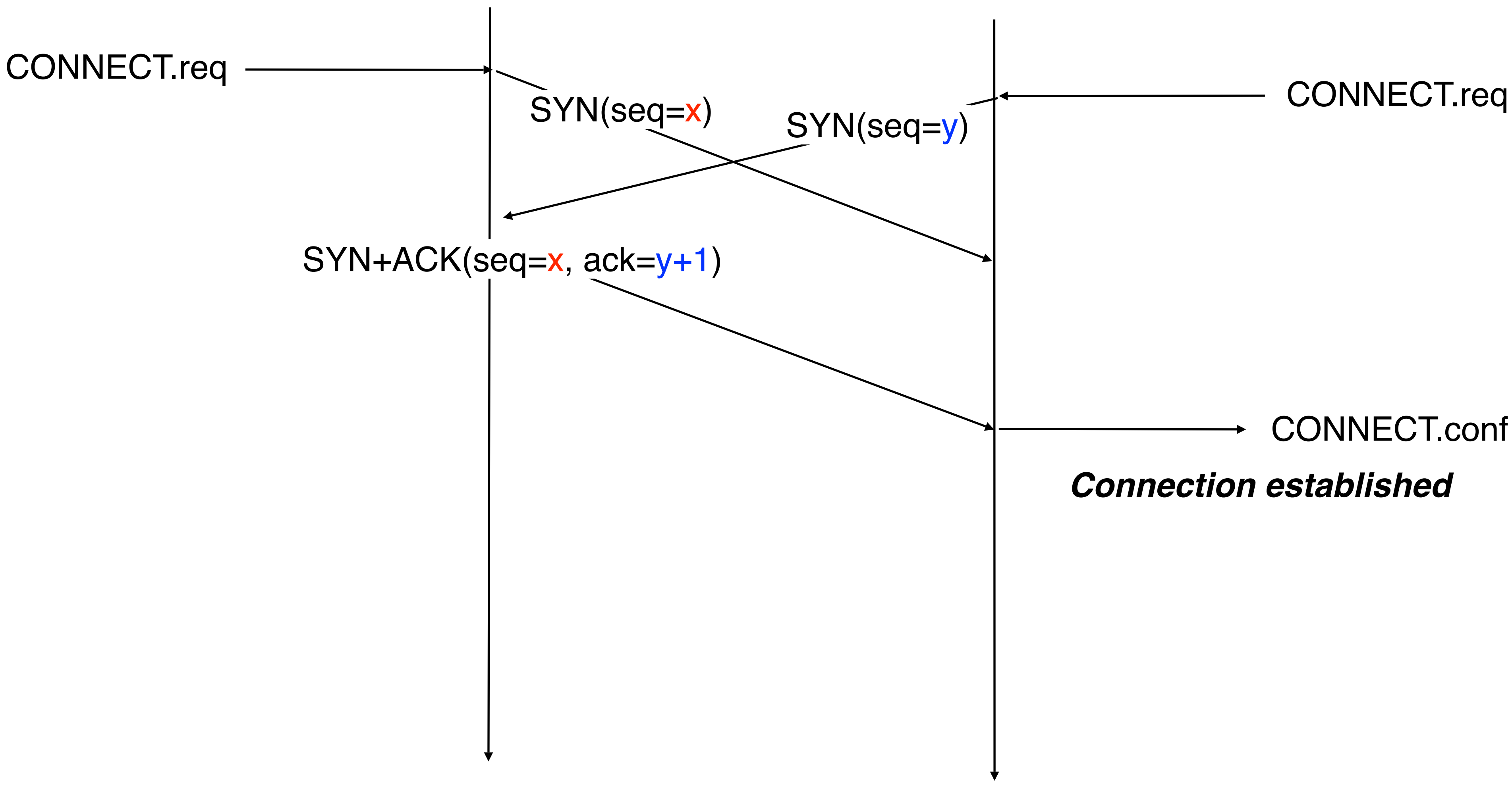

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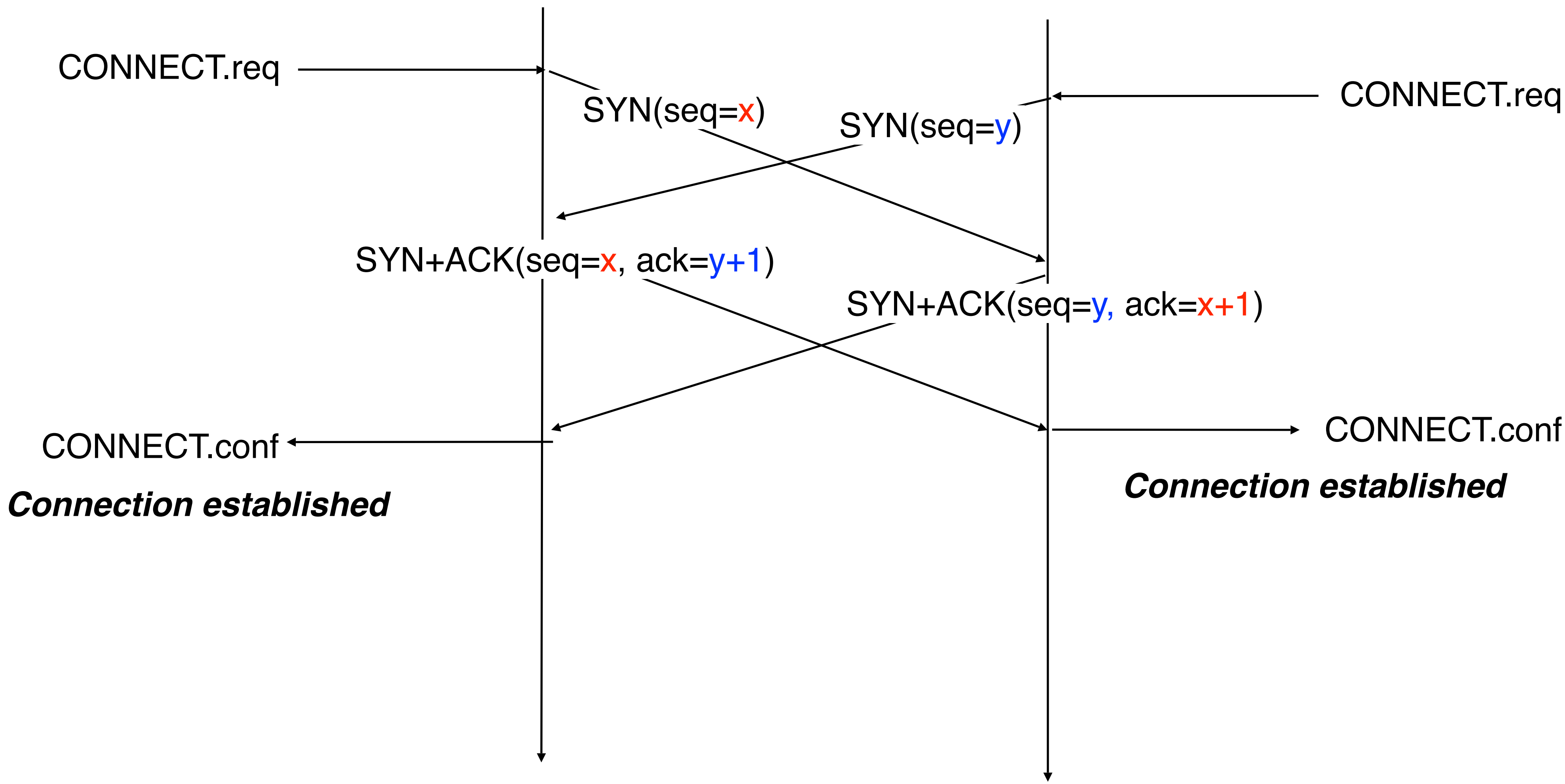
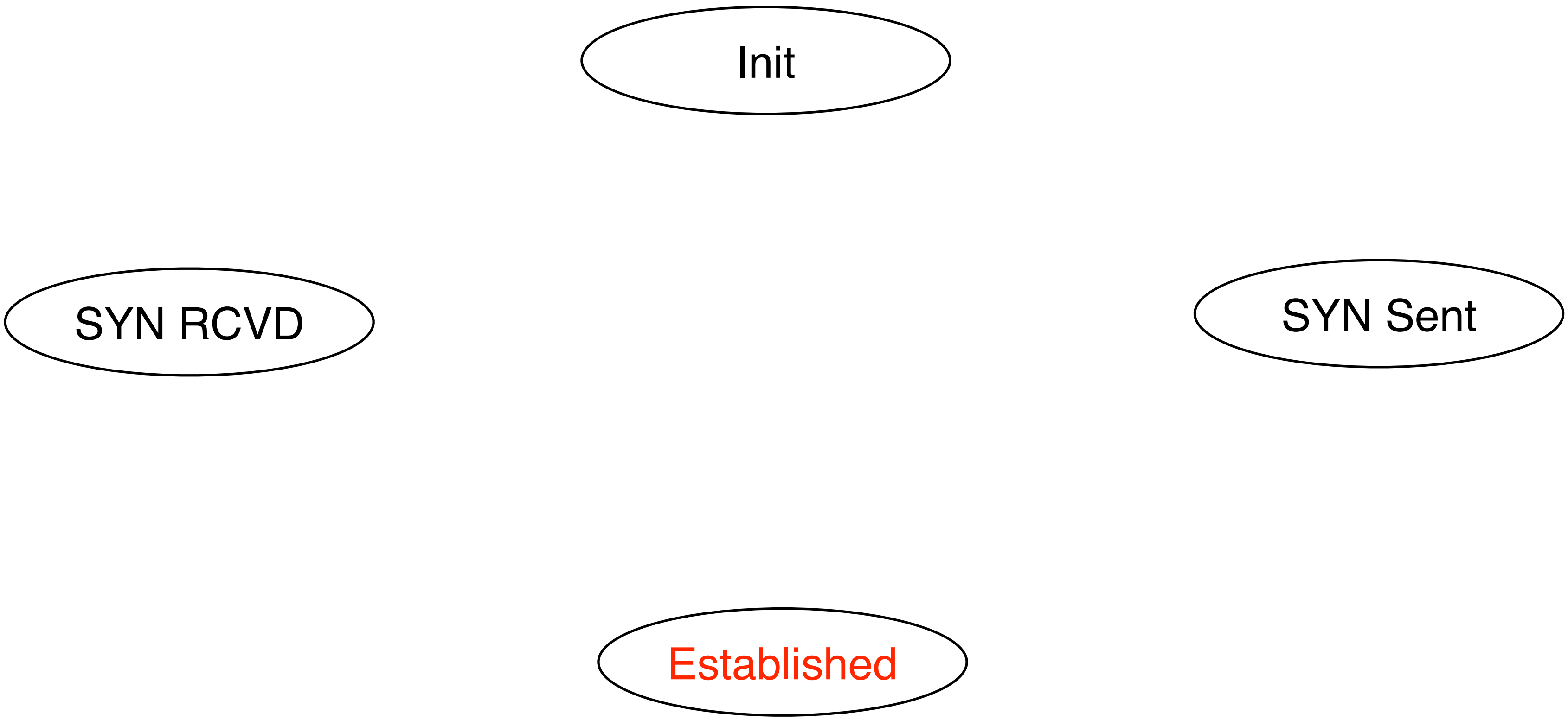


TCP connection establishment (5)

- Representation as a finite state machine



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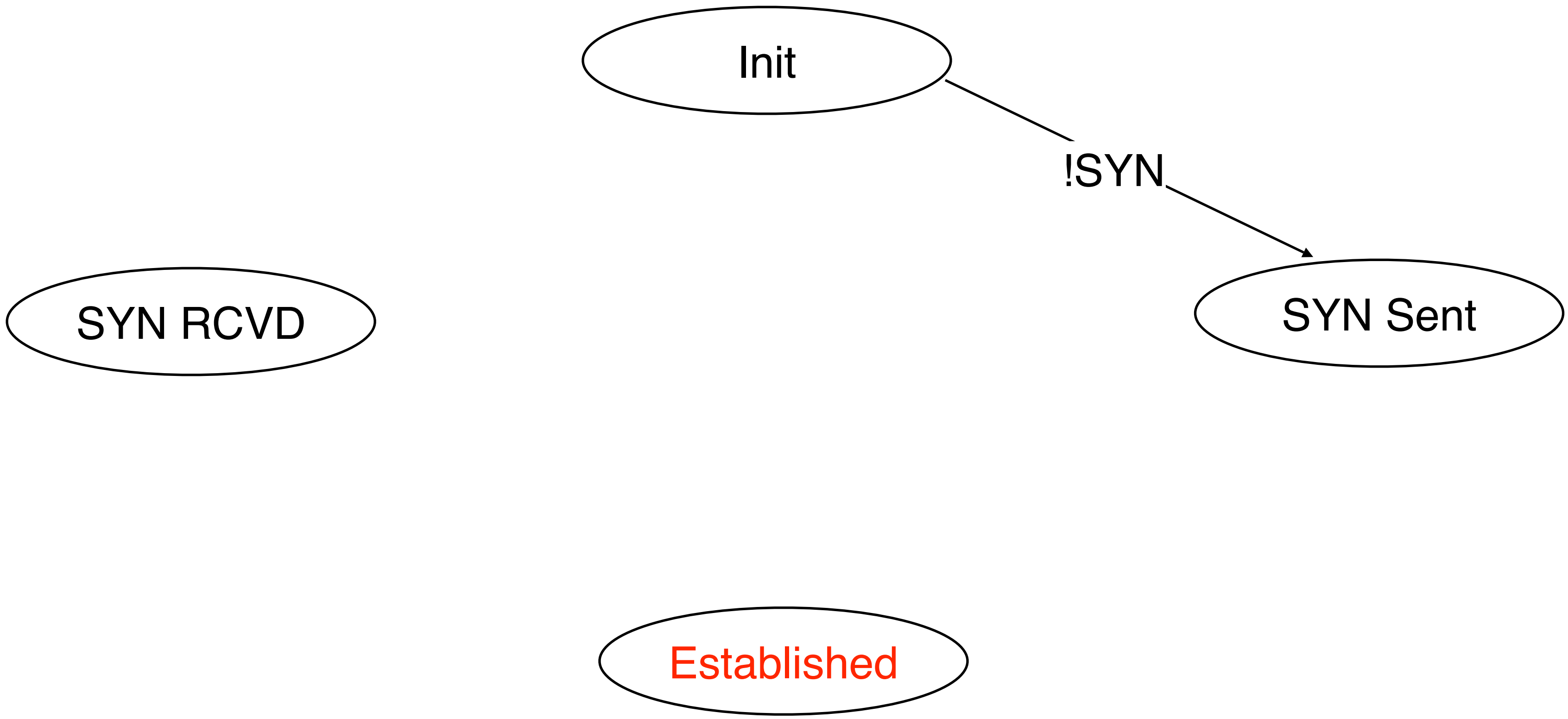

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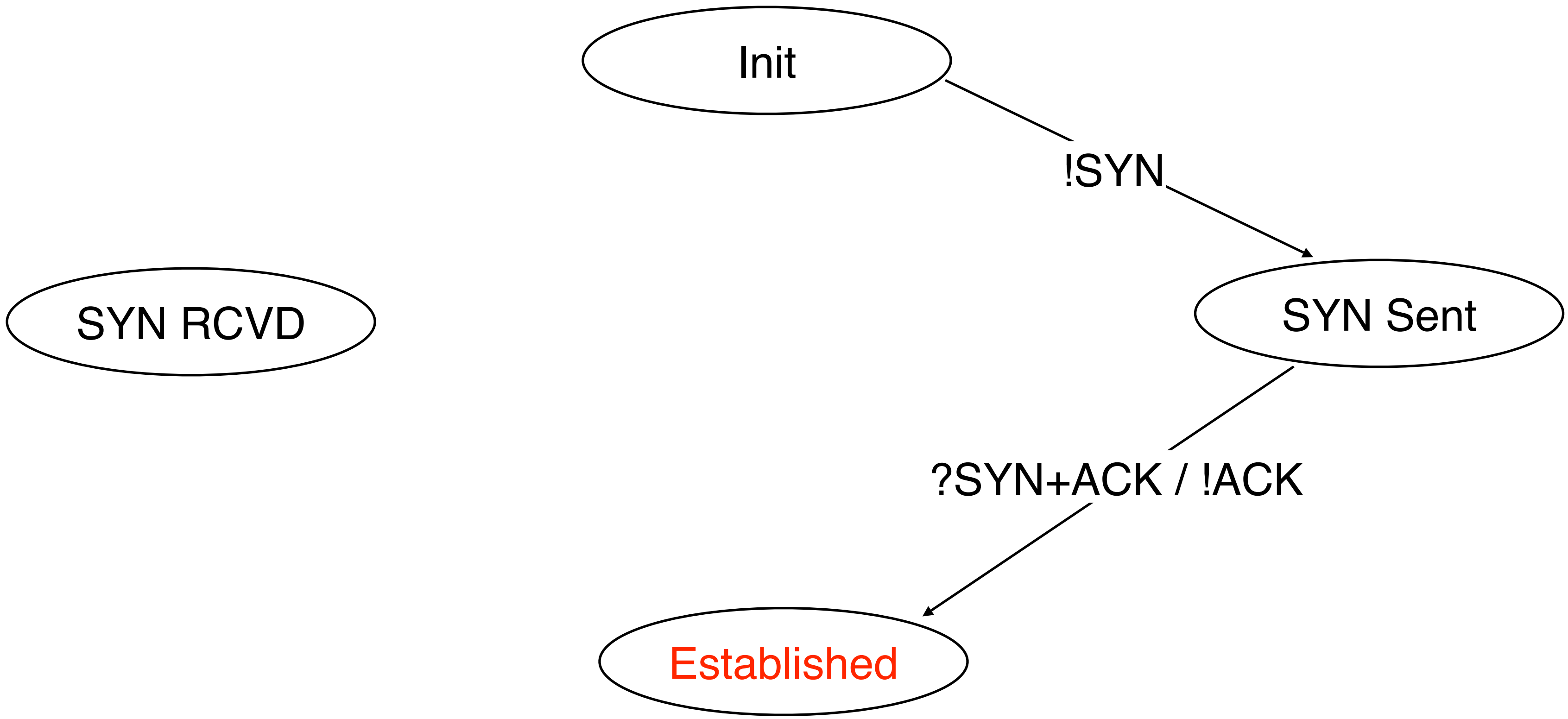

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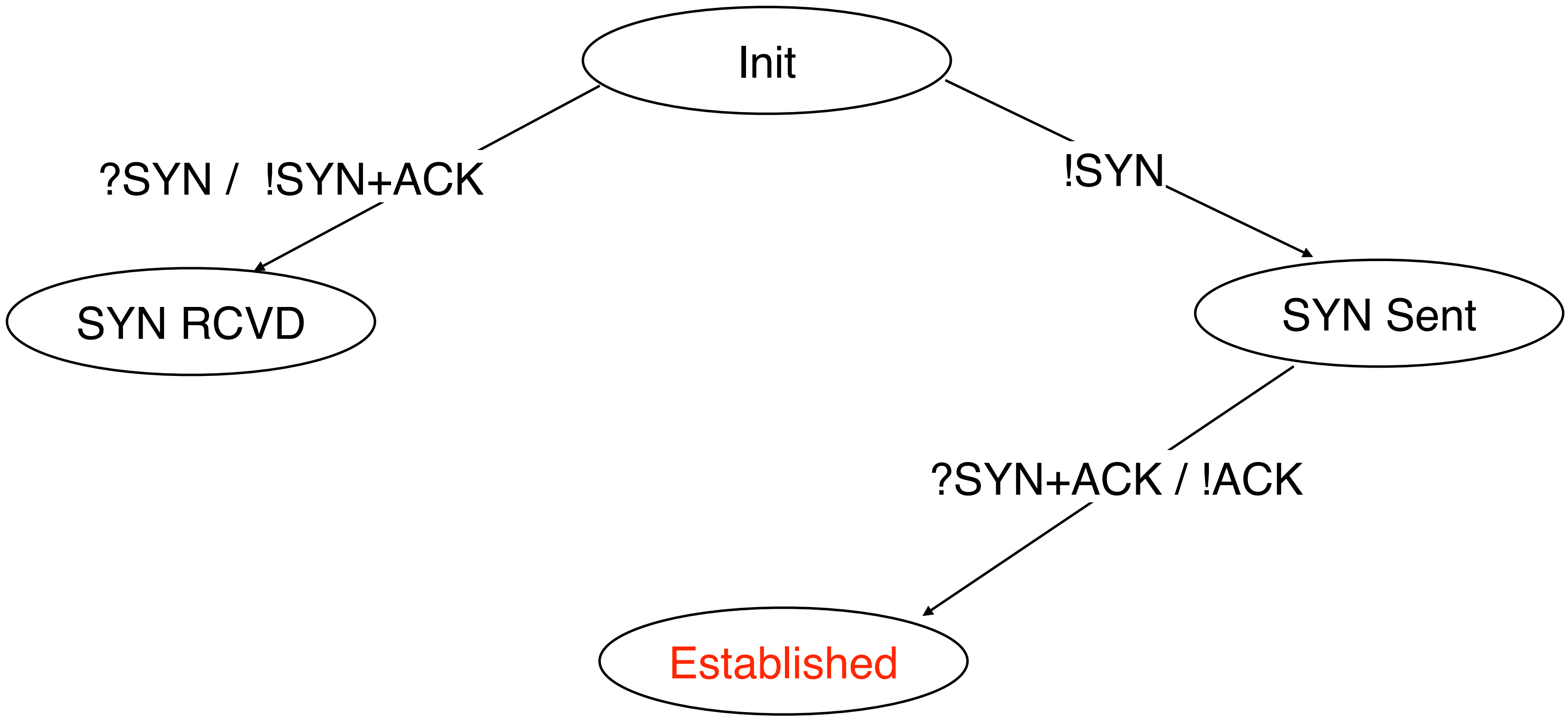

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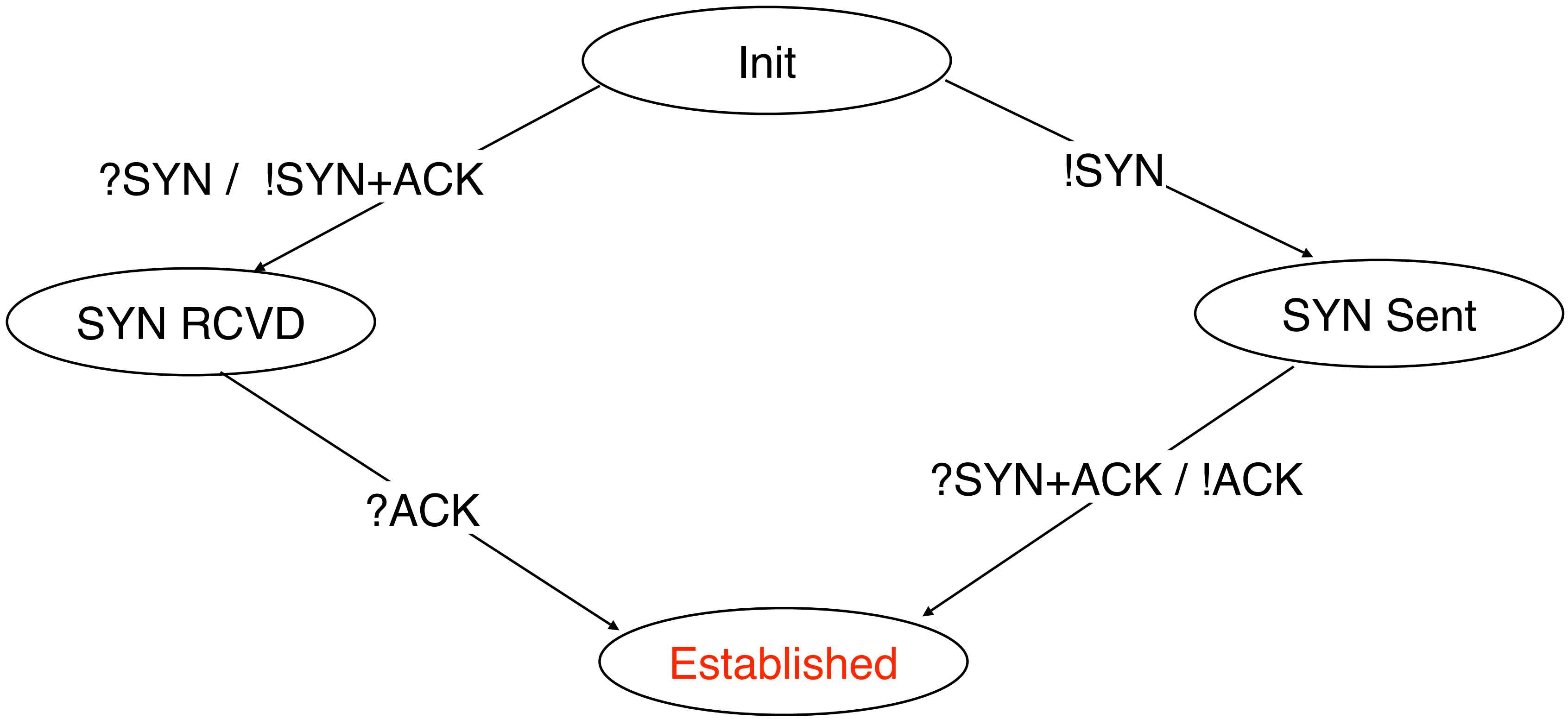

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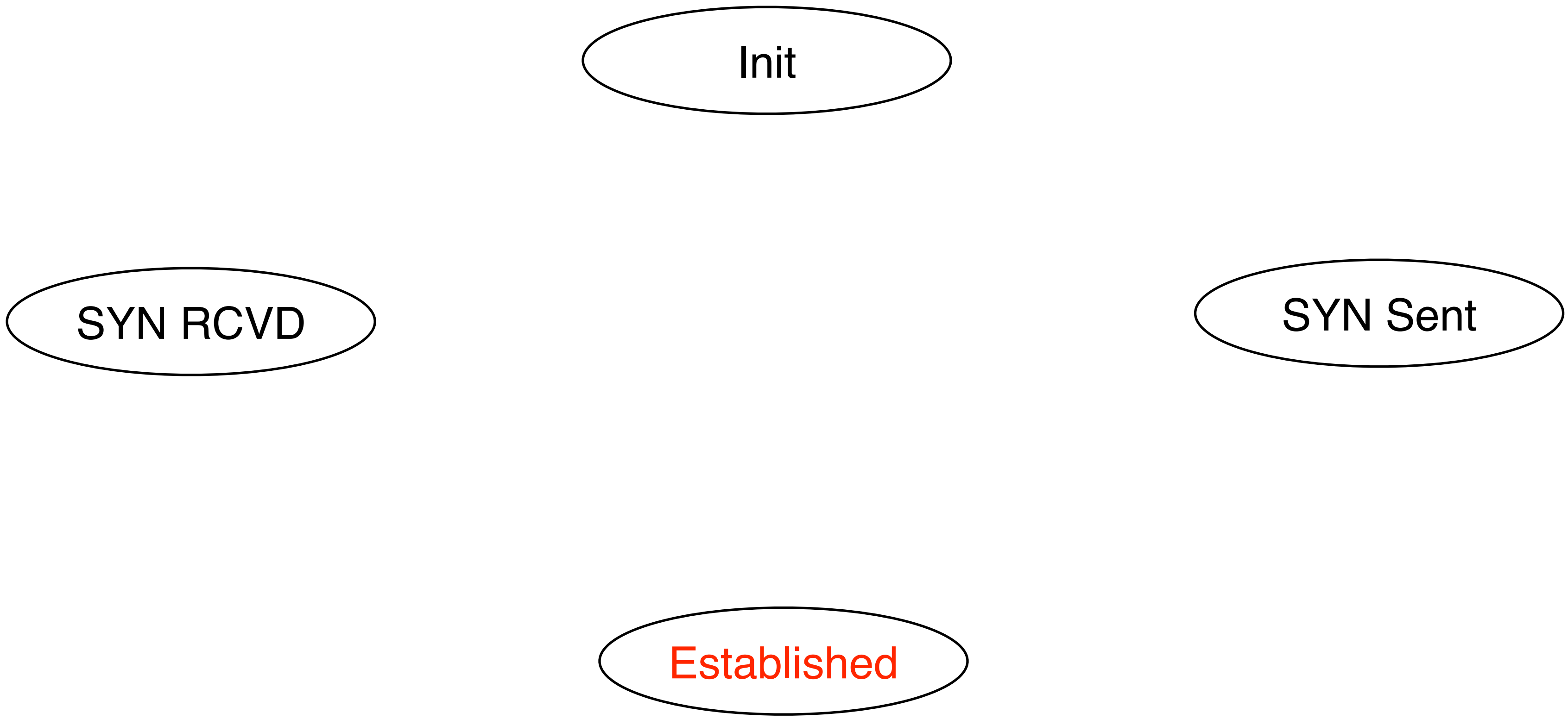

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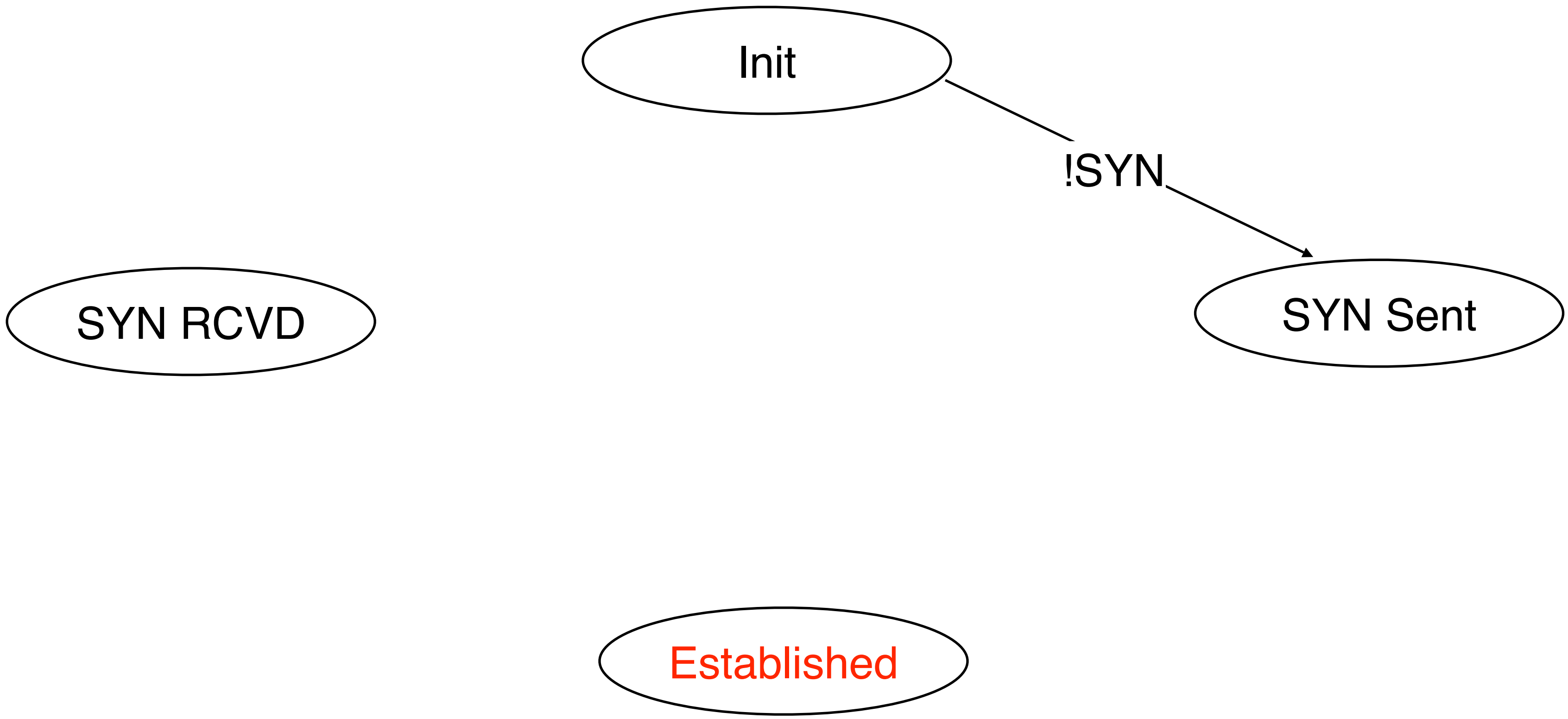

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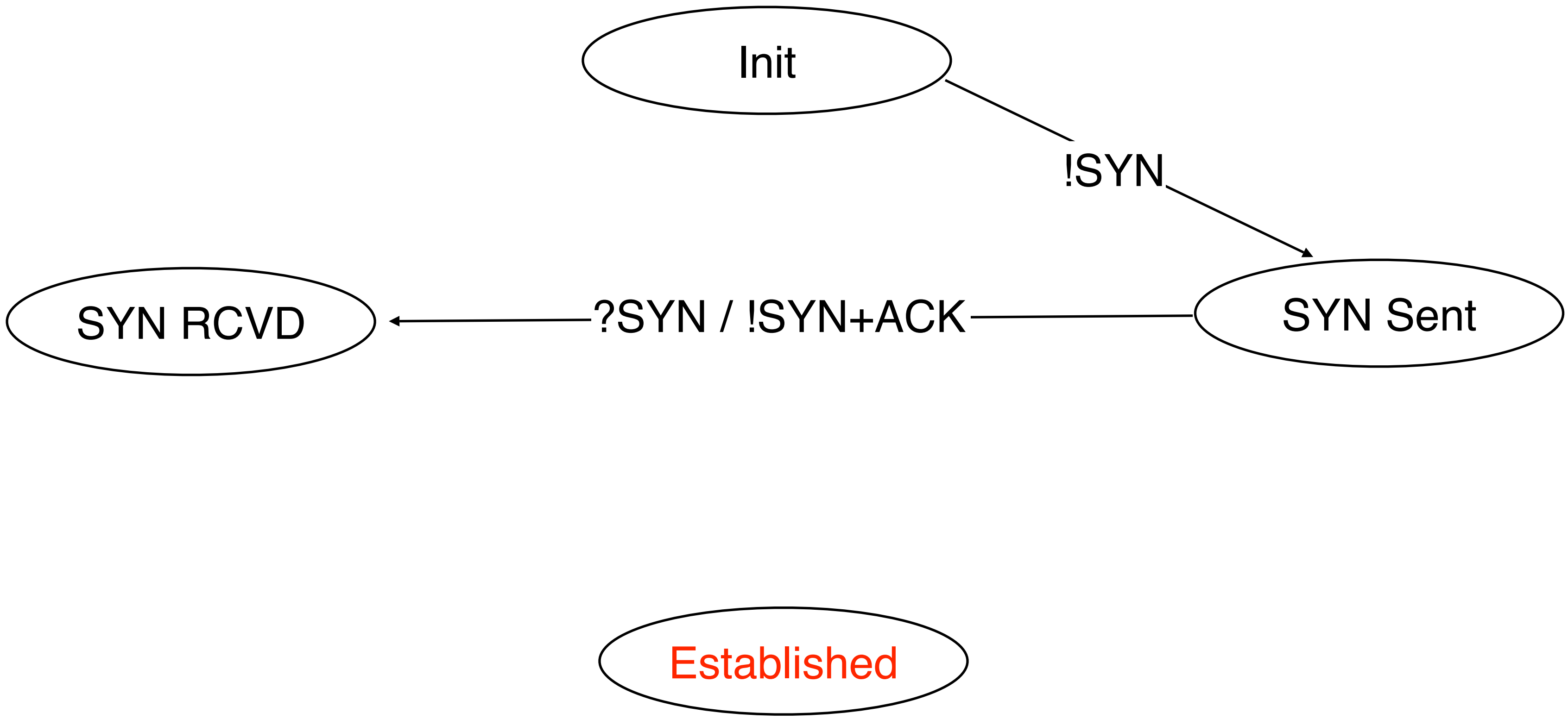

TCP connection establishment (5)

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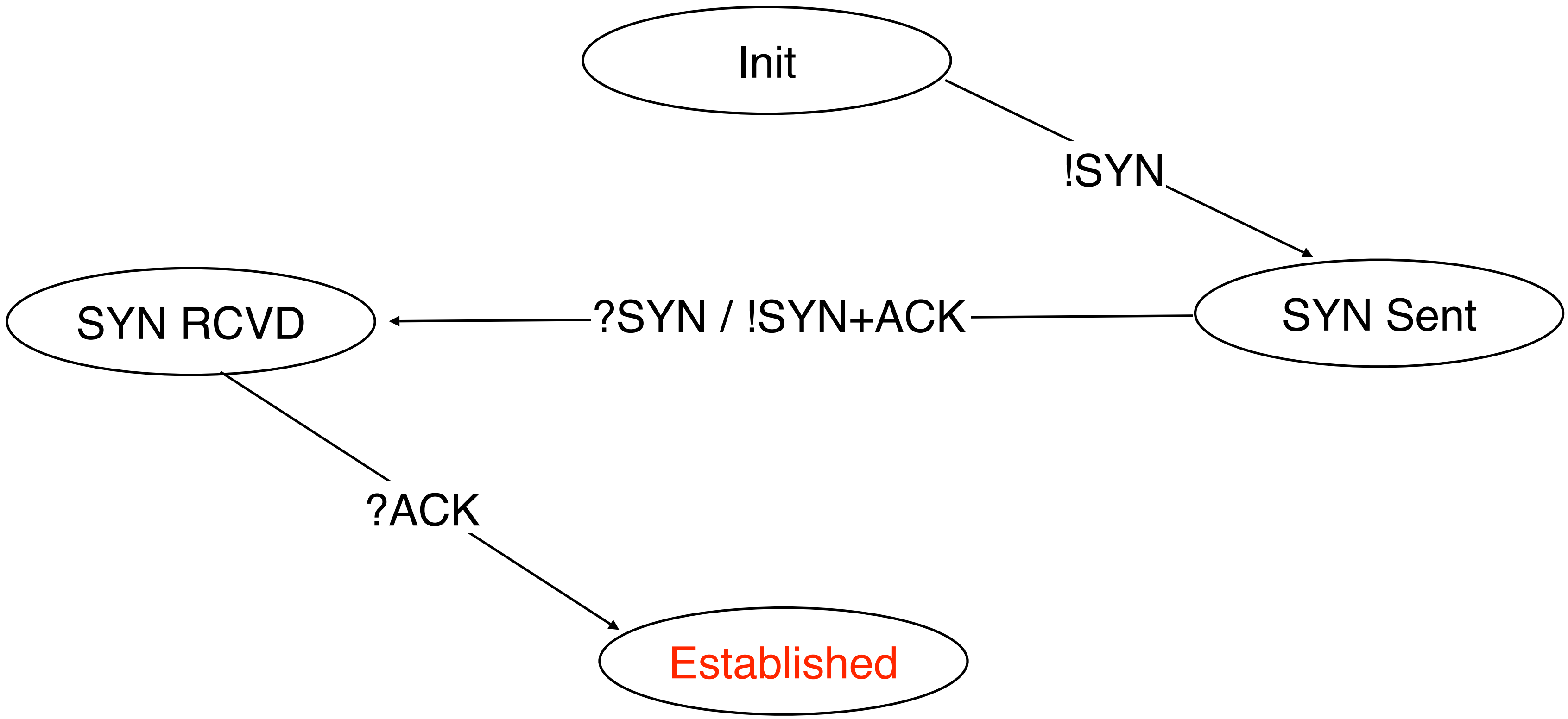
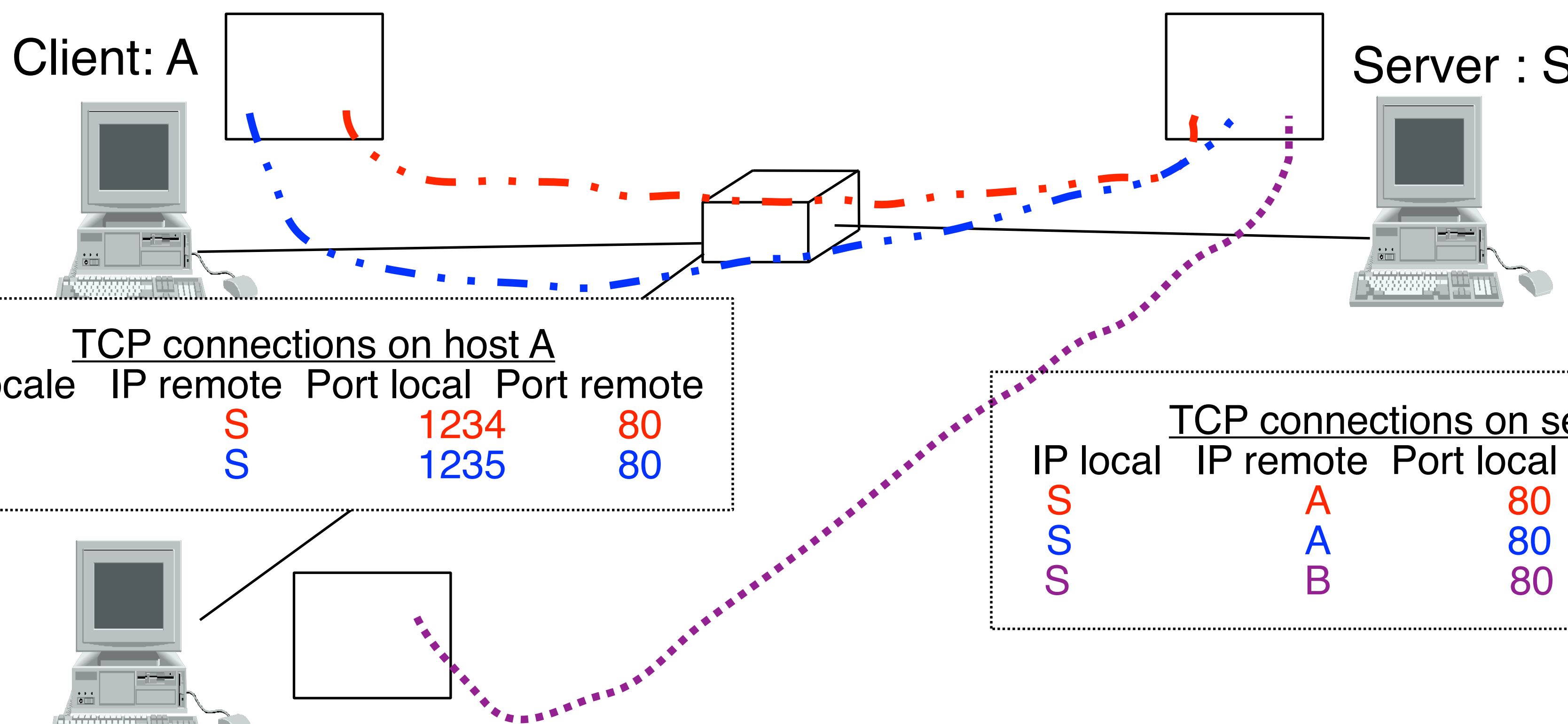


TCP connection establishment (6)

- How to open several TCP connections at the same time ?



TCP connections on host A

IP locale	IP remote	Port local	Port remote
A	S	1234	80
A	S	1235	80

TCP connections on server

IP local	IP remote	Port local	Port remote
S	A	80	1234
S	A	80	1235
S	B	80	1235

TCP connections on host B

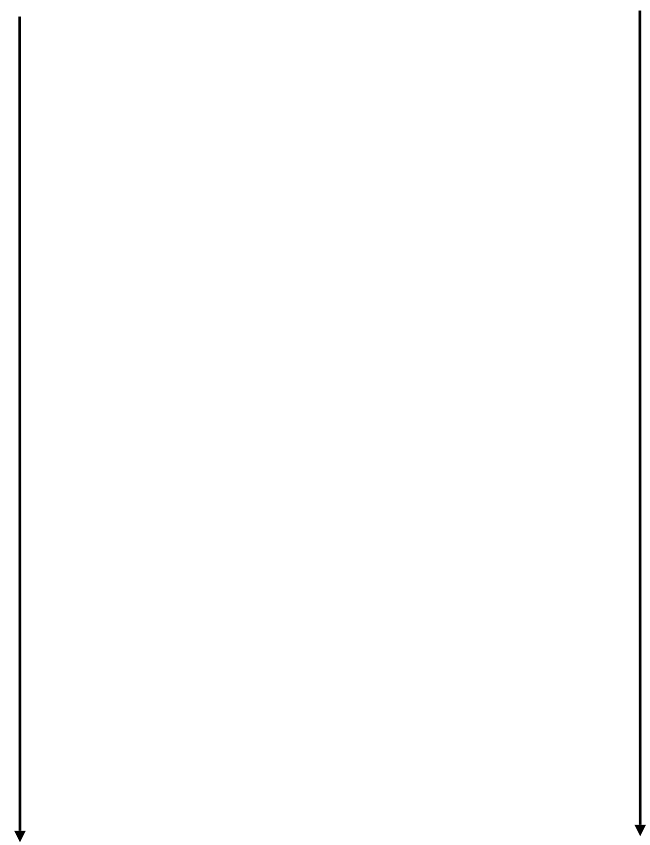
IP locale	IP remote	Port local	Port remote
B	S	1235	80

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



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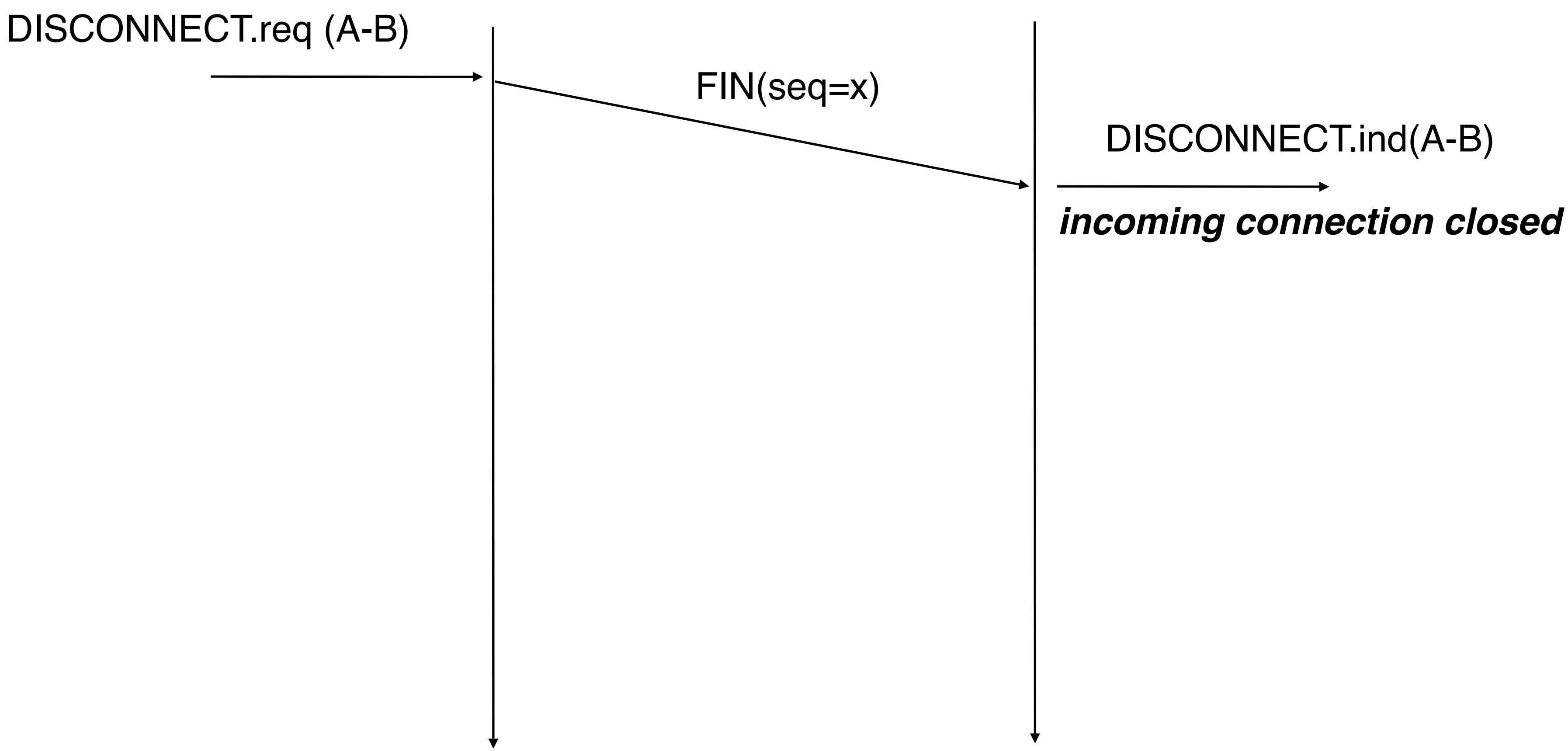

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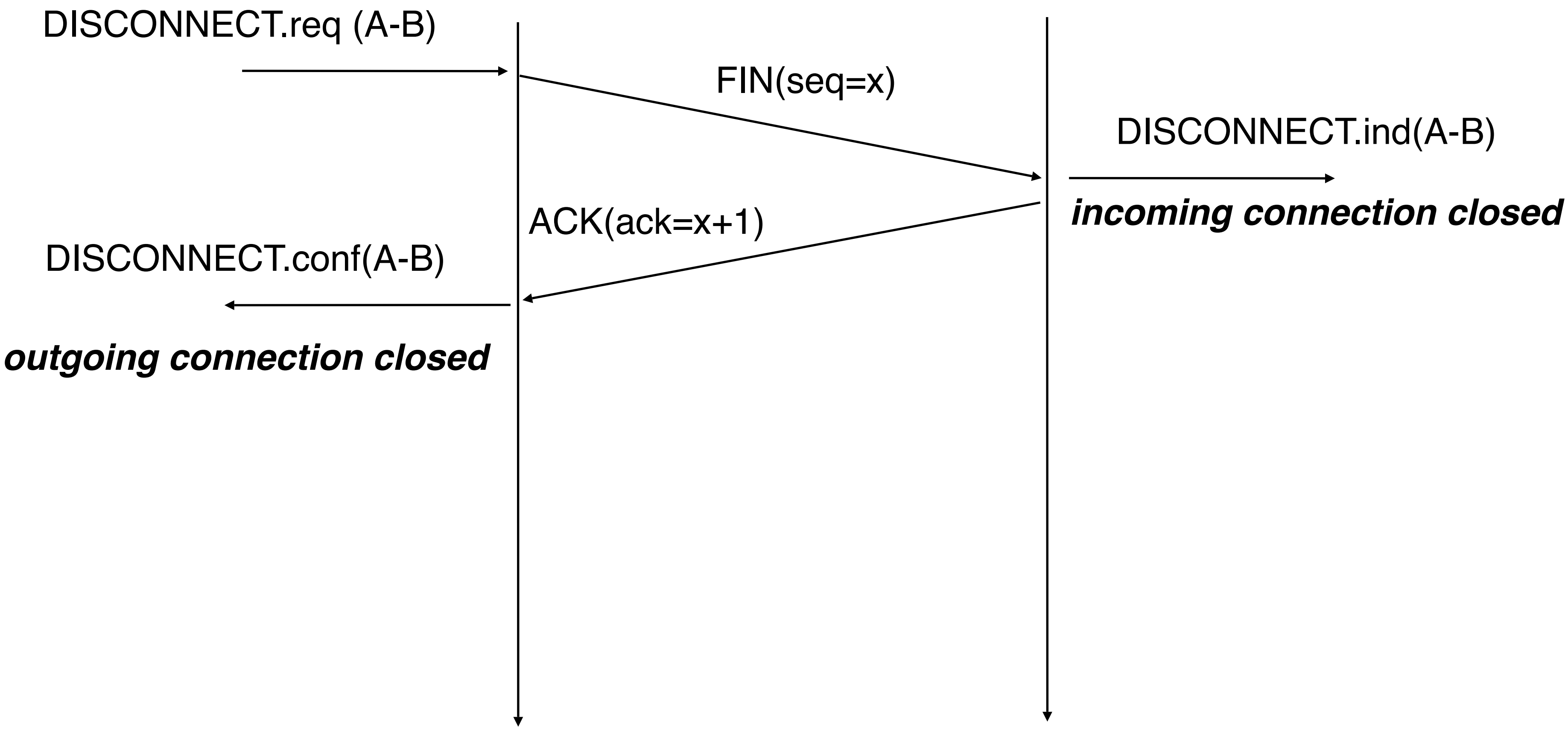

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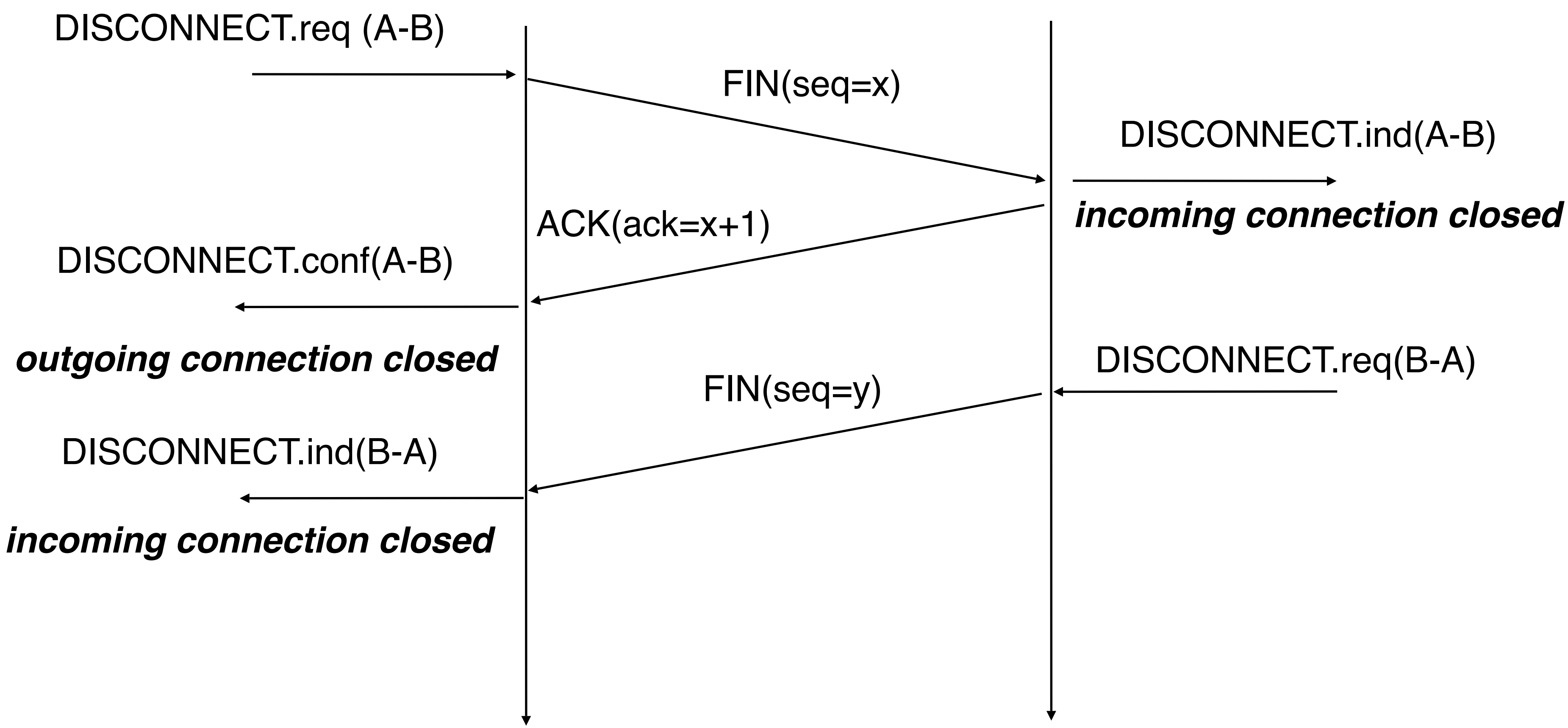

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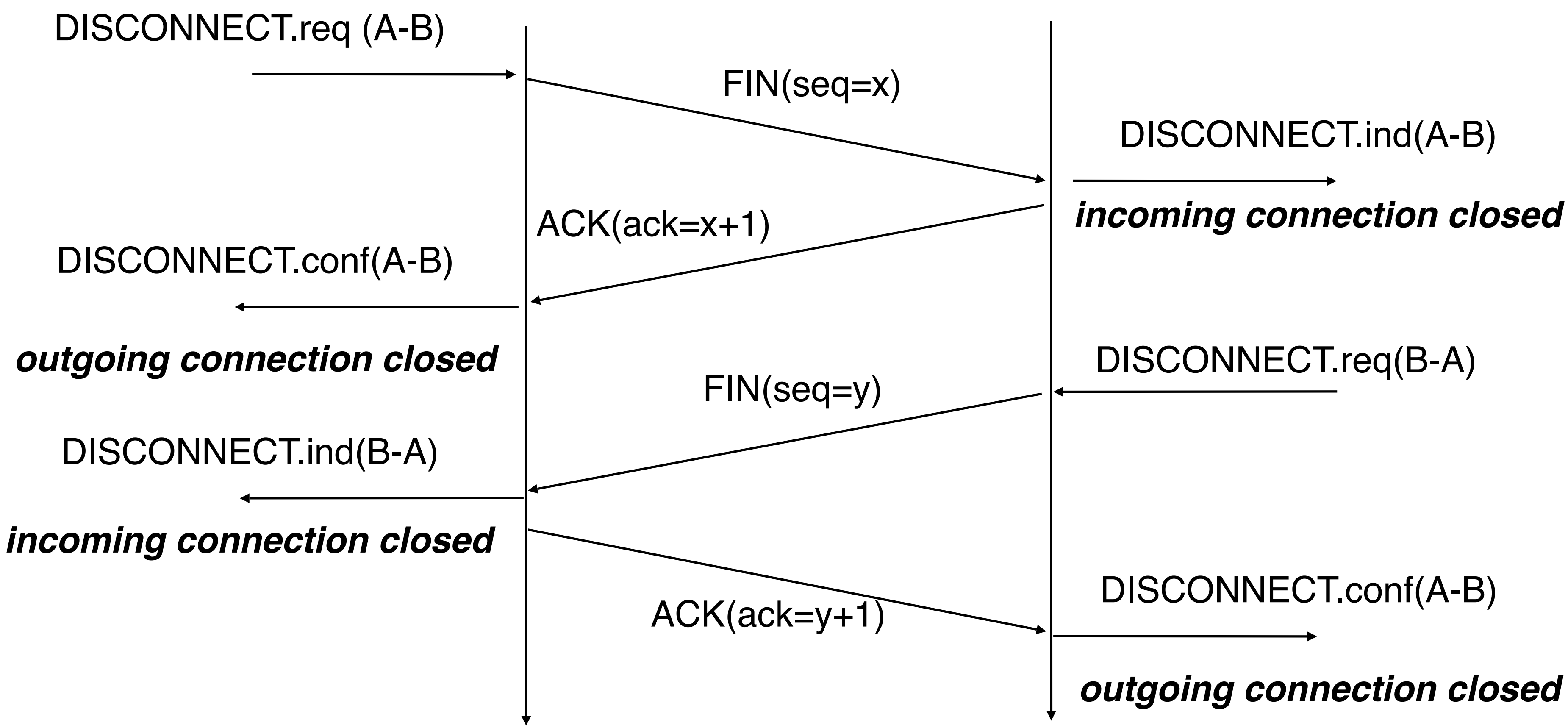

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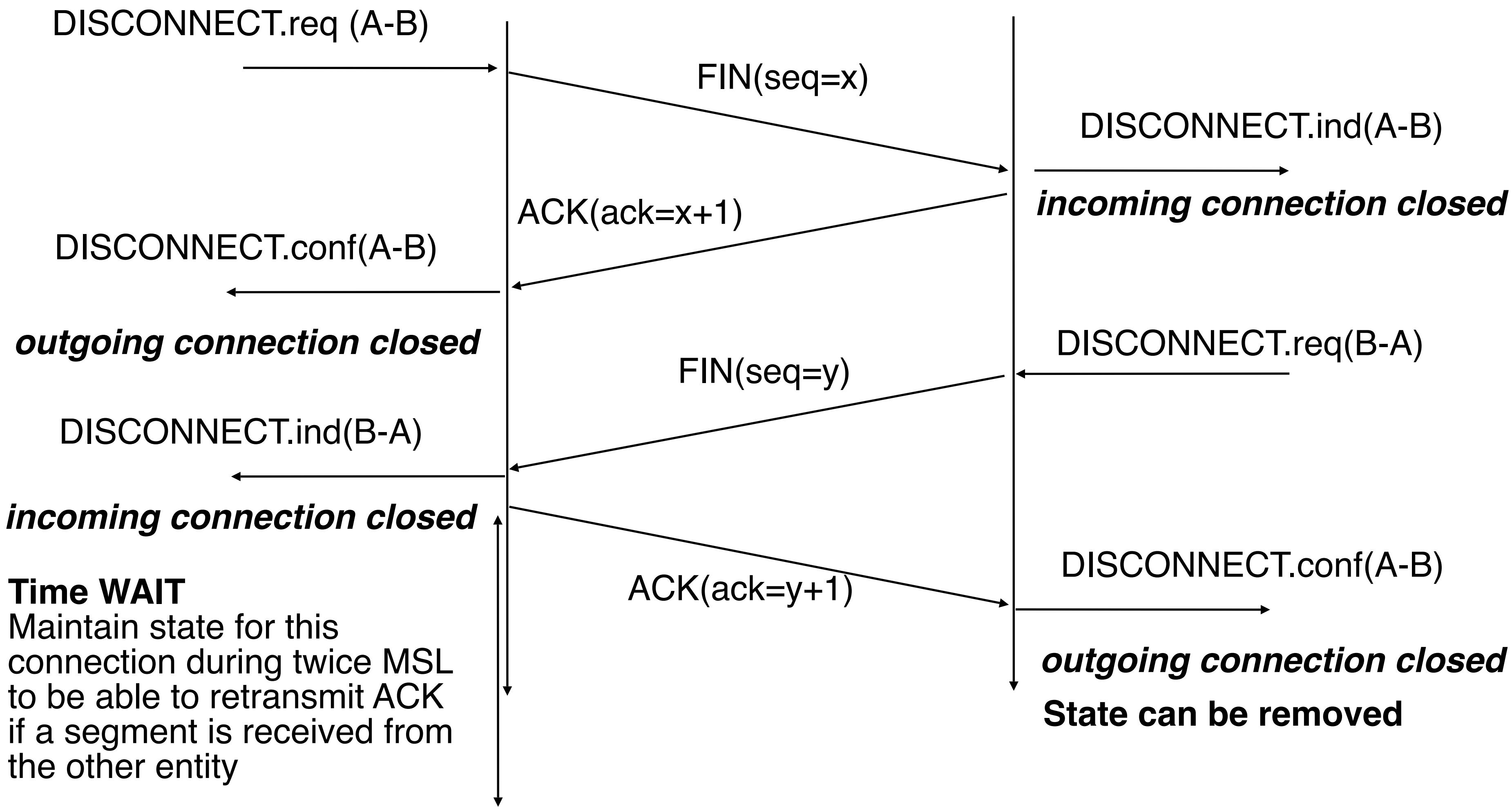

Abrupt TCP connection release

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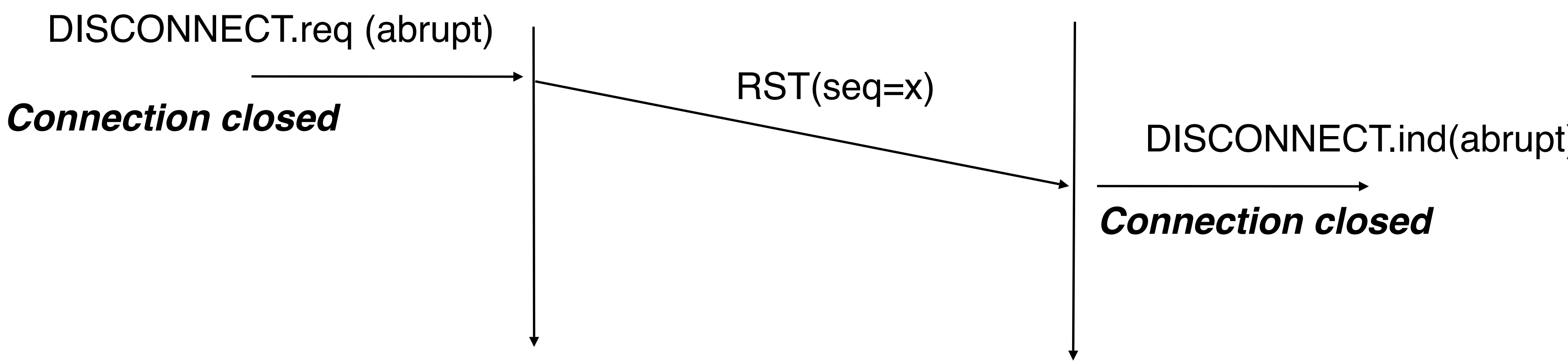

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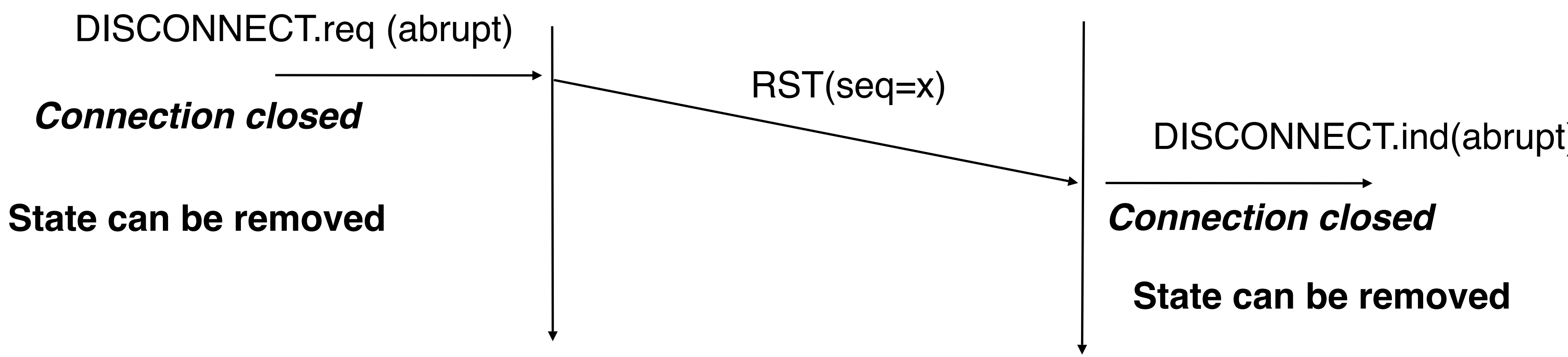

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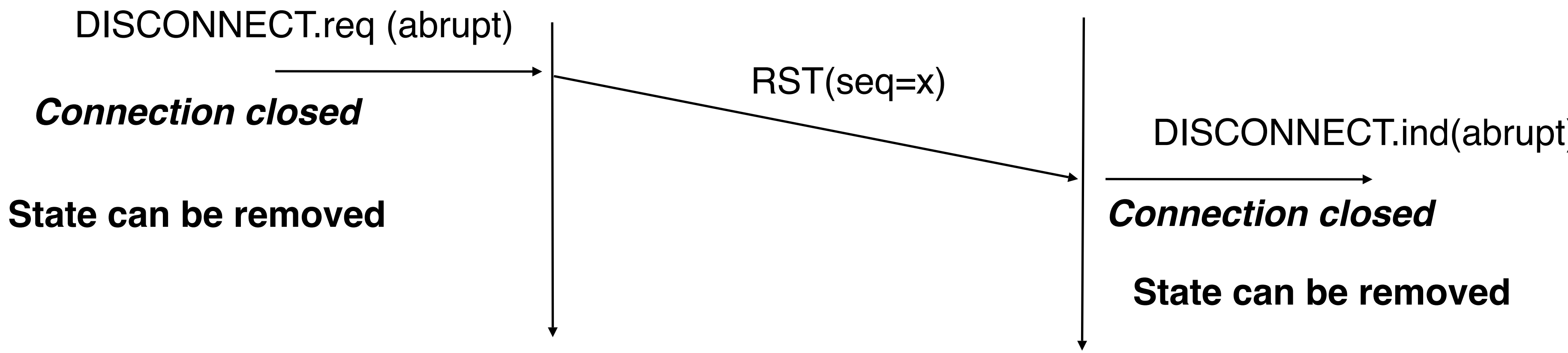
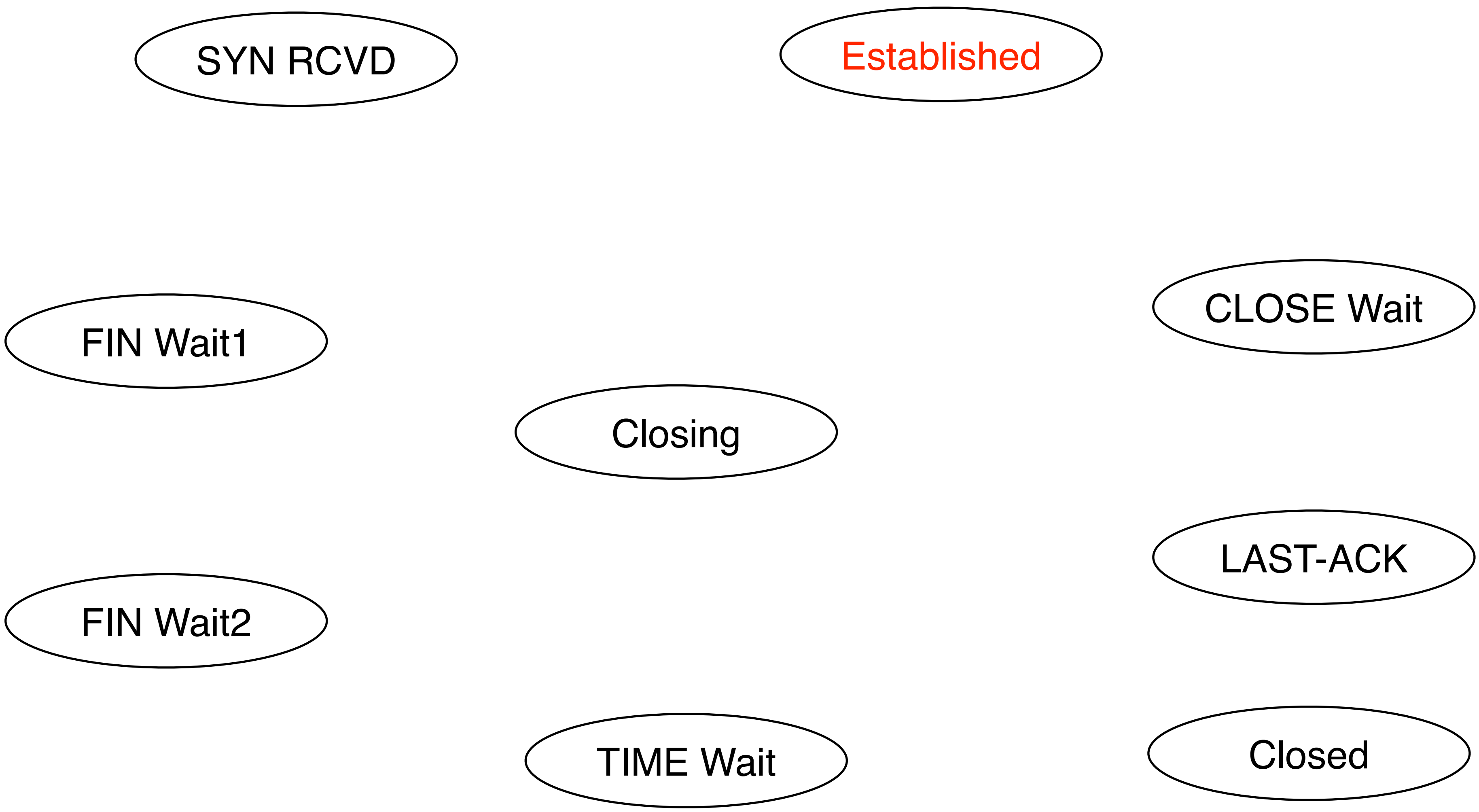


- Data segments can be lost during such an abrupt release
- No entity needs to wait in TIME_WAIT state after such a release
  - anyway, any segment received when there is no state causes the transmission of a RST segment

TCP connection release



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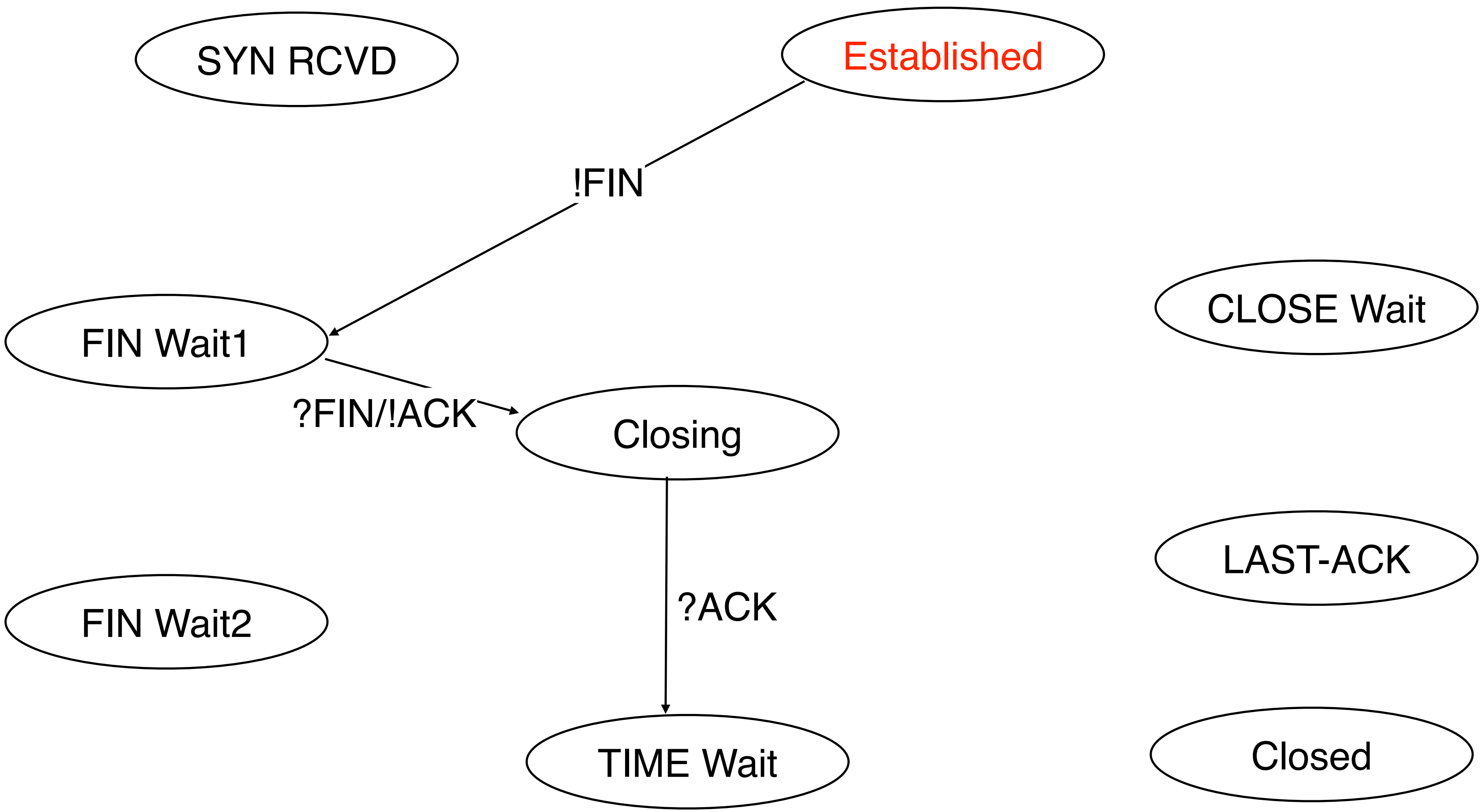

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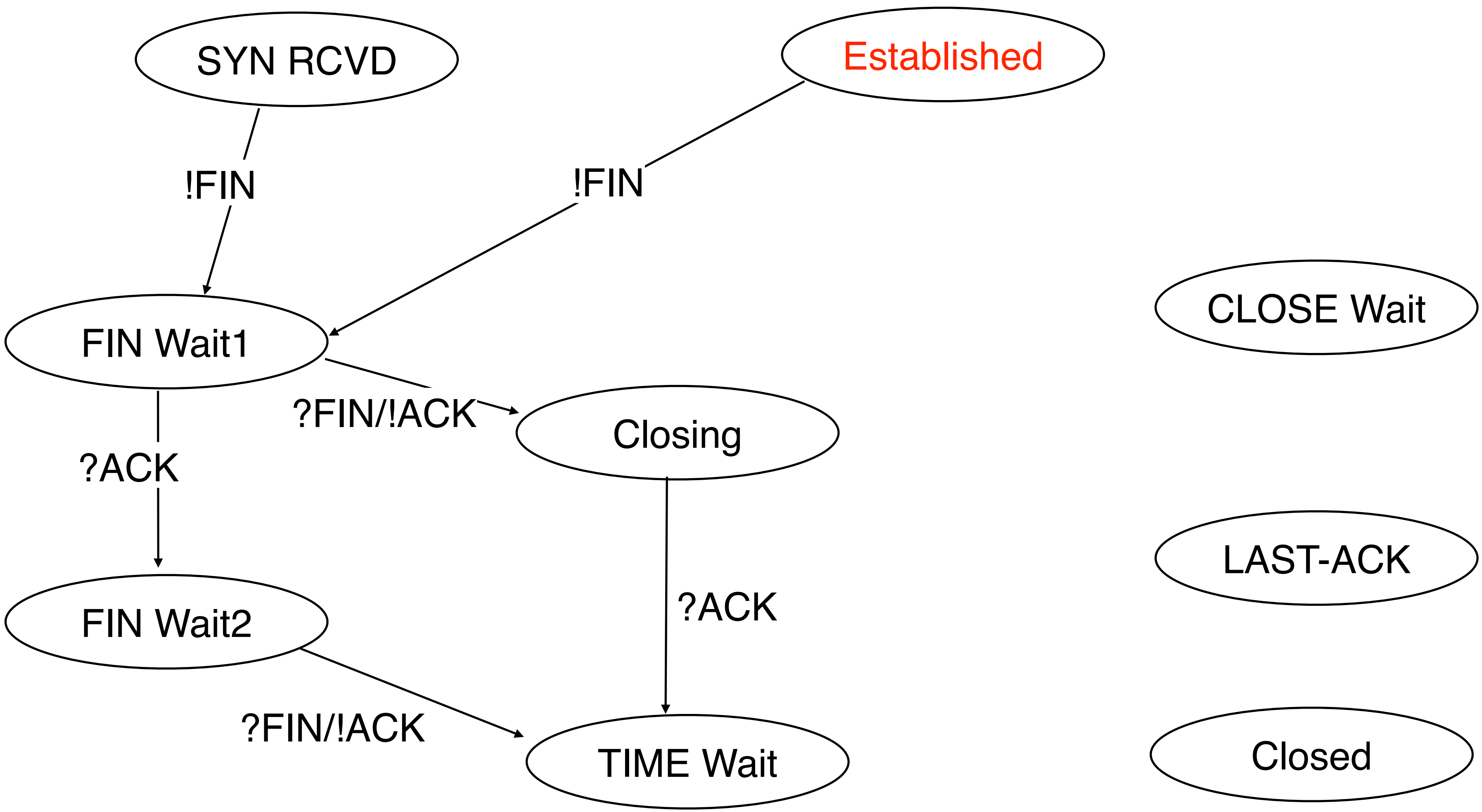

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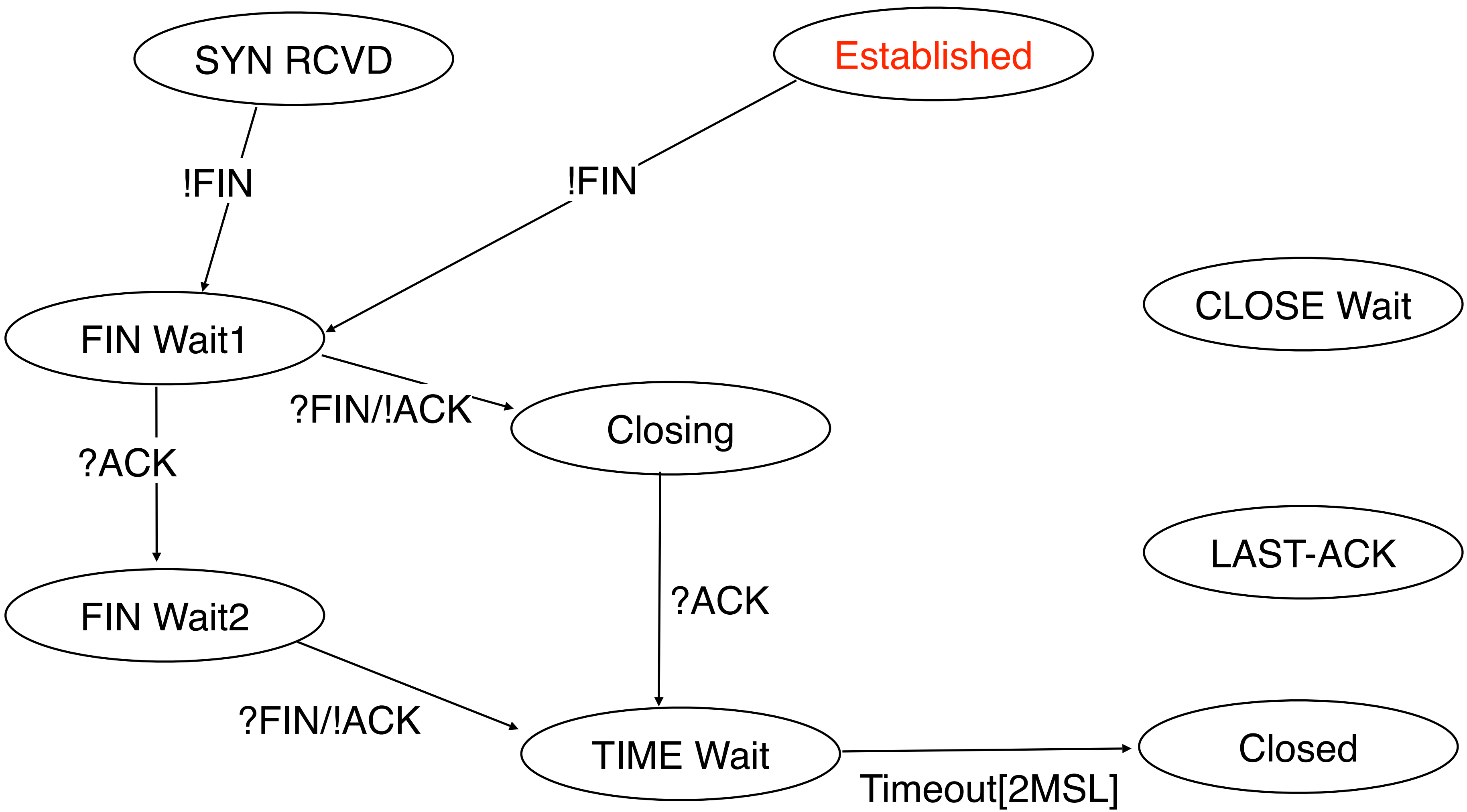

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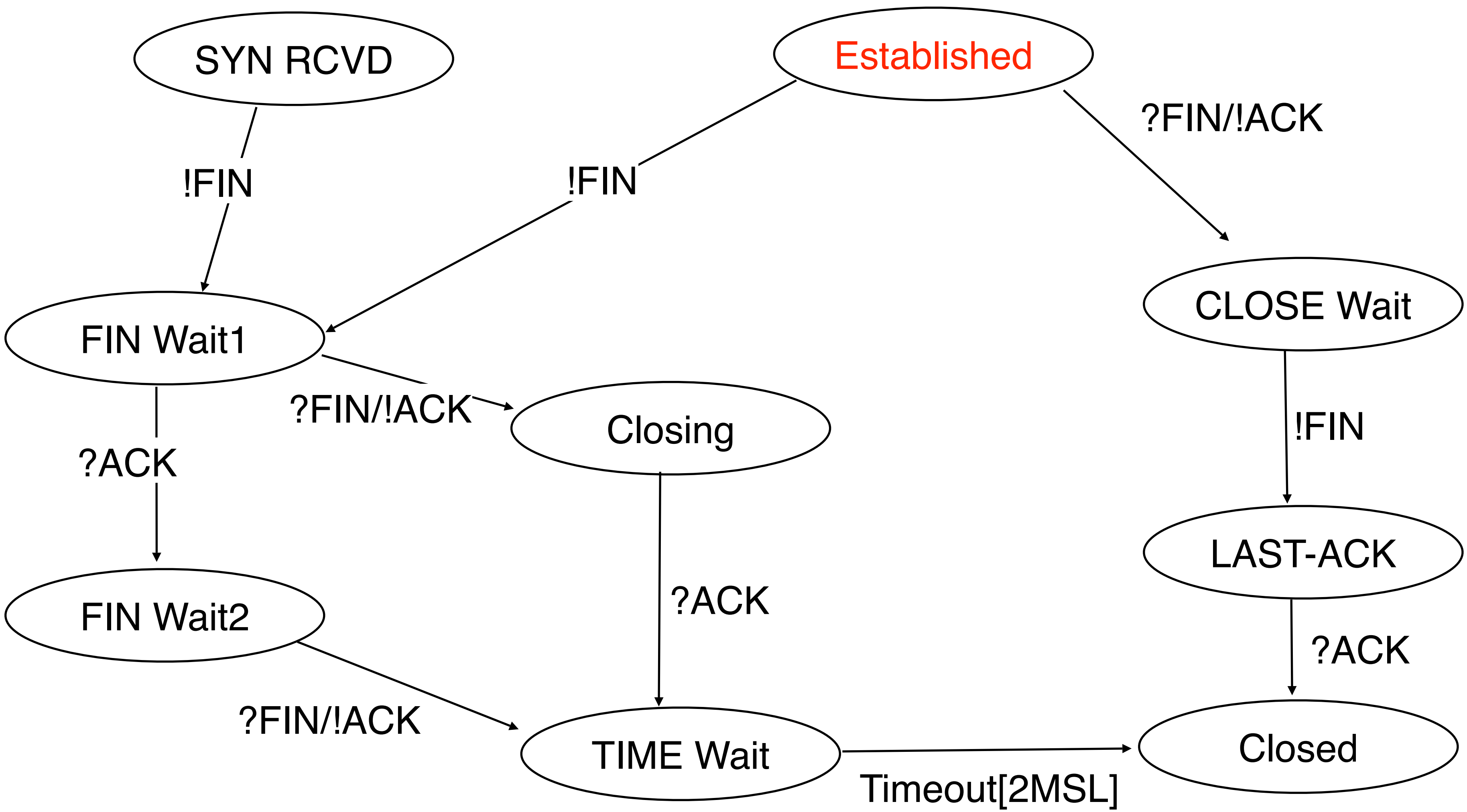

Module 3 : Transport Layer

- Basics
- Building a reliable transport layer
- 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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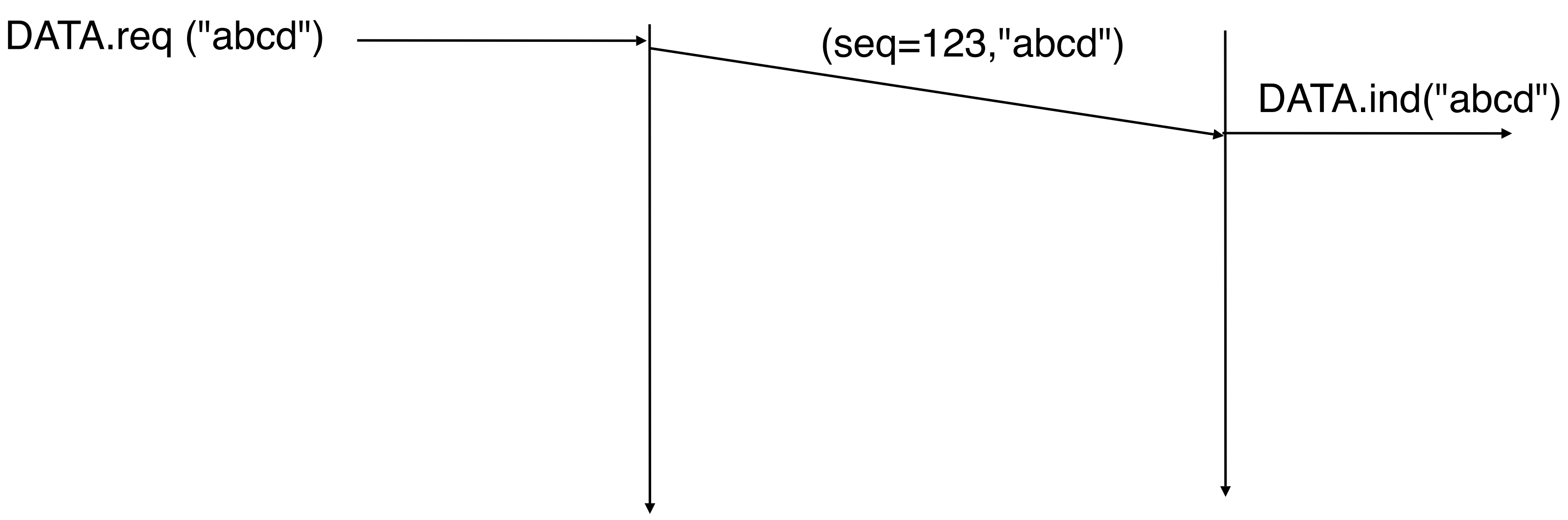

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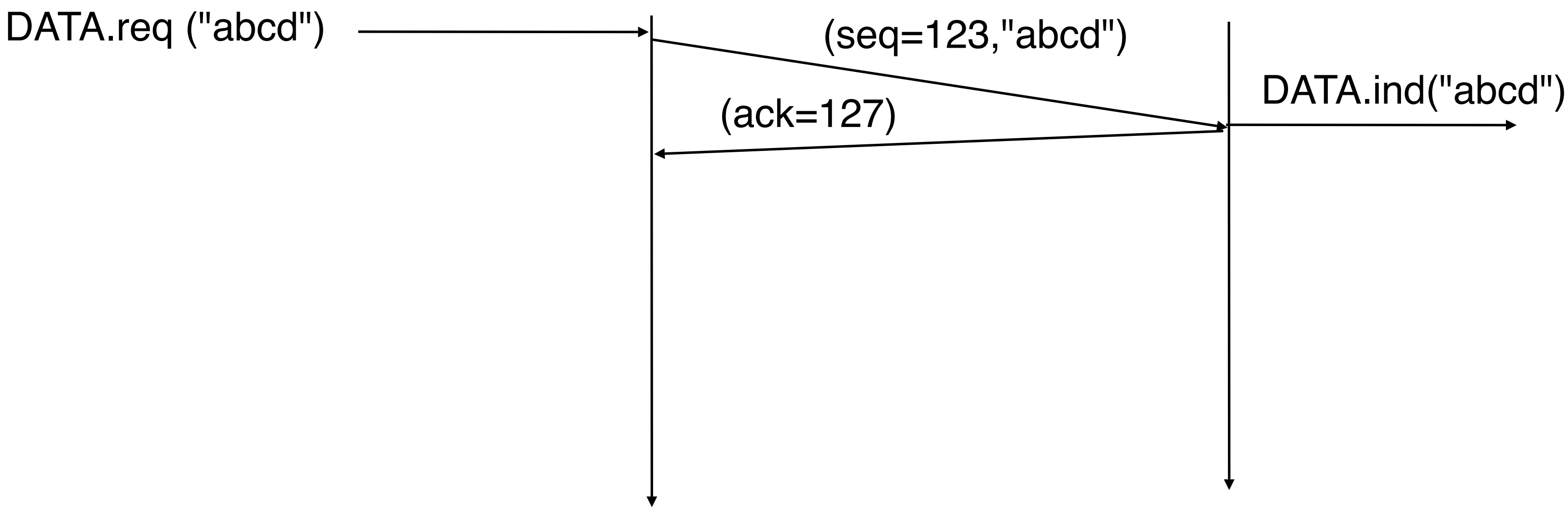

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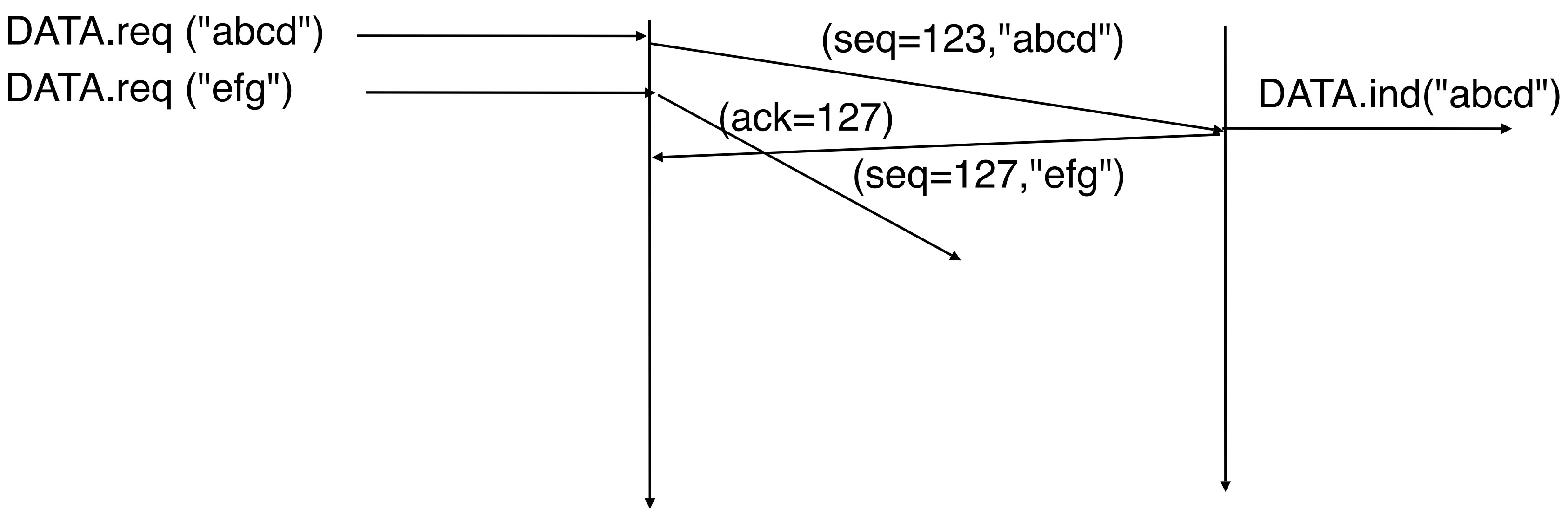

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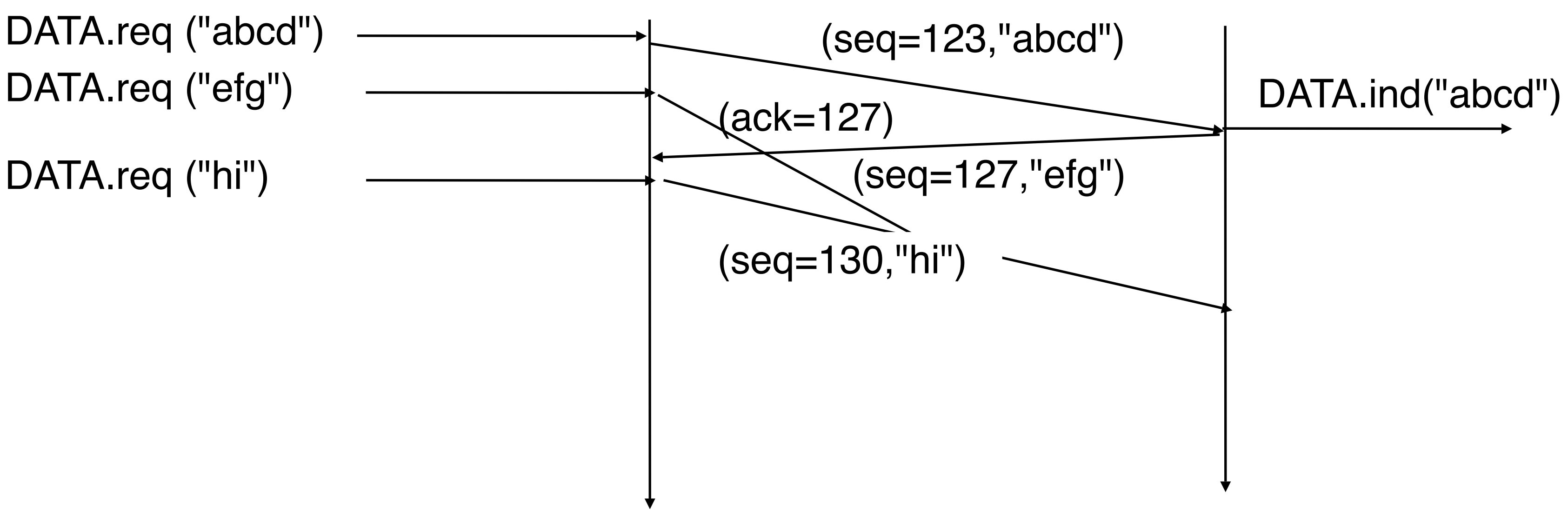

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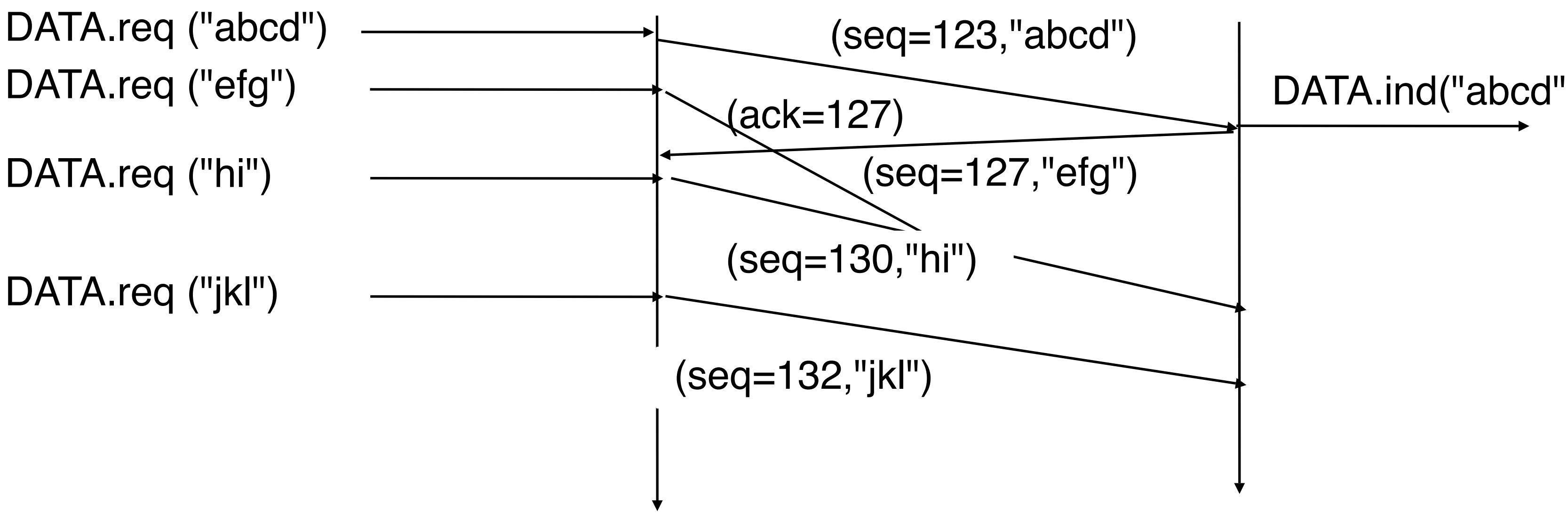

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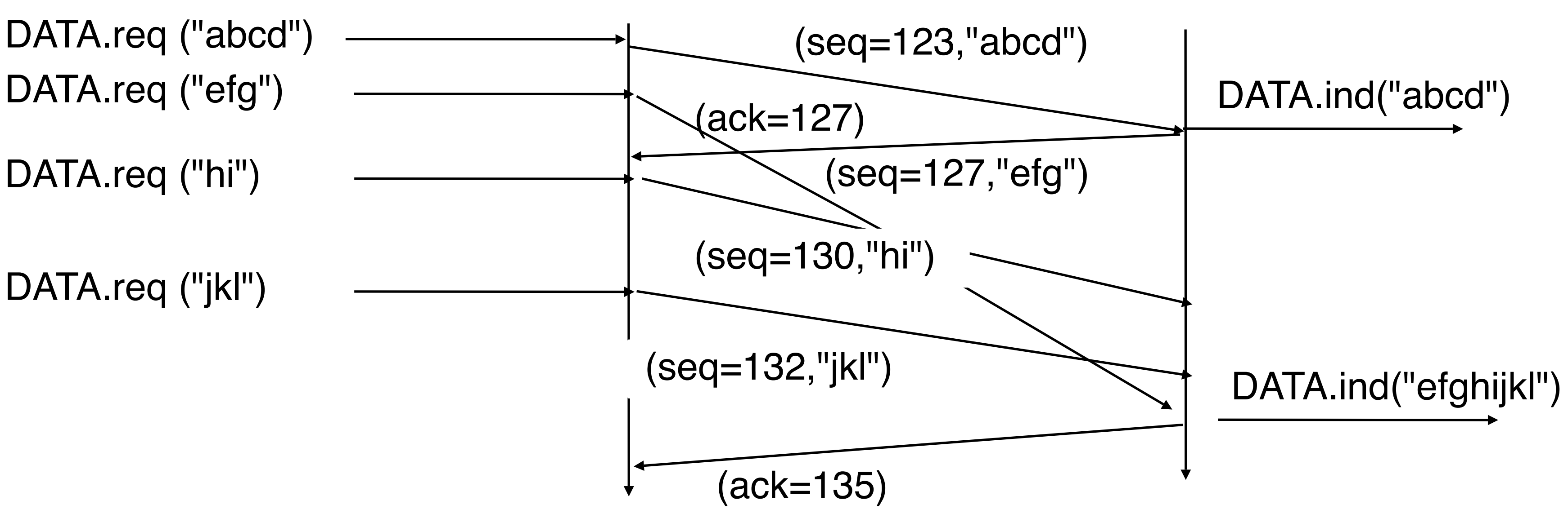

Reliable data transfer

- 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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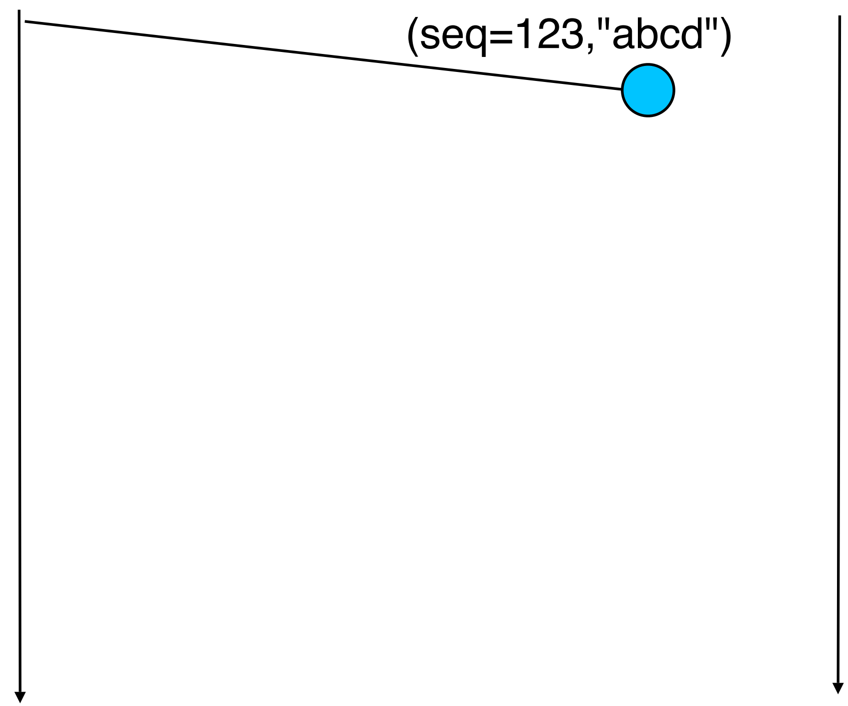

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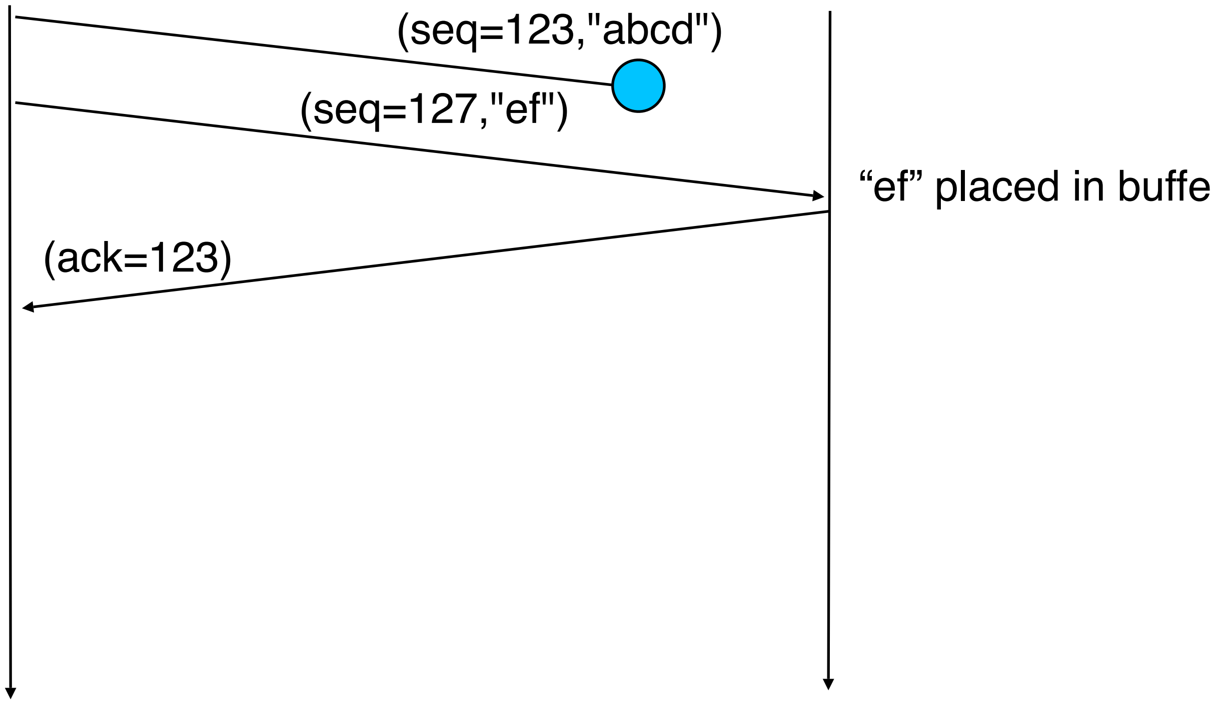

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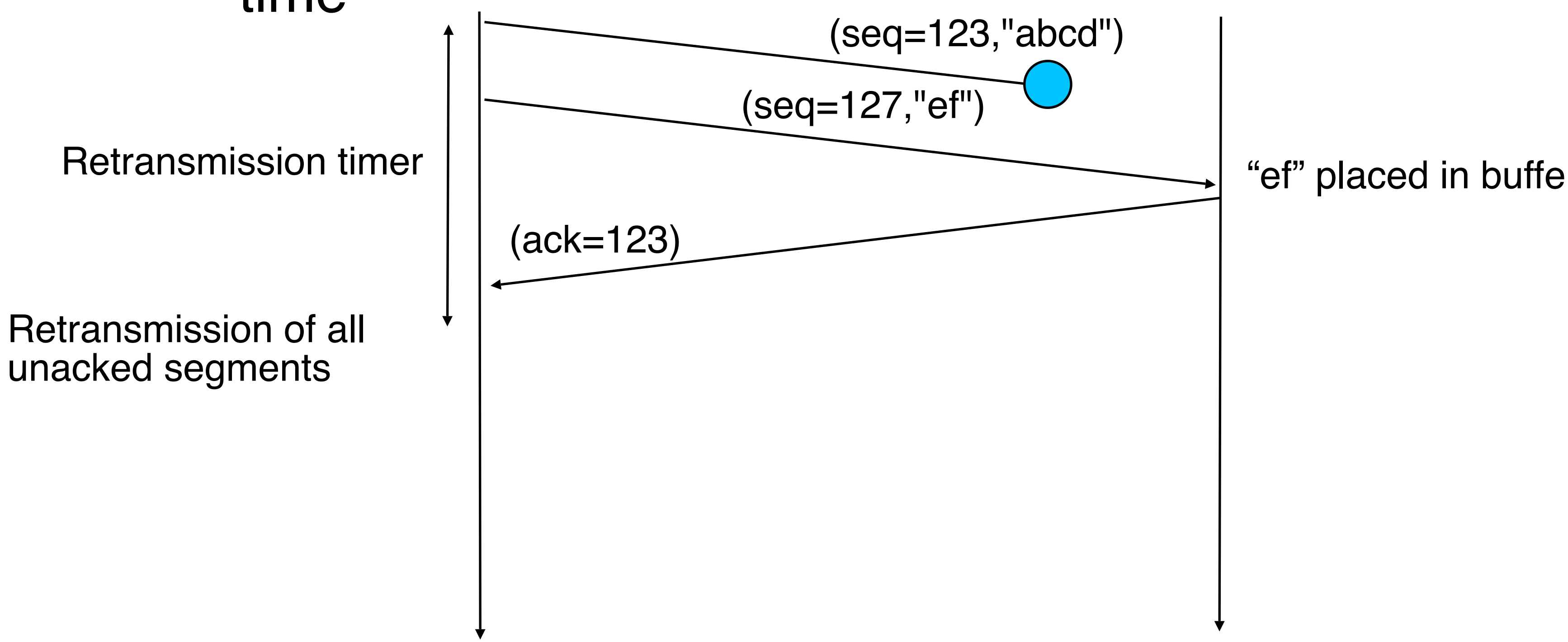

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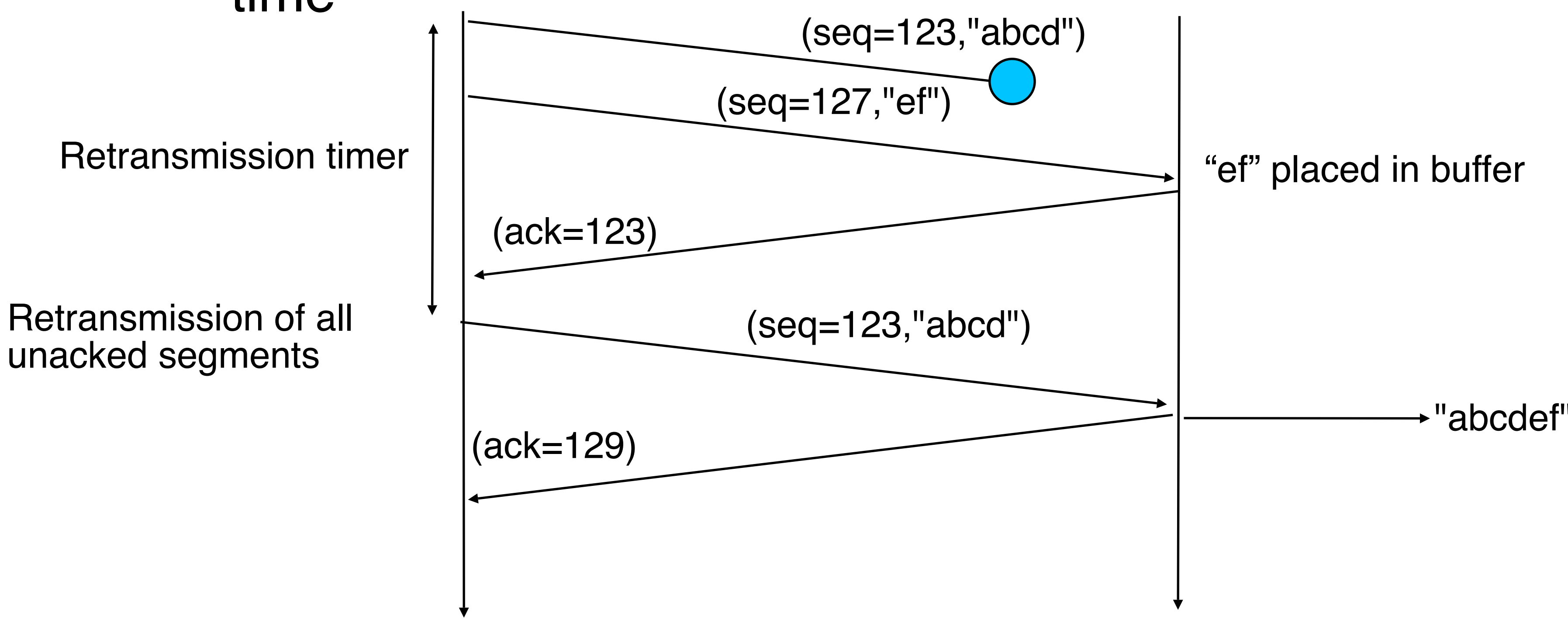

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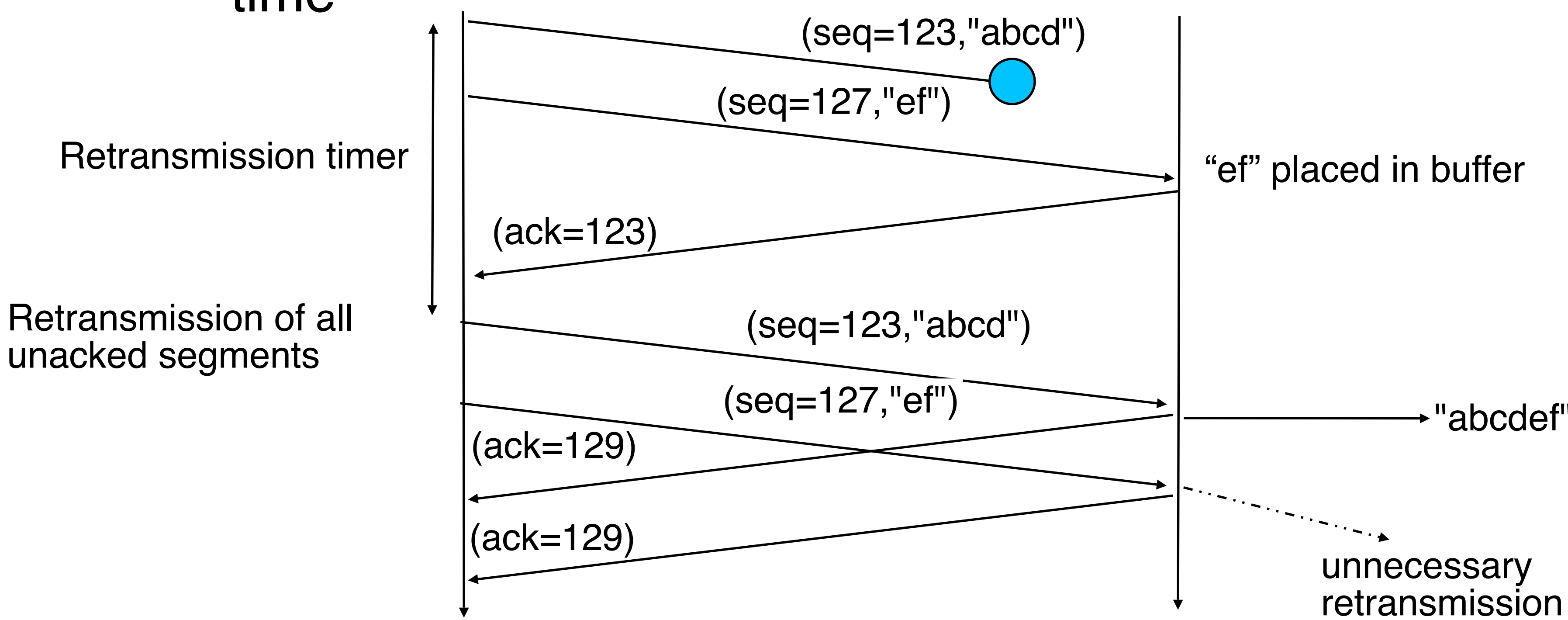
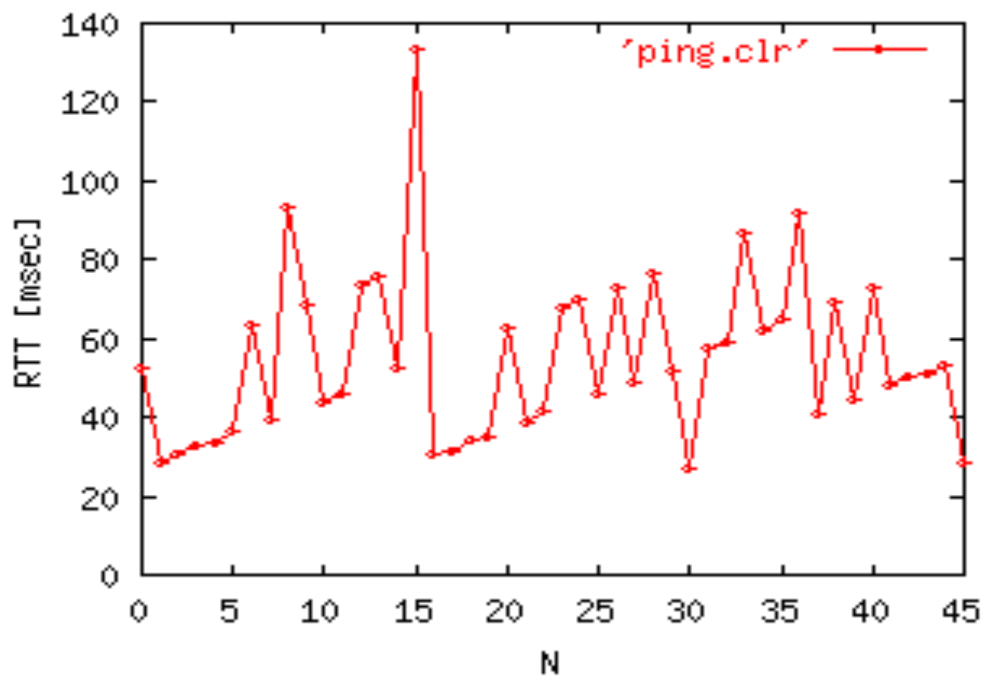


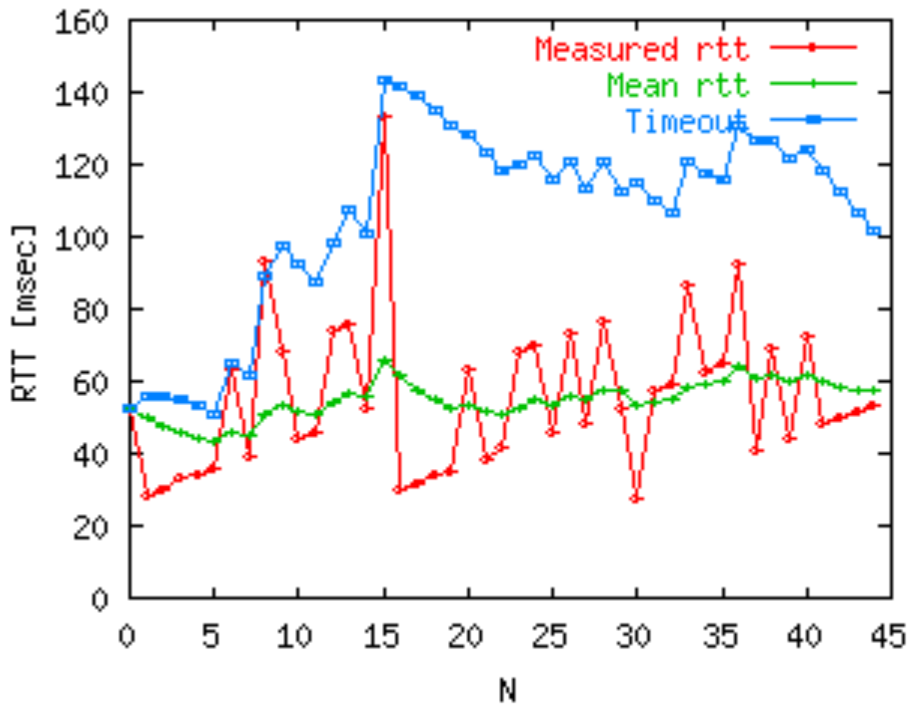
Retransmission timer

- How to compute it ?
  - Issue
    - round-trip-time may change frequently during the lifetime of a TCP connection



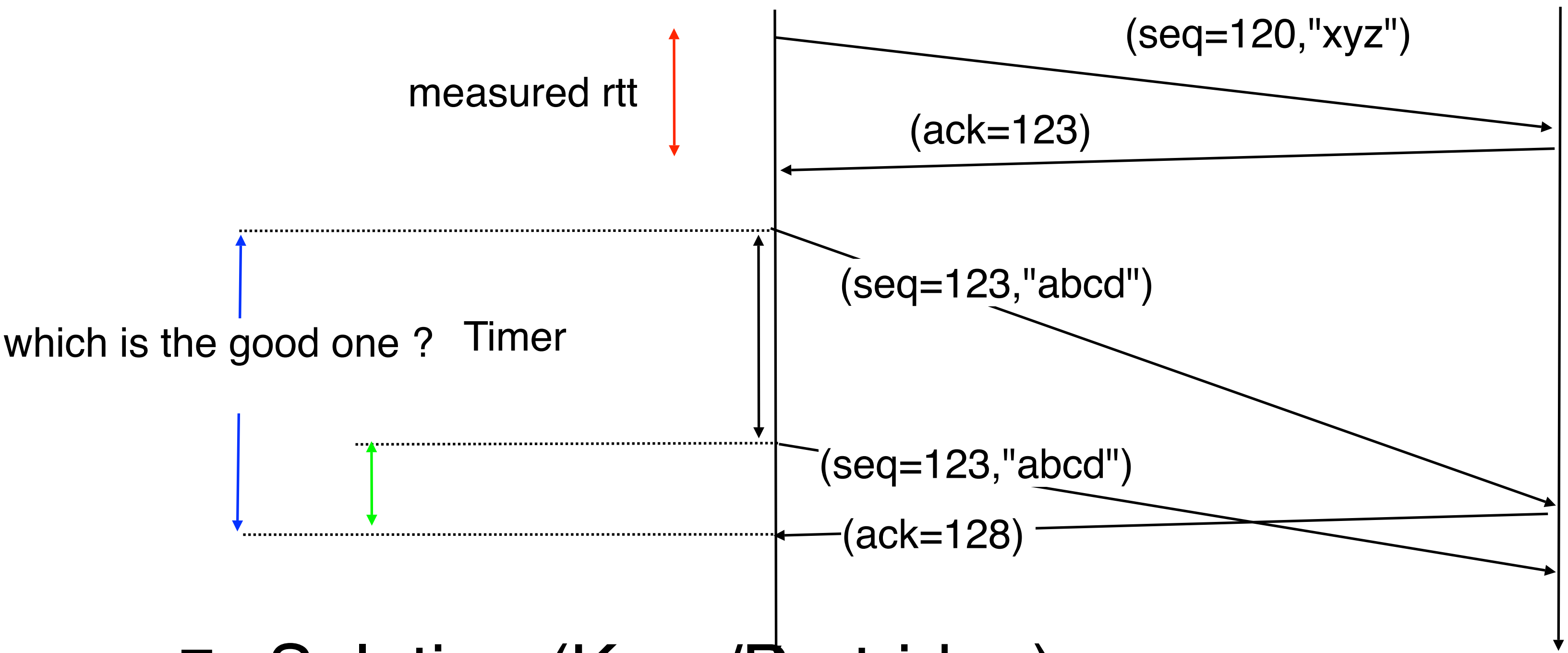
Retransmission timer

- 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

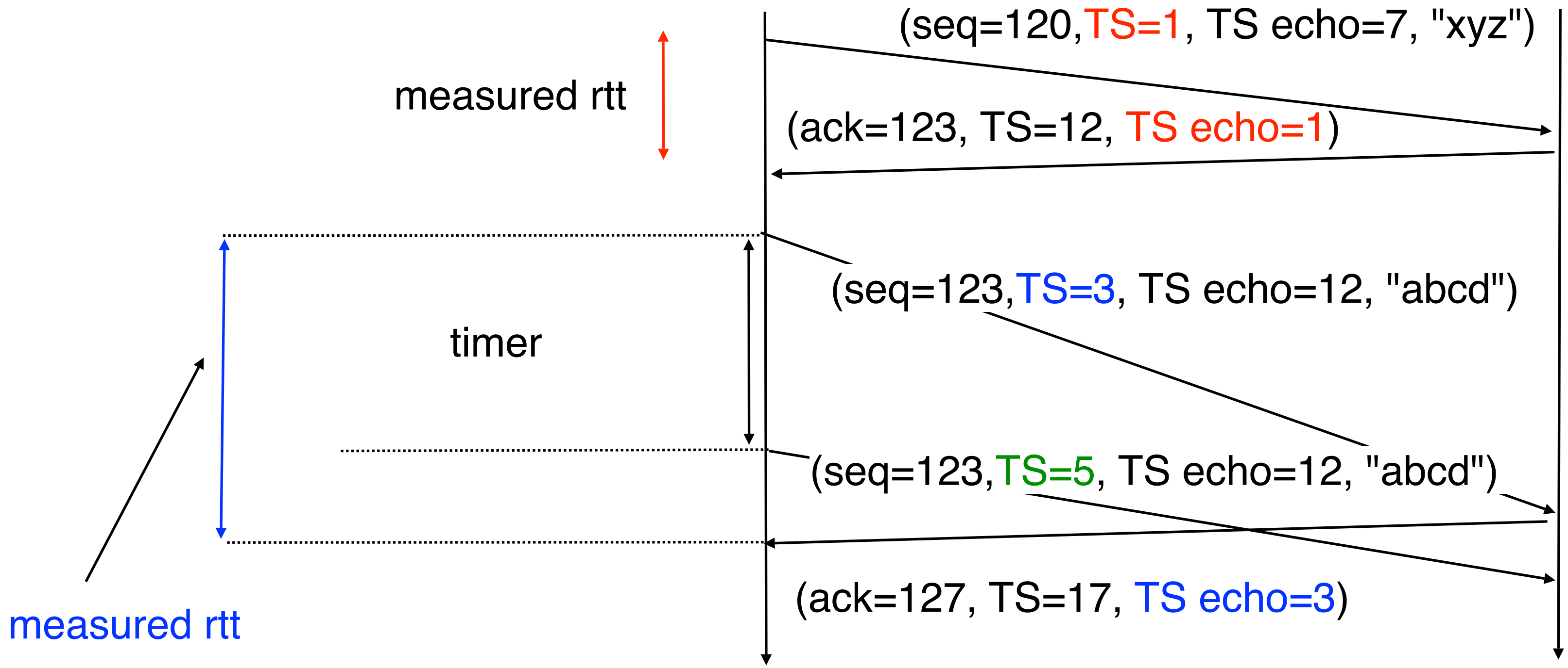
- Problem
  - How to measure rtt after retransmissions ?



- 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)



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- 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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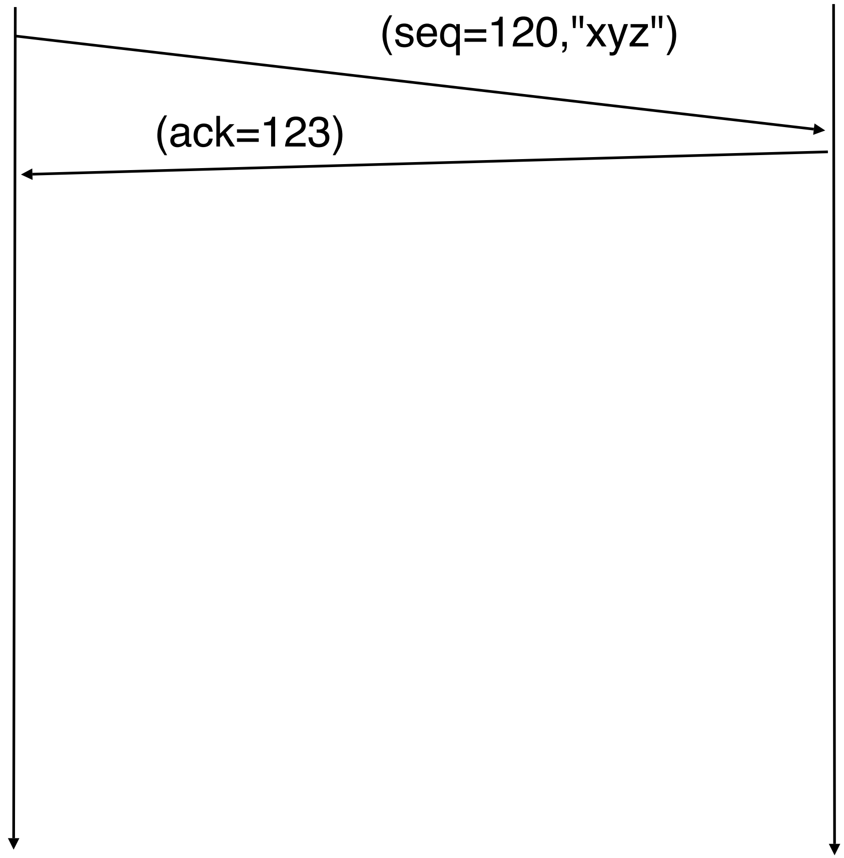

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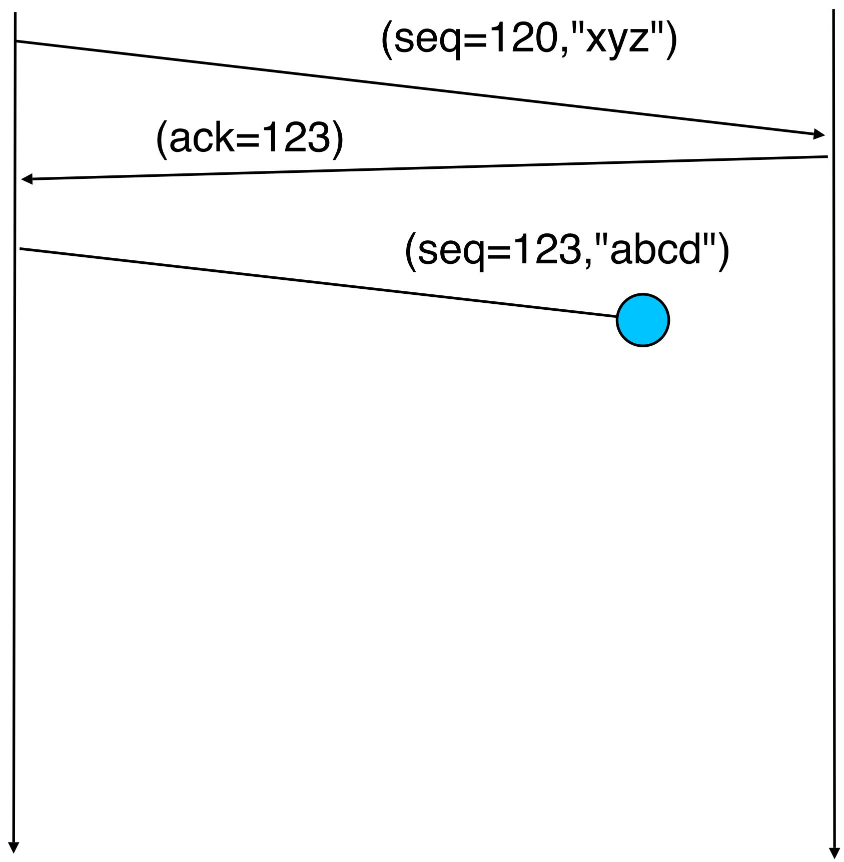

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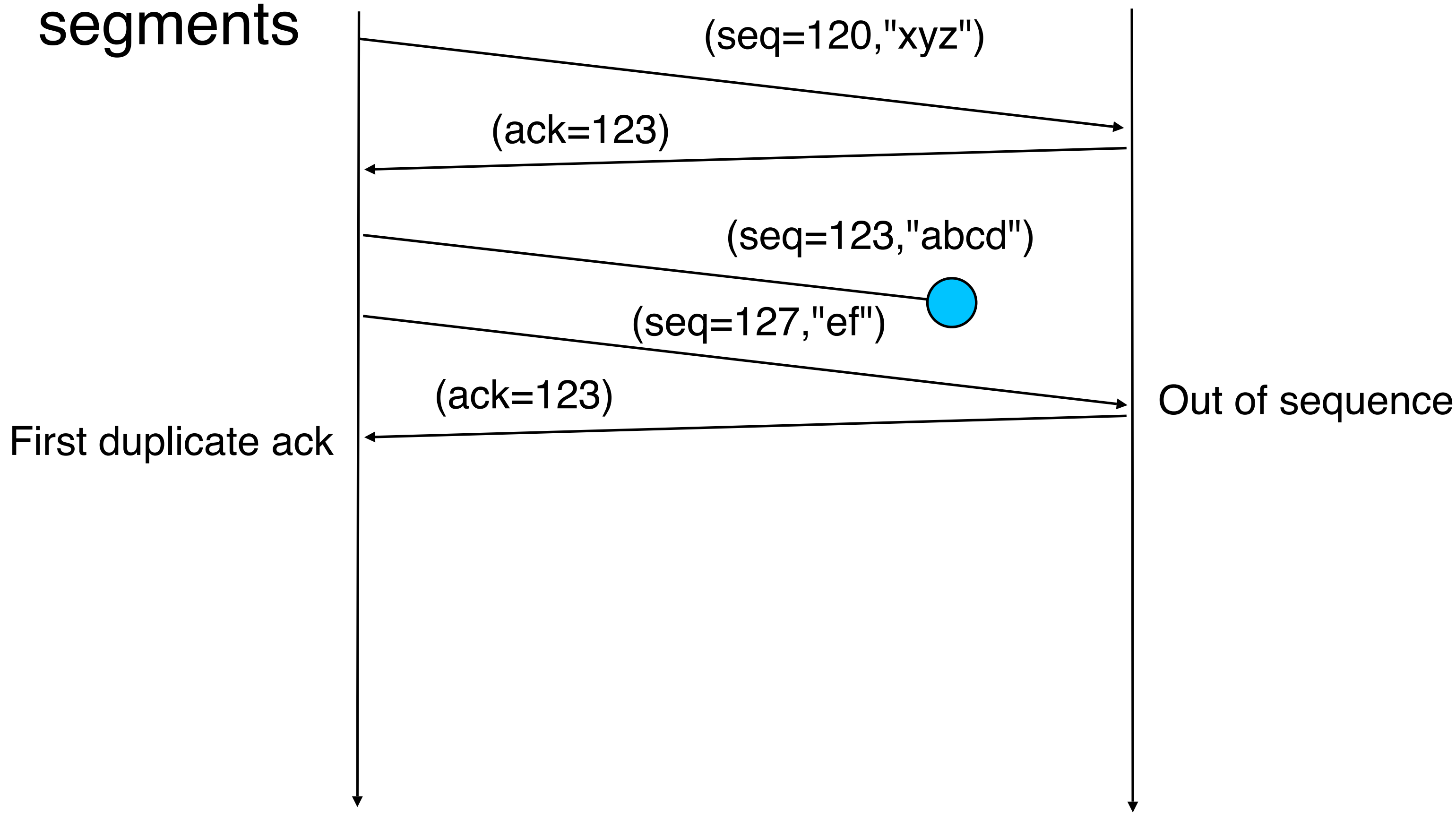

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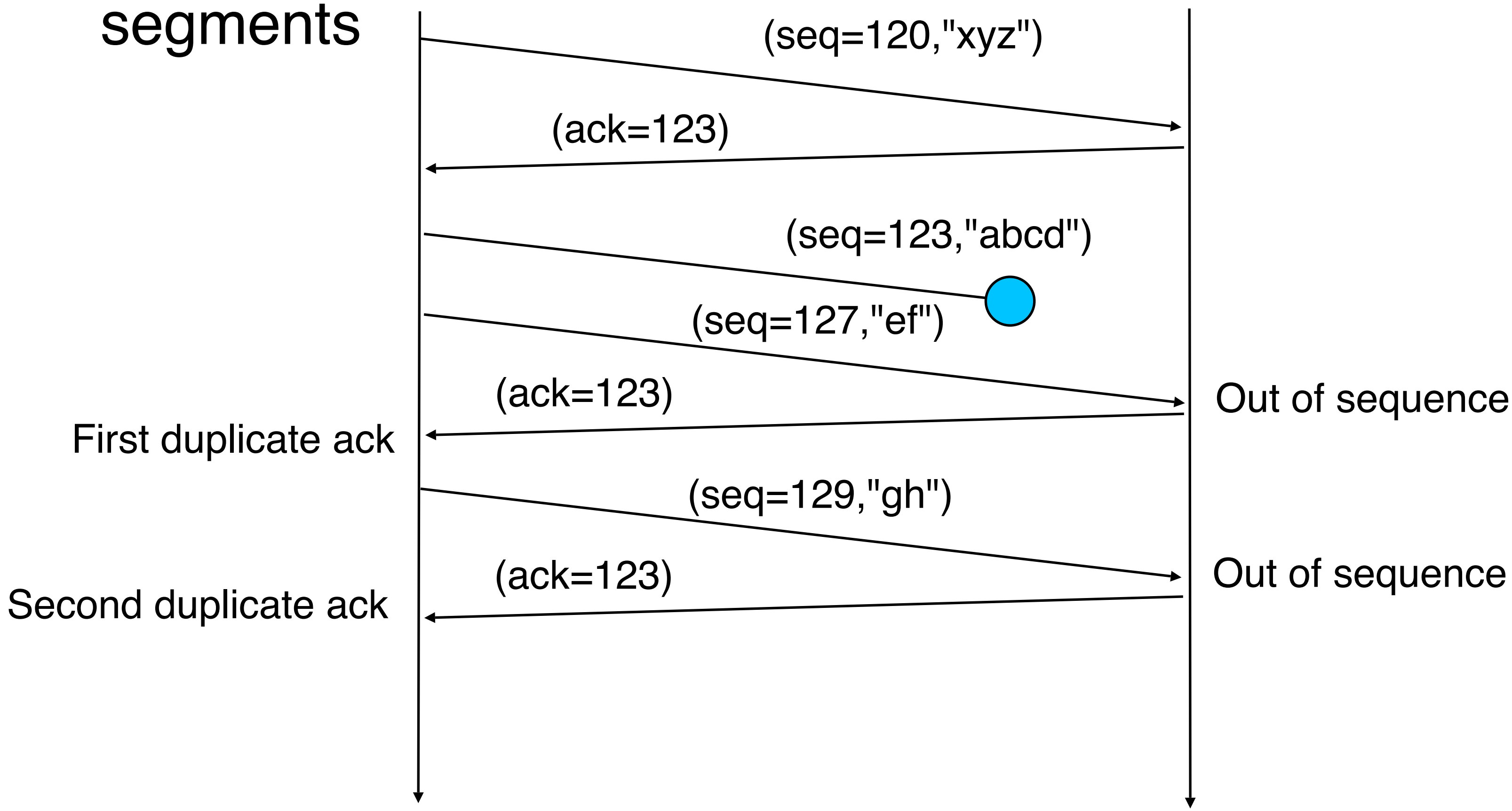

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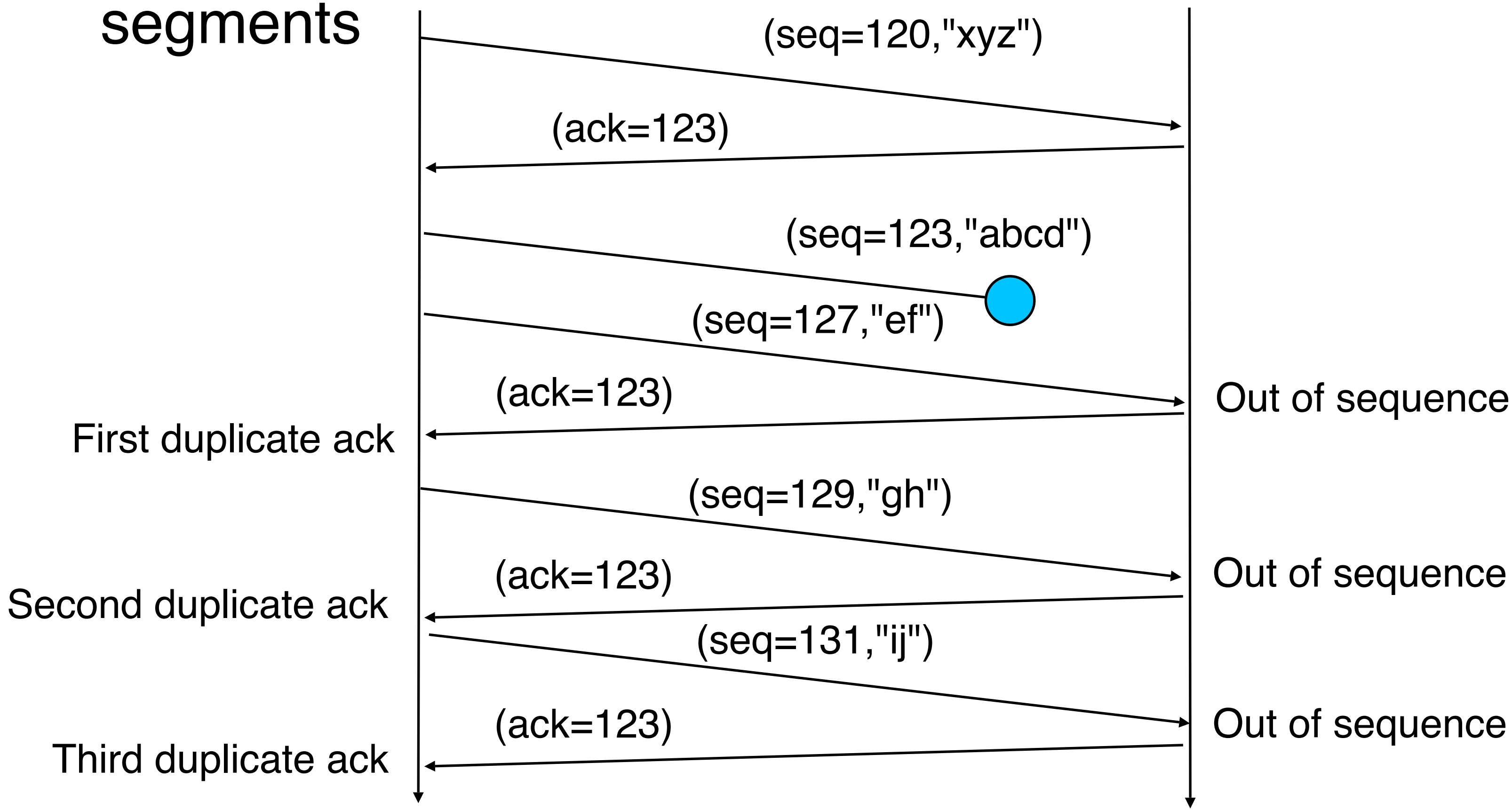

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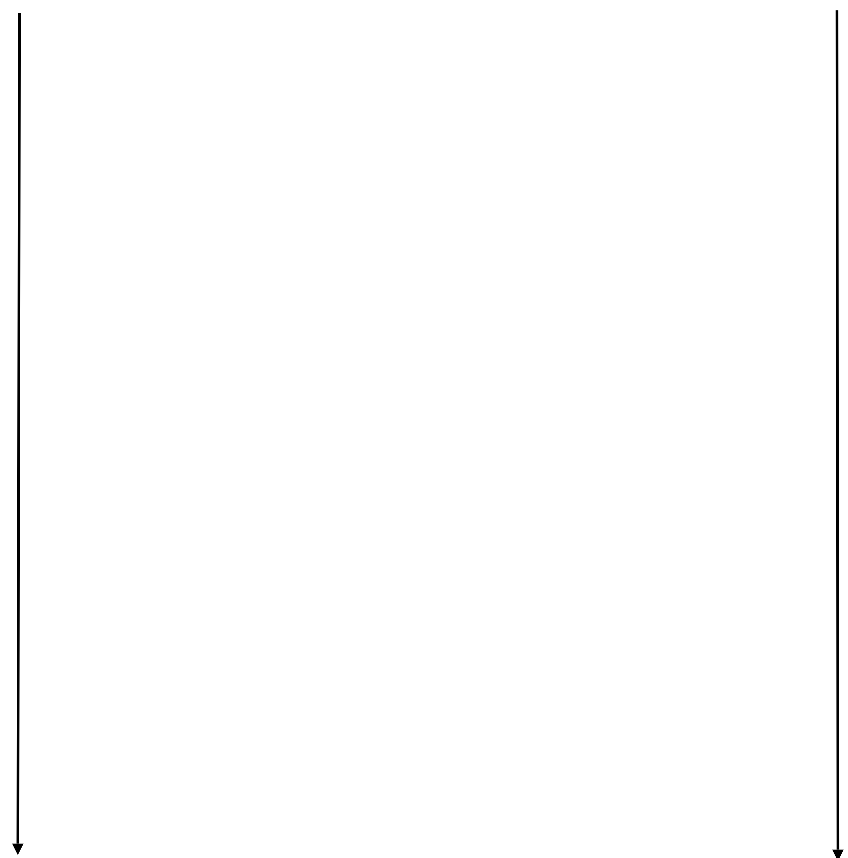
- How to retransmit the lost segments
  - Upon reception of three duplicate acks, retransmit <u>the first unacked segment</u>
    - Fast retransmit, used by most TCP implementations



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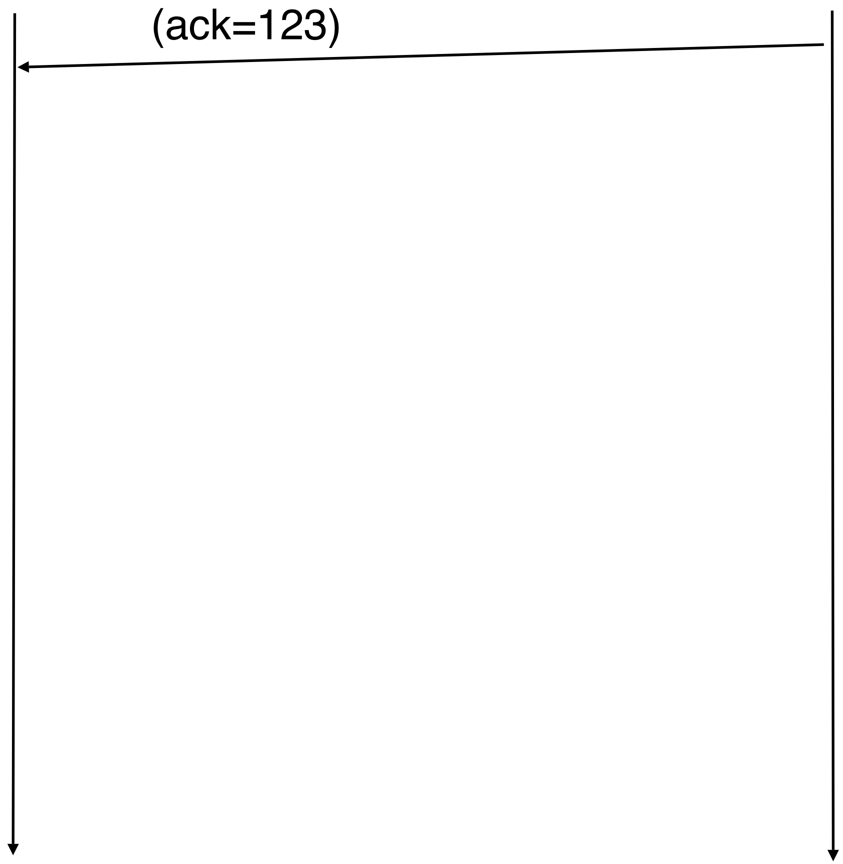

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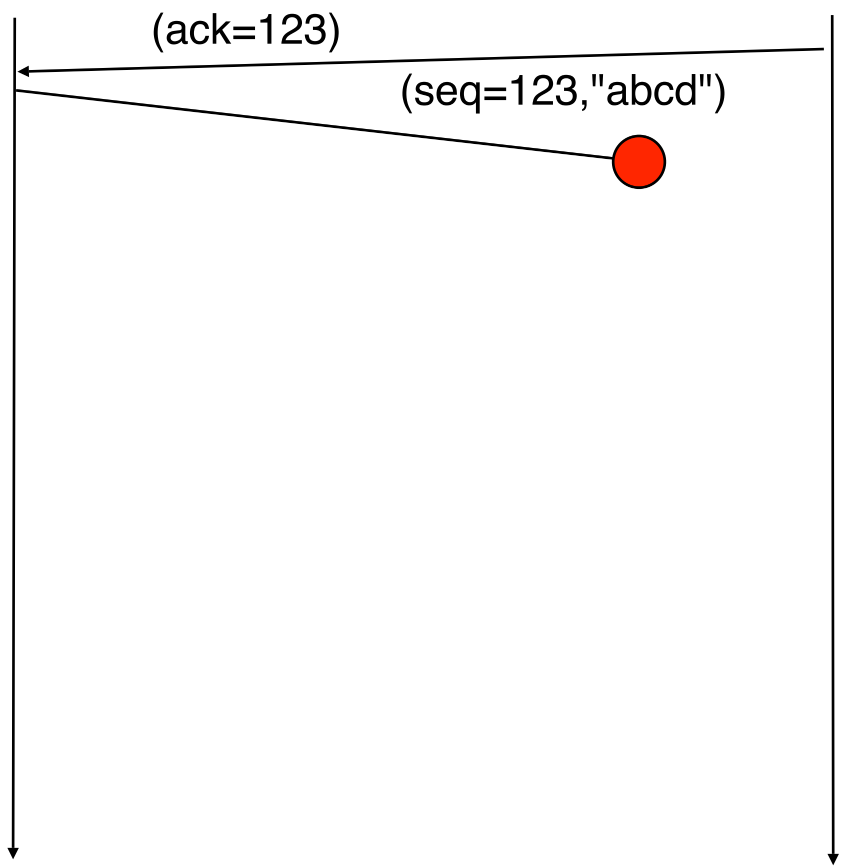

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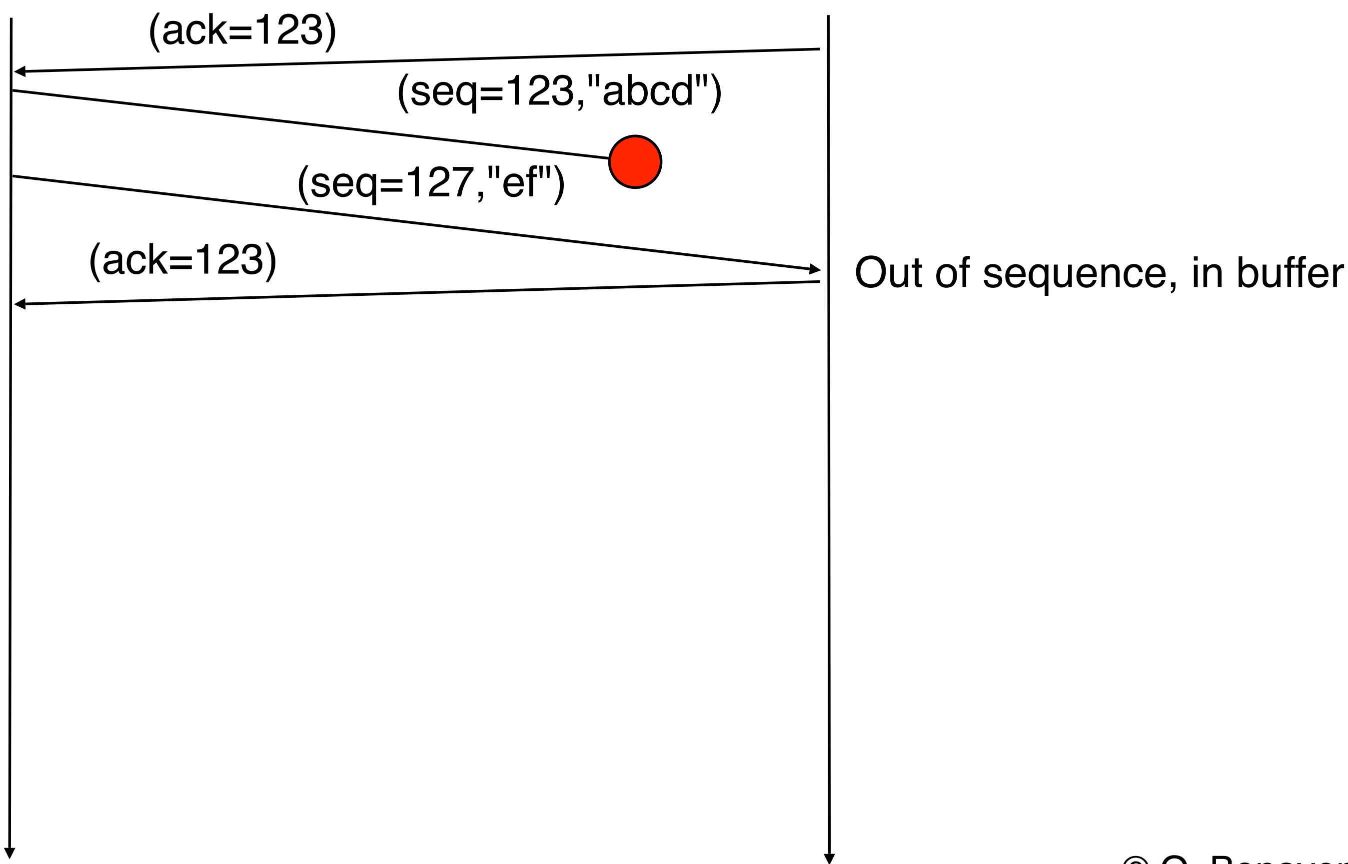

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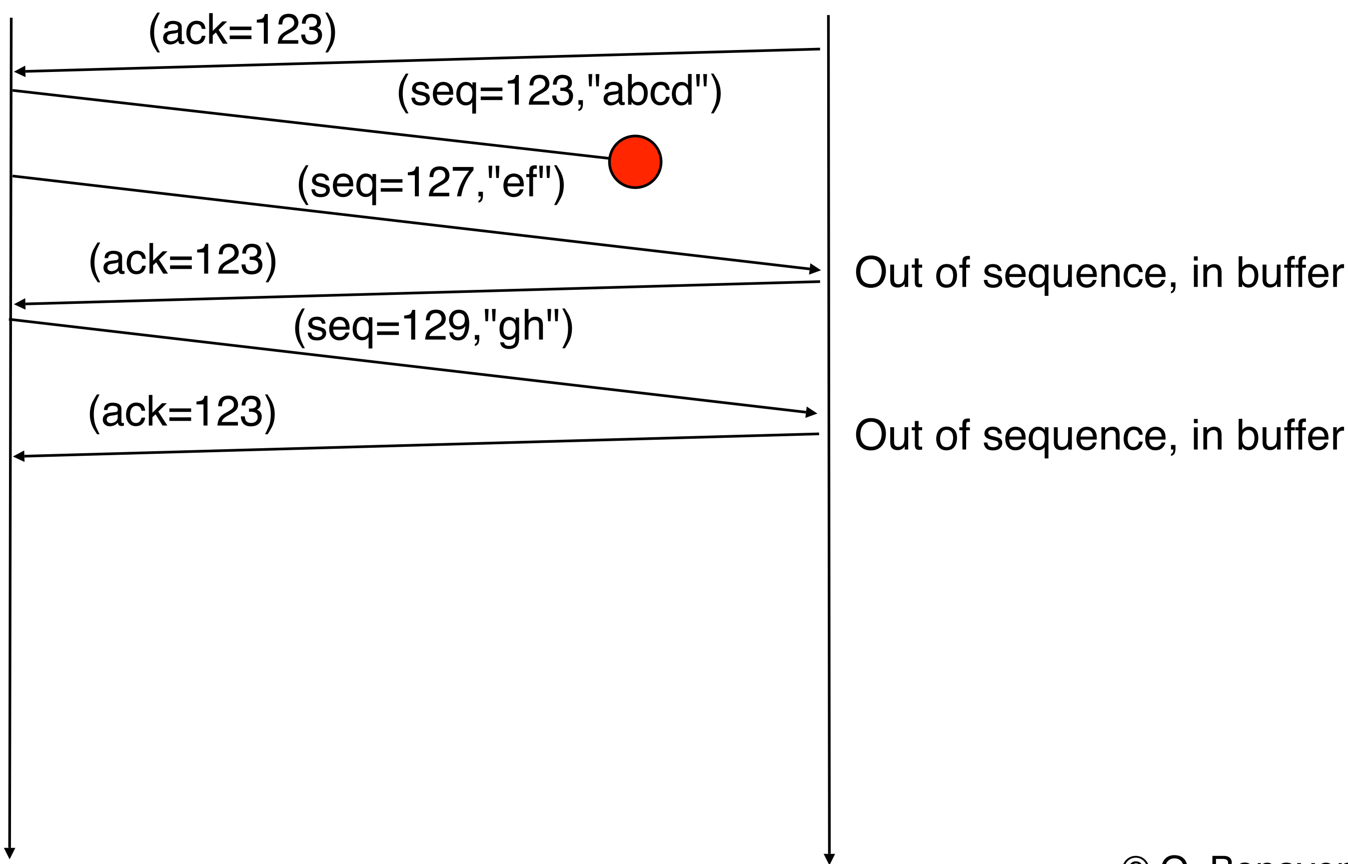

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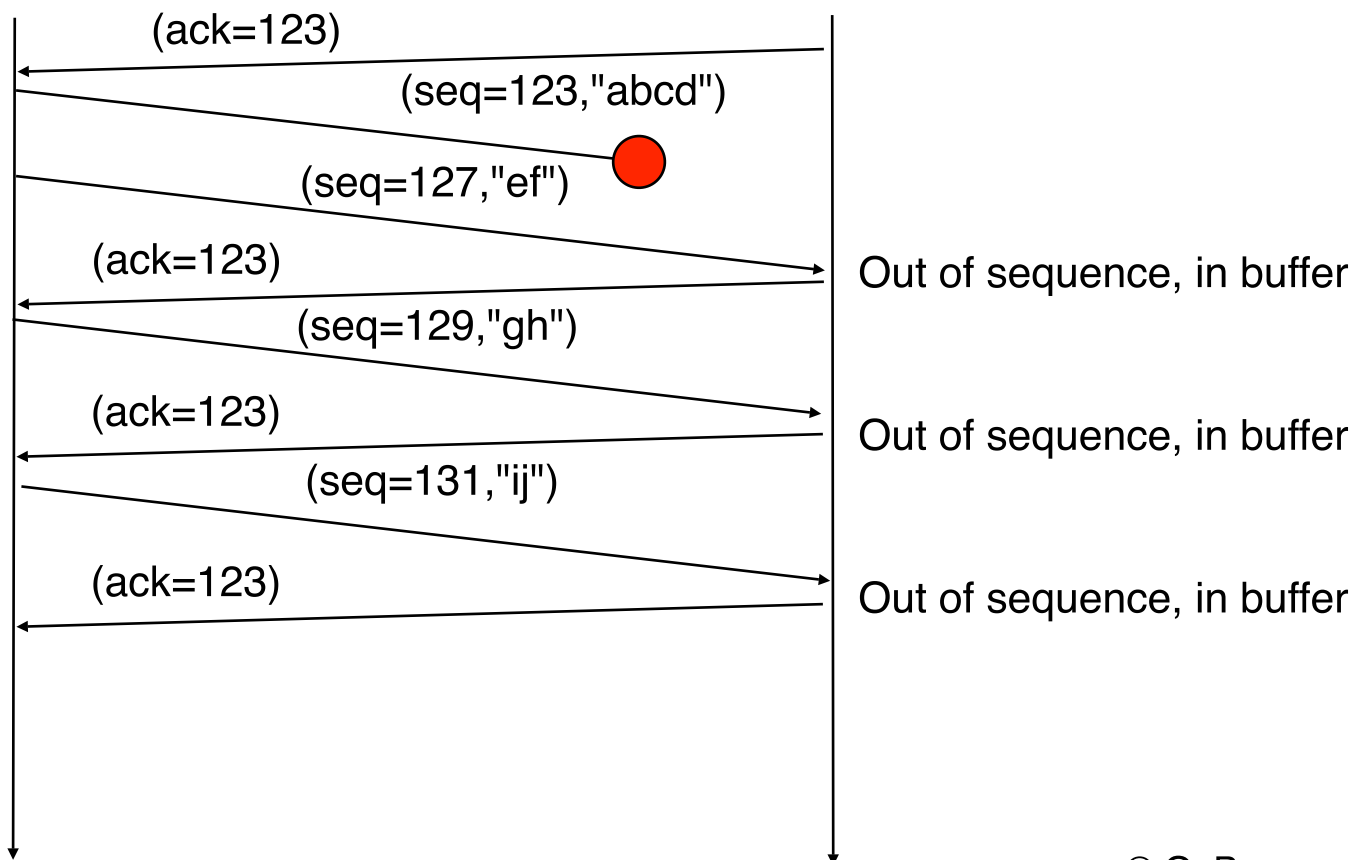

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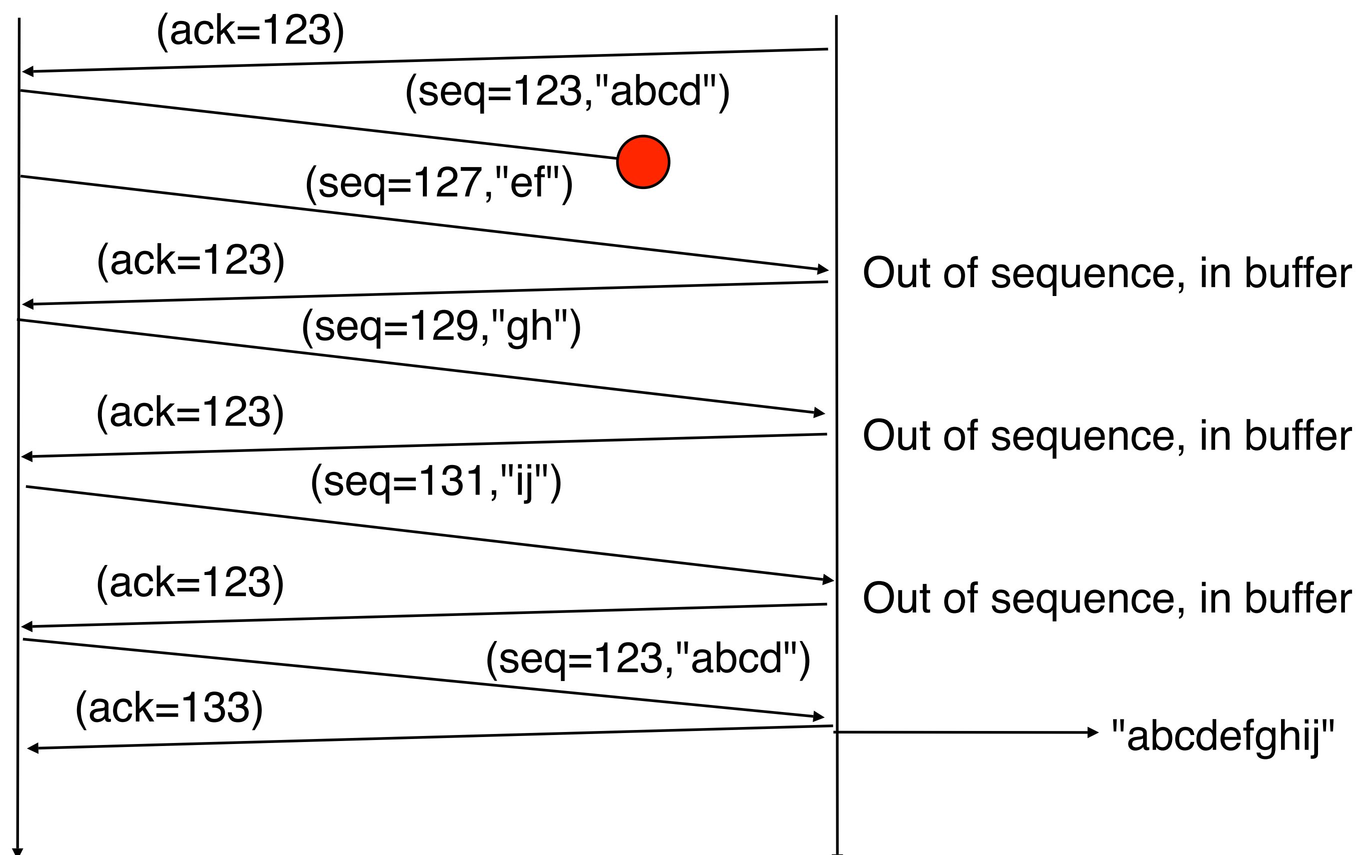
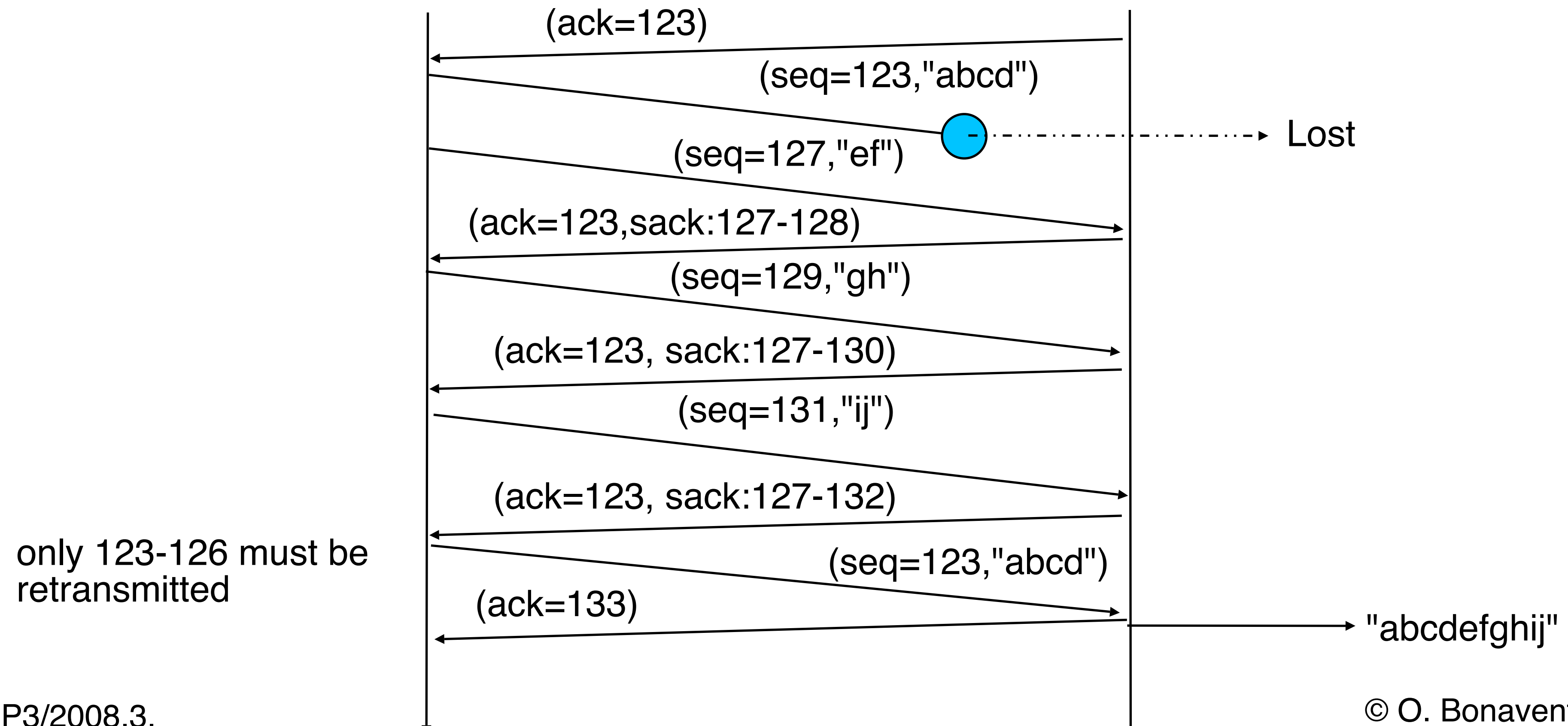


Improving the reliable data transfer

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



Sending acknowledgements

- When to send a pure ack ?
  - upon reception of a data segment
  - inside data segments in the other direction (piggyback)
- TCP tradeoff
  - Insequence segment arrival
    - If there is no ack waiting to be sent, start ack timer (50 msec) and wait wait until
      - transmission of a data segment (piggyback)
      - expiration of acktimer
    - If there is already an ack waiting
      - send pure ack immediately
  - Out-of-sequence segment
    - send ack immediately

Flow control

- Goal : protect the receiver's buffers
- Principle
  - Advertise receiving window in all segments
  - State variables maintained by each TCP entity
    - last_ack, swin, rwin

Last_ack=122, swin=100, rwin=4
To transmit : abcdefghijklm

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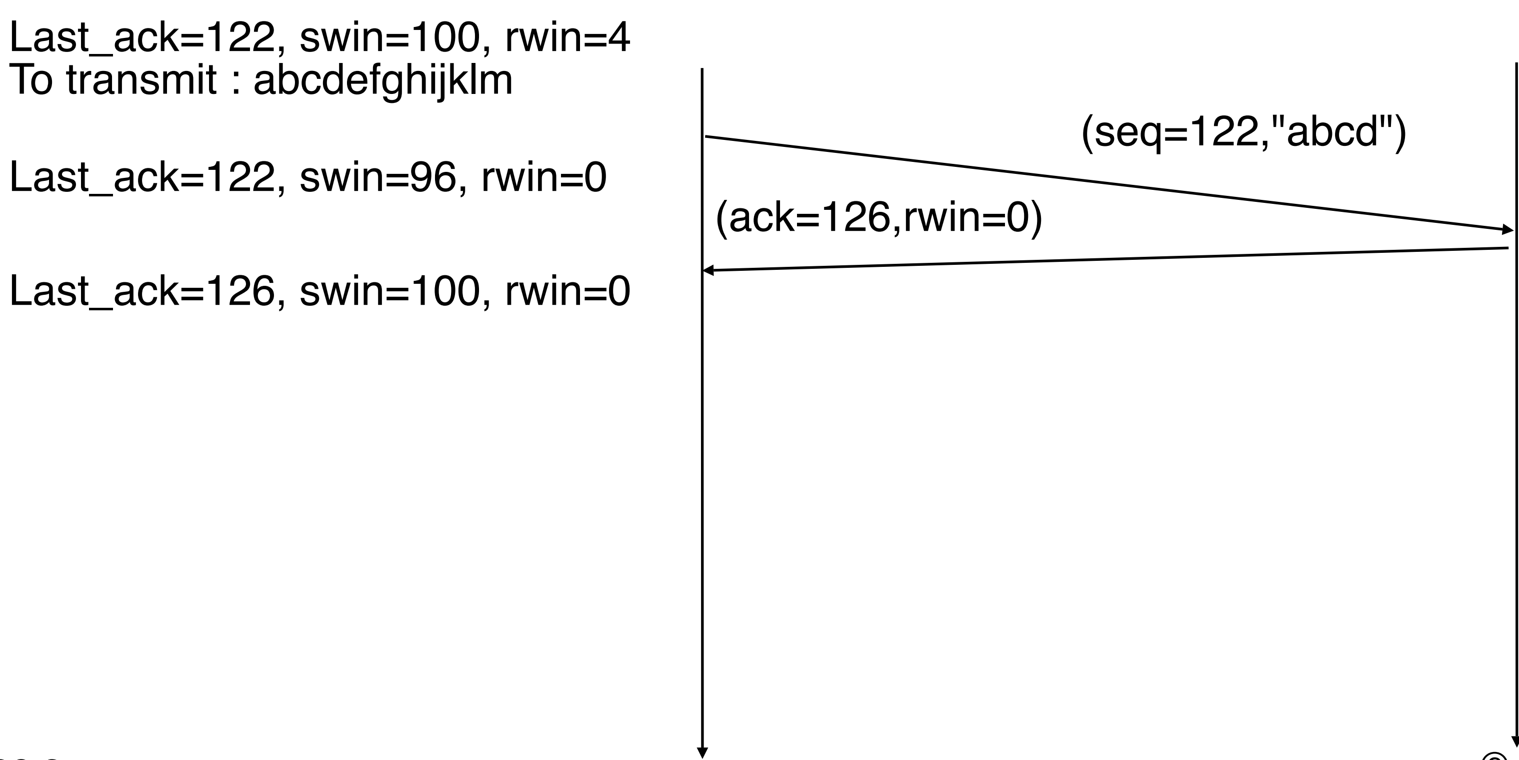

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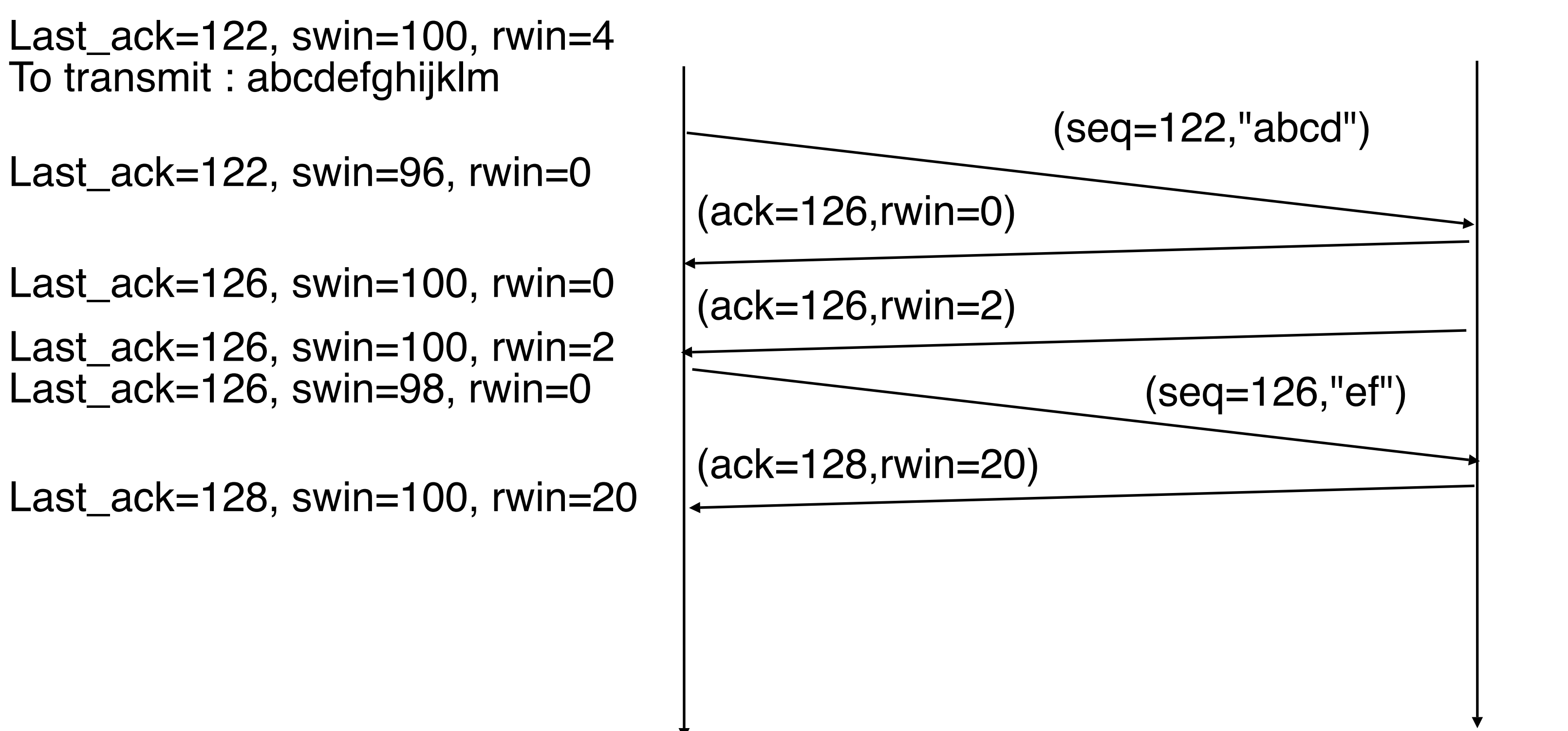

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Last_ack=122, swin=96, rwin=0

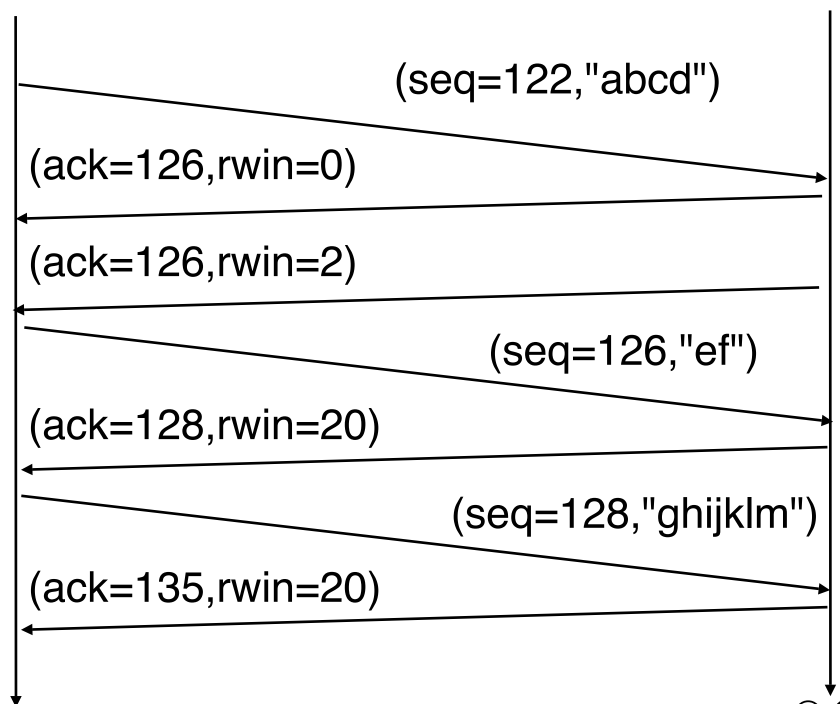
Last_ack=126, swin=100, rwin=0

Last_ack=126, swin=100, rwin=2
Last_ack=126, swin=98, rwin=0

Last_ack=128, swin=100, rwin=20

Last_ack=128, swin=93, rwin=13

Last_ack=135, swin=100, rwin=20



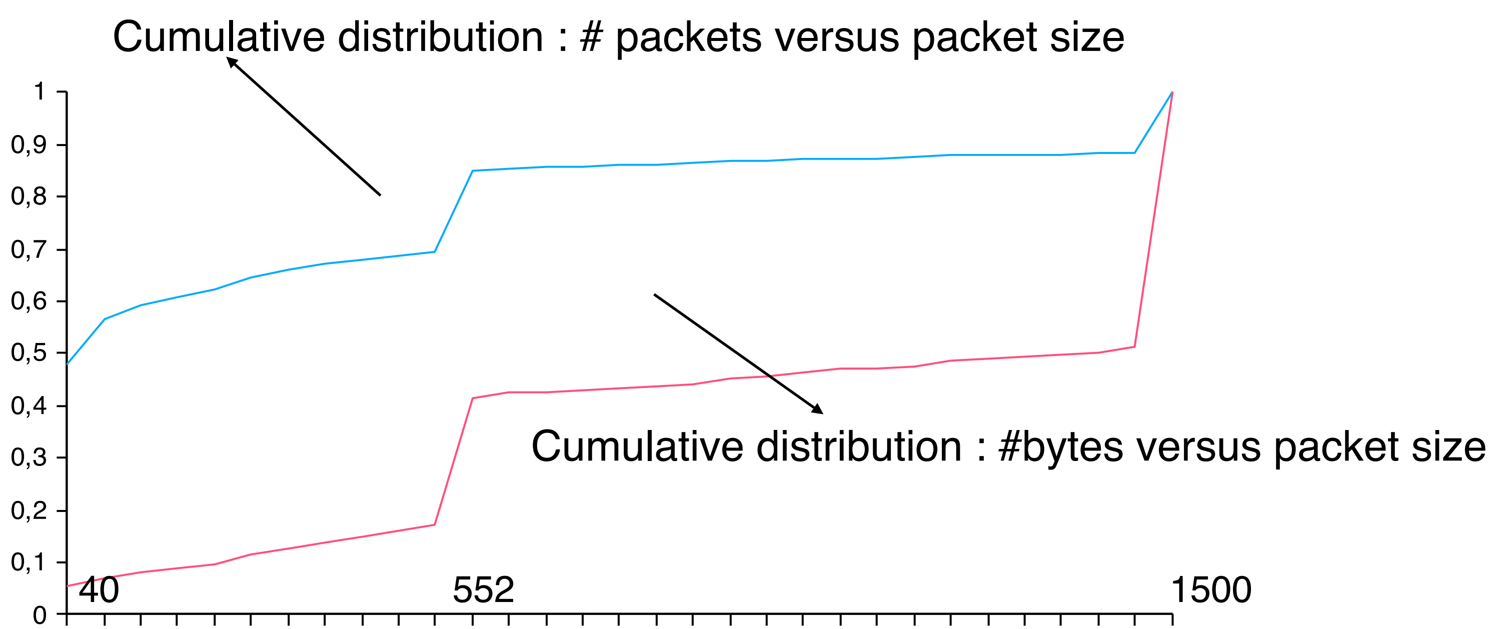
Flow control (2)

- Limitations
  - TCP uses a 16 bits window field in the segment header
    - Maximum window size for normal TCP : 65535 bytes
    - Extension RFC1323 for larger windows
  - After having transmitted a window full of data, TCP sender must remain idle waiting for ack
  - Maximum throughput on TPC connection
    - ~ window / round-trip-time

Window \ **rtt**	**1 msec**	**10 msec**	**100 msec**
8 Kbytes	65.6 Mbps	6.5 Mbps	0.66 Mbps
64 Kbytes	524.3 Mbps	52.4 Mbps	5.2 Mbps

Transmission of data and control segments

- Nagle algorithm
  - A new data segment can be sent provided that
    - This is a maximum sized segment (MSS bytes)
    - There are currently no unacknowledged bytes
- Consequence
  - Most TCP/IP packets are small or MSS-sized



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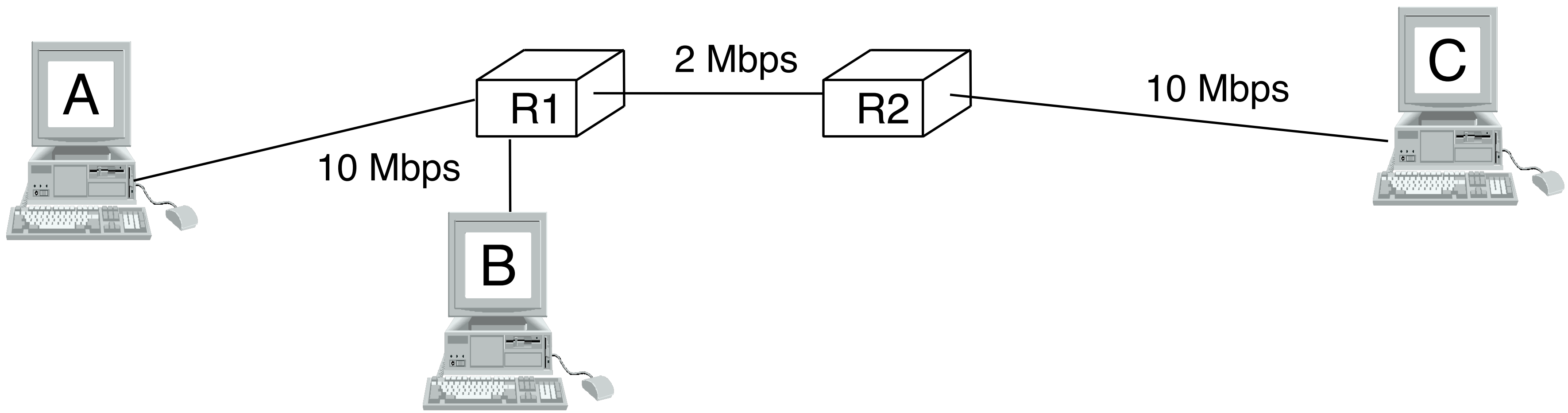
- Basics
- Building a reliable transport layer
- UDP : a simple connectionless transport protocol
- TCP : a reliable connection oriented transport protocol
  - TCP connection establishment
  - TCP connection release
  - Reliable data transfer
  - Congestion control

Congestion in TCP/IP networks

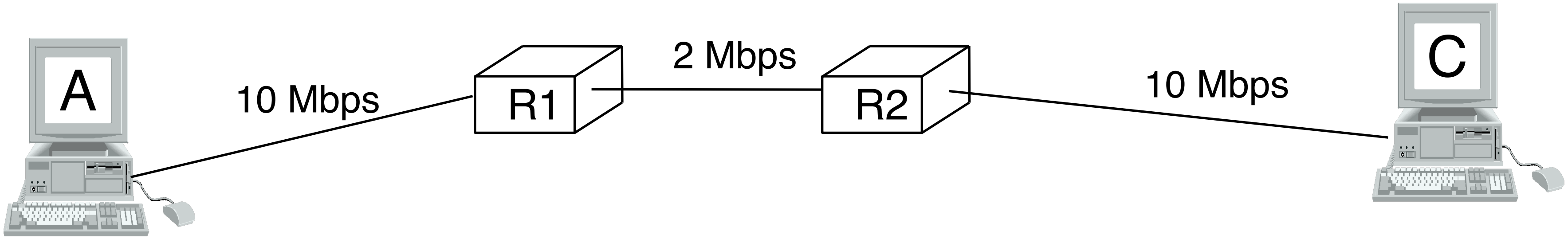


- TCP/IP networks are heterogeneous
  - A can send at 10 Mbps to B
  - B can send at 2 Mbps to C
- How to share the network among multiple hosts ?
  - A and B send data to C at the same time

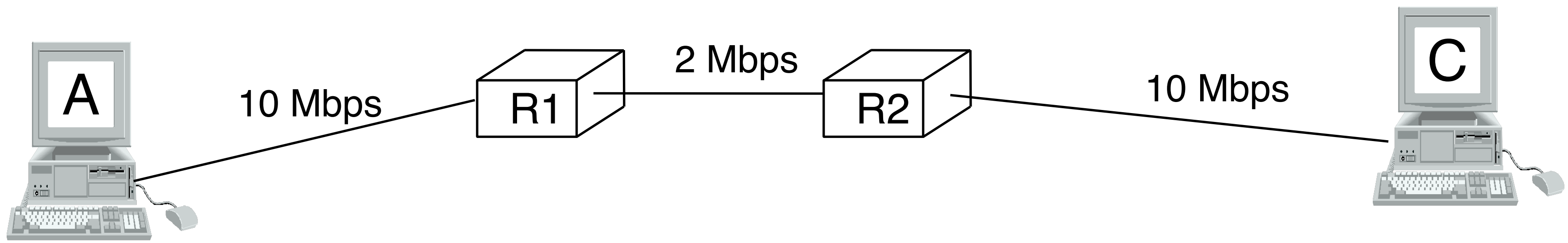
Congestion in TCP/IP networks

- Possible solutions
  - The network indicates explicitly the bandwidth allocated to each host
    - network sends regularly control information to hosts
    - Available Bit Rate in ATM networks
  - Endhosts measure the state of the network and adapt their bandwidth to the network state
    - Endhosts must be able to measure the amount of congestion inside the network
    - Solution used by TCP in the Internet

Simple congestion

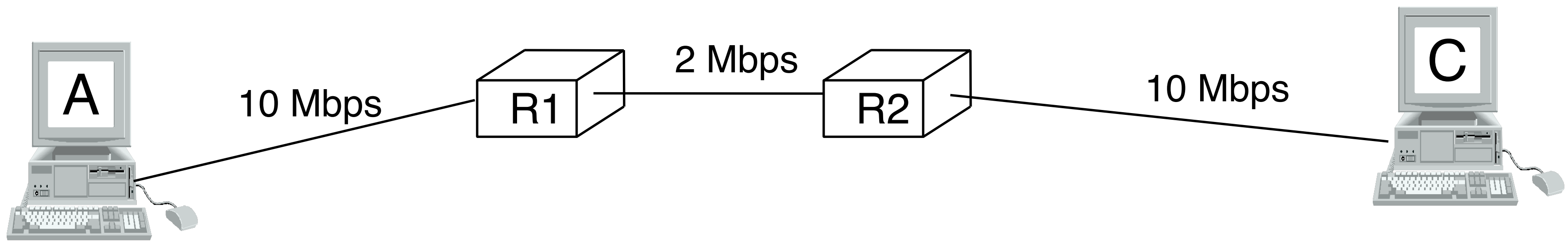


Simple congestion

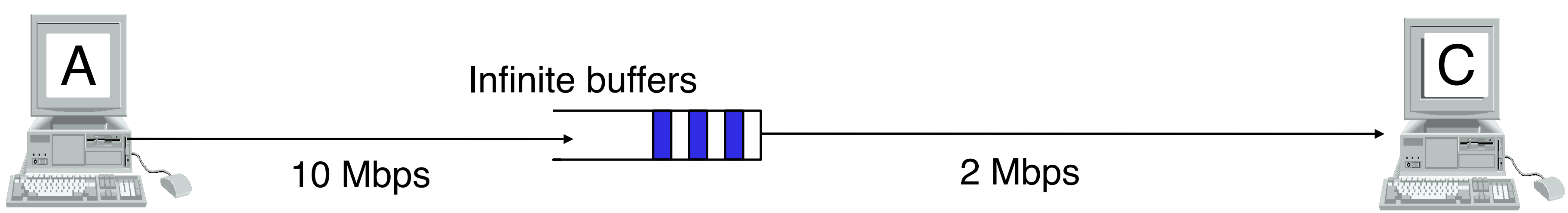


- Simplified model

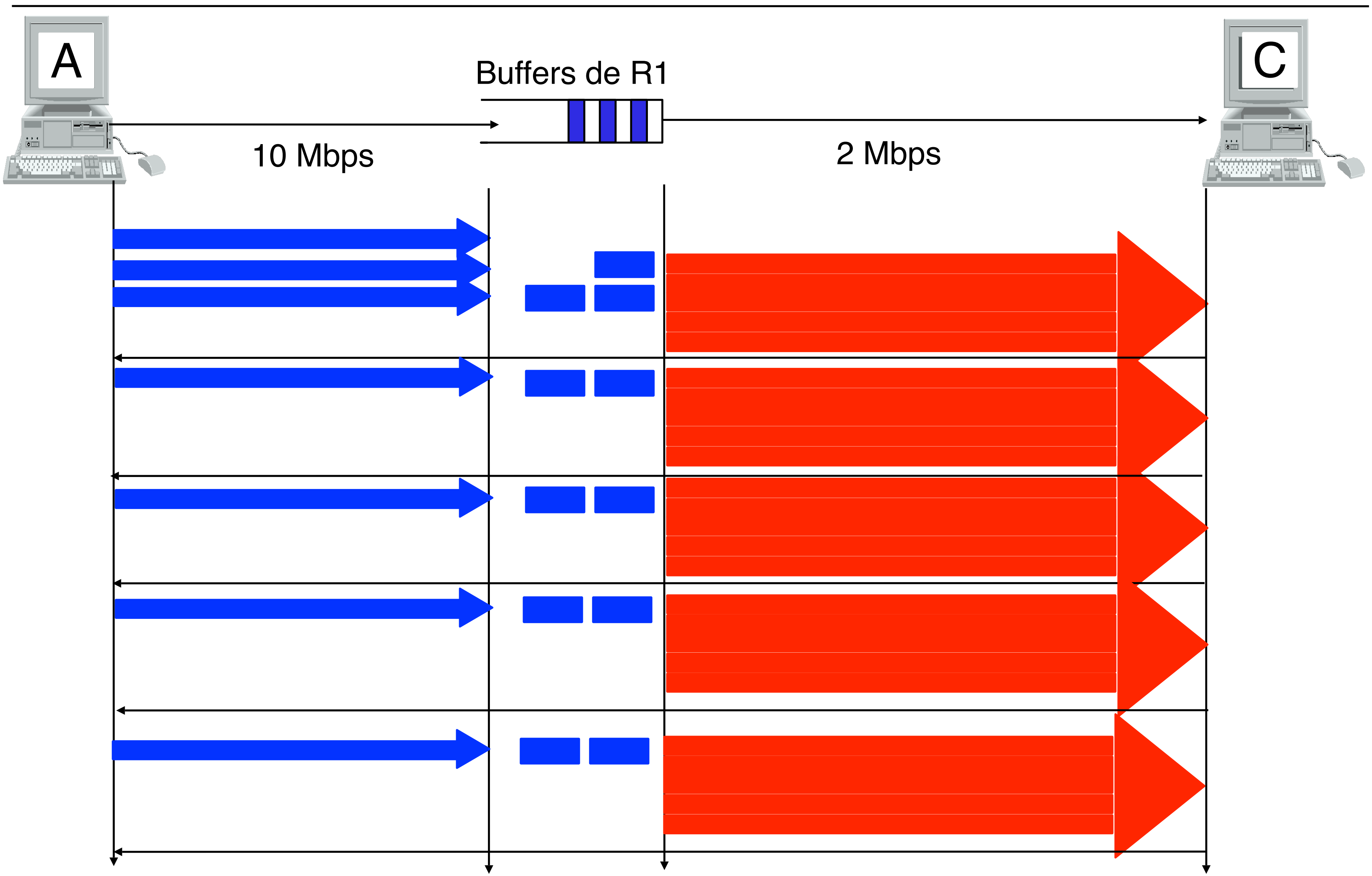
Simple congestion



- Simplified model



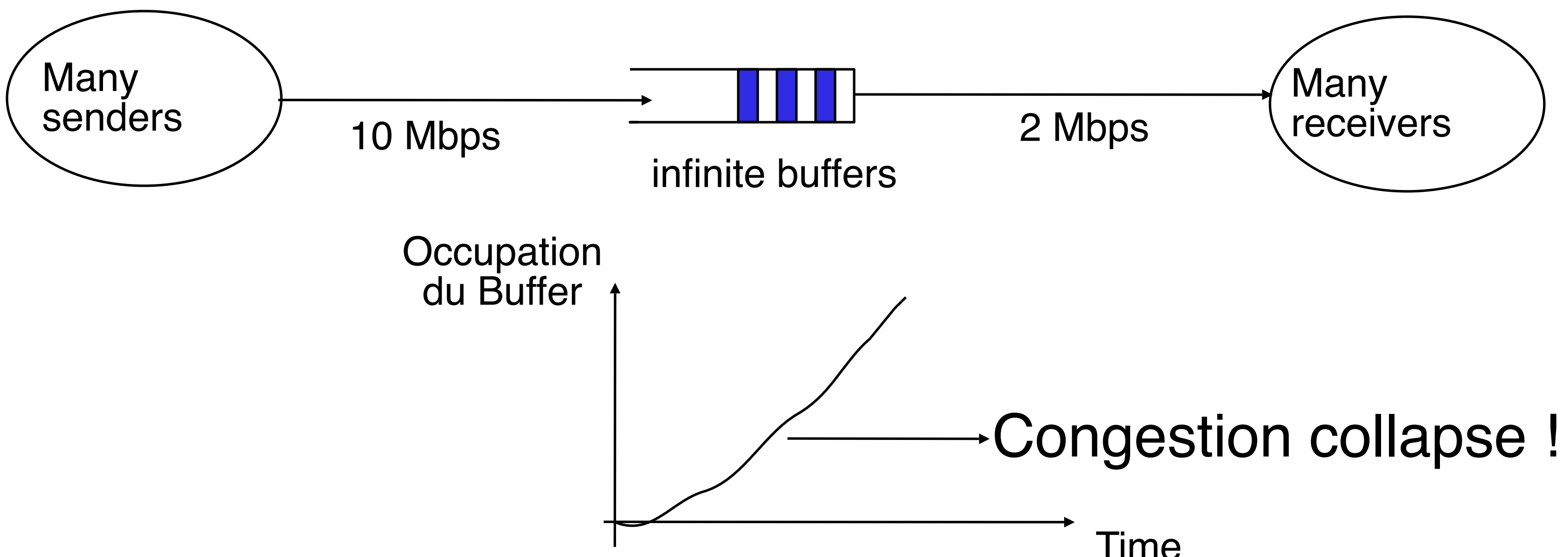
Simple congestion



- TCP self-clocking

Simple congestion

- TCP self-clocking
  - Can be sufficient when a single TCP connection uses a low bandwidth link if the intermediate buffer can store a window full of segments
  - What happens if several TCP connections need to share one link

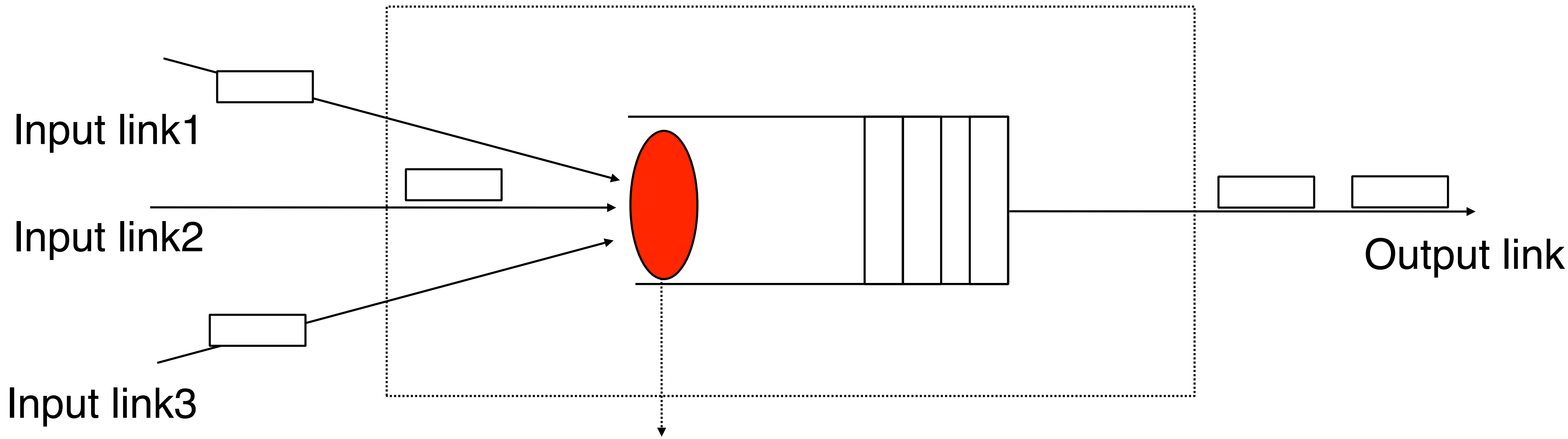


TCP congestion control

- How to adapt a TCP connection to the network state ?
  - How to measure the current congestion state ?
    - TCP uses segment losses in routers as an implicit indication of congestion
      - This is valid in most environments besides some wireless networks where transmission errors can cause segment losses
  - Adapt the bandwidth of the TCP connection
    - TCP adapts its transmission rate by using a new congestion window (cwnd) which is controlled by the sender based on the current congestion status

A simple router

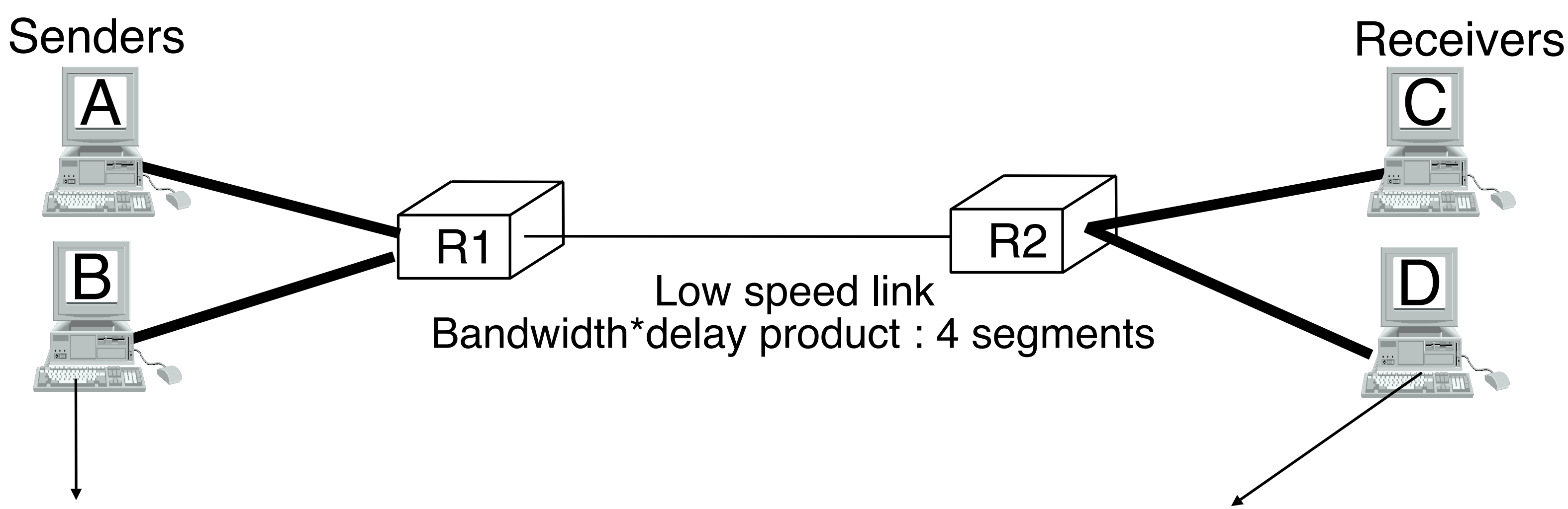
- Output buffer



Buffer acceptance algorithm
When a packet arrives in the output buffer, decides whether the packet is accepted or discarded

- taildrop
  - the arriving packet is discarded if the buffer is full

TCP congestion control



Segment transmission
a new TCP segment can be sent if
it is contained inside the current window :
[last_ack , last_ack + min(cwnd,min(swin,rwin))]

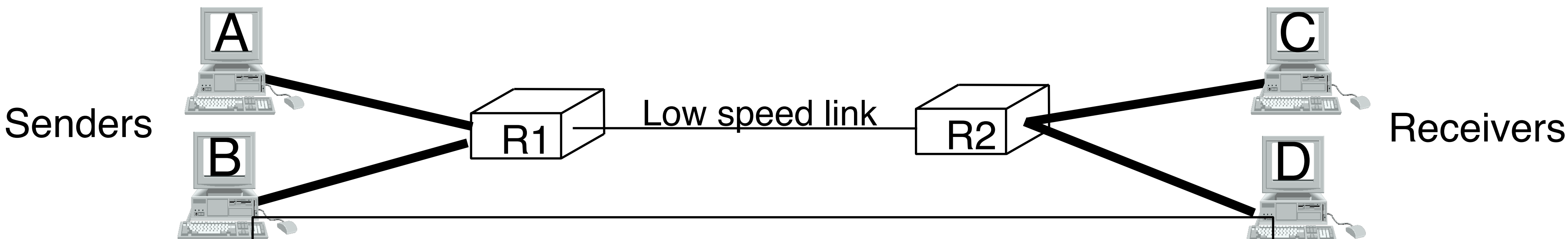
Segment reception
send acks as usual and
use TCP flow control

cwnd[A] \ Cwnd[B]	1	2	3
1	underused	underused	ok, but unfair
2	underused	ok, fair	congestion
3	ok, but unfair	congestion	congestion

- How to dynamically update cwnd ?

TCP congestion control

- Additive Increase / Multiplicative Decrease



Segment transmission
a new TCP segment can be sent if
it is contained inside the current window :
[last_ack , last_ack + min(cwnd,min(swin,rwin))]

Ack reception : Additive Increase
// <u>congestion avoidance</u>
if (network not congested) // no segment losses
{ // increase slowly cwnd
  // increase cwnd by one mss every rtt
  cwnd = cwnd+ mss*(mss/cwnd);
}

Congestion : Segment loss : Multiplicative decrease
// retransmsit lost segments
ssthresh=max(cwnd/2,2*MSS);
cwnd=MSS;

Segment reception
send acks as usual and
use TCP flow control

TCP congestion control

- How to select cwnd when connection starts ?
  - Congestion avoidance increases cwnd slowly

Slowstart

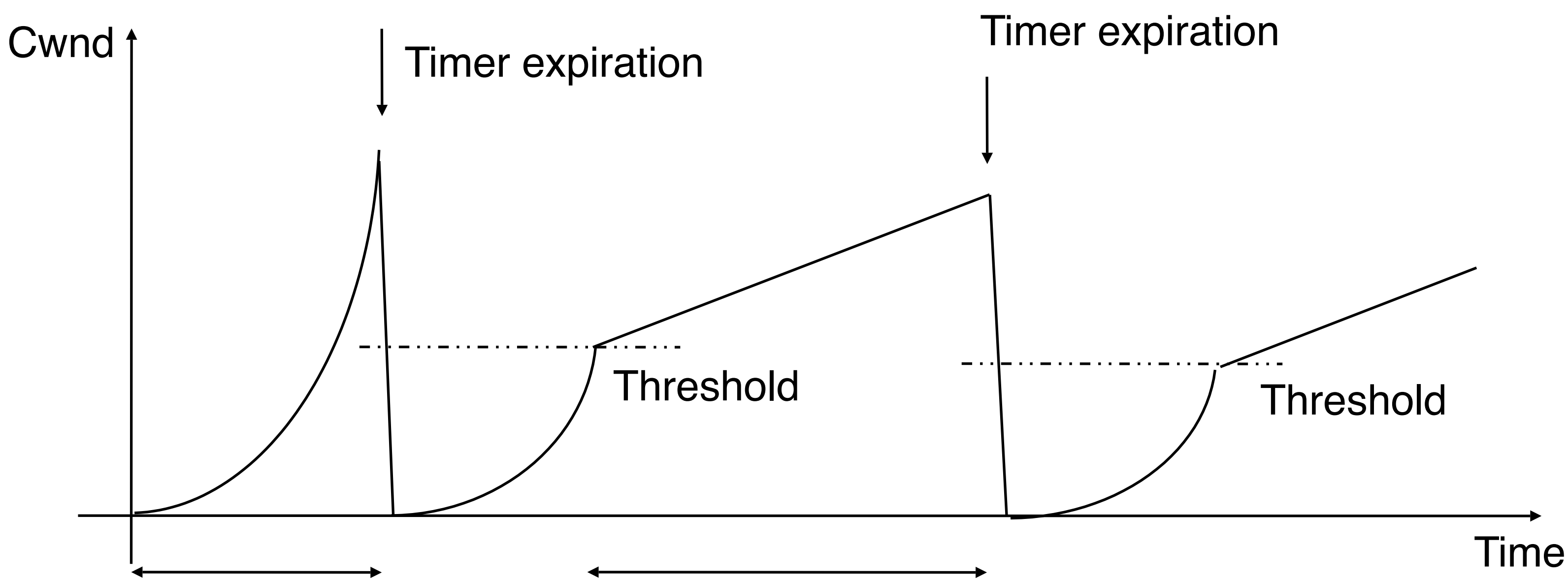
Congestion avoidance

```
Initialisation :
cwnd = MSS;
ssthresh= swin;

Ack reception :
if (network not congested ) // no segment losses
{
  if (cwnd < ssthresh)
   {  // increase quickly cwnd
      // double cwnd  every rtt
      cwnd = cwnd+ MSS;
   }
   else
   {  // increase slowly cwnd
       // increase cwnd by one mss every rtt
       cwnd = cwnd+ mss*(mss/cwnd);
   }
}
```

TCP congestion control

- Example



Slow-start
exponential increase of cwnd

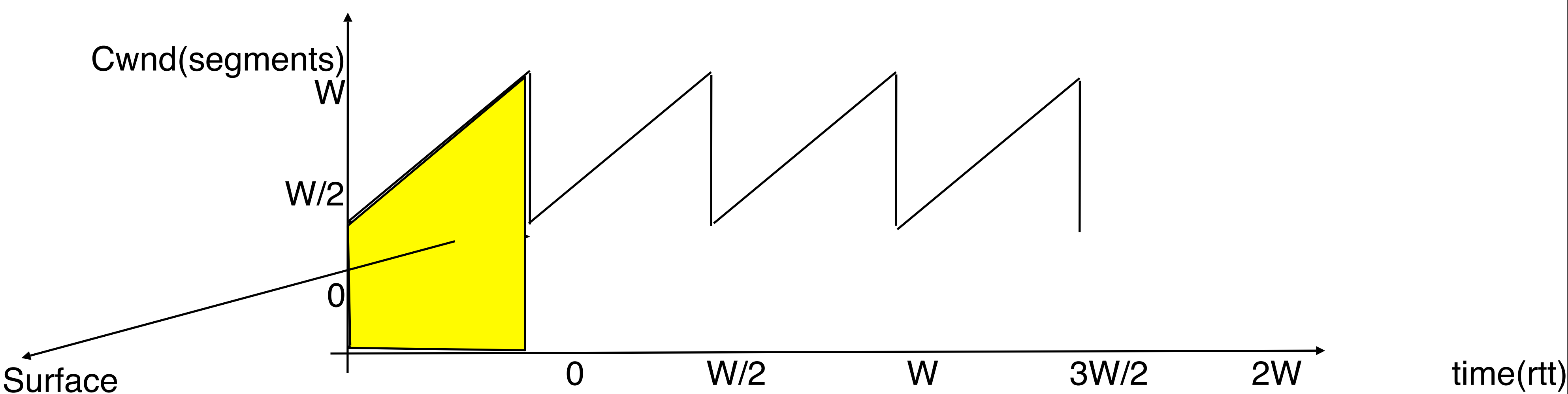
Congestion avoidance
linear increase of cwnd

TCP congestion control

- How to react to segment losses ?
  - Two different types of multiplicative decrease
  - Severe loss [several lost segments]
    - wait until expiration of retransmission timer
      - sstresh=ssthresh/2
      - retransmit lost segments
      - slow-start (until cwnd=ssthresh)
      - congestion avoidance
  - Isolated loss [a single lost segment]
    - fast retransmit can recover from lost segment
    - If a single segment was lost : fast recovery
      - retransmit lost segment
      - sstresh=cwnd / 2
      - cwnd=ssthresh ; congestion avoidance

TCP congestion control

- Simplified model
  - Assume that all segment losses are periodic and the every 1/p segment is lost



$$(\frac{W}{2})^2 + \frac{1}{2}(\frac{W}{2})^2 = \frac{1}{p}$$

It can be shown that the throughput of a TCP connection can be approximated by :

$$BW < Min[\frac{Window}{RTT}, (\frac{MSS}{RTT})\frac{k}{\sqrt{p}}]$$

Maximum throughput without losses

Throughput with losses/ congestion