运输层

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Outline

- UDP: User Datagram Protocol
- TCP: Transmission Control Protocol
- TCP Connection Setup
- TCP Connection Teardown

UDP: User Datagram Protocol

- Lightweight communication between processes
  - ➤ Avoid overhead and delays of order & reliability

- UDP described in RFC 768 – (1980!)
  - ➤ Destination IP address and port to support demultiplexing

UDP (cont'd)

- **"Best effort" service**, UDP segments may be:
  - lost
  - delivered out-of-order to app

- **Connectionless**:
  - no handshaking between UDP sender, receiver
  - each UDP segment handled independently of others

- **UDP use**:
  - streaming multimedia apps (loss tolerant, rate sensitive)
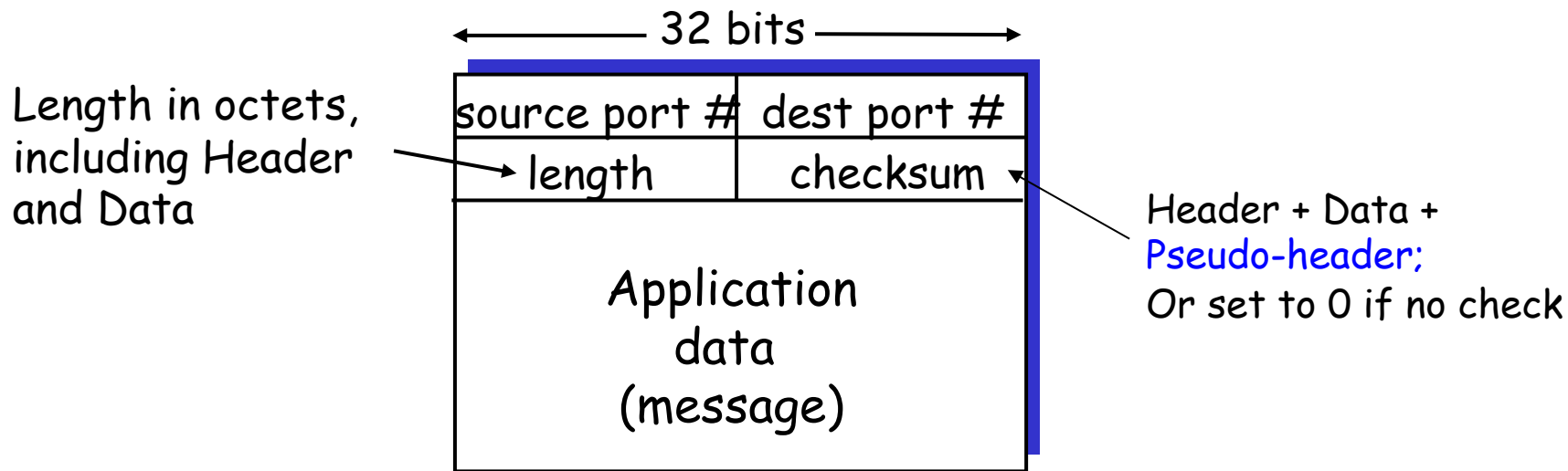 - DNS
  - SNMP

Why is there a UDP?

- no connection establishment (which can add delay)

- simple: no connection state at sender, receiver

- small header size

- no congestion control: UDP can blast away as fast as desired

UDP Segment Format

Length in octets, including Header and Data

←————— 32 bits —————→

source port #	dest port #
length	checksum
Application data (message)	

Header + Data + Pseudo-header; Or set to 0 if no check

UDP checksum

Goal: detect "errors" (e.g., flipped bits) in transmitted segment

sender:

- treat segment contents, including header fields, as sequence of 16-bit integers

- checksum: addition of segment contents, and its complement sum

- sender puts checksum value into UDP checksum field

receiver:

- compute checksum of received segment

- check if the sum of computed checksum and checksum field value equals 1111….1111:

  – NO - error detected

  – YES - no error detected. But maybe errors nonetheless?

Internet checksum: example

example: add two 16-bit integers

```
1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1
```
_____

wraparound (1) 1 0 1 1 1 0 1 1 1 0 1 1 1 0 1 1
_____

sum   1 0 1 1 1 0 1 1 1 0 1 1 1 **1 0 0**
checksum 0 1 0 0 0 1 0 0 0 1 0 0 0 0 1 1

Note: when adding numbers, a carryout from the most significant bit needs to be added to the result

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The TCP Abstraction

- TCP delivers a reliable, in-order, byte stream

- Reliable: TCP resends lost packets (recursively)
  - ➢ Until it gives up and shuts down connection

- In-order: TCP only hands consecutive chunks of data to application

- Byte stream: TCP assumes there is an incoming stream of data, and attempts to deliver it to app
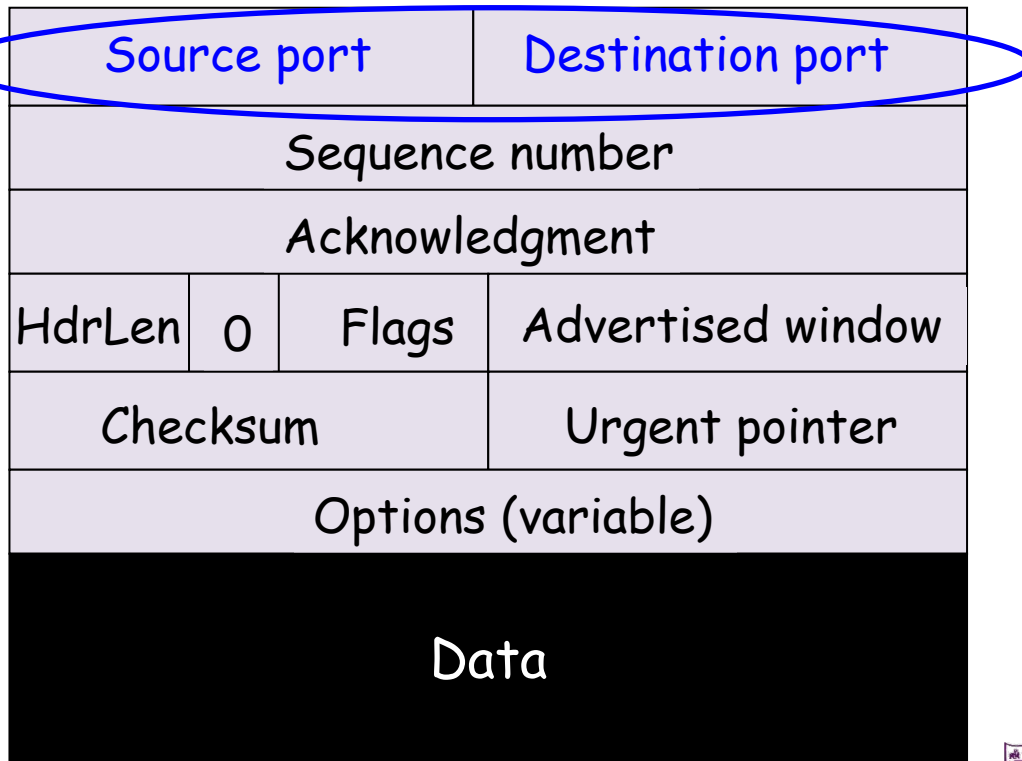
What does TCP use from what we've seen so far?

- Most of what we've seen
  - ➤ Checksums
  - ➤ Sequence numbers are byte offsets
  - ➤ Sender and receiver maintain a sliding window
  - ➤ Receiver sends cumulative acknowledgements (like GBN)
    - ✓ Sender maintains a single retransmission timer
  - ➤ Receivers buffer out-of-sequence packets (like SR)
- Few more: fast retransmit, timeout estimation algorithms etc.

TCP header

Source port	Destination port

Used to Mux and Demux

Sequence number		

Acknowledgment		

HdrLen	0	Flags	Advertised window

Checksum	Urgent pointer

Options (variable)

Data

TCP header

Computed over pseudo-header and data

Source port	Destination port
Sequence number	
Acknowledgment	

HdrLen	0	Flags	Advertised window

Checksum	Urgent pointer
Options (variable)	

Data

TCP header

Number of 4-byte words in the header;
5: No options

Source port	Destination port
Sequence number	
Acknowledgment	

HdrLen	0	Flags	Advertised window
Checksum		Urgent pointer	
Options (variable)			
Data			

What does TCP do?

- Most of what we've seen
  - ➤ Checksum
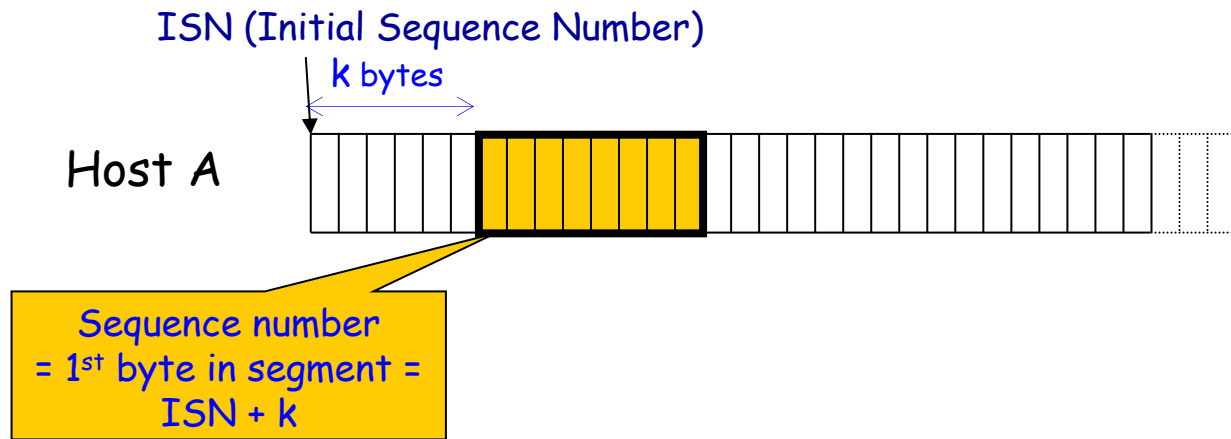 - ➤ Sequence numbers are byte offsets

TCP header

Byte offsets
(NOT packet id),
because TCP is a
byte stream

Source port	Destination port
Sequence number	
Acknowledgment	
HdrLe	0	Flags	Advertised window
Checksum	Urgent pointer
Options (variable)	
Data	

Sequence numbers

ISN (Initial Sequence Number)

k bytes

Host A

Sequence number
= 1st byte in segment =
ISN + k

Sequence numbers

ISN (Initial Sequence Number)

k

Host A

Sequence number
= 1st byte in segment =
ISN + k

TCP Data | TCP HDR

ACK sequence number
= next expected byte
= seqno + length(data)

TCP Data | TCP HDR

Host B

TCP segment

IP Data		
TCP Data (segment)	TCP Hdr	IP Hdr
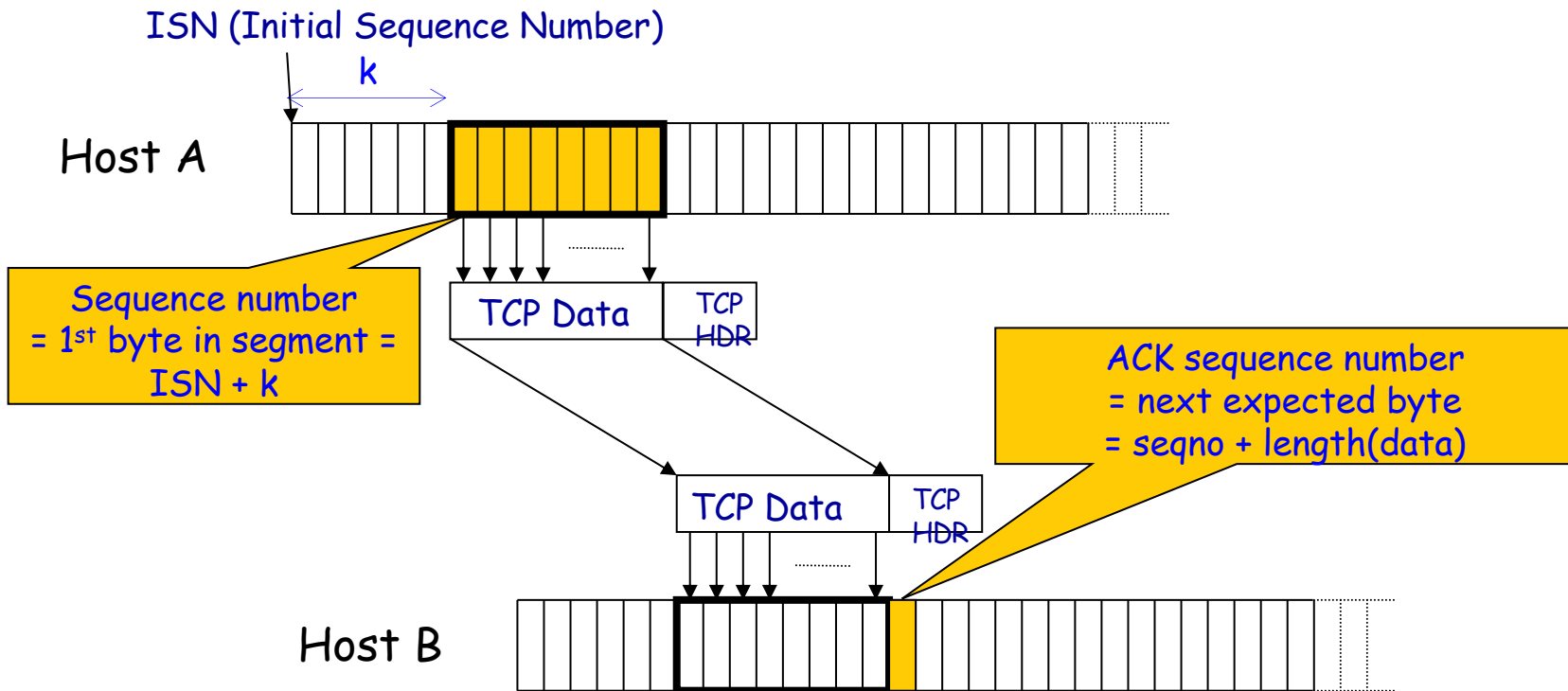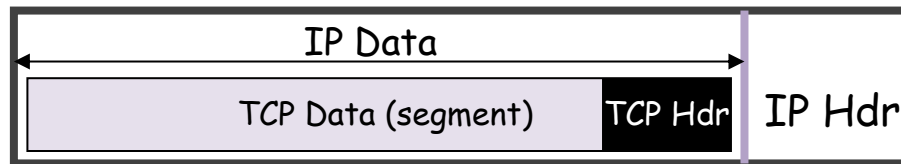
- IP packet
  - ➢ No bigger than Maximum Transmission Unit (MTU)
  - ➢ E.g., up to 1500 bytes with Ethernet
- TCP packet
  - ➢ IP packet with a TCP header and data inside
  - ➢ TCP header ≥ 20 bytes long
- TCP segment
  - ➢ No more than Maximum Segment Size (MSS) bytes
  - ➢ E.g., up to 1460 consecutive bytes from the stream
  - ➢ MSS = MTU – (IP header) – (TCP header)

What does TCP do?

- Most of what we've seen
  - ➤ Checksum
  - ➤ Sequence numbers are byte offsets
  - ➤ Receiver sends cumulative acknowledgements (like GBN)

ACKs and sequence numbers

- **Sender sends packet**
  - Data starts with sequence number X
  - Packet contains B bytes [X, X+1, X+2, ….X+B-1]

- Upon receipt of packet, **receiver sends an ACK**
  - If all data prior to X already received:
    - ACK acknowledges X+B (because that is next expected byte)
  - If highest in-order byte received is Y s.t. (Y+1) < X
    - ACK acknowledges Y+1
    - Even if this has been ACKed before

Typical operation

- Sender: seqno=X, length=B
- Receiver: ACK=X+B
- Sender: seqno=X+B, length=B
- Receiver: ACK=X+2B
- Sender: seqno=X+2B, length=B

- Seqno of next packet is same as last ACK field

TCP header

Acknowledgment gives seqno just beyond highest seqno received in order

Source port	Destination port
Sequence number	
Acknowledgment	
HdrLen	0	Flags	Advertised window
Checksum	Urgent pointer
Options (variable)	
Data	

What does TCP do?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
- Receivers can buffer out-of-sequence packets (like SR)

What does TCP introduce?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
  - Receivers can buffer out-of-sequence packets (like SR)

- Introduces fast retransmit: duplicate ACKs trigger early retransmission

Loss with cumulative ACKs

- Duplicate ACKs are a sign of an isolated loss
  - ➢ The lack of ACK progress means 500 hasn't been delivered
  - ➢ Stream of ACKs means some packets are being delivered

- Trigger retransmission upon receiving k duplicate ACKs
  - ➢ TCP uses k=3
  - ➢ Faster than waiting for timeout

Loss with cumulative ACKs

- Two choices after resending:
  - ➤ Send missing packet and move sliding window by the number of dup ACKs
    - ✓ Speeds up transmission, but might be wrong
  - ➤ Send missing packet, and wait for ACK to move sliding window
    - ✓ Is slowed down by single dropped packets

- Which should TCP do?

What does TCP introduce?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
  - Receivers buffer out-of-sequence packets (like SR)
- Introduces fast retransmit: duplicate ACKs trigger early retransmission
- Sender maintains a single retransmission timer (like GBN) and retransmits on timeout

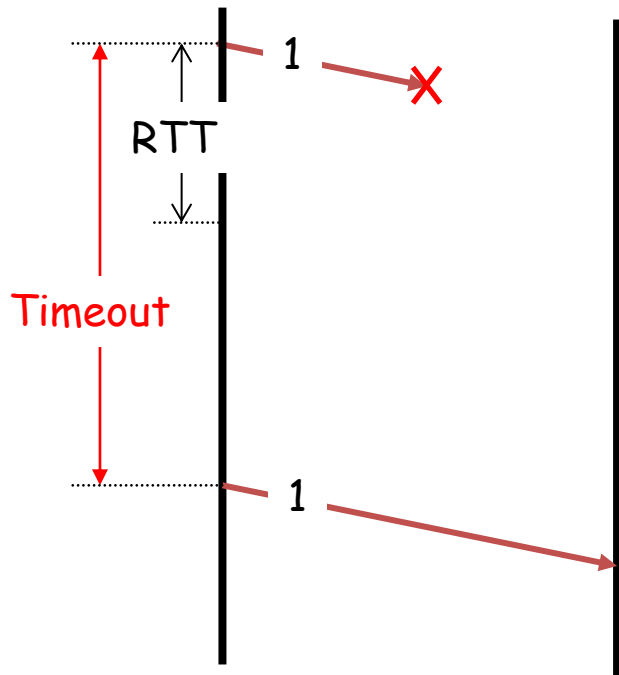# Retransmission timeout

- If the sender hasn't received an ACK by timeout, retransmit the first packet in the window
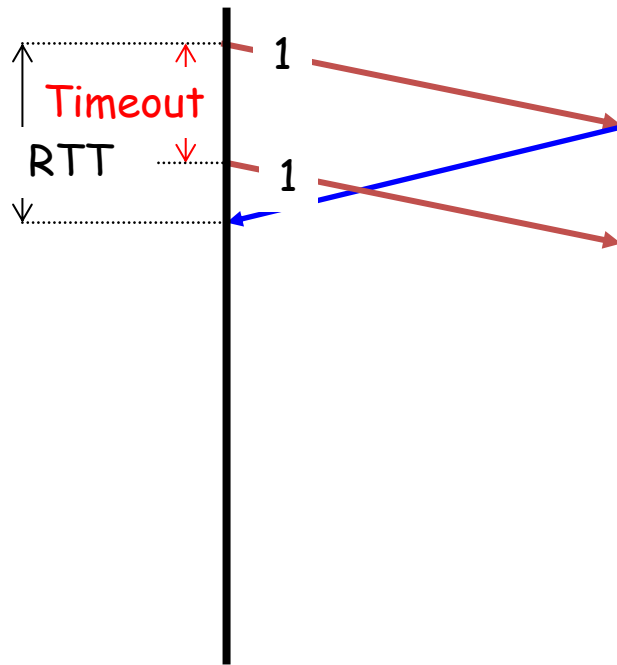- How do we pick a timeout value?

Timeout too long → inefficient

Timeout too short →
duplicate packets

Retransmission timeout

- If the sender hasn't received an ACK by timeout, retransmit the first packet in the window

- How to set timeout?
  - Too long: connection has low throughput
  - Too short: retransmit packet that was just delayed

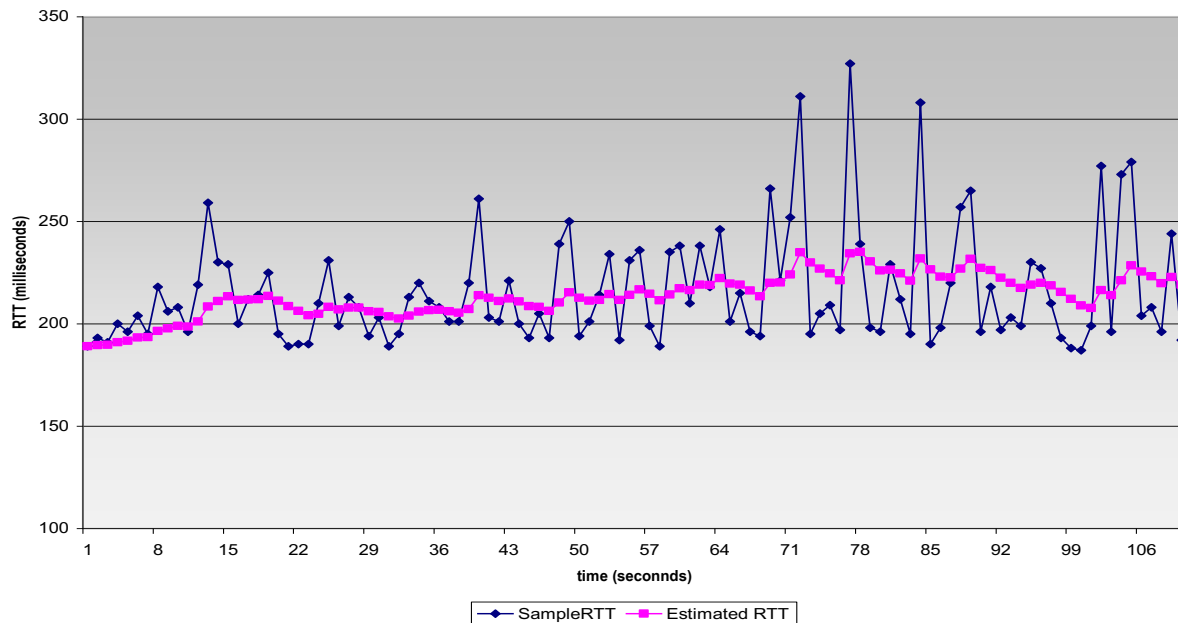- Solution: make timeout proportional to RTT
  - But how do we measure RTT?

RTT estimation

- Exponential weighted average of RTT samples

EstimatedRTT = (1- α)*EstimatedRTT + α*SampleRTT

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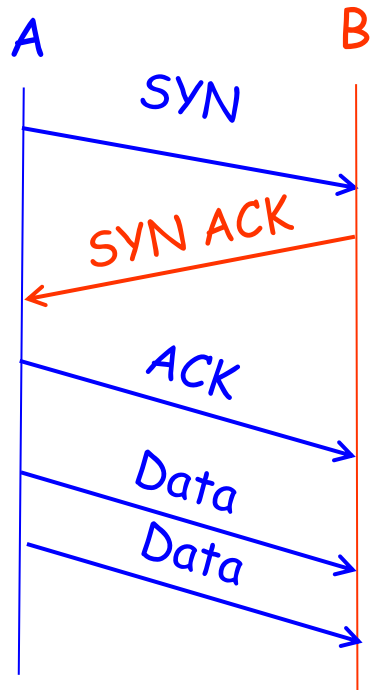- TCP header field for connection establishment and teardown

Connection: three-way handshake

- **Three-way handshake** to establish connection
  - ➢ Host A sends a SYN (open; "synchronize sequence numbers") to host B
  - ➢ Host B returns a SYN acknowledgment (SYN ACK)
  - ➢ Host A sends an ACK to acknowledge the SYN ACK

A   B

SYN

SYN ACK

ACK

Data

Data

三方握手：确认对方的SYN和序号

TCP header

Flags:
SYN
ACK
FIN
RST
PSH
URG

Source port	Destination port
Sequence number	
Acknowledgment	

HdrLen	0	Flags	Advertised window

Checksum	Urgent pointer
Options (variable)	
Data	
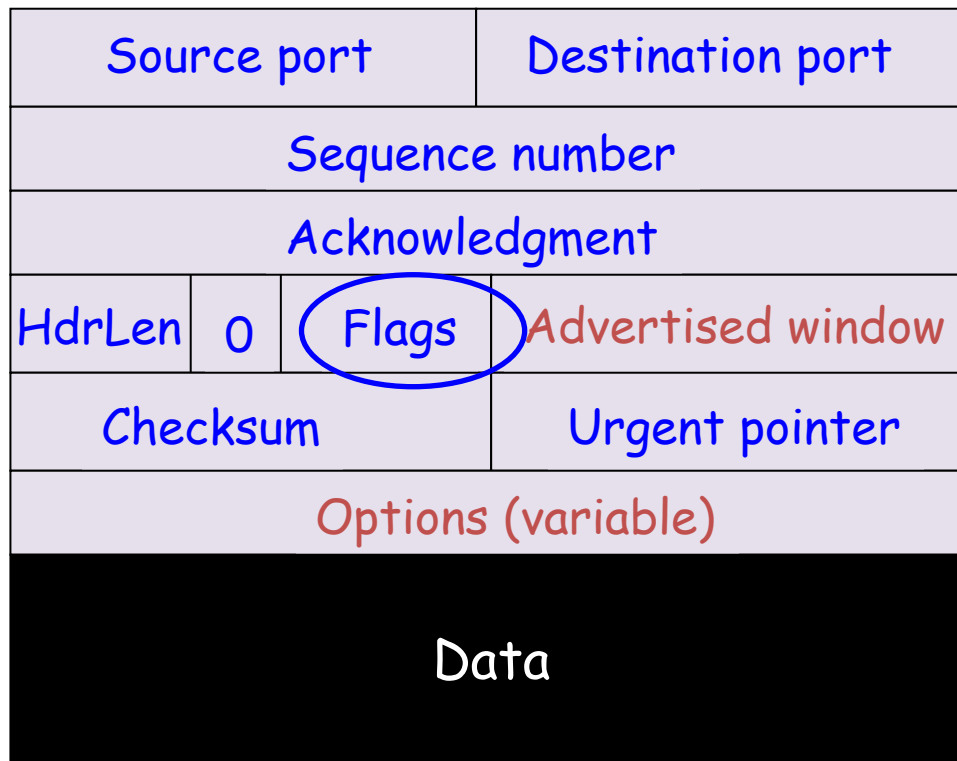
Step 1: A's initial SYN packet

A tells B to open a connection

A's port			B's port	
A's Initial Sequence Number				
N/A				
5	0	SYN	Advertised window	
Checksum			Urgent pointer	

Step 1: B's SYN-ACK packet

B tells it accepts and is ready to accept next packet

B's port			A's port	
B's Initial Sequence Number				
ACK=A's ISN+1				
5	0	SYN|ACK	Advertised window	
Checksum			Urgent pointer	

Step 1: A's ACK to SYN-ACK

A tells B to open a connection

A's port			B's port
A's Initial Sequence Number			
ACK=B's ISN+1			
5	0	ACK	Advertised window
Checksum			Urgent pointer

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TCP's 3-Way handshaking

Active
Open

Passive
Open

Client (initiator)

Server

connect()

listen()

SYN, SeqNum = x

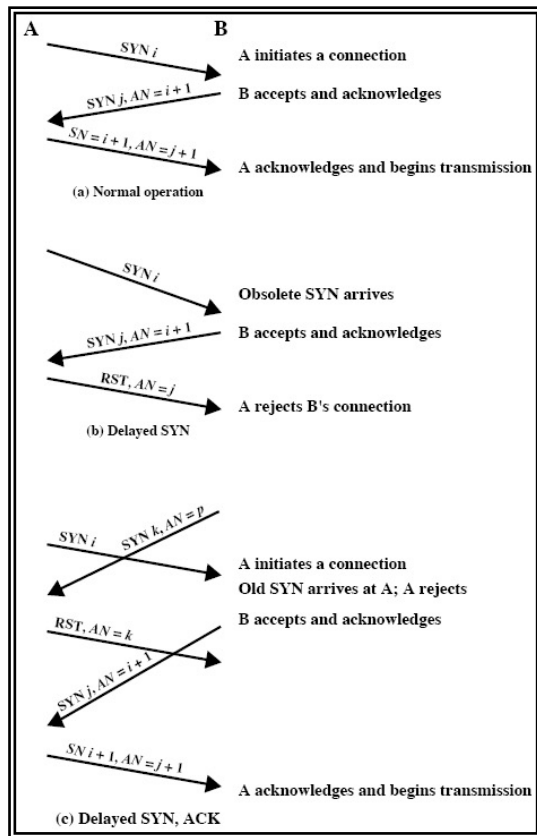SYN + ACK, SeqNum = y, Ack = $x + 1$

ACK, Ack = $y + 1$
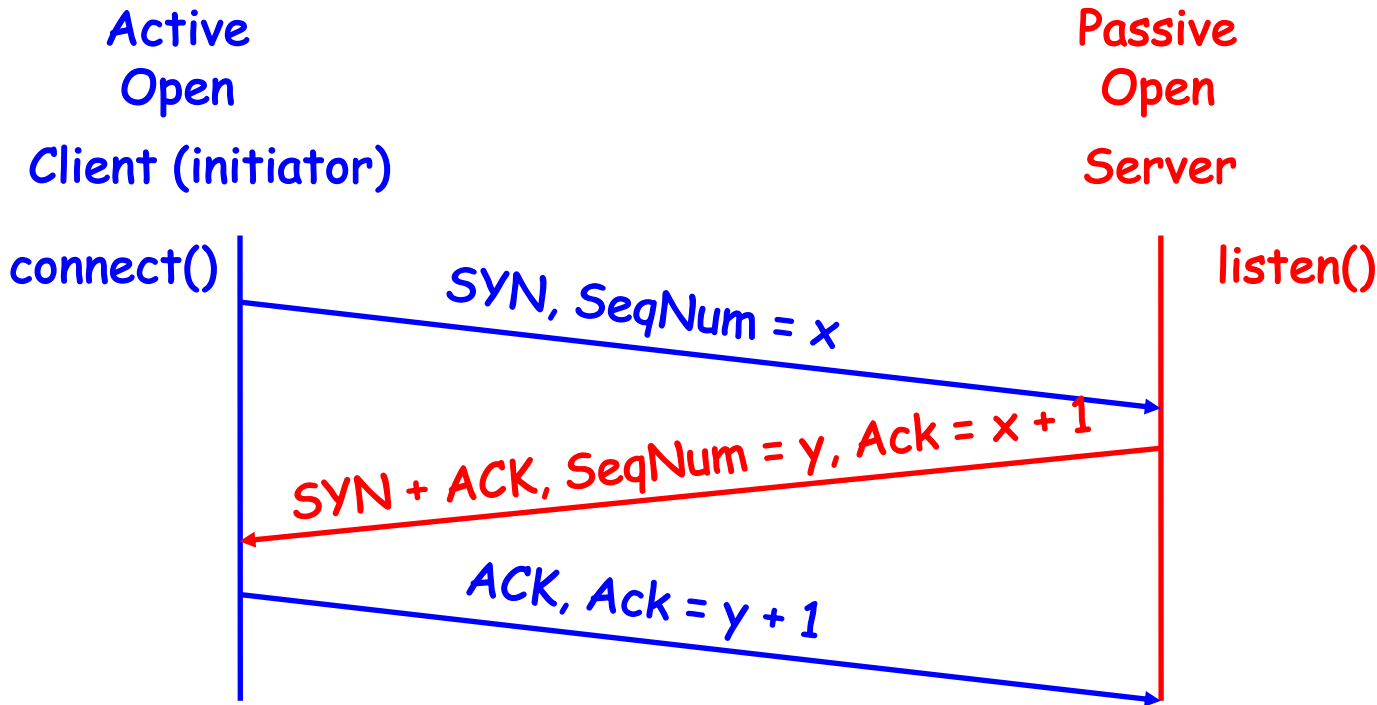
What if the SYN Packet Gets Lost?

- Suppose the SYN packet gets lost
  - ➢ Packet dropped by the network or server is busy

- Eventually, no SYN-ACK arrives
  - ➢ Sender retransmits the SYN on timeout

- How should the TCP sender set the timer?
  - ➢ Sender has no idea how far away the receiver is
  - ➢ Hard to guess a reasonable length of time to wait
  - ➢ SHOULD (RFCs 1122 & 2988) use default of 3 seconds
    - ✓ Some implementations instead use 6 seconds

A initiates a connection
B accepts and acknowledges
A acknowledges and begins transmission

(a) Normal operation

Obsolete SYN arrives
B accepts and acknowledges
A rejects B's connection

(b) Delayed SYN

A initiates a connection
Old SYN arrives at A; A rejects
B accepts and acknowledges
A acknowledges and begins transmission
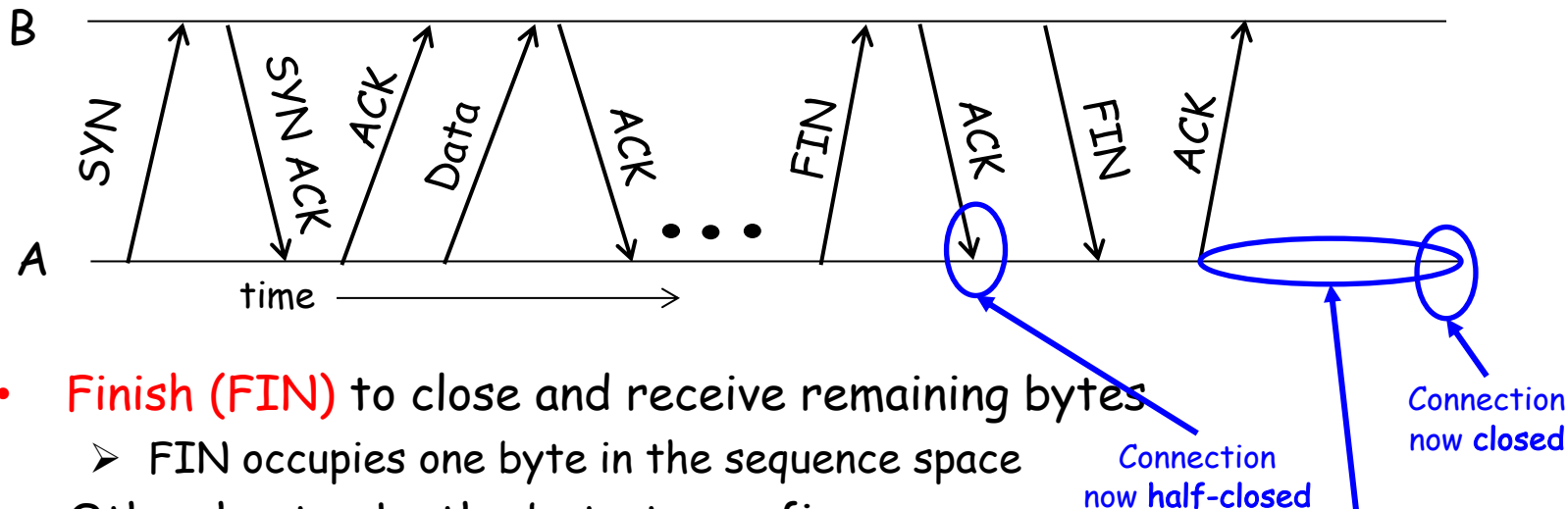
(c) Delayed SYN, ACK

Outline

- UDP: User Datagram Protocol
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Normal termination, one side at a time

- Finish (FIN) to close and receive remaining bytes
  - ➤ FIN occupies one byte in the sequence space
- Other host acks the byte to confirm
- Closes A's side of the connection, but not B's
  - ➤ Until B likewise sends a FIN
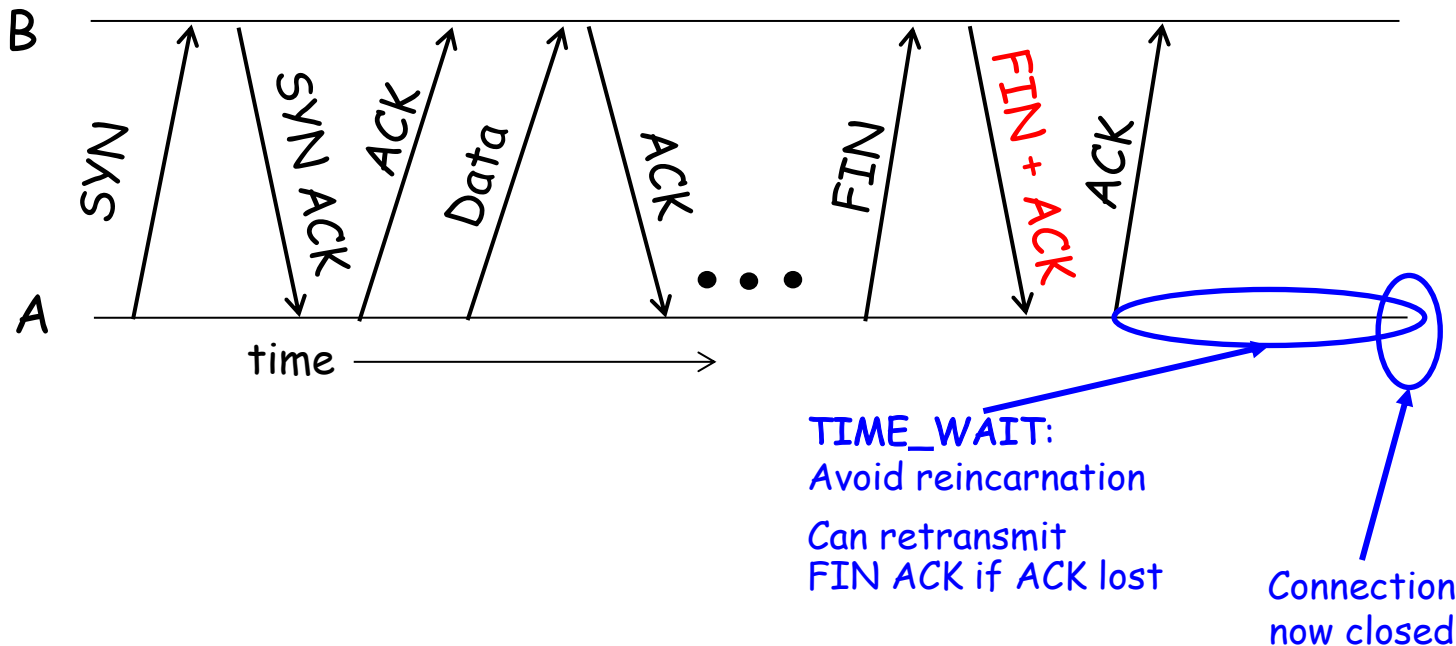 - ➤ Which A then acks

Connection now **half-closed**

Connection now **closed**

TIME_WAIT:

Avoid reincarnation

B will retransmit FIN if ACK is lost

Normal termination, both together

B ──

SYN SYN ACK ACK Data ACK FIN FIN + ACK ACK

• • •

A ──

time ──────────→

TIME_WAIT:
Avoid reincarnation

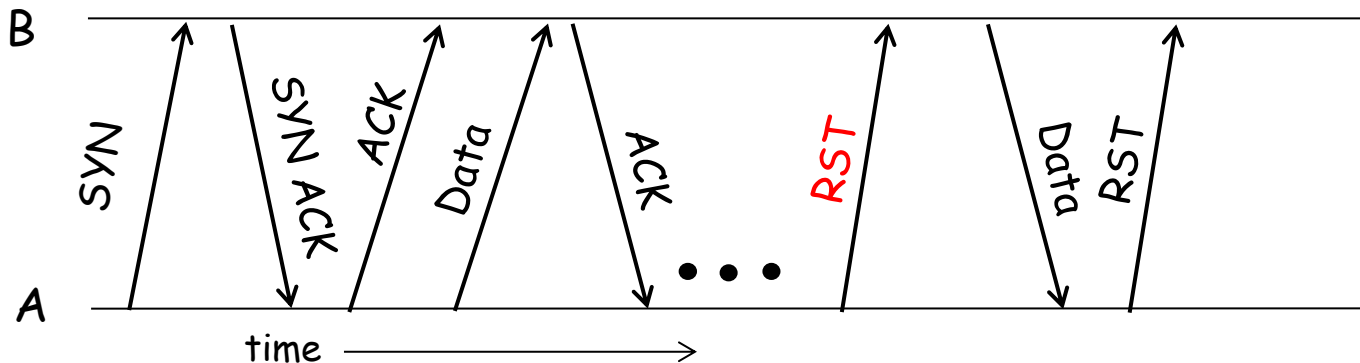Can retransmit
FIN ACK if ACK lost

Connection
now closed

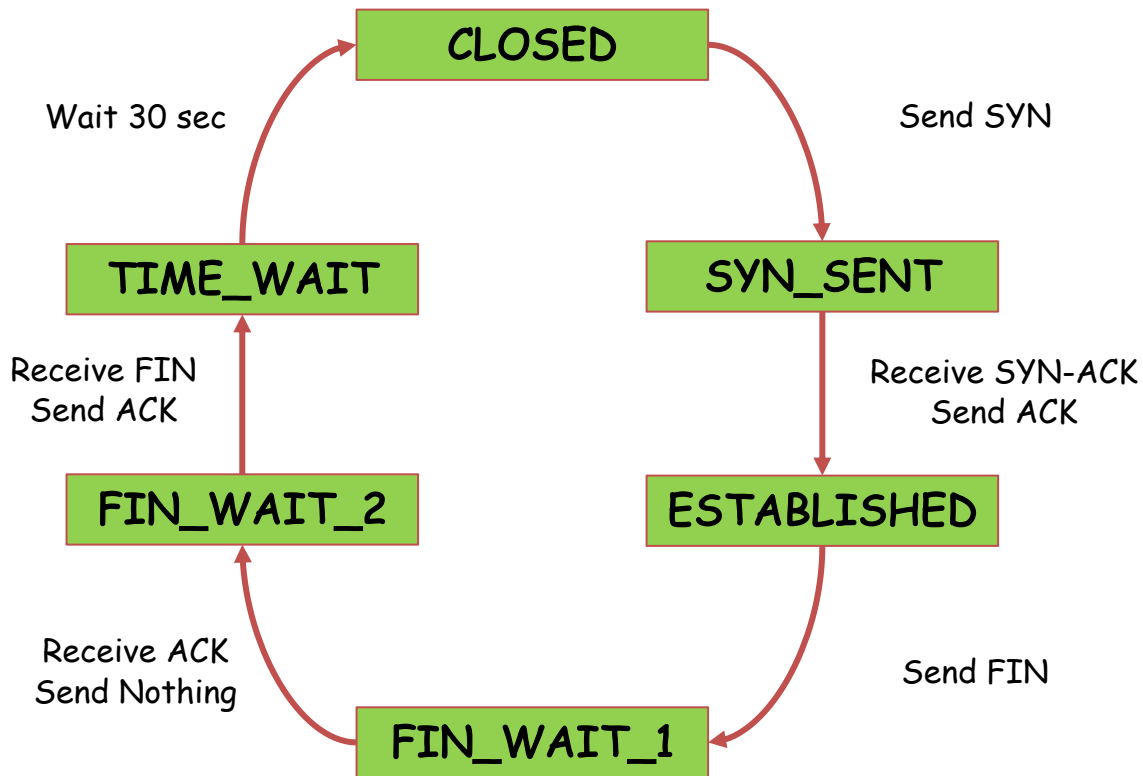• Same as before, but B sets FIN with their ack of A's FIN

Abrupt termination

- A sends a RESET (RST) to B
  - ➤ E.g., because application process on A crashed
- That's it
  - ➤ B does not ack the RST
  - ➤ Thus, RST is not delivered reliably, and any data in flight is lost
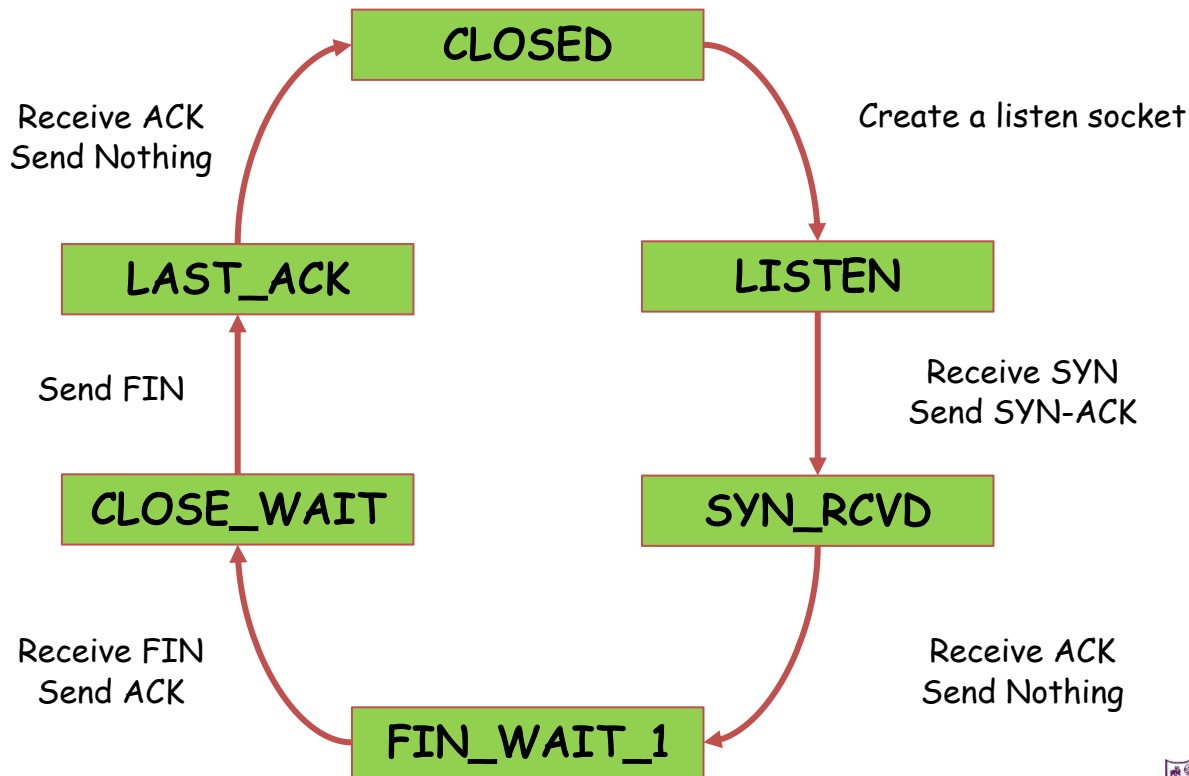 - ➤ But: if B sends anything more, will elicit another RST

TCP client lifecycle

TCP server lifecycle

CLOSED

Receive ACK
Send Nothing

Create a listen socket

LAST_ACK

LISTEN

Send FIN

Receive SYN
Send SYN-ACK

CLOSE_WAIT

SYN_RCVD

Receive FIN
Send ACK

Receive ACK
Send Nothing

FIN_WAIT_1

课程习题（作业）——截止日期：4月1日晚23:59

- **课本187-195页**：第R5、R8、R14、P1、P3、P5题

- 提交方式：https://selearning.nju.edu.cn/（教学支持系统）

教学支持系统

▼ 2025 Spring
- ▶ 本科生一年级
- ▶ 本科生二年级
- ▶ 本科生三年级
- ▷ 本科生四年级
- ▶ 研究生一年级
- ▶ 智能软件与工程学院

互联网计算-智软院

教师: 殷亚凤

第1章-计算机网络和因特网

第2章-应用层

第3章-运输层(1)

第3章-运输层(1)

课本110-115页：第R3、R5、R16、P9、P22题

- 命名：学号+姓名+第*章。

- 若提交遇到问题请及时发邮件或在下一次上课时反馈。

R5. 在今天的因特网中，为什么语音和图像流量常常是经过 TCP 而不是经 UDP 发送。（提示：我们寻找的答案与 TCP 的拥塞控制机制没有关系。）

R8. 假定在主机 C 端口 80 上运行的一个 Web 服务器。假定这个 Web 服务器使用持续连接，并且正在接收来自两台不同主机 A 和 B 的请求。被发送的所有请求都通过位于主机 C 的相同套接字吗？如果它们通过不同的套接字传递，这两个套接字都具有端口 80 吗？讨论和解释之。

R14. 是非判断题：

    a. 主机 A 经过一条 TCP 连接向主机 B 发送一个大文件。假设主机 B 没有数据发往主机 A。因为主机 B 不能随数据捎带确认，所以主机 B 将不向主机 A 发送确认。

    b. 在连接的整个过程中，TCP 的 rwnd 的长度决不会变化。

    c. 假设主机 A 通过一条 TCP 连接向主机 B 发送一个大文件。主机 A 发送但未被确认的字节数不会超过接收缓存的大小。

    d. 假设主机 A 通过一条 TCP 连接向主机 B 发送一个大文件。如果对于这条连接的一个报文段的序号为 m，则对于后继报文段的序号将必然是 $m+1$。

    e. TCP 报文段在它的首部中有一个 rwnd 字段。

    f. 假定在一条 TCP 连接中最后的 SampleRTT 等于 1 秒，那么对于该连接的 TimeoutInterval 的当前值必定大于等于 1 秒。

    g. 假设主机 A 通过一条 TCP 连接向主机 B 发送一个序号为 38 的 4 个字节的报文段。在这个相同的报文段中，确认号必定是 42。

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P1. 假设客户 A 向服务器 S 发起一个 Telnet 会话。与此同时，客户 B 也向服务器 S 发起一个 Telnet 会话。给出下面报文段的源端口号和目的端口号：

a. 从 A 向 S 发送的报文段。

b. 从 B 向 S 发送的报文段。

c. 从 S 向 A 发送的报文段。

d. 从 S 向 B 发送的报文段。

e. 如果 A 和 B 是不同的主机，那么从 A 向 S 发送的报文段的源端口号是否可能与从 B 向 S 发送的报文段的源端口号相同？

f. 如果它们是同一台主机，情况会怎么样？

P3. UDP 和 TCP 使用反码来计算它们的检验和。假设你有下面 3 个 8 比特字节：01010011，01100110，01110100。这些 8 比特字节和的反码是多少？（注意到尽管 UDP 和 TCP 使用 16 比特的字来计算检验和，但对于这个问题，你应该考虑 8 比特和。）写出所有工作过程。UDP 为什么要用该和的反码，即为什么不直接使用该和呢？使用该反码方案，接收方如何检测出差错？1 比特的差错将可能检测不出来吗？2 比特的差错呢？

P5. 假定某 UDP 接收方对接收到的 UDP 报文段计算因特网检验和，并发现它与承载在检验和字段中的值相匹配。该接收方能够绝对确信没有出现过比特差错吗？试解释之。

Q & A

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