Transmission Control Protocol (TCP)

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Textbook Chap. #3 Section 3.5

Outline

- Introduction to TCP
- Sequence numbers and acknowledgment numbers
- Timeouts and RTT estimation
- Reliable data transfer in TCP
- Connection management

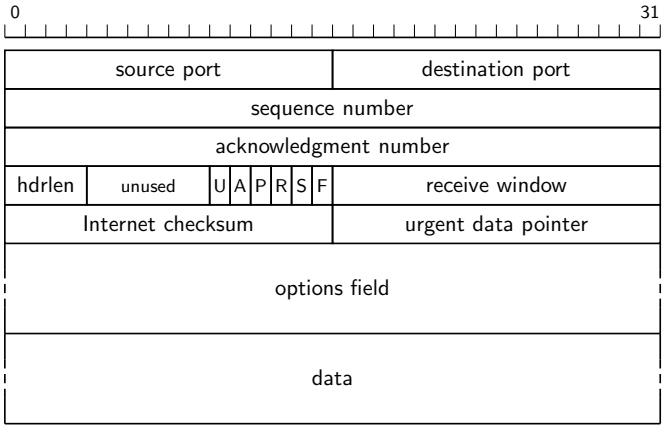
Transmission Control Protocol

- The Internet's primary transport protocol
  - defined in RFC 793, RFC 1122, RFC 1323, RFC 2018, and RFC 2581
- Connection-oriented service
  - endpoints "shake hands" to establish a connection
  - not a circuit-switched connection, nor a virtual circuit
- Full-duplex service
  - both endpoints can both send and receive, at the same time

Preliminary Definitions

- **TCP segment :** envelope for TCP data
  - TCP data are sent within TCP segments
  - TCP segments are usually sent within an IP packet
- **Maximum segment size (MSS) :** maximum amount of application data transmitted in a single segment
  - typically related to the MTU of the connection, to avoid network-level fragmentation (we'll talk about all of this later)
- **Maximum transmission unit (MTU) :** largest link-layer frame available to the sender host
  - **path MTU :** largest link-layer frame that can be sent on all links from the sender host to the receiver host

TCP Segment Format



TCP Header Fields

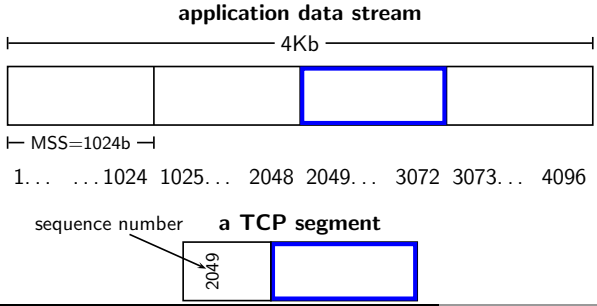
- **Source and destination ports :** (16-bit each) application identifiers
- **Sequence number :** (32-bit) used to implement reliable data transfer
- **Acknowledgment number :** (32-bit) used to implement reliable data transfer
- **Receive window :** (16-bit) size of the "window" on the receiver end
- **Header length :** (4-bit) size of the TCP header in 32-bit words
- **Optional and variable-length options field :** may be used to negotiate protocol parameters

TCP Header Fields

- **ACK flag :** (1-bit) signals that the value contained in the **acknowledgment number** represents a valid acknowledgment
- **SYN flag :** (1-bit) used during connection setup and shutdown
- **RST flag :** (1-bit) used during connection setup and shutdown
- **FIN flag :** (1-bit) used during connection shutdown
- **PSH flag :** (1-bit) "push" flag, used to solicit the receiver to pass the data to the application immediately
- **URG flag :** (1-bit) "urgent" flag, used to inform the receiver that the sender has marked some data as "urgent". The location of this urgent data is marked by the **urgent data pointer** field
- **Checksum :** (16-bit) used to detect transmission errors

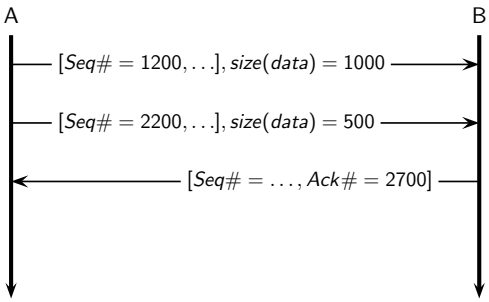
Sequence Numbers

- Sequence numbers are associated with **bytes** in the data stream
  - not with segments, as we have used them before
- The sequence number in a TCP segment indicates the sequence number of the first byte carried by that segment



Acknowledgment Numbers

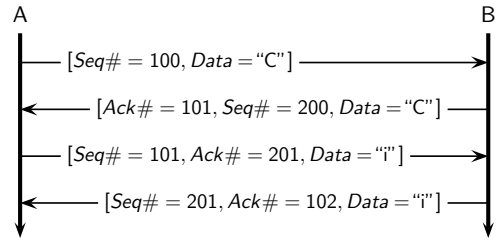
- An acknowledgment number represents the first sequence number not yet seen by the receiver
  - TCP acknowledgments are **cumulative**



Sequence Numbers and ACK Numbers

- Notice that a TCP connection is a **full-duplex** link
  - therefore, there are two streams
  - two different sequence numbers

E.g., consider a simple "Echo" application :

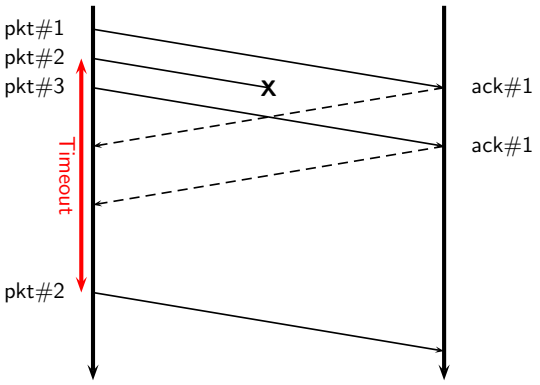


- Acknowledgments are "piggybacked" on data segments

Reliability and Timeout

- TCP provides reliable data transfer using a **timer** to detect lost segments
  - timeout without an ACK → lost packet → retransmission
- How long to wait for acknowledgments ?
- Retransmission timeouts should be larger than the round-trip time
  - but as close as possible to the RTT
- TCP controls its timeout by continuously **estimating the current RTT**

TCP timeout



Round-Trip Time Estimation

- RTT is measured using ACKs
  - only for packets transmitted once
- Given a single sample S at any given time
- **Exponential weighted moving average (EWMA)**

$$\overline{RTT} = (1-\alpha)\overline{RTT}' + \alpha S$$

  - RFC 2988 recommends $\alpha = 0.125$
- TCP also measures the **variability of RTT**

$$\overline{DevRTT} = (1-\beta)\overline{DevRTT}' + \beta|\overline{RTT}' - S|$$

  - RFC 2988 recommends $\beta = 0.25$

Timeout Value

- The timeout interval T must be larger than the RTT
  - so as to avoid unnecessary retransmission
- However, T should not be too far from RTT
  - so as to detect (and retransmit) lost segments as quickly as possible
- TCP sets its timeouts using the estimated RTT ($\overline{RTT}$) and the variability estimate $\overline{DevRTT}$:

$$T = \overline{RTT} + 4\overline{DevRTT}$$

Reliable Data Transfer (Sender)

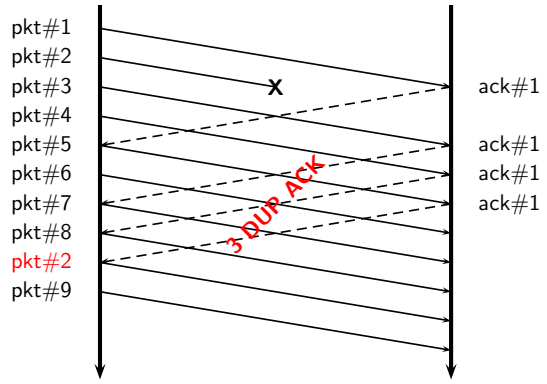
A simplified TCP sender

- r_send(*data*)
  if (timer not running)
  start_timer()
  u_send([*data*,*next_seq_num*])
  next_seq_num ← *next_seq_num* + *length*(*data*)
- timeout
  u_send(pending segment with smallest sequence number)
  start_timer()
- u_recv([ACK,*y*])
  if ($y > base$)
  $base \leftarrow y$
  if (there are pending segments)
  start_timer()
  else . . .

Acknowledgment Generation (Receiver)

- Arrival of in-order segment with expected sequence number ; all data up to expected sequence number already acknowledged
  - **Delayed ACK :** wait 500ms for another in-order segment ; If that does not arrive, send ACK
- Arrival of in-order segment with expected sequence number. One other in-order segment waiting for ACK (see above)
  - **Cumulative ACK :** immediately send cumulative ACK (for both segments)
- Arrival of out of order segment with higher-than-expected sequence number (gap detected)
  - **Duplicate ACK :** immediately send duplicate ACK
- Arrival of segment that (partially or completely) fills a gap in the received data
  - **Immediate ACK :** immediately send ACK if the packet start at the lower end of the gap

TCP duplicate ACK

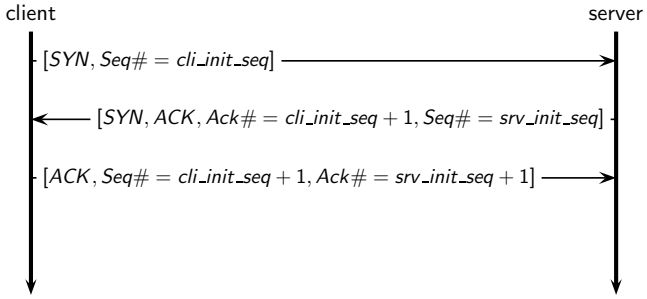


Reaction to ACKs (Sender)

- u_recv([ACK,y])
  if ($y > base$)
    $base \leftarrow y$
    if (there are pending segments)
      start_timer()
  else
    $ack\_counter[y] \leftarrow ack\_counter[y] + 1$
    if ($ack\_counter[y] = 3$)
      u_send(segment with sequence number y)

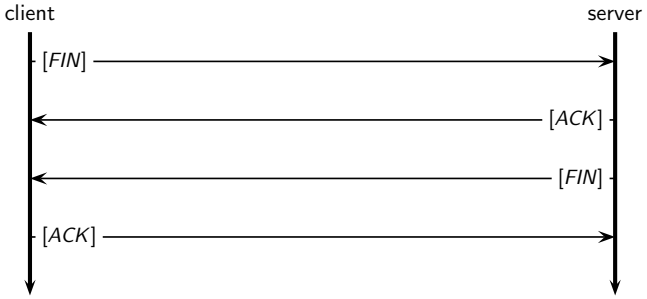
Connection Setup

Three-way handshake

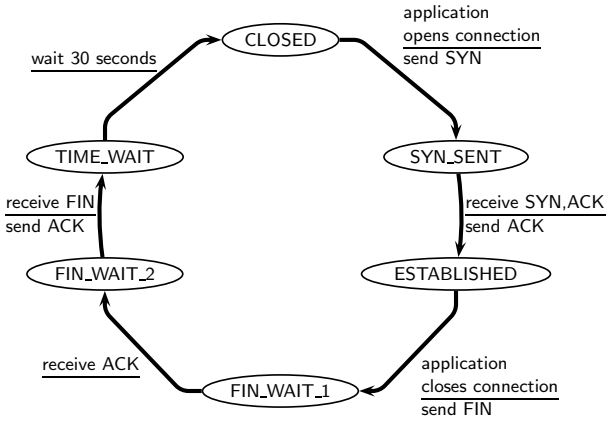


Connection Shutdown

"This is it."
"Okay, Bye now."
"Bye."



The TCP State Machine (Client)



The TCP State Machine (Server)