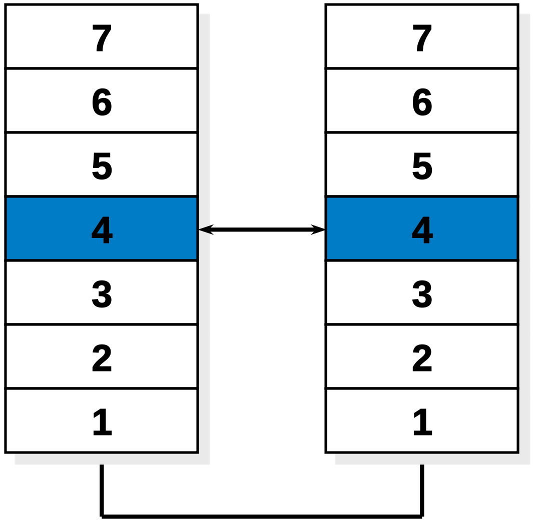
Operating Systems & Computer Networks

Transport Layer

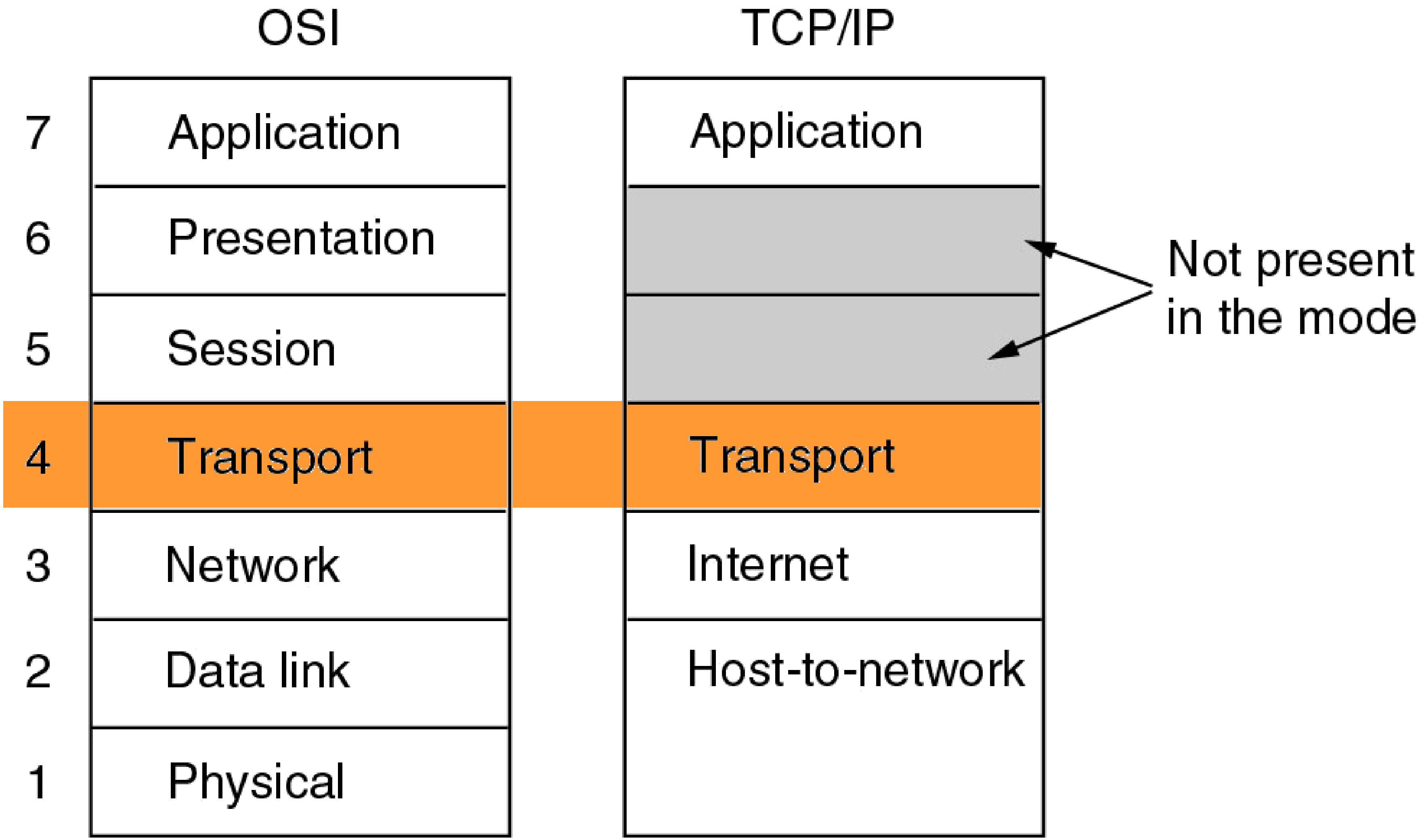
- Protocol Mechanisms
- TCP, UDP
- Addressing, Ports



Content (2)

8. Networked Computer & Internet
9. Host-to-Network I
10. Host-to-Network II
11. Host-to-Network III
12. Internetworking
13. **Transport Layer**

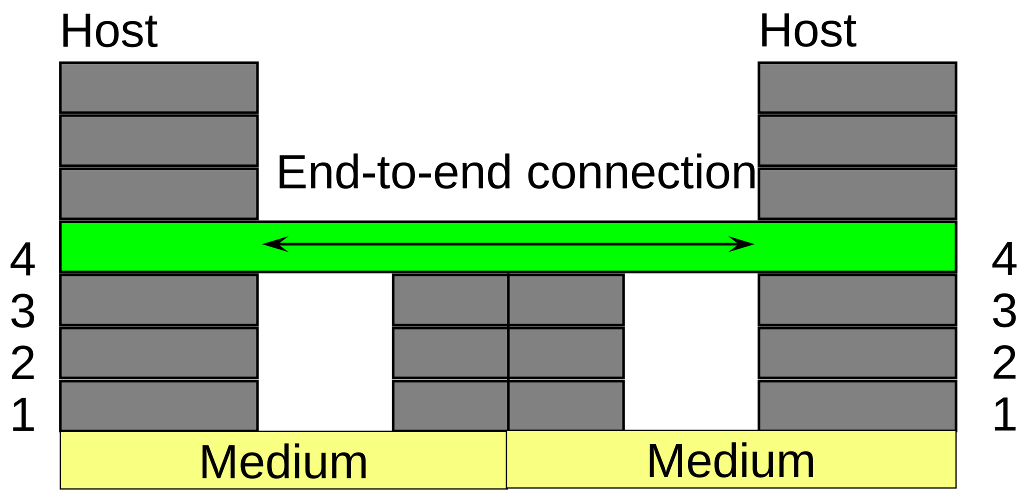
Data Link Layer



Tasks of Transport Layer

End-to-end connection:

- From process to process (not node-to-node)



- Insulation of higher layers from technology, structure and impairments of lower layers, e.g., packet loss
- Transparent transmission of user data
- Support of Quality of Service (QoS)
  - Not widely deployed in the classical Internet
- Independent addressing of processes, i.e., independent of Layer 3
  - Exception: The Internet – Socket (IP-address + port)

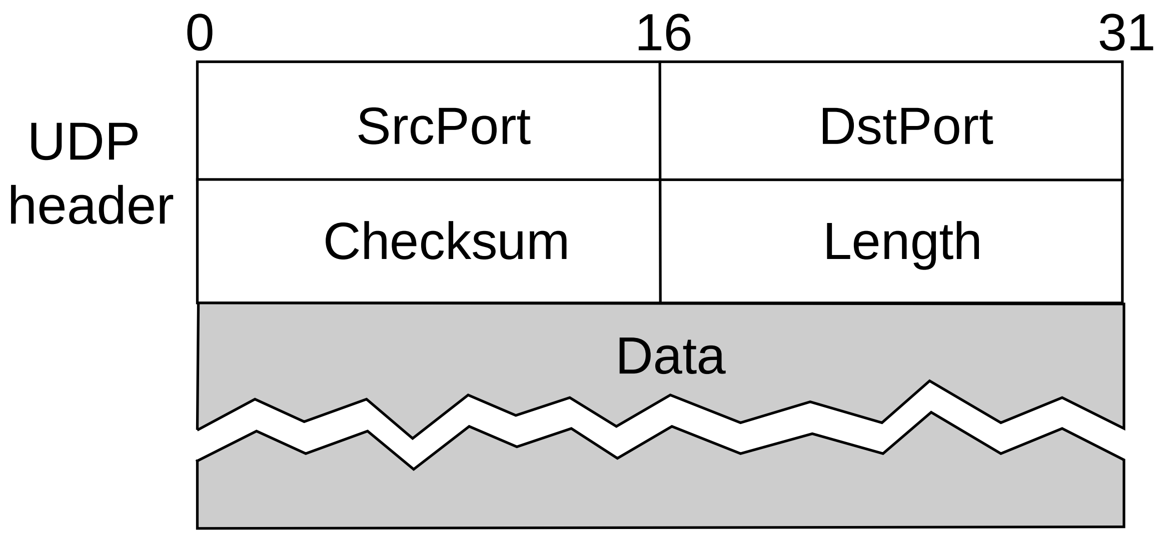
Services of Transport Protocols

Services provided to upper layers:

- Connection-less and connection-oriented transport service
  - Connection management (setup and teardown) necessary as auxiliary service
- Reliable or unreliable transport
  - In-order delivery
  - Reliability, i.e., all packets
- Congestion control – be a good citizen in the network
- Demultiplexing, i.e., support several transport endpoints in a single host
- Support different interaction models
  - Byte stream, messages
  - Remote Procedure Calls (RPC)

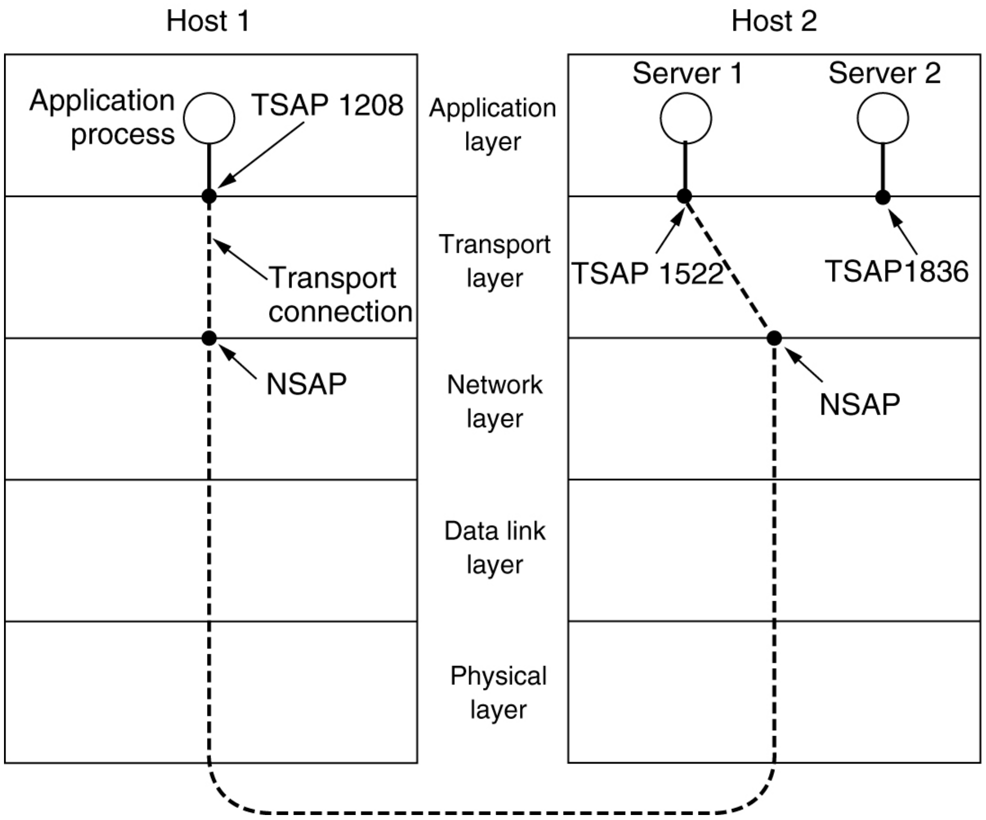
Example: User Datagram Protocol (UDP)

- Unreliable, datagram protocol
- (De)multiplex several data flows onto IP layer and back to applications
- Ensures packet's correctness
  - Checksum of pseudoheader (IP source/destination, protocol ID and length of data), UDP header and data



Addressing / Demultiplexing

- Provide multiple service access points (SAPs) to multiplex several applications
  - SAPs can identify connections or data flows
- Example: Port numbers as Transport SAP identifiers in TCP/UDP
  - Dynamically allocated
  - Predefined for “well-known” services, e.g., port 80 for HTTP/Web server
  - Privileges required to bind to certain ports
- TCP/UDP connection is thus identified by four tuple (known as socket pair):



(Source Port, Source IP Address, Destination Port, Dest. IP Address)

TCP – Some Well-known Ports

- Many applications choose TCP/UDP as transport protocol
- Correct port must be used to communicate with respective application on server side:
  - 13: Day time
  - 20: FTP data
  - 25: SMTP
    (Simple Mail Transfer Protocol)
  - 53: DNS
    (Domain Name Server)
  - 80: HTTP
    (Hyper Text Transfer Protocol)
  - 119: NNTP
    (Network News Transfer Protocol)

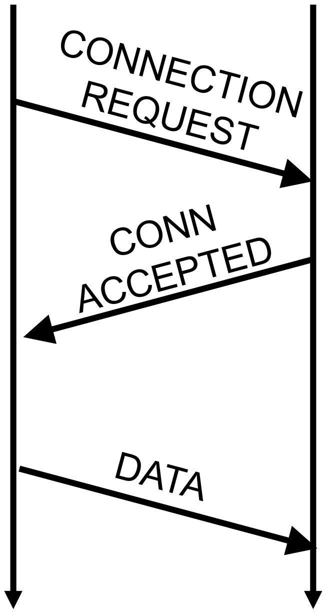
```
> telnet walapai 13
Trying 129.13.3.121...
Connected to walapai.
Escape character is '^]'.
Sun Jan  21 16:57:19 2007
Connection closed by foreign host
```

```
> telnet mailhost 25
Trying 129.13.3.161...
Connected to mailhost .
Escape character is '^]'.
220 mailhost ESMTP Sendmail 8.8.5/8.8.5; Sun,
21 Jan 2007 17:02:51 +0200
HELP
214-This is Sendmail version 8.8.5
214-Topics:
214-    HELO    EHLO    MAIL    RCPT    DATA
214-    RSET    NOOP    QUIT    HELP    VRFY
214-    EXPN    VERB    ETRN    DSN
214-For more info use "HELP <topic>".
...
214 End of HELP info
```

Connection Establishment

- How to establish join context and connection between sender and receiver?
  - Only relevant in end-system (not for routers), network layer (IP) assumed to be connection-less

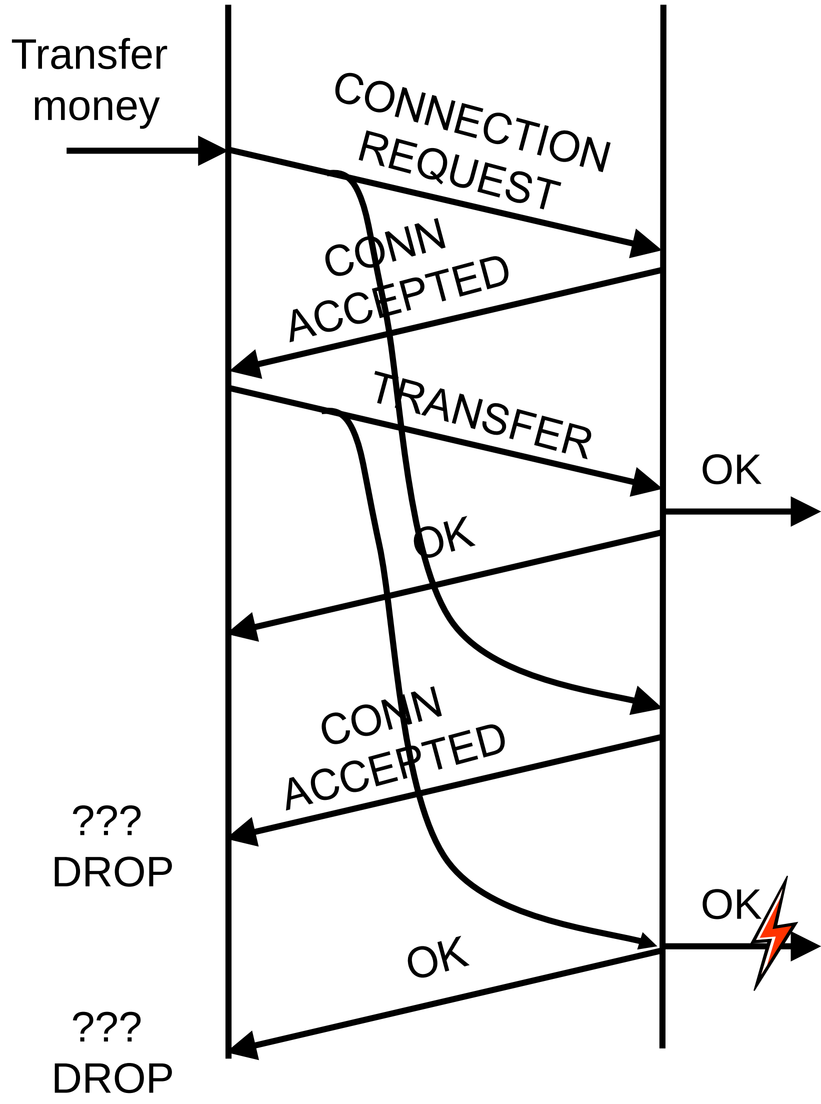
- Naïve solution:
  - Sender sends CONNECTION REQUEST
  - Receiver answers with CONNECTION ACCEPTED
  - Sender proceeds once that message is received



Failure of Naïve Solution

- Naïve solution fails in realistic networks
  - In which packets can be lost, stored/reordered, and duplicated
- Example failure scenario: All packets are duplicated and delayed
  - Due to congestion, errors, re-routing, …
- Result: Two independent transactions performed, while only one was intended
  - Similar to replay attack

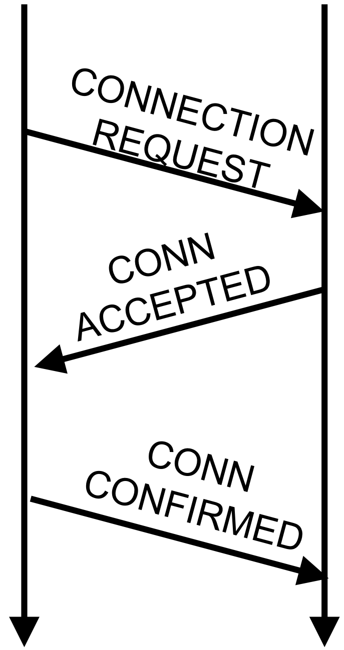
➢ Problem are *delayed duplicates*



More Sophisticated Solution

- Idea: Add additional handshake
  - Sender has to re-confirm to receiver that it actually wants to set up this connection
- Add third message to connection setup phase:

➢ ***Three-way handshake***
  - This third message can already carry data for efficiency (piggy backing)



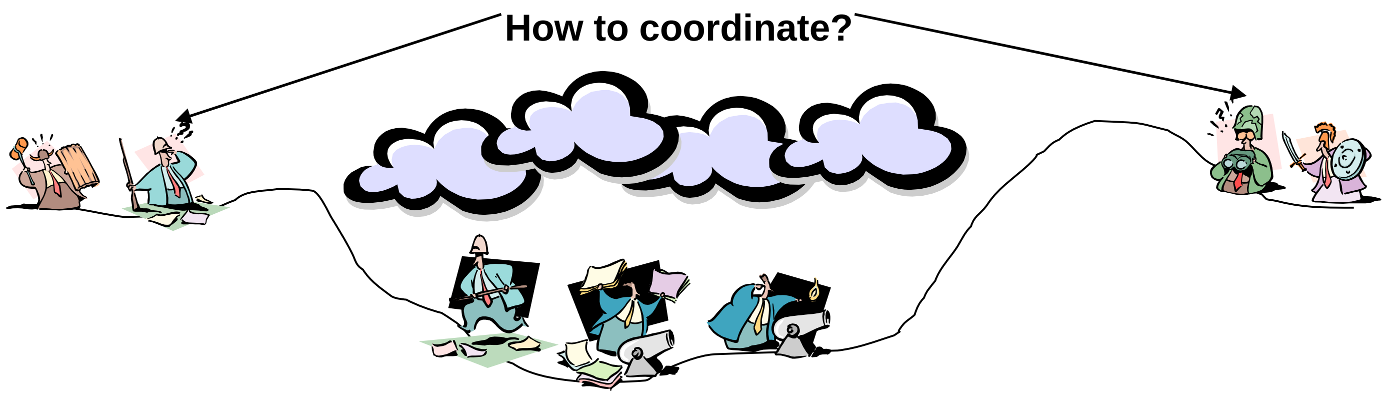
Connection Setup – Further Issues

- Terminology for TCP:
  - SYN (synchronize) packet – connection setup
  - SYN/ACK packet – Connection accepted
    - Previous sequence number is acknowledged; new sequence number from receiver is proposed
  - ACK packet – Connection confirmation
    - Combined with DATA, as a rule

- Sequence numbers used for:
  - Identification of duplicate connection setup messages
  - Acknowledgement of following data packets
- Crashing or malicious nodes may leave connections half open, i.e., not reply to SYN/ACK
  - Tie up some resources (kernel-space memory)
  - Resources need to be freed after timeout
  - ➢ Possible attack: SYN-Flooding

Connection Release

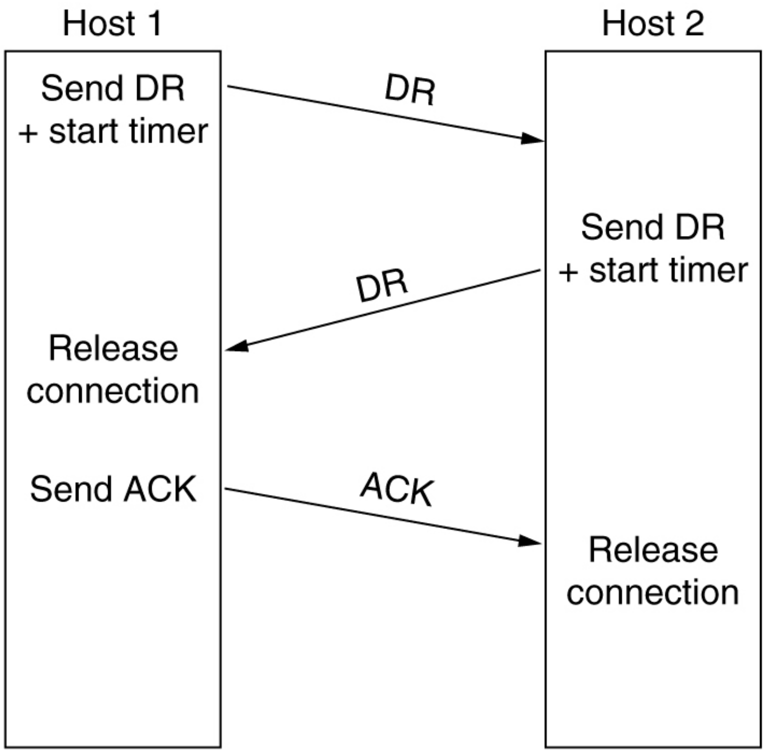
- Goal: Release connection when both peers have agreed that they have received all data and have nothing more to say
  - ➢ Both sides must have invoked a “Close”-like service primitive
- Problem:
  - Given that packets may be lost, how to acknowledge *reliably* that no further communication is required
  - ACKs would require to be ACKed, which would require to be ACKed...
- Analogy: Two army problem (coordinated attack)
  - Two armies form up for an attack against each other
  - One army is split into two parts that *must* attack together
  - Communication via messengers who can be captured
- ➢ Which rules shall commanders use to agree on attack date?
- ➢ Provably unsolvable if messages can be lost



Connection Release in Practice

➢ Take some risks when releasing a connection

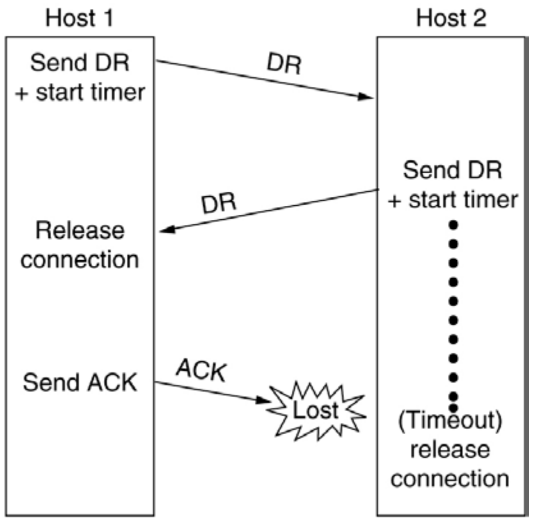
- Usual approach:
  Three-way handshake again
  - Send disconnect request (DR)
  - Set timer
  - Wait for DR from peer
  - Acknowledge DR
  - Possibly retry
  - Possibly time out

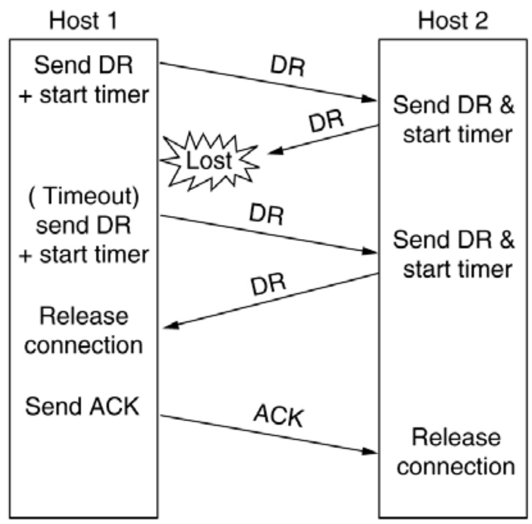


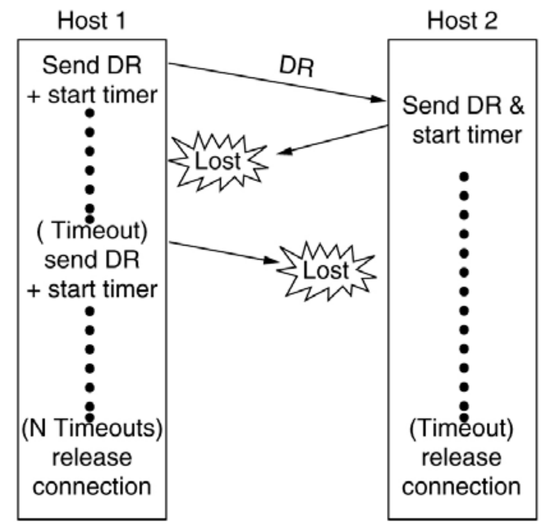
Problems for Connection Release

Problem cases for connection release with three-way handshake:

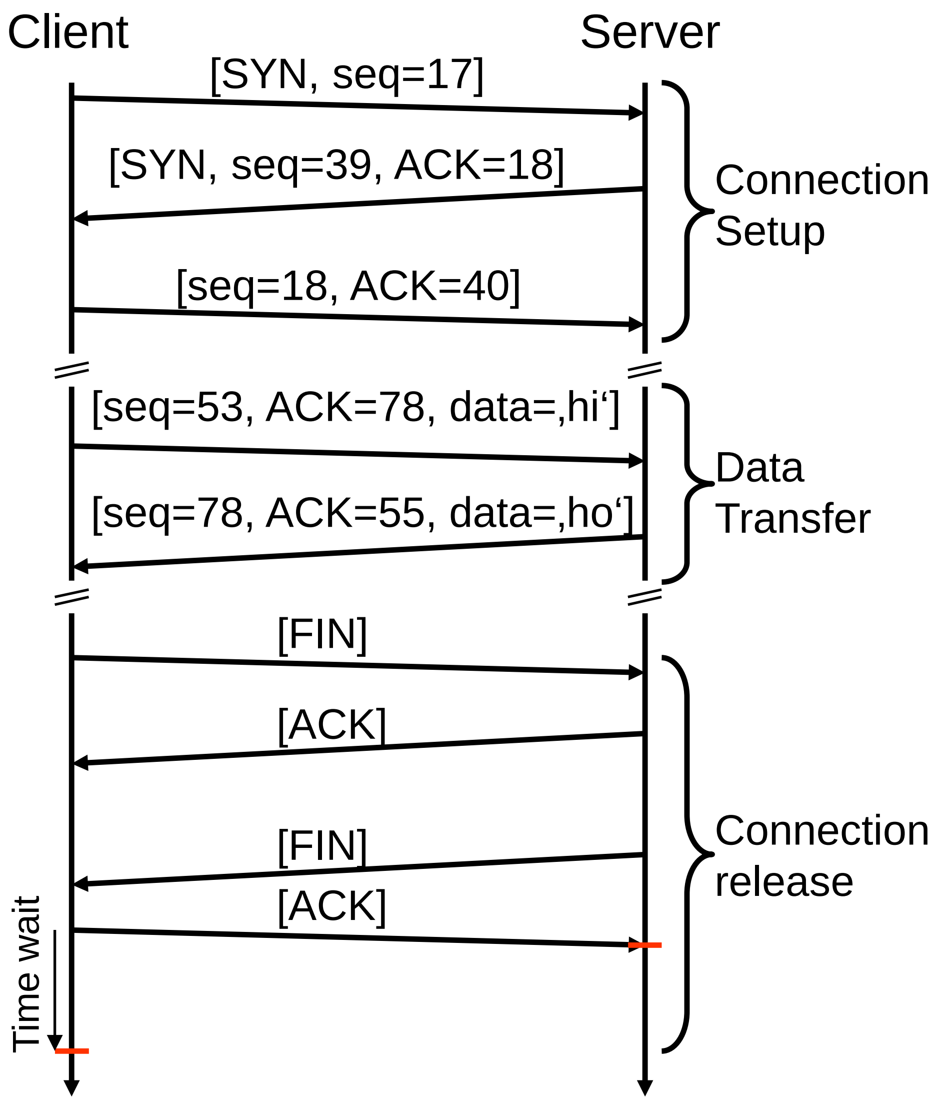
- Lost ACK solved by (optimistic) timer in Host 2
- Lost second DR solved by retrans-mission of first DR
- Timer solves (optimistically) case when 2nd DR and ACK are lost





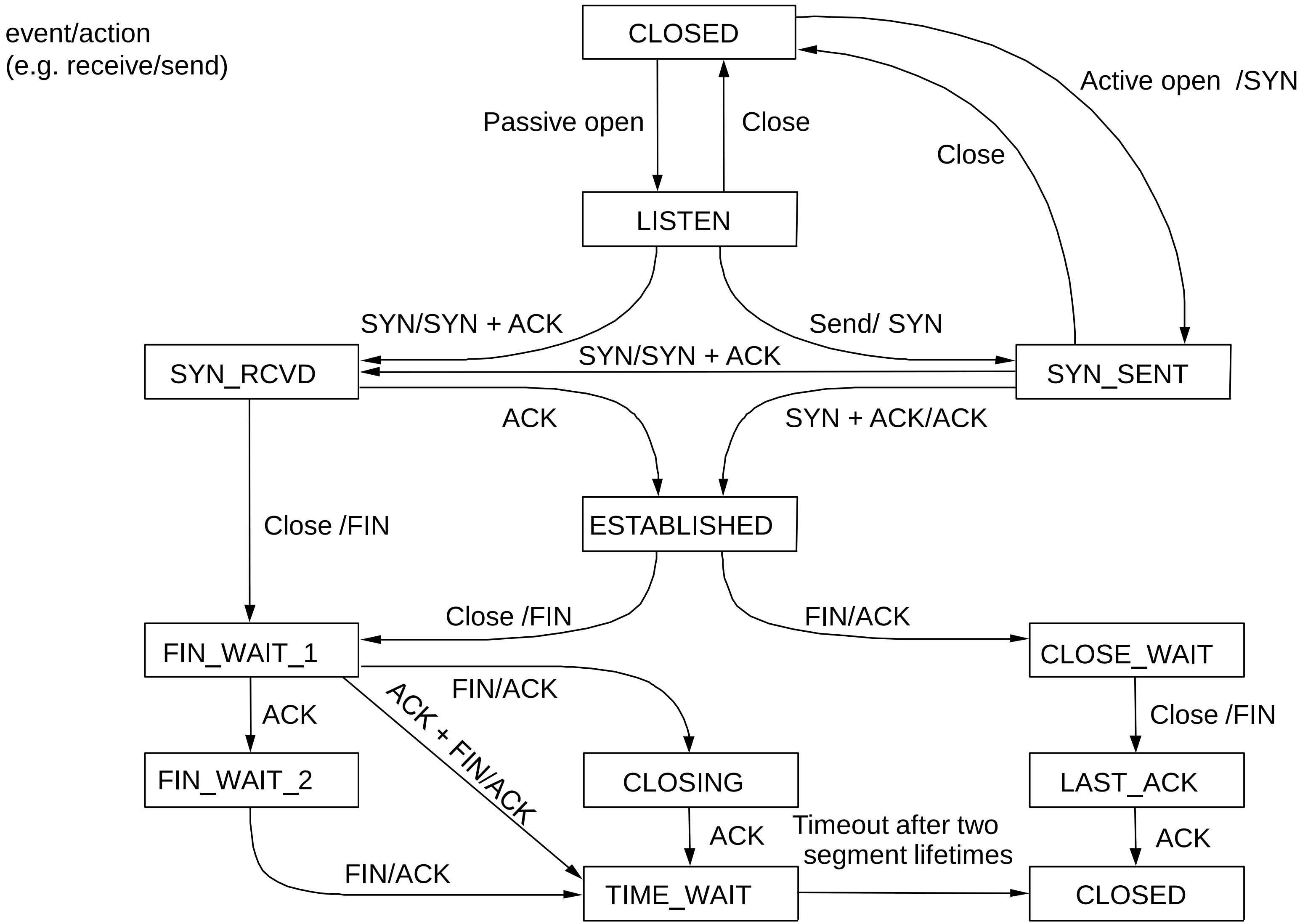


Example: TCP Setup, Transmission, Release



- Connection setup:
  - Three-way handshake
  - Negotiation of window size, sequence numbers, TCP options
- Data transfer:
  - Piggybacked acknowledgements
- Connection release:
  - Confirmed
  - Resources on client-side released after time-wait (frozen reference)
    - E.g. 30 s, 1 min, 2 min

TCP State Transition Diagram



Flow Control in TCP

- Recall: Flow control serves to prevent a fast sender from overrunning a slow receiver
- ➢ Similar issue in link and transport layer

- Additional problems in transport layer flow control:
  - Many connections, need to adapt the amount of buffer per connection dynamically
    - Instead of simply allocating fixed amount of buffer space per outgoing link
  - Unlike link layer frames, transport layer PDUs can differ widely in size
  - Network's packet buffering capability clouds the picture
    - Need to estimate how many packets are currently in transit

Flow Control
Buffer Allocation

- To support outstanding packets, sender either has to
  - … rely on receiver to process packets as they come in
    - ➢ Out-of-order delivery, no applicable to all protocols, e.g. TCP
  - … assume that receiver has sufficient buffer space available

- More buffer allows for more outstanding packets
  - ➢ Necessary to obtain highly efficient transmission
    - See bandwidth-delay product

- How does sender have buffer assurance?
  - Sender can request buffer space
  - Receiver can tell sender about available buffer space
    - ➢ For sliding window protocols: Set size of sender’s send window

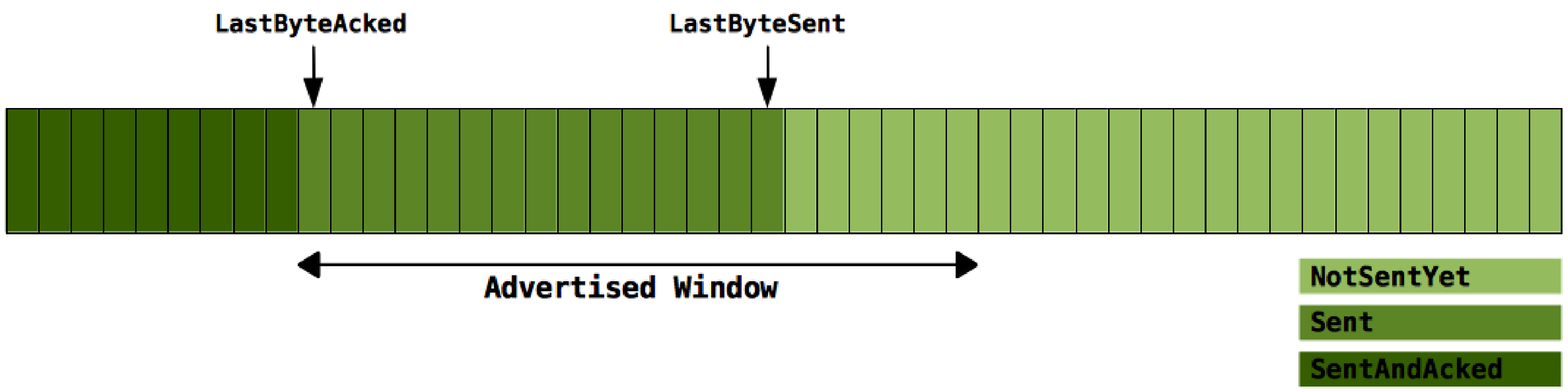
Flow Control
Permits and Acknowledgements

- Two separate mechanisms:
  - Permits
    - “Receiver has buffer space, go ahead and send more data”
    - ➢ Flow control
  - Acknowledgements
    - “Receiver has received certain packets”
    - ➢ Error control
- Can be combined with dynamically changing buffer space at receiver
  - Due to different speed with which application actually retrieves received data from transport layer
  - ➢ Example: TCP combines ACKs with sequence numbers

➢ Combination of mechanisms has implications:
  - ➢ TCP cannot distinguish between packet loss at receiver and in transit

TCP Sender

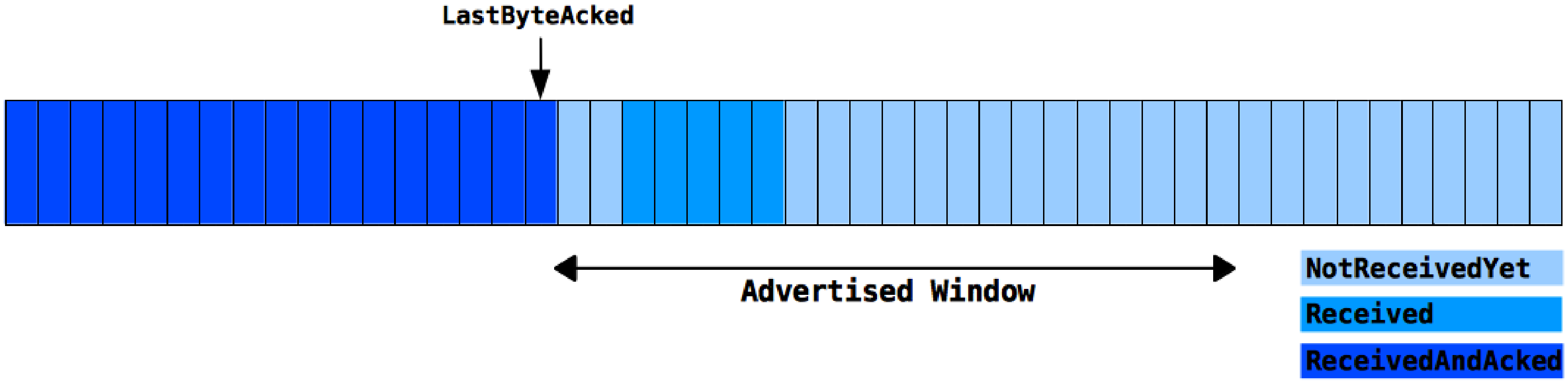
- Sent bytes need to be saved until they are acked
  - ➢ When timer expires before a byte has been acked it is resent
- Each time a packet is acked a new window size is advertised
  - ➢ The window is moved to the right



TCP Receiver

Freie Universität Berlin

- Application expects the data it receives to be in the correct order
  - When bytes arrive out of order, the receiver must keep space in the buffer free (gaps)



Timeout Computations

- Timeouts protect against lost packets

- Timeouts should reflect round-trip time (RTT) between sender and receiver
  - Problem: RTTs can be highly variable
    - Range over several orders of magnitude
  - ➢ Dynamic measurements/adaptation of RTTs

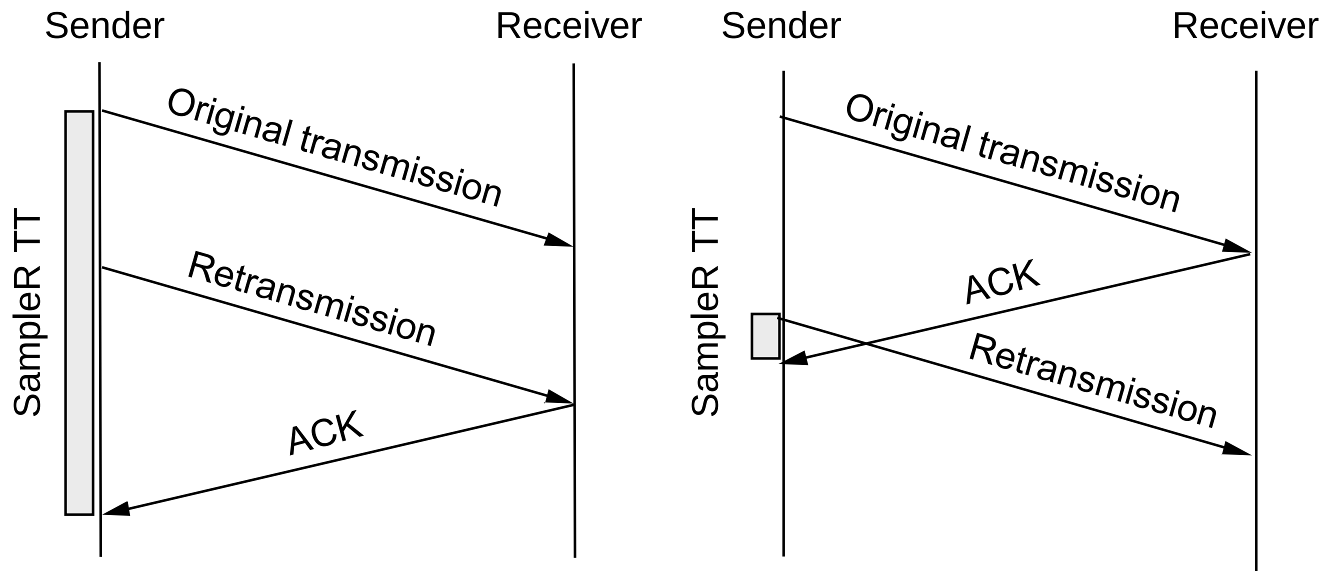
- Simple approach: Keep a running average of RTTs
  - Computed by an autoregressive model:

    $\text{EstimatedRTT}_n = \alpha \, \text{EstimatedRTT}_{n-1} + (1-\alpha) \, \text{RTTSample}_n$
    - Parameter α smoothes estimation (α = 0.8, ..., 0.9)
  - (Conservative) timeout choice: 2 * EstimatedRTT

Problems with Timeout Computations

Freie Universität Berlin

- Simple algorithm cannot obtain correct RTT samples if packets have been retransmitted
  - ACKs refer to data/sequence numbers, not to individual packets
- Two examples:



➢ Solutions:
  - Karn/Partridge algorithm: Do not take RTT samples for retransmitted packets
  - Jacobsen/Karels algorithm: Also consider variance of RTT

Timer and Packet Loss

Reaction to packet loss:

- After packet loss is detected by timeout, transmission speed needs to slow down
- Basic idea: Use successively larger timeout values

➢ ***Exponential backoff:*** Double timeout value for each additional retransmission

  - Multiplicative factor for exponential backoff is reset upon ACK arrival
  - Reset connections if maximal timeout value (given by number of retries) is exceeded

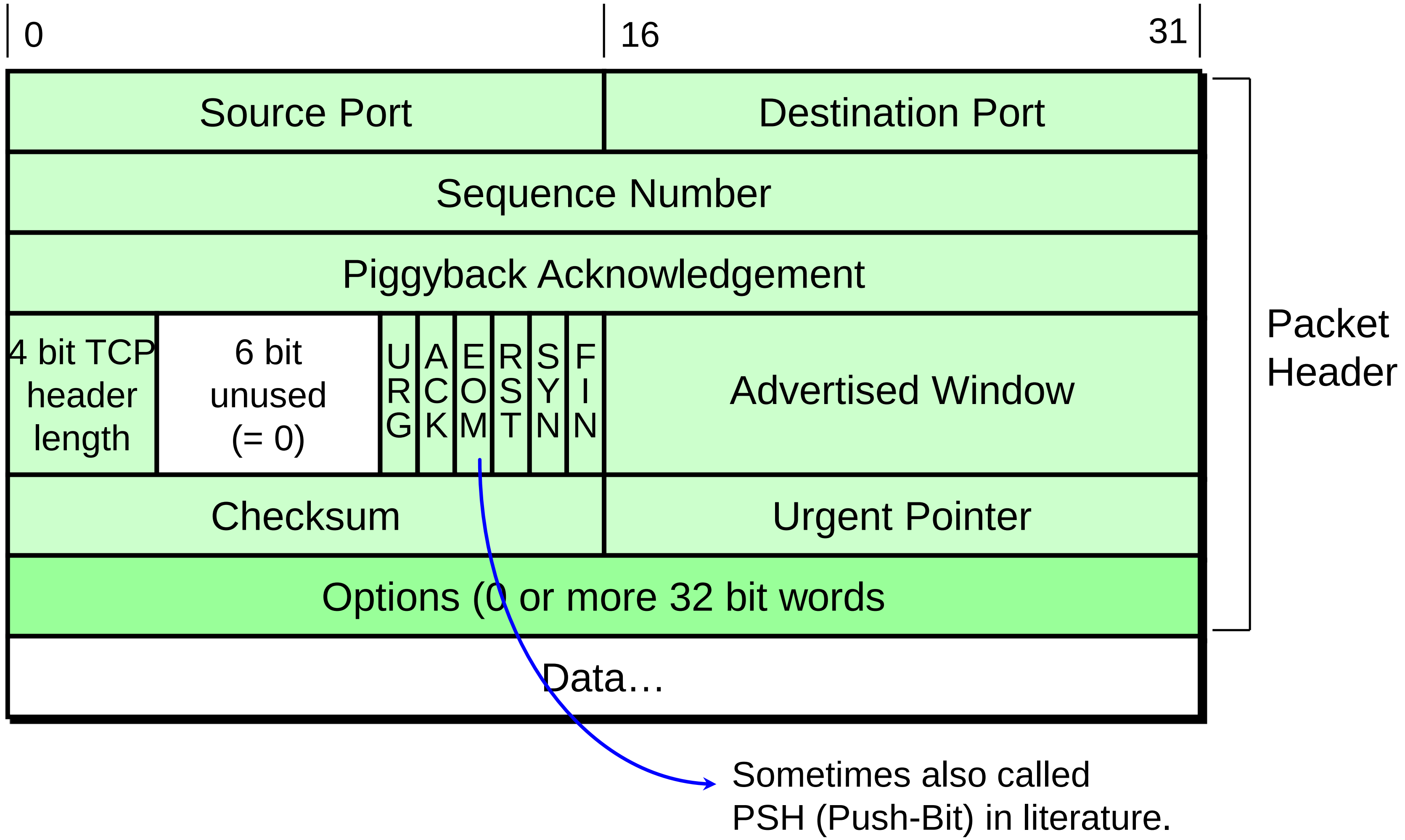
TCP Fairness & TCP Friendliness

- TCP Fairness:
  - Adjust dynamically to available bandwidth
  - Fairly share bandwidth among all connections
    - ➢ If n connections share a given bottleneck link, each connection obtains 1/n of its bandwidth (in the long run)

- Interaction with other protocols:
  - Bottleneck bandwidth also depends on load of other protocols
    - Example: UDP, which is has *no* built-in congestion control
  - ➢ UDP traffic can potentially squeeze out TCP traffic

➢ Other transport protocols should be *TCP friendly:*
  - They should not consume more bandwidth than a TCP connection in a comparable situation
  - UDP is *not* TCP friendly
    - Workarounds using queuing and dropping techniques in routers
    - Alternatives are available but little used up to now, e.g. Datagram Congestion Control Protocol (DCCP)

TCP Packet Header



TCP – Summary

- TCP provides a reliable byte stream using
  - Connection management – three-way handshake for setup and teardown
  - Error control via Go-Back-N or Selective Repeat (depending on version)
  - Flow control using advertised receiver window
  - Congestion control using exponential backoff, AIMD, slow start, congestion threshold (see literature)
- TCP semantics/parameters are quite subtle
  - ➢ Non-trivial step from unreliable datagram service to *efficient* reliable byte stream
  - Interaction of TCP with other layers is more complicated than it looks because of hidden, implicit assumptions
    - Example: Packet loss is *not* an indication of congestion in wireless networks
  - Many little details and extensions are not discussed here

Conclusion

- Transport protocols can be anything from trivial to highly complex, depending on the purpose they serve

- They determine to a large degree the dynamics of a network and – in particular – its stability
  - It is trivial to build TCP protocols “faster” than, but they are less stable

- Interdependencies of various mechanisms in a transport protocols can be very subtle with big consequences
  - Examples: Fairness, coexistence of different TCP flavors, …
- More in Telematics
  - SCTP, DCCP, MP-TCP... still ongoing research!

Content (2)

Content (3)

14. Applications
    - Domain Name System
    - Email
    - World Wide Web
15. Network Security
    - Basic Concepts & Terms
    - Cryptology
    - Examples
        - Firewalls
        - Virtual Private Networks (VPNs)
        - IP Security
        - Email Security with PGP
16. Example
    - Under the Hood of Surfing the Web