

TCP: Transmission Control Protocol

- IP is an *unreliable* datagram protocol
 - congestion or transmission errors cause lost packets
 - multiple routes may lead to out-of-order delivery
- If senders send too fast, routers or receivers cannot keep up (making congestion worse)
- When many senders compete, capacity must be fairly shared
- TCP's job is to fix those three problems
 - flow control
 - retransmission after errors

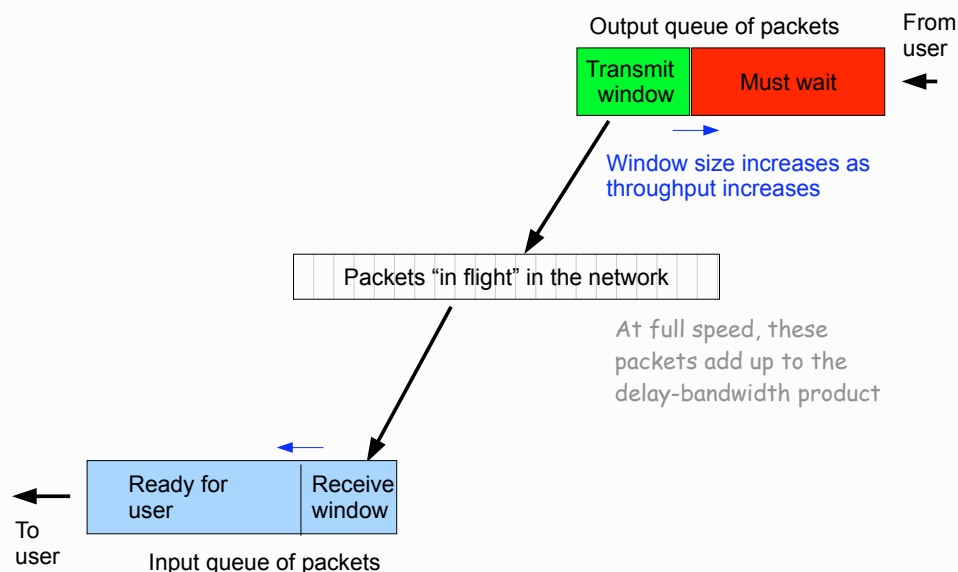
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Two approaches to Flow Control

- Rate Control - sender determines the maximum safe sending rate and never exceeds it
- Sliding Window - sender sends up to a “window” full of data but then pauses for an acknowledgement
 - Window size is adjusted dynamically to match network capacity
 - Window size is also known as "credit"
 - Missing acknowledgement causes retransmission
- TCP is a sliding window protocol

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Sliding windows in action



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Cranking up to speed

- TCP starts slowly
 - Initial window size is small
 - Send packets until window is empty
 - Increase window size as data flow accelerates
 - Decrease window size if data flow slows down
 - Retransmit when acknowledgments don't arrive
- Note that when A is talking to B and B is talking to A, the paths may be asymmetric, so TCP windows work independently in the two directions
- Note that TCP transmits a stream of *bytes* as far as user programs are concerned, broken up into *segments* by TCP itself

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Why is this better than rate control?

- The sliding window approach works over an enormous range of speeds
 - It was designed in the days of 9600 baud modems, and it works (with some tuning) in the days of 10 Gb/s links
 - Rate control works best in fixed-speed networks
- It works reasonably well as router load increases towards 100%
 - Sharing between thousands or millions of competing TCP sessions is reasonably fair
 - Rate control has real trouble sharing fairly at that scale
- Retransmission fits naturally into TCP
 - Rate control protocols have to “break step” to deal with retransmissions

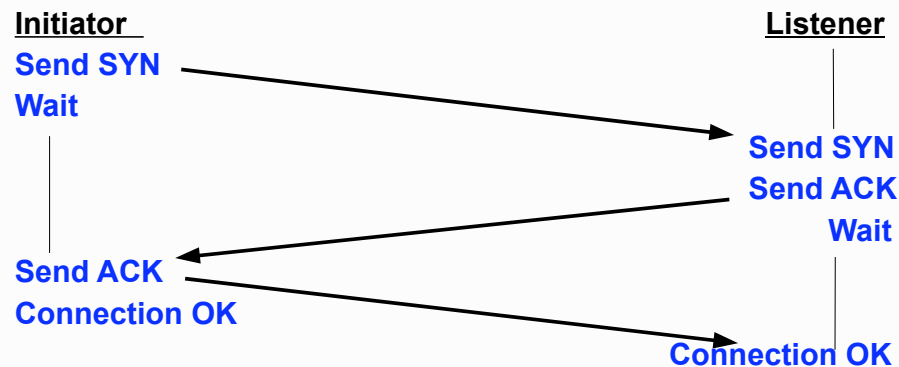
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TCP connection phases

- A TCP connection has three main phases:
 - Establishment
 - Data transfer
 - Disconnection
- One end (the “listener”) has to be willing to accept incoming TCP connections, and the other end (the “initiator”) has to choose to start
- The listener is listening to a specific *port number* which serves as a meeting point
 - IP address + port number = *Layer 4* address

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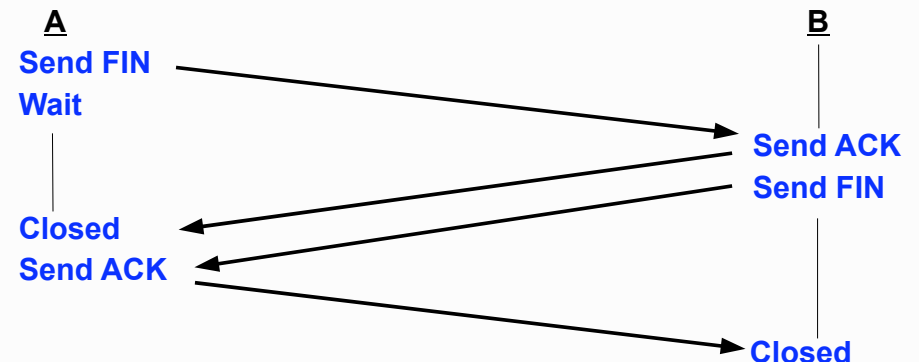
Connection establishment



- Note that whoever goes first, there is one SYN and one ACK in each direction
 - This will work even if both initiate simultaneously
 - Listener's SYN and ACK are usually sent in a single packet

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Disconnection



- Doesn't matter which end closes first
 - If one end dies, a timeout will eventually close the other end
 - B may continue to send bytes from its buffer before sending its FIN

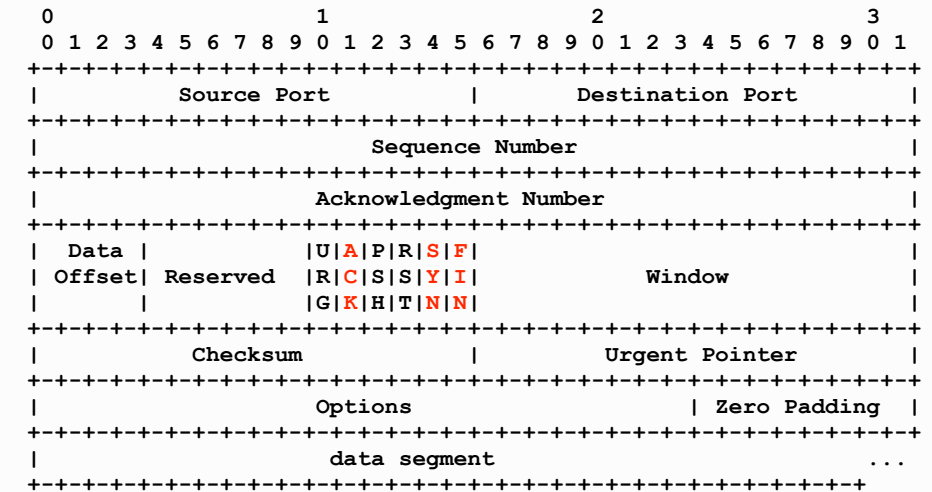
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TCBs

- During connection establishment, each end creates a TCB (transmission control block) data structure
 - A TCB links the user program at each end to the TCP process
- Typical TCB contents:
 - local and remote port numbers for this connection
 - current send and receive window sizes
 - pointers into the send and receive buffers
 - status of send and receive sequence numbers
- To understand this we need to look at the TCP header format
 - The TCP header follows the IP header in a packet, when Protocol Number (IPv4) or Next Header (IPv6) is 6

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TCP header



- Protocol Number or Next Header is 6

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TCP header fields (1)

- Port numbers - used to find TCBs at each end
- Sequence number
 - the sequence number of the first data byte in this TCP segment
 - goes up by 1 for each data byte sent on the connection
 - initialised in SYN packet (random value)
- Acknowledgement number
 - only valid in ACK packet
 - next sequence number the sender of the segment is expecting
 - in other words, sending Ack Number 12345 means "I have correctly received up to byte 12344"
 - a duplicate ACK means "I've **still** only received up to byte 12344"

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TCP header fields (2)

- Data offset
 - Size of TCP header in 32 bit words
- URG - urgent bit (not too important)
- ACK - this is an ACK packet
- PSH - push bit (kick received data to the user)
- RST - reset bit (emergency disconnect)
- SYN - SYN packet ("synchronise sequence numbers")
- FIN - FIN packet ("finished," starts normal disconnect)

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TCP header fields (3)

- Window
 - The number of data bytes beginning with the one indicated in the acknowledgment field which the sender of this segment is willing to accept
- Checksum (next slide)
- Urgent pointer (not too important)
- Options
 - For example, specify maximum receive segment size

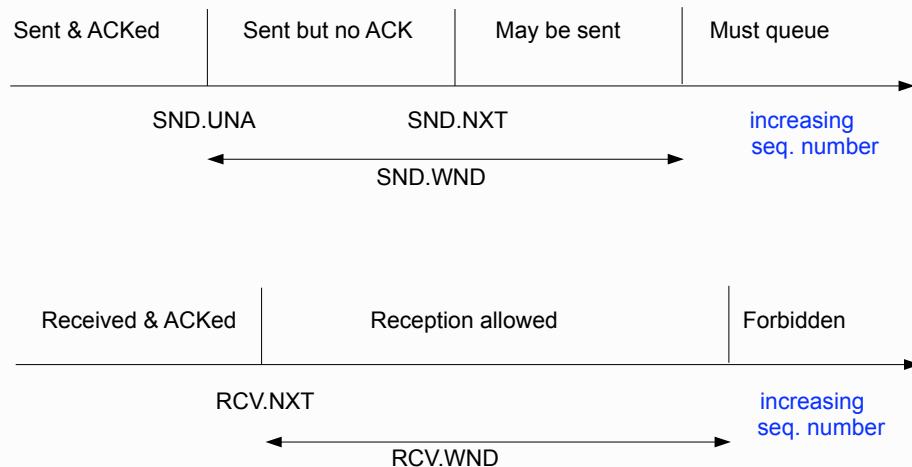
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TCP checksum

- *This is the primary protection against transmission errors in the Internet*
 - 16 bit one's-complement of the one's-complement sum of all 16 bit words in the TCP header and data
 - If a segment contains an odd number of bytes to be checksummed, the last byte is padded on the right with zeros to form a 16 bit word for checksum purposes. (The padding is not transmitted as part of the segment)
 - While computing the checksum, the checksum field itself is replaced with zeros
 - The checksum also covers a “pseudo header” conceptually prefixed to the TCP header. This pseudo header contains the Source & Destination IP Addresses, the Protocol or Next Header Number, and TCP segment length

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Sequence number state at sender and receiver



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TCP data transfer phase

- After SYN/ACK, the two ends know initial sequence numbers and initial window sizes
- Both ends may start sending, as long as they stay within the allowed sending window
 - sending a segment moves SND.NXT along
 - receiving an ACK for a given sequence number moves SND.UNA along
 - if $\text{SND.NXT} = \text{SND.UNA} + \text{SND.WND}$, wait
- Both ends receive
 - when a segment arrives, increase RCV.NXT and send ACK
 - if RCV.NXT reaches end of window (i.e. $\text{RCV.WND} = 0$), only ACKs will be treated. Incoming data is discarded and not ACKed

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Adjusting the Window

- The size of the send window (SND.WND) decides how much data can be sent without waiting for an ACK
 - SND.WND must be decreased when things are going slowly, and can be increased when things are going well
 - SND.WND tracks RCV.WND via ACK messages
 - The algorithm for adjusting RCV.WND is the most critical feature of a TCP implementation and has been modified many times
- See comments below on congestion control

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Retransmission

- If an ACK does not arrive within a certain timeout, all segments since the previous ACK will be retransmitted
 - no difference whether packet was discarded due to congestion or lost due to transmission fault or checksum error
 - can be optimised with “Selective ACK” to avoid retransmitting correctly received segments
- The retransmission timeout is dynamically calculated
 - Typically by measuring a running average Round Trip Time (RTT) between sending a segment and receiving its ACK
 - Then set the timeout to, say, 2xRTT

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Background slide

Algorithm for Send Window to track Receive Window

- Variables
 - SND.NXT - next sequence number to be sent
 - SND.WND - current send window size
 - LatestAckSeq - acknowledgement number in latest ACK
 - CurrentSeq - sequence number of segment carrying ACK
 - AckWindow - receiver's window size in ACK
 - PreviousSeq, PreviousAck - from previous window update
- Algorithm

```
if LatestAckSeq <= SND.NXT then      # waiting for ACKs
if (PreviousSeq < CurrentSeq or      # don't use stale
    (PreviousSeq == CurrentSeq       # window size
     and PreviousAck <= LatestAckSeq))
then {SND.WND := AckWindow;          # update window
      PreviousSeq := CurrentSeq;
      PreviousAck := LatestAckSeq;}
```

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Clarification about delay-bandwidth product

- The one-way delay in a TCP session is roughly half the RTT
- Therefore, the delay-bandwidth product is roughly
$$\frac{\text{bandwidth} \times \text{RTT}}{2}$$
- The TCP window size in a stable state is roughly
$$\text{bandwidth} \times \text{RTT}$$
which is double the delay-bandwidth product, because the window has to allow for ACKs to come back
 - 'roughly' because the outbound delay (for data) and the return (for ACKs) will never be exactly equal
 - some web references get this wrong
- **bandwidth** = link transmission rate (b/s)

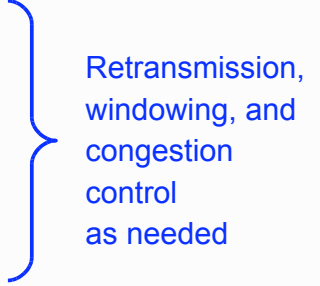
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Congestion control

- TCP as described above is “greedy” - it will pump as much data as the path will take
 - With millions of connections, this leads to “congestive collapse” where saturated routers must discard most packets
- Modern TCPs use various techniques to avoid this, all of which amount to being “good neighbours”
 - Slow Start: start small and expand window gently
 - Congestion Avoidance: when duplicate ACKs indicate that later segments were lost, limit number of (re)transmissions
 - Fast Recovery: after 3 duplicate ACKs, retransmit once and wait. If still no ACK, revert to Slow Start
- Modern routers keep an eye out for greedy “cheats” and selectively discard their packets

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A day in the life of a TCP session

- User A: Listen (portA)
 - User B: Open (AddressA, portA)
 - SYN/ACK exchange
 - Data transfer phase
 - User A: Send (DataA)
 - User B: Receive (DataA)
 - User B: Send (DataB)
 - User A: Receive (DataB)
 - (repeat as required by application)
 - User B: Close
 - FIN/ACK exchange
 - User A: Listen (portA)
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- Retransmission,
windowing, and
congestion
control
as needed

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References

- Shay 11.4
- Any of the TCP/IP books listed for IPv4
- RFCs:
 - RFC 793, the original definition
 - Many advisory RFCs and other publications on implementation techniques to tune performance. (Implementing TCP is not for amateurs!)
 - RFC 2460 (IPv6) modifies TCP’s checksum formula
 - RFC 3168 adds *Explicit Congestion Notification* to TCP and IP
 - RFC 4614 is a roadmap for TCP specifications

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