Transport Layer: TCP and UDP

CS 161 Fall 2022 - Lecture 18

Last Time: Low-Level Network Attacks

- Classes of attackers:
  - Off-path: Can’t see, modify, or drop packets
  - On-path: Can see packets, but can’t modify or drop packets
  - MITM: Can see, modify, and drop packets
- ARP: A protocol to translate local IP addresses to MAC addresses
  - Ask everyone on the network, “Who has the IP 1.2.3.4?”
  - Attack: The attacker can respond instead of the true device with 1.2.3.4, and packets will get routed to the attacker!
  - Defense: Switches
  - Defense: Rely on higher layers
- DHCP: A protocol for a new client to receive a network configuration
  - Ask everyone on the network, “What is the network configuration to use?”
  - Attack: The attacker can respond with a malicious configuration
  - Defense: Rely on higher layers

Last Time: Low-Level Network Attacks

- WPA: A protocol to encrypt Wi-Fi connections at layer 1
  - Messages between the client and the AP are encrypted with keys
  - Handshake uses MICs (cryptographic MACs) to verify that both parties have the same PSK and nonces
  - WPA-PSK: Use a password to derive a PSK, which is used in a handshake to arrive at a key
    - Attack: Attacker can pretend to be an AP
    - Attack: Brute-force the password after recording a handshake
    - Vulnerability: No forward secrecy
  - WPA-Enterprise: Use a third party to provide a one-time “replacement PSK,” used in the same handshake
    - Solves the attacks on WPA-PSK

Last Time: BGP

- Border Gateway Protocol (BGP): Routing packets
  - The Internet is made of smaller **autonomous systems** (**AS**)
  - Each AS broadcasts the shortest routes it knows of (dependent on the shortest routes of its neighbors and distance to neighbors)

Today: Transport Layer Protocols

- Transmission Control Protocol (TCP): Reliably sending packets
- User Datagram Protocol (UDP): Non-reliably sending packets

Transmission Control Protocol (TCP)

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Review: IP Reliability

- **Reliability** ensures that packets are received correctly
  - If the packet has been changed (random error or malicious tampering), it should not be correctly received
  - IP packets include a checksum (unkeyed function, protects against random errors)
  - However, there is no cryptographic MAC, so there are no guarantees if an attacker maliciously modifies packets (and modifies the checksum accordingly)
- IP is **unreliable** and only provides a **best effort** delivery service, which means:
  - Packets may be lost (“dropped”)
  - Packets may be corrupted
  - Packets may be delivered out of order
- It is up to higher level protocols to ensure that the connection is reliable

Scratchpad: Let’s Design It Together

- Problem: IP packets have a limited size. To send longer messages, we have to manually break messages into packets
  - When sending packets: TCP will automatically split up messages
  - When receiving packets: TCP will automatically reassemble the packets
  - Now the user doesn’t need to manually split up messages!
- Problem: Packets can arrive out of order
  - When sending packets: TCP labels each byte of the message with increasing numbers
  - When receiving packets: TCP can use the numbers to rearrange bytes in the correct order
- Problem: Packets can be dropped
  - When receiving packets: TCP sends an extra message acknowledging that a packet has been received
  - When sending packets: If the acknowledgement doesn’t arrive, re-send the packet

Transmission Control Protocol (TCP)

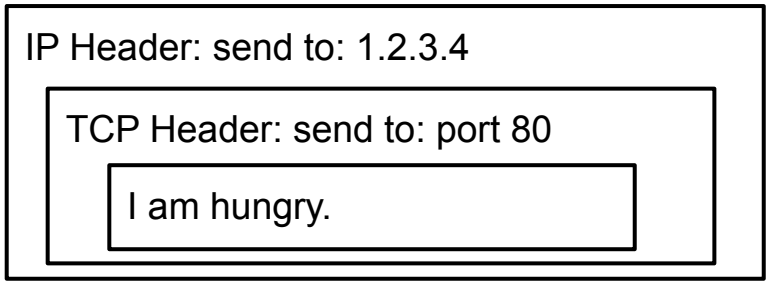
- Provides a byte stream abstraction
  - Bytes go in one end of the stream at the source and come out at the other end at the destination
  - TCP automatically breaks streams into **segments**, which are sent as layer 3 packets
- Provides ordering
  - Segments contain sequence numbers, so the destination can reassemble the stream in order
- Provides reliability
  - The destination sends **acknowledgements** (ACKs) for each sequence number received
  - If the source doesn't receive the ACK, the source sends the packet again
- Provides ports
  - Multiple services can share the same IP address by using different ports

Ports: An Analogy

- Alice is pen pals with Bob. Alice's roommate, Carol, is also pen pals with Bob
- Bob's replies are addressed to the same global (IP) address
  - How can we tell which letters are for Alice and which are for Bob?
- Solution: Add a room number (port number) inside the letter
  - In private homes, usually a port number is meaningless
  - But, in public offices (servers), like Cory Hall, the port numbers are constant and known

Ports

- **Ports** help us distinguish between different applications on the same computer or server
  - On private computers, port numbers can be random
  - On public servers, port numbers should be constant and well-known (so users can access the right port)
- Remember: TCP is built on top of IP, so the IP header (and therefore the IP address) is still present



Establishing Sequence Numbers

- Each TCP connection requires two sets of sequence numbers
  - One sequence number for messages from the client to the server
  - One sequence number for messages from the server to the client
- Before starting a TCP connection, the client and server must agree on two **initial sequence numbers** (ISNs)
  - The ISNs are different and random for every connection (for security reasons, as we'll see soon)

H	e	l	l	o		s	e	r	v	e	r
50	51	52	53	54	55	56	57	58	59	60	61

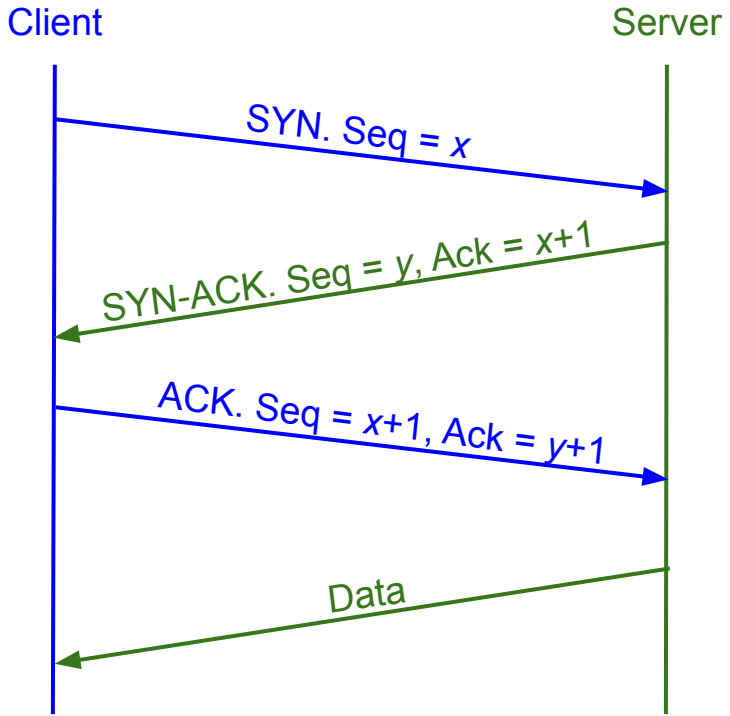
Messages from the client are numbered starting at 50.

H	e	l	l	o		c	l	i	e	n	t
25	26	27	28	29	30	31	32	33	34	35	36

Messages from the server are numbered starting at 25.

TCP: 3-Way Handshake

1. Client chooses an initial sequence number *x* its bytes and sends a SYN (synchronize) packet to the server
2. Server chooses an initial sequence number *y* for its bytes and responds with a SYN-ACK packet
3. Client then returns with an ACK packet
4. Once both hosts have synchronized sequence numbers, the connection is "established"



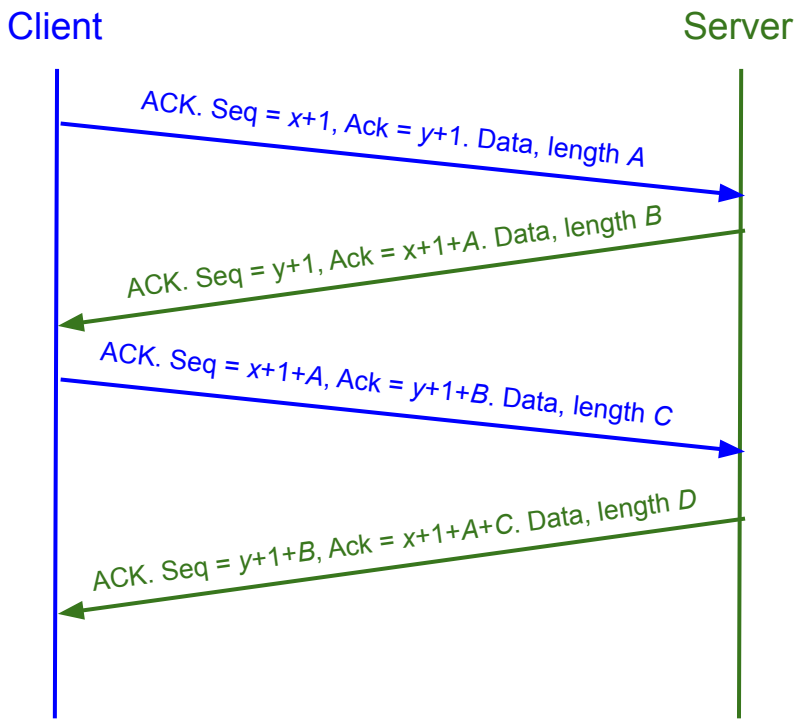
TCP: Sending and Receiving Data

- The TCP handlers on each side track which TCP segments have been received for each connection
  - A connection is identified by these 5 values (sometimes called a 5-tuple)
    - Source IP
    - Destination IP
    - Source Port
    - Destination Port
    - Protocol
- Data from the bytestream can be presented to the application when all data before has been received and presented
  - Recall: TCP presents data to the application as a bytestream, so the order must be preserved from one end to the other, even if packets are received out of order

TCP: Sending and Receiving Data

- Byte *i* of the bytestream is represented by sequence number *x* + *i*
  - The first byte is byte *i* = 1, since sequence number *x* was used for the SYN packet and *y* for the SYN-ACK packet
- A packet's sequence number is the number of the first byte of its data
  - This number is from the sender's set of sequence numbers
- A packet's ACK number, if the ACK flag is set, is the number of the byte immediately after the last received byte
  - This number is from the receiver's set of sequence numbers
  - This would be (sequence number) + (length of data) for the last received packet

TCP: Sending and Receiving Data



TCP: Retransmission

- If a packet is dropped (lost in transit):
  - The recipient will not send an ACK, so the sender will not receive the ACK
  - The sender repeatedly tries to send the packet again until it receives the ACK
- If a packet is received, but the ACK is dropped:
  - The sender tries to send the packet again since it didn't receive the ACK
  - The recipient ignores the duplicate data and sends the ACK again
- When packets are dropped in TCP, TCP assumes that there is congestion and sends the data at a slower rate

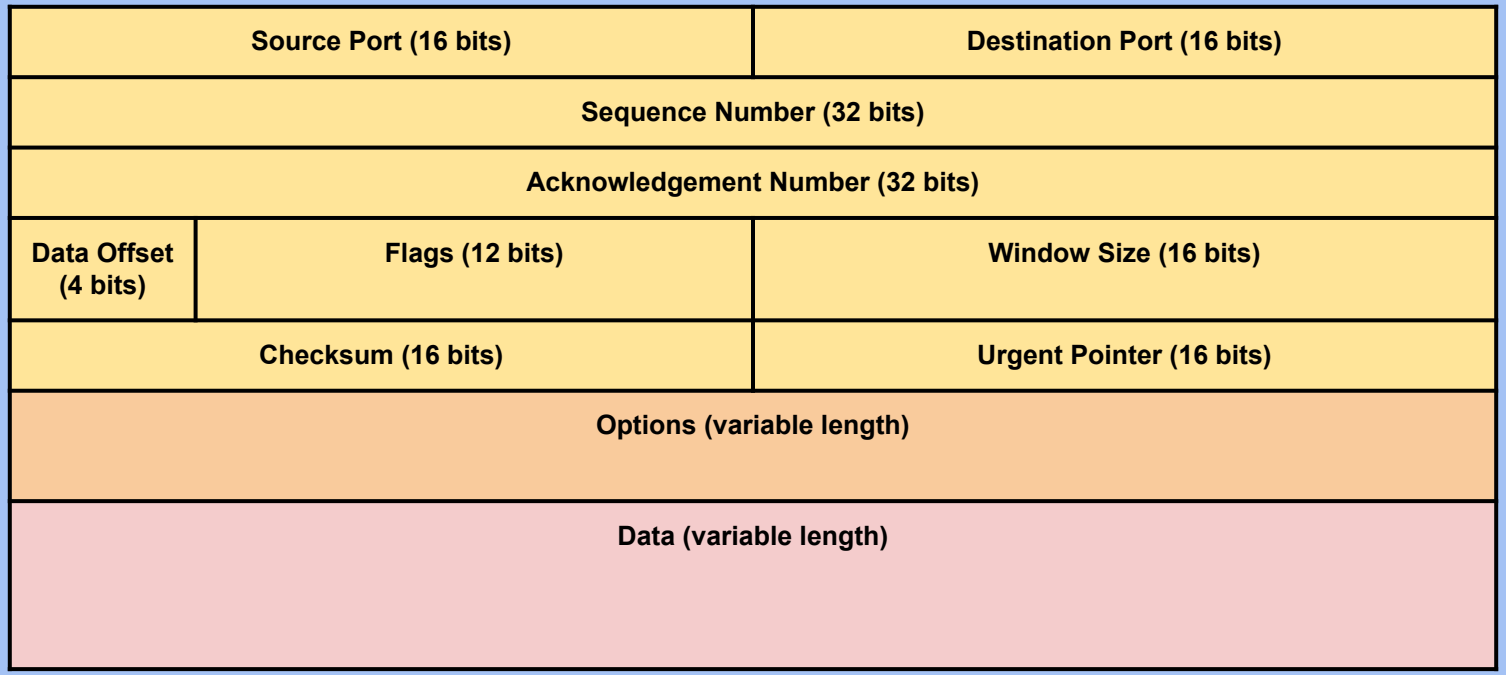
TCP: Ending/Aborting a Connection

- To **end** a connection, one side sends a packet with the FIN (finish) flag set, which should then be acknowledged
  - This means “I will no longer be sending any more packets, but I will continue to receive packets”
  - Once the other side is no longer sending packets, it sends a packet with the FIN flag set
- To **abort** a connection, one side sends a packet with the RST (reset) flag set
  - This means “I will no longer be sending nor receiving packets on this connection”
  - RST packets are not acknowledged since they usually mean that something went wrong

TCP Flags

- ACK
  - Indicator that the user is acknowledging the receipt of something (in the ack number)
  - Pretty much always set except the very first packet
- SYN
  - Indicator of the beginning of the connection
- FIN
  - One way to end the connection
  - Requires an acknowledgement
  - No longer sending packets, but will continue to receive
- RST
  - One way to end a connection
  - Does not require an acknowledgement
  - No longer sending or receiving packets

TCP Packet Structure

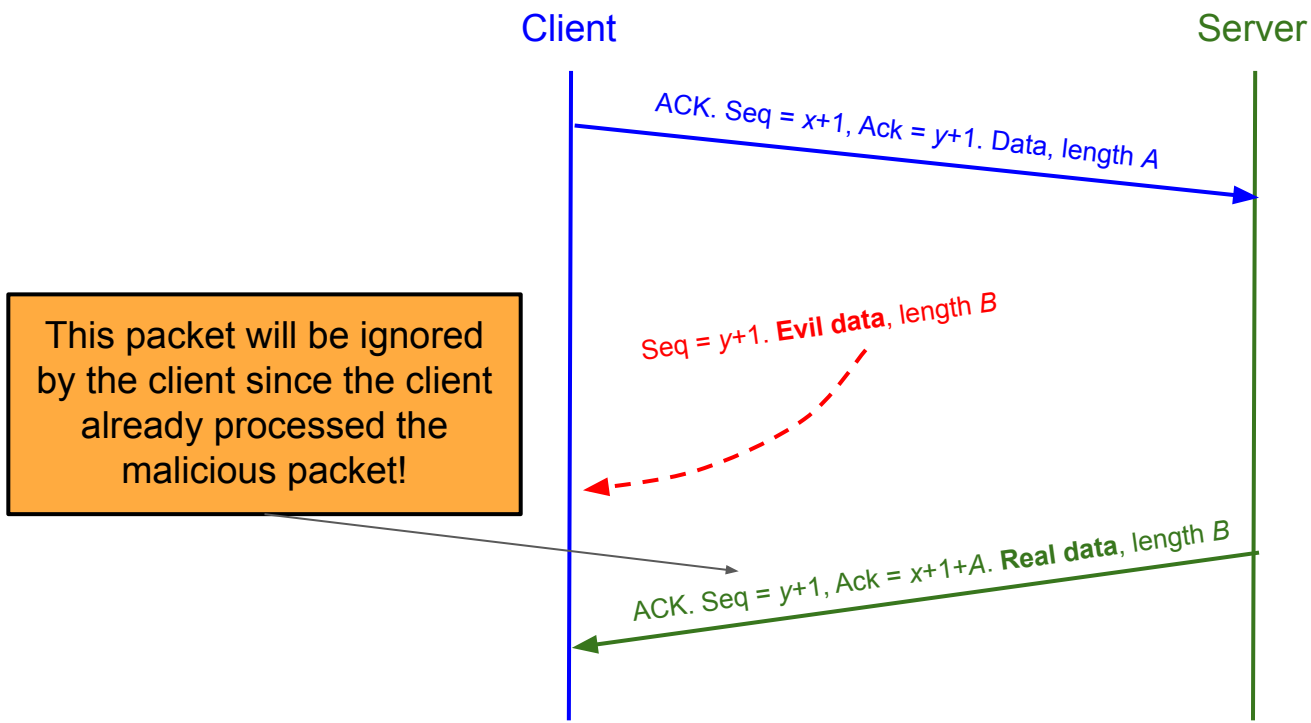


TCP segment header

TCP Attacks

- **TCP hijacking**: Tampering with an existing session to modify or inject data into a connection
  - **Data injection**: Spoofing packets to inject malicious data into a connection
    - Need to know: The sender's sequence number
    - Easy for MITM and on-path attackers, but off-path attackers must guess 32-bit sequence number (called **blind injection/hijacking**, considered difficult)
    - For on-path attackers, this becomes a race condition since they must beat the server's legitimate response
  - **RST injection**: Spoofing a RST packet to forcibly terminate a connection
    - Same requirements as packet injection, so easy for on-path and MITM attackers, but hard for off-path attackers
    - Often used in censorship scenarios to block access to sites

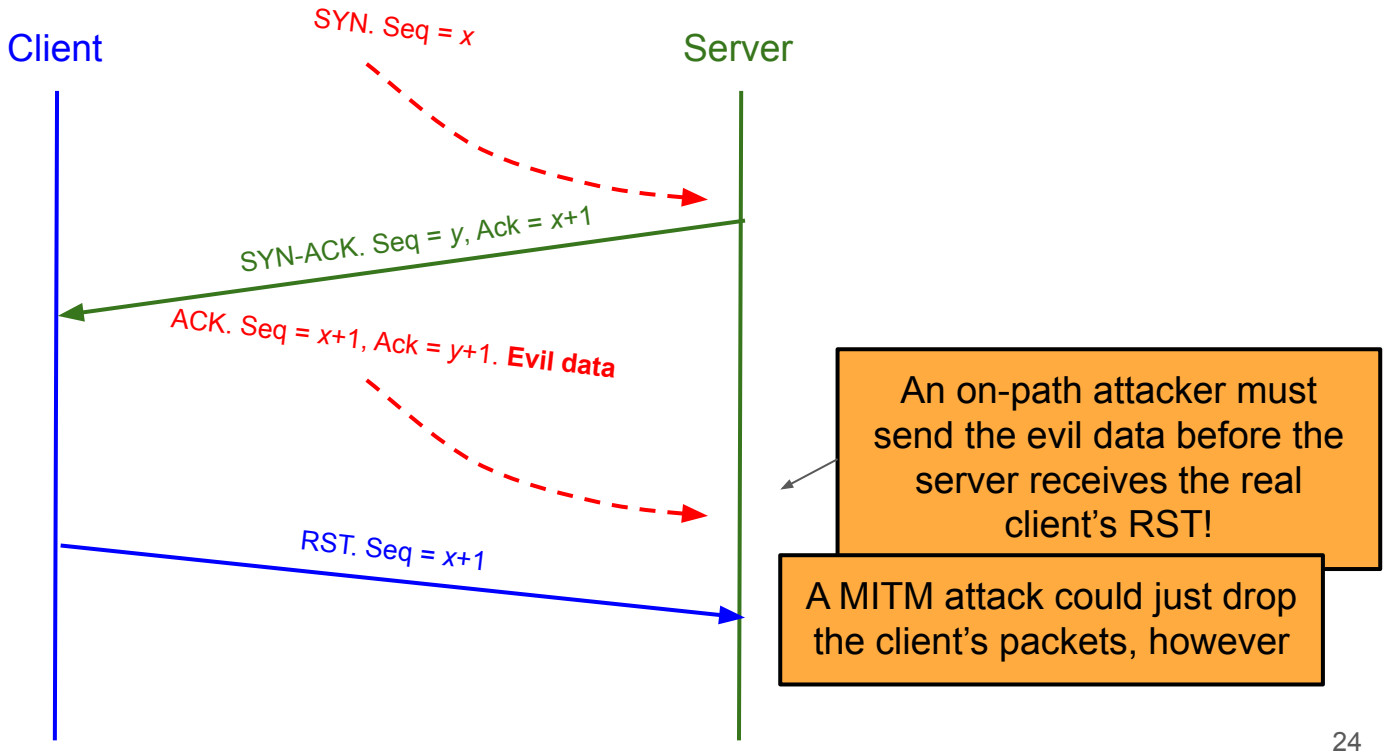
TCP Data Injection



TCP Attacks

- **TCP spoofing**: Spoofing a TCP connection to appear to come from another source IP address
  - Recall: IP packets can often be spoofed if the AS doesn't block source addresses
  - Need to know: Sequence number in the server's response SYN-ACK packet
  - Easy for MITM and on-path attackers, but off-path attackers must guess 32-bit sequence number (called **blind spoofing**, also considered difficult)
  - For on-path attackers, this is a race condition, since the real client will send a RST upon receiving the server's SYN-ACK!

TCP Spoofing



TCP Attacks

- TCP provides no confidentiality or integrity
  - Instead, we rely on higher layers (like TLS, more on this next time) to prevent those kind of attacks
- Defense against off-path attackers rely on choosing random sequence numbers
  - Bad randomness can lead to trivial off-path attacks: TCP sequence numbers used to be based on the system clock!

User Datagram Protocol (UDP)

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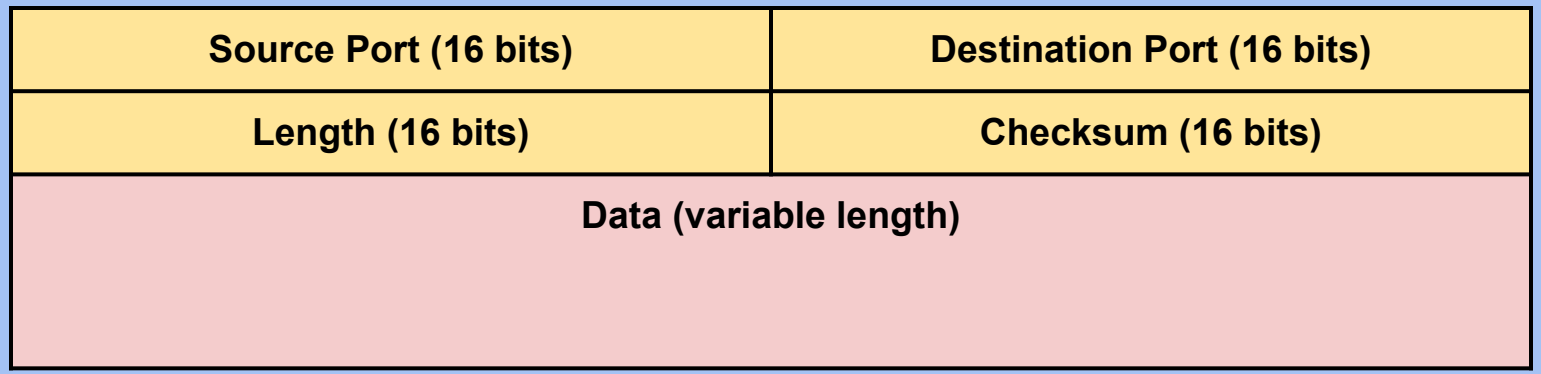
User Datagram Protocol (UDP)

- Provides a **datagram** abstraction
  - A message, sent in a single layer 3 packet (though layer 3 could fragment the packet)
  - Max size limited by max size of packet
  - Applications break their data into datagrams, which are sent and received as a single unit
    - Contrast with TCP, where the application can use a bytestream abstraction
- No reliability or ordering guarantees, but adds ports
  - It still has *best effort* delivery
- Much faster than TCP, since there is no 3-way handshake
  - Usually used by low-latency, high-speed applications where errors are okay (e.g. video streaming, games)

UDP Attacks

- No sequence numbers, so relatively easy to inject data into a connection or spoof connections
  - Higher layers must provide their own defenses against these attacks!

UDP Packet Structure



UDP datagram header

Summary

- Transmission Control Protocol (TCP): Reliably sending packets
  - 3-way handshake: Client sends SYN, server sends SYN-ACK, client sends ACK
  - Provides reliability, ordering, and ports
  - Attack: TCP hijacking through data injection or RST injection
    - Blind attacks must guess the client's or server's sequence numbers
  - Attack: TCP spoofing by sending a spoofed SYN packet
    - Blind attacks must guess the server's sequence number
- User Datagram Protocol (UDP): Non-reliably sending packets
  - No reliability or ordering, only ports
  - Same injection and spoofing attacks as TCP, but easier