

BGP and Transport Layer (TCP and UDP)

CS 161 Spring 2024 - 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

Today: Transport Layer Protocols

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

Border Gateway Protocol (BGP)

Textbook Chapter 29

Review: Internet Protocol (IP)

- **Internet Protocol (IP):** The universal layer-3 protocol that all devices use to transmit data over the Internet
- **IP address:** An address that identifies a device on the Internet
 - IPv4 is 32 bits (e.g. 35.163.72.93)
 - IPv6 is 128 bits (e.g. 2607:f140:8801:0000:0000:0000:0001:0023)
 - Shorthand: omit sets of zeros: 2607:f140:8801::1:23
 - Globally unique from any single perspective
 - For now, you can think of them as just being globally unique
 - IP addresses help nodes make decisions on where to forward the packet

Subnets

- Recall: Layer 3 routes packets across multiple nodes on different LANs
 - A packet might make many hops across different local networks before it can reach its destination
- IP routes by **subnets**, which are groups of addresses with a common prefix
 - A subnet is written as a prefix followed by the length of the prefix
 - Example: **128.32.0.0/16** is an IPv4 subnet with all addresses that begin with the prefix of **128.32.***
 - Since an IPv4 is a 32-bit address and there are 16 bits in the prefix, this subnet represents $2^{32 - 16} = 2^{16}$ addresses

Routing Packets

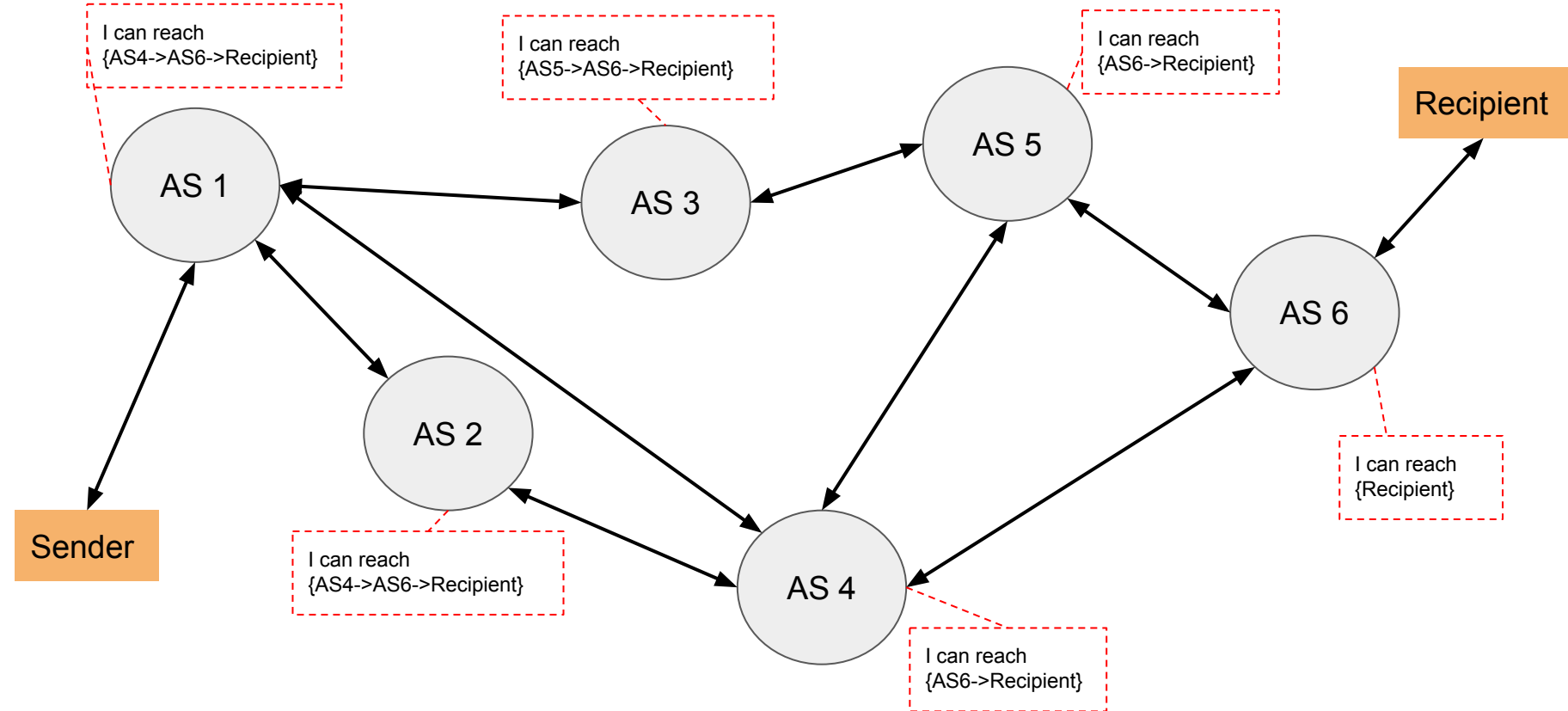
- To send a packet to a computer within the local network:
 - Verify that the destination IP is in the same subnet
 - Use ARP (or contact a switch) to get the destination MAC address
 - Send the packet directly to the destination using the destination MAC address
- To send a packet to a computer that is not within the local network:
 - Send the packet to the gateway
 - Past the gateway, the packet goes to the Internet
 - It's the gateway's job to deliver the packet closer to the destination

Autonomous Systems

- Once your system sends the packet to the gateway, the packet has to be routed through the Internet
- The Internet is a network of networks, comprised of many **autonomous systems (AS)**
 - Each AS handles its own internal routing
 - Each AS is uniquely identified by its **autonomous system number (ASN)**
 - Each AS is comprised of one or more LANs
 - The AS can forward packet to other connected ASes
- The protocol for communicating between different Autonomous Systems is **Border Gateway Protocol (BGP)**
 - Each router announces what networks it can provide and the path onward from the router
 - The most precise route with the shortest path and no loops is the preferred route

BGP

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IP and BGP Attacks

- Each AS implicitly trusts the surrounding ASes and accepts advertised routes
- **IP spoofing:** Malicious clients can send IP packets with source IP values set to a spoofed value
 - Edge ASes should block packets with source IPs set to the wrong value, but some don't
 - Enables packets that look like they're coming from someone else!
 - We rely on defenses provided by higher layers to further prevent this ("defense in depth")
- **BGP hijacking:** A malicious autonomous system can lie and claims itself to be responsible for a network which it isn't
 - Example: AS3 broadcasts that it is responsible for 128.32.0.0/16
 - Now, the malicious AS can act as a MITM for traffic to 128.32.0.0!
 - No real defenses on this level, so we rely on defenses from higher levels

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

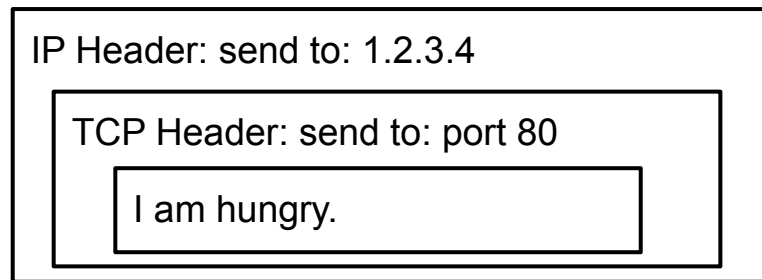
Ports: An Analogy

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- 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 Carol?
- 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

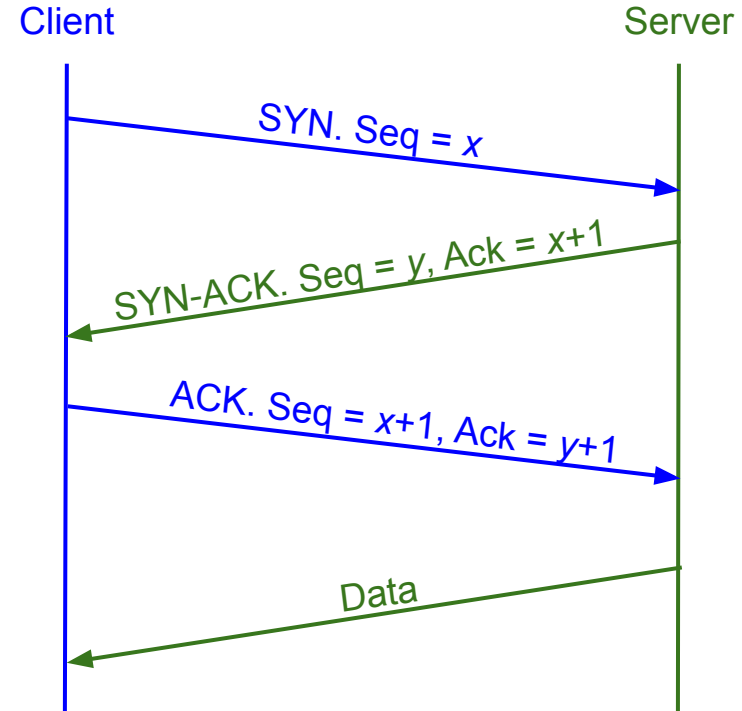
Messages from the client are numbered starting at 50.

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”



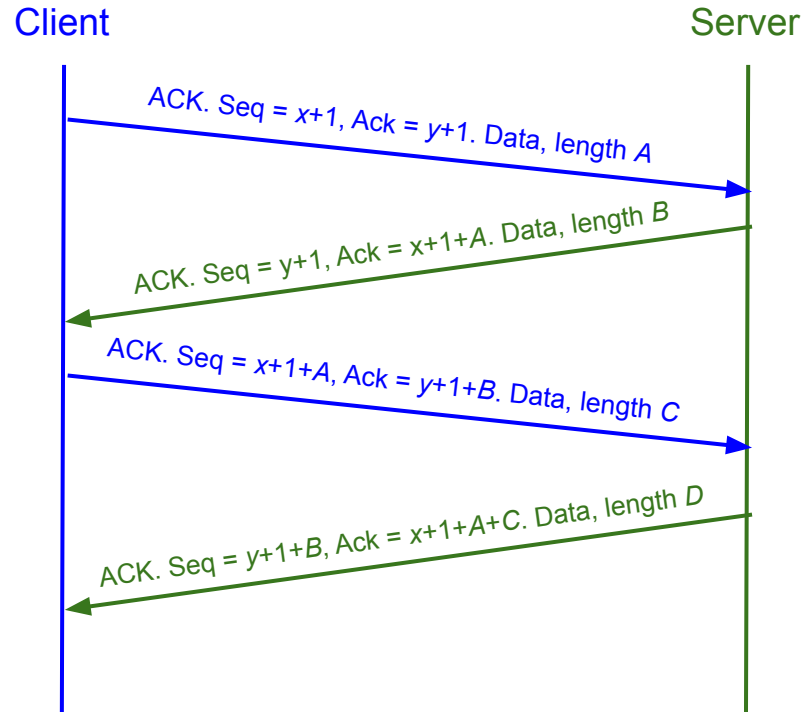
TCP: Sending and Receiving Data

- 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

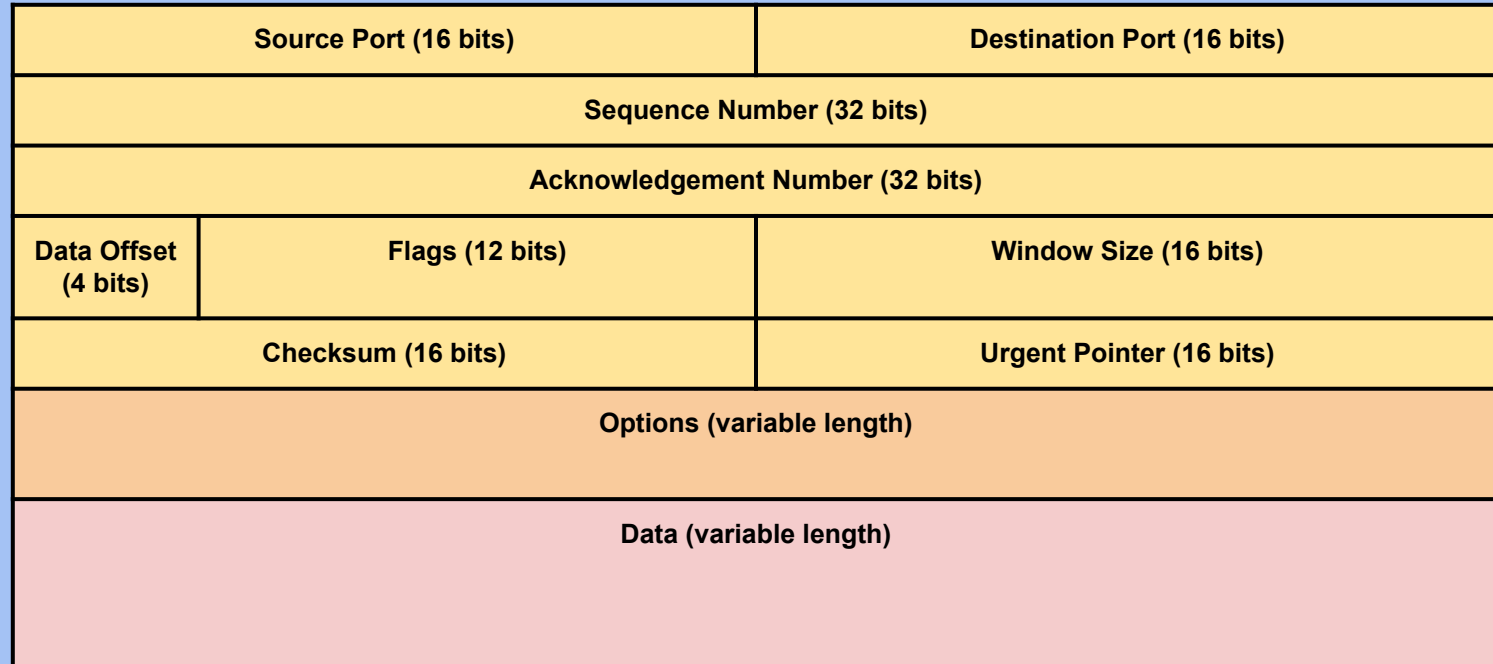
- To **end** a connection, one side sends a packet with the FIN (finish) flag set, which should then be acknowledged
 - This means “I will no longer be sending any more packets, but I will continue to receive packets”
 - Once the other side is no longer sending packets, it sends a packet with the FIN 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

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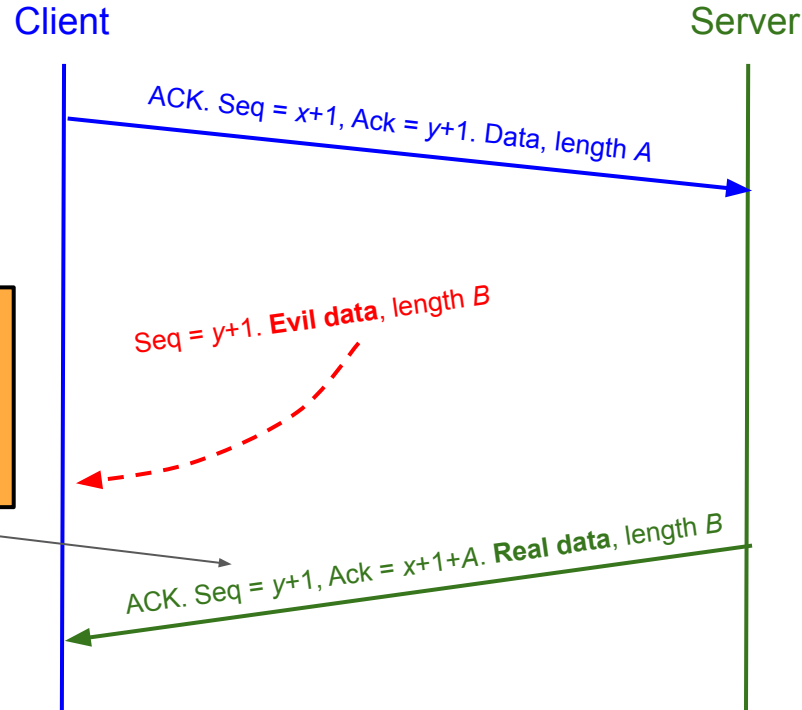
TCP segment header

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

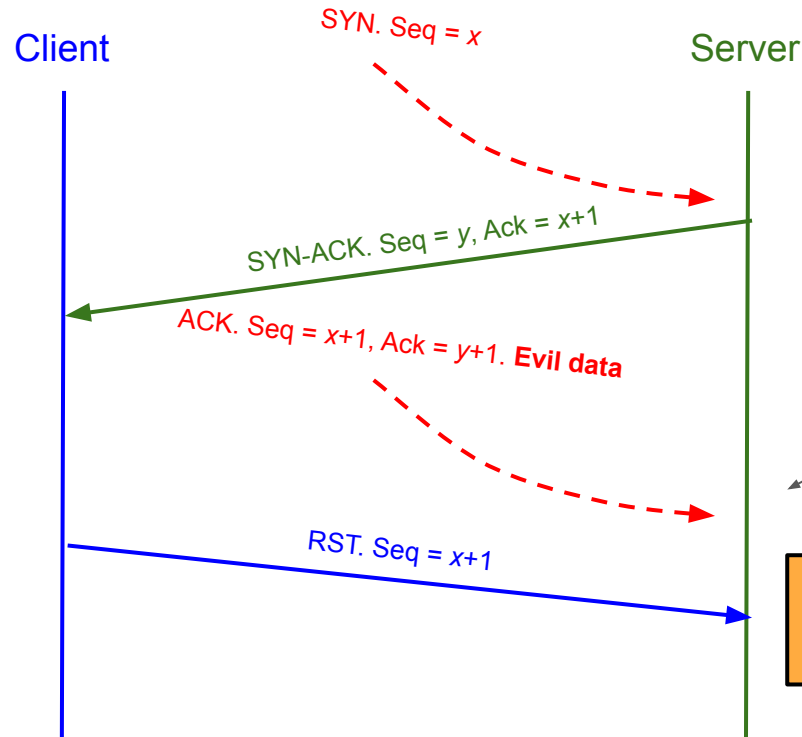
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TCP Attacks

- **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



An on-path attacker must send the evil data before the server receives the real client's RST!

A MITM attack could just drop the client's packets, however

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

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Source Port (16 bits)	Destination Port (16 bits)
Length (16 bits)	Checksum (16 bits)
Data (variable length)	

UDP datagram header

Summary

- 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)

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