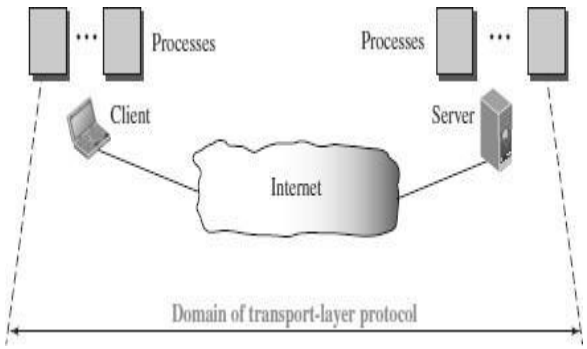
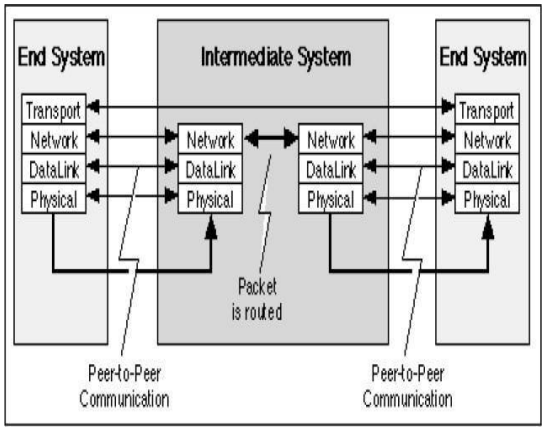
Transport Layer

1. INTRODUCTION

The **Transport Layer** is the fourth layer in the OSI model and plays a central role in the Internet model. It serves as a crucial intermediary, ensuring that data is transmitted smoothly across the network.

1. **Position in the OSI Model:**
    - As the fourth layer, the transport layer bridges the gap between the higher layers (like the session layer) and the lower layers (such as the network layer).
    - It responds to service requests from the session layer and, in turn, issues service requests to the network layer.
2. **Core Functions:**
    - **Transparent Data Transfer:** The transport layer ensures that data is transferred transparently between hosts, handling the complexities of data segmentation, reassembly, and error correction.
    - **End-to-End Control:** It provides robust end-to-end control, ensuring that data is reliably delivered from the source to the destination, across the entire network.
3. **Quality of Service (QoS):**
    - The transport layer is responsible for maintaining the quality of service required by the application program, managing factors like speed, reliability, and efficiency.
4. **End Systems Implementation:**
    - This layer is the first true end-to-end layer in the OSI model, meaning it is implemented in all End Systems (ES), ensuring consistent communication across the network.





2. Transport Layer Functions and Services

The **Transport Layer** is the bridge between the network layer and the application layer, playing a pivotal role in managing data transmission across the network. Its key functions and services ensure that data is delivered reliably, efficiently, and correctly to the intended application process. Let's explore these functions:

1. Process-to-Process Communication

- **Purpose:** The transport layer ensures that data reaches the correct application process on the destination host, not just the correct machine. This function is crucial because multiple processes can run on the same machine, each requiring specific data.
- **Mechanism:**
    - **Multiplexing:** The transport layer collects data from various application processes, forms data packets, and adds unique source and destination port numbers to each packet. This multiplexing allows multiple data streams to be handled simultaneously.
    - **Network Socket:** The combination of an IP address and port number forms a network socket, a unique identifier for the process-to-process communication, ensuring that data is directed to the correct process at the receiving end.

2. Addressing: Port Numbers

- **Role of Ports:** Port numbers serve as specific identifiers within a host, allowing multiple applications to use the network concurrently without interference.
- **Types of Port Numbers:**
    - **Well-Known Ports (0-1023):** Reserved for standard services like HTTP (port 80) and FTP (port 21), these are used by server processes to listen for incoming requests.
    - **Registered Ports (1024-49151):** These are available for user or software applications that are not standard but are still widely recognized.
    - **Ephemeral Ports (49152-65535):** Temporarily assigned to client processes during communication sessions, these ports are dynamic and short-lived, used for establishing connections.

3. Encapsulation and Decapsulation

- **Encapsulation (Sender Site):**
    - **Process:** When sending data, the transport layer encapsulates the message by attaching a transport-layer header, which includes important control information such as port numbers and sequence numbers.
- **Decapsulation (Receiver Site):**
    - **Process:** At the receiving end, the transport layer removes the header

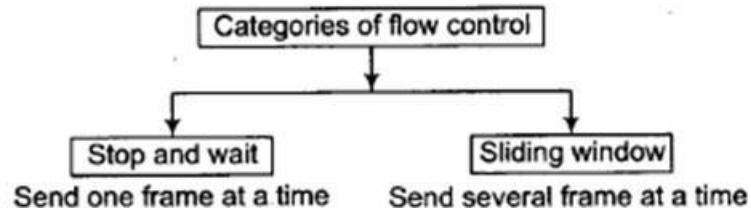
(decapsulation) and passes the original data to the appropriate application layer process, ensuring that the message is delivered intact and in the correct sequence.

4. Multiplexing and Demultiplexing

- **Multiplexing:**
  - The transport layer at the source gathers data from multiple applications and combines it into a single data stream, which is then sent over the network. This process allows multiple applications to share the same network resources effectively.
- **Demultiplexing:**
  - At the destination, the transport layer splits the incoming data stream back into individual data streams for each application, delivering the right data to the right process.

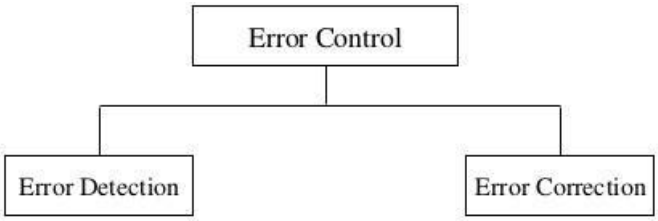
5. Flow Control

- **Purpose:** Flow control prevents the receiver from becoming overwhelmed by regulating the speed of data transmission. This is particularly important when the sending and receiving devices have different data processing speeds.
- **Mechanism:** The transport layer adjusts the rate of data flow based on feedback from the receiver, ensuring that data is transmitted at a manageable pace. This prevents data loss and ensures smooth communication.



6. Error Control

- **Purpose:** Error control mechanisms are essential for ensuring data integrity and reliability during transmission. Errors can occur due to various reasons, including network noise, signal degradation, or packet loss.
- **Key Functions:**
  - **Detection and Correction:** The transport layer detects errors in received data packets, corrects them when possible, and requests retransmission of any lost or corrupted packets.
  - **Duplicate Handling:** It identifies and discards duplicate packets to prevent redundant data from being processed.
  - **Buffering:** Out-of-order packets are buffered until all missing packets are



received, ensuring that data is delivered in the correct sequence.

7. Congestion Control

- **Purpose:** Congestion control ensures that the network operates efficiently even under heavy load. Without congestion control, network performance can degrade, leading to slow communication and data loss.
- **Mechanisms:**
    - **Open Loop Control:** Prevents congestion by regulating traffic before it enters the network, based on predetermined policies.
    - **Closed Loop Control:** Manages congestion after it occurs by dynamically adjusting data transmission rates and rerouting traffic to alleviate network bottlenecks.

3. Port Numbers in the Transport Layer

Port numbers are critical components of the transport layer, serving as unique identifiers for processes running on hosts. These numbers enable process-to-process communication by providing end-to-end addressing at the transport layer. They also facilitate multiplexing and demultiplexing of data, allowing multiple applications to share the same network connection without interference.

Overview of Port Numbers

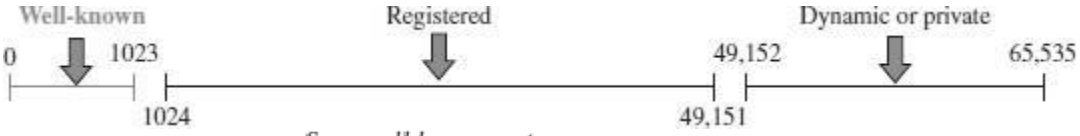
- **Definition:** Port numbers are 16-bit integers ranging from 0 to 65,535.
- **Purpose:** They are used to identify specific processes on a host, allowing communication between client and server processes.
- **Responsibility:** The transport layer assigns port numbers to processes, ensuring that data is directed to the correct application.

Port Number Ranges

ICANN (Internet Corporation for Assigned Names and Numbers) has classified port numbers into three distinct ranges:

1. **Well-Known Ports (0-1023)**
    - **Purpose:** These are permanent port numbers reserved for server processes. Every client process must know the well-known port number of the corresponding server to establish communication.
    - **Examples:**

        - **HTTP:** Port 80
        - **FTP:** Port 21
        - **Daytime Server:** Port 13 (used by the daytime client process, which may use an ephemeral port number like 52,000).
    - **Characteristics:**
        - These port numbers are globally recognized and standardized.
        - They cannot be chosen randomly by users.
2. **Registered Ports (1024-49,151)**
    - **Purpose:** Registered ports are not controlled or strictly assigned but are registered for use by user or software applications.
    - **Characteristics:**
        - These ports are often used by applications that are not part of standard services but are still widely recognized and used.
        - They allow more flexibility compared to well-known ports.
3. **Ephemeral Ports (Dynamic Ports) (49,152-65,535)**
    - **Purpose:** These are temporary port numbers used by client processes. The term "ephemeral" refers to their short-lived nature, as client processes typically have a brief lifespan.
    - **Characteristics:**
        - Ephemeral ports are neither controlled nor registered, making them available for temporary or private use.
        - They are automatically assigned by the operating system when a client process initiates a connection.
        - For example, while the daytime client process, a well-known client program, can use an ephemeral (temporary) port number, 52,000, to identify itself, the daytime server process must use the well-known (permanent) port number 13.



Some well-known ports

Port	*Protocol*	*Description*
7	Echo	Echoes back a received datagram
9	Discard	Discards any datagram that is received
11	Users	Active users
13	Daytime	Returns the date and the time
17	Quote	Returns a quote of the day
19	Chargen	Returns a string of characters
20	FTP-data	File Transfer Protocol
21	FTP-21	File Transfer Protocol
23	TELNET	Terminal Network
25	SMTP	Simple Mail Transfer Protocol
53	DNS	Domain Name Service
67	DHCP	Dynamic Host Configuration Protocol
69	TFTP	Trivial File Transfer Protocol
80	HTTP	HyperText Transfer Protocol
111	RPC	Remote Procedure Call
123	NTP	Network Time Protocol
161	SNMP-server	Simple Network Management Protocol
162	SNMP-client	Simple Network Management Protocol

How Port Numbers Work

- **Multiplexing and Demultiplexing:**
  - **Multiplexing:** The transport layer at the sender's side combines data from multiple applications, assigns appropriate port numbers, and sends it over the network.
  - **Demultiplexing:** At the receiving end, the transport layer uses the port numbers to deliver the data to the correct application process.
- **End-to-End Communication:**
  - **Client-Server Model:** In a typical client-server model, the client initiates communication by sending a request to a server's well-known port. The client uses an ephemeral port number for its process, allowing multiple clients to connect to the same server without conflicts.

4. TRANSPORT LAYER PROTOCOLS

Three protocols are associated with the Transport layer. They are UDP –User Datagram Protocol TCP – Transmission Control Protocol SCTP - Stream Control Transmission Protocol Each protocol provides a different type of service and should be used appropriately.

UDP - UDP is an unreliable connectionless transport-layer protocol used for its simplicity and efficiency in applications where error control can be provided by the application-layer process.

TCP - TCP is a reliable connection-oriented protocol that can be used in any

application where reliability is important.

SCTP - SCTP is a new transport-layer protocol designed to combine some features of UDP and TCP in an effort to create a better protocol for multimedia communication.

4.1 User Datagram Protocol (UDP)

Overview

- **User Datagram Protocol (UDP)** is a connectionless and unreliable transport layer protocol that provides minimal services beyond the network layer's best-effort delivery.
- Unlike TCP, UDP does not establish a connection before sending data, making it faster and more efficient for certain types of communication where reliability is not a primary concern.

Key Characteristics of UDP

1. **Connectionless Communication**
    - UDP does not establish a connection before transmitting data. Each message (datagram) is sent independently of any other, and there is no guarantee that the data will arrive in the correct order, or at all.
    - This approach reduces the overhead associated with maintaining a connection, making UDP suitable for applications where speed is more critical than reliability.
2. **Unreliable Delivery**
    - UDP does not provide mechanisms for error correction, retransmission, or acknowledgment of received packets. If a packet is lost, duplicated, or arrives out of order, UDP does not attempt to correct the situation.
    - This characteristic is beneficial for applications where occasional data loss is acceptable, or where the application itself handles error detection and correction.
3. **Minimal Overhead**
    - UDP adds minimal overhead to the data being sent, making it lightweight and efficient. The UDP header is only 8 bytes long, compared to TCP's 20-byte header.
    - This minimal overhead is particularly advantageous in scenarios where bandwidth is limited or when dealing with small data transmissions.
4. **Process-to-Process Communication**
    - UDP extends IP's host-to-host communication by enabling communication between individual processes on the source and destination machines.
    - Each UDP datagram includes a source and destination port number, which allows data to be directed to the correct application process on the receiving host.
5. **No Flow Control**
    - Unlike TCP, UDP does not implement flow control. It does not adjust the rate of data transmission based on the receiver's ability to process the

incoming data.
    - This lack of flow control can lead to data being lost if the sender overwhelms the receiver, but it also ensures that the data is sent as quickly as possible.
6. **No Congestion Control**
    - UDP does not have built-in mechanisms to avoid network congestion. It does not adjust its transmission rate based on network conditions.
    - This absence of congestion control can lead to network congestion in high-traffic scenarios but allows for consistent data transmission in real-time applications.
7. **Use Cases**
    - **Real-Time Applications:** UDP is ideal for real-time applications such as video streaming, online gaming, and voice-over-IP (VoIP), where timely delivery of data is more important than perfect accuracy.
    - **Simple Query-Response Protocols:** Protocols like DNS (Domain Name System) and DHCP (Dynamic Host Configuration Protocol) use UDP because the overhead of establishing a connection is unnecessary for their simple, short-lived queries.
    - **Broadcast and Multicast:** UDP supports broadcast and multicast transmissions, making it useful for sending data to multiple recipients simultaneously, such as in live video broadcasts.

UDP PORTS

Table 4.1 Well-known port numbers used by UDP

Port	Protocol	Description
1	Echo	Echoes a received datagram back to the sender
9	Discard	Discards any datagram that is received
11	Users	Active users
13	Daytime	Returns the date and the time
17	Quote	Returns a quote of the day
19	Chargen	Returns a string of characters
53	Name server	Domain Name Service
67	BOOTPs	Server port to download bootstrap information
68	BOOTPc	Client port to download bootstrap information
69	TFTP	Trivial File Transfer Protocol
111	RPC	Remote Procedure Call
123	NTP	Network Time Protocol
161	SNMP	Simple Network Management Protocol
162	SNMP	Simple Network Management Protocol (trap)

UDP DATAGRAM (PACKET) FORMAT

UDP Datagram (Packet) Format

UDP (User Datagram Protocol) is a connectionless protocol that sends data in discrete packets called user datagrams. These datagrams have a fixed-size header of 8 bytes, composed of four fields, each 2 bytes (16 bits) long. Below is a breakdown of each field in

the UDP packet:

1. Source Port Number

- **Length**: 16 bits
- **Purpose**: Identifies the sending process's port number on the source host.
- **Description**:
    - This field specifies the port number used by the process running on the source host.
    - If the source host is a client (sending a request), this port number is typically a temporary (ephemeral) port chosen by the UDP protocol on the source host.
    - If the source host is a server (sending a response), the port number is usually a well-known port number (a predefined port number associated with a specific service).

UDP Header Format Notes

UDP (User Datagram Protocol) is a lightweight, connectionless protocol used for sending data as discrete packets known as user datagrams. Each UDP datagram consists of a fixed-size header of 8 bytes (64 bits), followed by the data payload. The header is composed of four fields, each 2 bytes (16 bits) long. Below is a detailed explanation of each field in the UDP header:

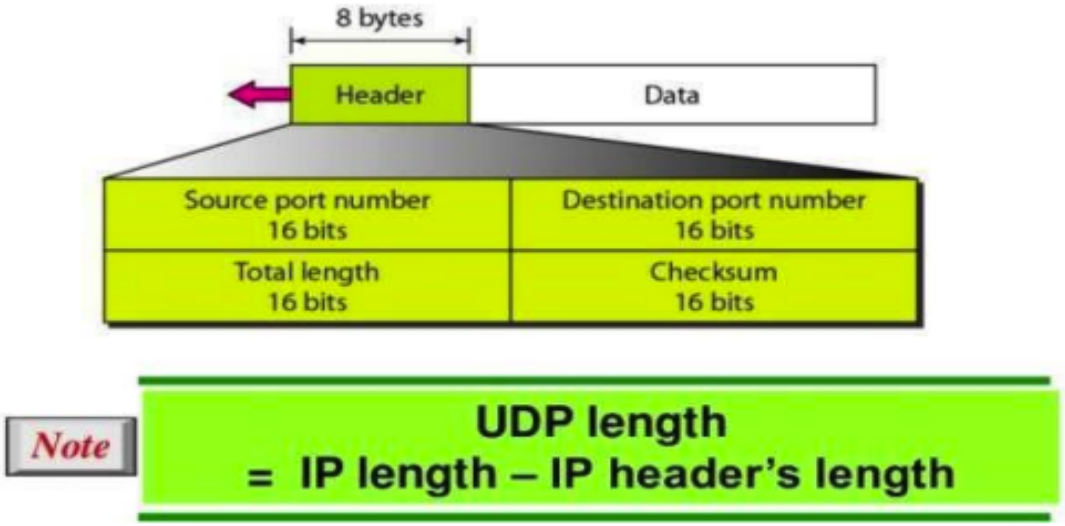


Figure 4.9 User datagram format

1. Source Port Number (16 bits)

- **Purpose**: Identifies the port number of the process on the source host.
- **Details**:
    - If the source host is a client (sending a request), this port number is typically a temporary (ephemeral) port chosen by the UDP protocol on the source host.

- If the source host is a server (sending a response), the port number is usually a well-known port number (a predefined port number associated with a specific service).

2. Destination Port Number (16 bits)

- **Purpose**: Identifies the port number of the process on the destination host.
- **Details**:
  - If the destination host is a server (receiving a request), the port number is typically a well-known port number corresponding to the requested service.
  - If the destination host is a client (receiving a response), the port number is usually an ephemeral port copied from the original request packet sent by the client.

3. Length (16 bits)

- **Purpose**: Specifies the total length of the UDP datagram, including the header and data.
- **Range**: 0 to 65,535 bytes.
- **Details**:
  - This field defines the total size of the datagram. Although the IP header also contains a length field, the UDP length field allows the UDP layer to determine the data length directly, without relying on the IP layer.
  - The formula to calculate the length of the UDP datagram when encapsulated in an IP datagram is: UDP Length=IP Length−IP Header

4. Checksum (16 bits)

- **Purpose**: Used for error-checking of the datagram to ensure data integrity.
- **Components**:
  - **Pseudoheader**: A combination of fields from the IP header (source IP, destination IP, protocol number, and UDP length) used to ensure the datagram is delivered to the correct protocol.

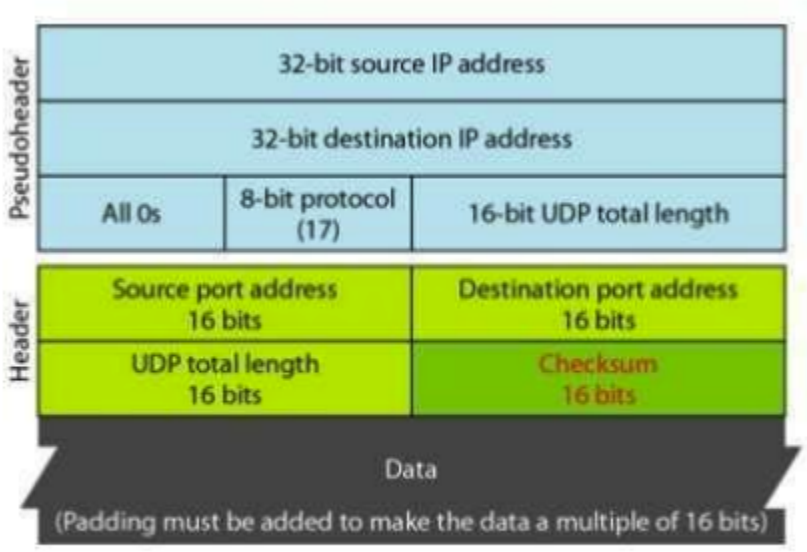


Figure 4.10 Pseudoheader for checksum calculation

  - **UDP Header**: The 8-byte header of the UDP packet.
  - **Data**: The actual application data contained in the datagram.
- **Function**: The checksum is computed over the pseudoheader, UDP header, and data. If the checksum at the receiver does not match, the packet is discarded.

5. Data (Variable Length)

- **Purpose**: Contains the application data being transmitted.
- **Size**: Varies depending on the application, up to a maximum of 65,507 bytes (subtracting the 8-byte header from the 65,535-byte total length).

Summary:

The UDP header is designed for simplicity, allowing for quick data transmission with minimal overhead. It is particularly well-suited for applications where speed is prioritized over reliability, such as in streaming media, online gaming, and DNS queries. The header provides essential routing and error-checking information, while the data field carries the actual content being transmitted.

UDP Services Overview

1. Process-to-Process Communication

- UDP enables communication between processes using **socket addresses**, which are a combination of **IP addresses and port numbers**.

2. Connectionless Service

- **No Connection Establishment/Termination**: UDP does not establish or terminate connections, making it connectionless.

- **Independent Datagrams**: Each user datagram is independent, with no relationship to others, even if sent from the same source to the same destination.
- **Unnumbered Datagrams**: Datagrams are not numbered, and each can travel on a different path.

3. Flow Control

- **Simple Protocol**: UDP does not implement flow control, meaning there's no mechanism to prevent the receiver from being overwhelmed with messages.
- **No Window Mechanism**: Unlike TCP, UDP does not use a window mechanism for flow control.
- **User Responsibility**: The application using UDP must implement flow control if necessary.

4. Error Control

- **Minimal Error Control**: UDP provides error control only through a checksum.
- **No Feedback**: The sender does not know if a message is lost or duplicated.
- **Checksum Handling**: If the checksum detects an error, the datagram is silently discarded.
- **User Responsibility**: Applications using UDP must handle error control if required.

5. Checksum

- **Calculation**: The UDP checksum covers three areas:
  - The **pseudoheader** (part of the IP header relevant to UDP),
  - The **UDP header**, and
  - The **data** from the application layer.
- **Optional Inclusion**: The sender can choose to include or exclude the checksum:
  - **No Checksum**: If excluded, the checksum field is filled with all zeros.
  - **Checksum Calculation**: If the calculated checksum is zero, it is sent as all ones to differentiate from the "no checksum" case.

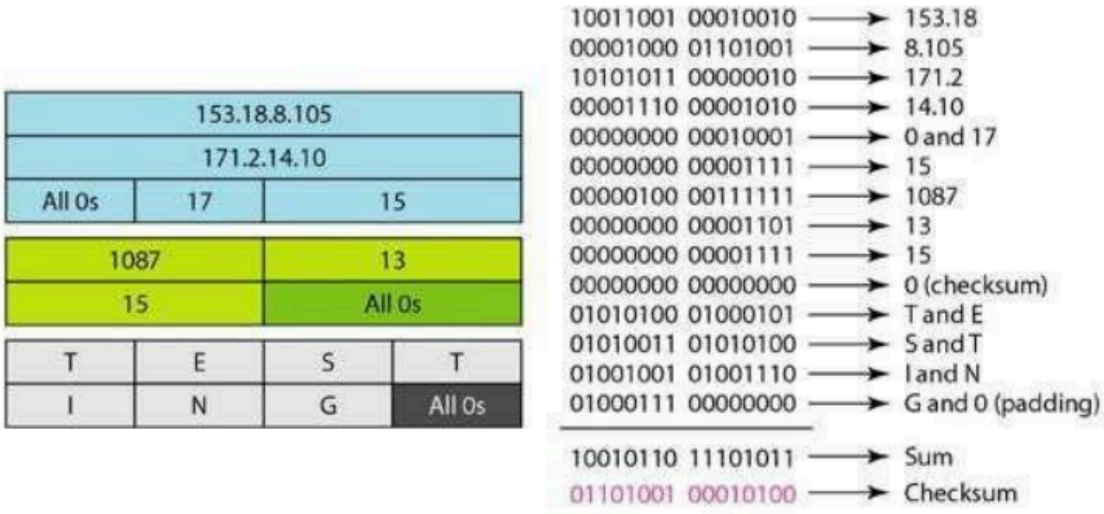


Figure 4.11 Checksum calculation of a simple UDP user datagram

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6. Congestion Control

- **No Congestion Control**: UDP does not include congestion control mechanisms.
- **Assumptions**: UDP assumes that packets are small and sporadic, minimizing the risk of network congestion.
- **Potential Issues**: This assumption may not hold true for applications like real-time audio and video streaming, which could potentially cause congestion.

7. Encapsulation and Decapsulation

- **Message Transmission**: UDP encapsulates messages from the application layer into datagrams before sending them. Upon receipt, it decapsulates these datagrams to deliver the message to the appropriate process.

8. Queuing

- **Port Queues**: UDP uses queues associated with ports to manage incoming and outgoing messages.
  - **Client Side**: When a process requests a port number from the operating system, it may create both incoming and outgoing queues.
  - **Implementation Variations**: Some systems create only an incoming queue for each process, while others may create both types.

9. Multiplexing and Demultiplexing

- **Multiple Processes**: On a host, multiple processes can use UDP simultaneously.
- **Handling Multiple Requests**: UDP handles multiple processes by multiplexing (combining) and demultiplexing (separating) the data streams based on socket addresses.

Q. Example UDP Header in C0A8 0035 0028 1A2B
A: **Source Port Number (C0A8)**: This is the port number of the sending process.

- Convert from hexadecimal to decimal: $(C0A8)_{16}=(49320)_{10}$
- So, the source port number is **49320**.

Destination Port Number (0035): This is the port number of the receiving process.

- Convert from hexadecimal to decimal: $(0035)_{16}=(53)_{10}$
- So, the destination port number is **53** (common for DNS).

Length (0028): This is the total length of the UDP datagram, including the header and data.

- Convert from hexadecimal to decimal: $(0028)_{16}=(40)_{10}$
- So, the total length is **40 bytes**.

Checksum (1A2B): This is the checksum value used to verify data integrity.

- The checksum is calculated over the entire UDP packet, including a pseudoheader derived from the IP header. It's often computed and verified by networking tools.

Applications of UDP

1. **Simple Network Management Protocol (SNMP):**
    - UDP is commonly used in network management processes like **SNMP**, where low overhead and simplicity are crucial.
2. **Routing Information Protocol (RIP):**
    - UDP serves as the transport protocol for routing protocols such as **RIP**, which periodically updates routing tables across the network.
3. **Multicasting:**
    - **UDP** is well-suited for multicasting, allowing a single packet to be sent to multiple recipients simultaneously. This capability is integrated directly into the UDP software.
4. **Trivial File Transfer Protocol (TFTP):**
    - UDP is ideal for processes like **TFTP**, which already have built-in mechanisms for flow and error control, eliminating the need for additional overhead.
5. **Simple Request-Response Communications:**
    - UDP is effective for simple **request-response** interactions where minimal concern for flow and error control is acceptable, such as in DNS queries.
6. **Real-Time Applications:**
    - UDP is preferred for **interactive real-time applications** (e.g., video conferencing, online gaming) that require consistent delivery speeds and cannot tolerate delays caused by retransmission or error correction.

4.2 Transmission Control Protocol (TCP)

1. Introduction to TCP

- **Reliable and Connection-Oriented:**
  - **TCP as a Reliable Protocol:** TCP ensures that data is delivered accurately and in the correct order from the sender to the receiver. This reliability is crucial for applications where data integrity is essential, such as file transfers, email, and web browsing.
  - **Connection-Oriented Communication:** TCP establishes a connection before data transfer begins. This connection setup involves a three-way handshake, ensuring that both the sender and receiver are ready to communicate. Once the connection is established, data can flow between the two devices.
  - **Byte-Stream Service:** TCP treats the data being transmitted as a continuous stream of bytes. Unlike protocols like UDP (User Datagram Protocol), which send data in discrete messages, TCP allows data to be sent as a sequence of bytes that the receiver can reassemble in the correct order.

- **Full-Duplex Communication:**
  - **Simultaneous Data Flow:** In a TCP connection, data can flow in both directions simultaneously. This full-duplex service means that each device in the connection can send and receive data at the same time.
  - **Independent Byte Streams:** Each direction of communication in a TCP connection has its own independent byte stream, with separate sequence numbers and acknowledgment numbers to track the data flow.
- **Flow Control Mechanism:**
  - **Prevention of Receiver Overload:** TCP implements flow control to prevent the sender from overwhelming the receiver with too much data at once. This is achieved using a mechanism called the "sliding window," which regulates the amount of unacknowledged data that can be in transit.
  - **Window Size:** The receiver advertises a window size, indicating the maximum amount of data it can accept at one time. The sender must respect this limit to avoid overloading the receiver’s buffer.
- **Congestion Control Mechanism:**
  - **Network Congestion Management:** TCP is designed to prevent network congestion, which can occur when too much data is sent too quickly. To manage congestion, TCP adjusts the rate of data transmission based on feedback from the network.
  - **Adaptive Transmission Rate:** Through mechanisms like Slow Start and Congestion Avoidance, TCP dynamically adjusts its transmission rate to match the current network conditions, reducing the likelihood of congestion.

2. TCP Services

a. Process-to-Process Communication:

- **Port Numbers:** TCP enables communication between specific processes on different devices using port numbers. Each process on a device is identified by a unique port number, allowing multiple applications to use TCP simultaneously without interfering with each other.

b. Stream Delivery Service:

- **Continuous Data Flow:** TCP allows data to be sent and received as a continuous stream of bytes. Unlike UDP, which handles discrete packets, TCP treats data as a sequence of bytes, ensuring that it arrives in the correct order.
- **Imaginary Tube Concept:** TCP creates an environment where the sending and receiving processes are connected by an "imaginary tube" that transmits the byte stream across the network. This abstraction simplifies the communication process for applications.
- **Buffering:**
    - **Sending Buffer:** At the sender's end, data is stored in a sending buffer before being transmitted. The buffer helps manage the pace at which data is sent to match the speed of the receiving process.
    - **Receiving Buffer:** On the receiving side, the incoming data is stored in a receiving buffer. This buffer holds the data until the receiving process is ready to process it, ensuring smooth and efficient data handling.

c. Full-Duplex Communication:

- **Simultaneous Data Exchange:** TCP supports full-duplex communication, meaning that data can flow in both directions at the same time. Each side of the connection has its own sending and receiving buffer, allowing for efficient data transfer.

d. Multiplexing and Demultiplexing:

- **Multiple Simultaneous Connections:** TCP enables multiplexing, where data from multiple applications is combined for transmission. Upon reaching the destination, TCP performs demultiplexing, separating the data and delivering it to the appropriate applications based on port numbers.

e. Connection-Oriented Service:

- **Three Phases of Connection:**
    1. **Connection Establishment:** A TCP connection begins with a three-way handshake between the sender and receiver, ensuring both are ready to communicate.
    2. **Data Transfer:** Once the connection is established, data is exchanged in both directions. TCP ensures that the data is delivered accurately and in the

correct order.

3. **Connection Termination:** After the data transfer is complete, the connection is terminated using a four-step process that ensures both sides agree to end the communication.

- **Virtual Connection:** The connection in TCP is virtual, not physical. Data segments can take different paths through the network, and TCP ensures they are reassembled in the correct order at the destination.

f. Reliable Service:

- **Acknowledgment Mechanism:** TCP uses acknowledgments to confirm that data has been received correctly. If a segment is lost or corrupted during transmission, TCP will retransmit the data until it is correctly received, ensuring reliability.

3. TCP Segment Structure

a. Segments in TCP:

- **Segment Definition:** A TCP segment is the basic unit of data transmission in TCP. Each segment contains a header and a portion of the data stream.
- **Encapsulation:** TCP segments are encapsulated within IP datagrams for transmission over the network. The IP layer handles routing the datagrams to their destination, where the TCP layer reassembles the segments into the original data stream.

b. Byte-Oriented Protocol:

- **Data as a Stream of Bytes:** In TCP, data is treated as a continuous stream of bytes, not as discrete messages. The sender writes bytes into the TCP connection, and the receiver reads them out in the correct order.
- **Buffering and Packet Formation:** TCP buffers data from the application until it has enough to form a segment. This segment is then sent to the receiver, where it is stored in a buffer until the receiving process is ready to process it.

c. Sequence and Acknowledgment Numbers:

- **Byte Numbering:** TCP assigns a sequence number to each byte in the data stream. This numbering ensures that the data is delivered in the correct order, even if segments arrive out of order.
- **Acknowledgment Mechanism:** TCP uses acknowledgment numbers to confirm receipt of data. The acknowledgment number indicates the next expected byte, allowing the sender to know which data has been received successfully.
- **Example of Sequence Numbers:**
    - Suppose a TCP connection is transferring a file of 5000 bytes. If the first byte is numbered 10,001, the sequence numbers for segments carrying 1000 bytes each would be:
        - Segment 1: Sequence Number 10,001 (bytes 10,001 to 11,000)
        - Segment 2: Sequence Number 11,001 (bytes 11,001 to 12,000)

    - Segment 3: Sequence Number 12,001 (bytes 12,001 to 13,000)
    - Segment 4: Sequence Number 13,001 (bytes 13,001 to 14,000)
    - Segment 5: Sequence Number 14,001 (bytes 14,001 to 15,000)

d. Acknowledgment Number:

- **Acknowledging Received Data:** In full-duplex communication, both parties send and receive data simultaneously. Each party assigns an acknowledgment number, which confirms the receipt of data and indicates the next expected byte.
- **Cumulative Acknowledgment:** TCP uses cumulative acknowledgment, meaning that the acknowledgment number represents all the bytes received up to that point. If the acknowledgment number is 5643, it means all bytes up to 5642 have been received correctly.

4. TCP Flow Control

- **Sliding Window Protocol:**
    - **Preventing Buffer Overload:** TCP uses a sliding window protocol to manage the flow of data between the sender and receiver. The window size controls the amount of data the sender can transmit before receiving an acknowledgment.
    - **Dynamic Adjustment:** The receiver dynamically adjusts the window size based on its buffer availability, ensuring that it is not overwhelmed with data.

- **Window Size Field:**
    - The window size field in the TCP header indicates the number of bytes the sender can transmit before waiting for an acknowledgment. This mechanism allows for efficient and controlled data flow.

5. TCP Error Control

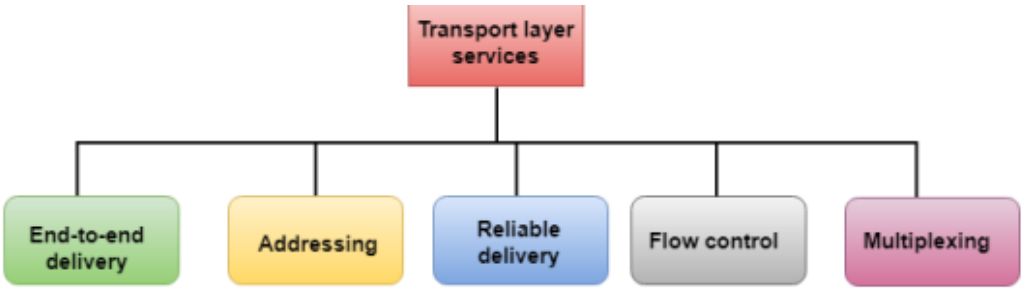
- **Checksum for Error Detection:**
    - **Data Integrity:** TCP includes a checksum in the segment header to detect errors in the transmitted data. If the checksum does not match, the segment is considered corrupted and discarded.
    - **Retransmission:** When an error is detected or a segment is lost, TCP uses retransmission to ensure the correct data is delivered. The sender retransmits the data until it receives an acknowledgment from the receiver.
- **Retransmission Timeouts (RTO):**
    - **Adaptive Timing:** TCP calculates a retransmission timeout (RTO) based on the round-trip time (RTT) of the segments. If an acknowledgment is not received within the RTO, TCP assumes the segment is lost and retransmits it.

6. TCP Congestion Control

- **Congestion Avoidance Mechanisms:**
    - **Slow Start:** TCP begins transmission slowly and increases the rate

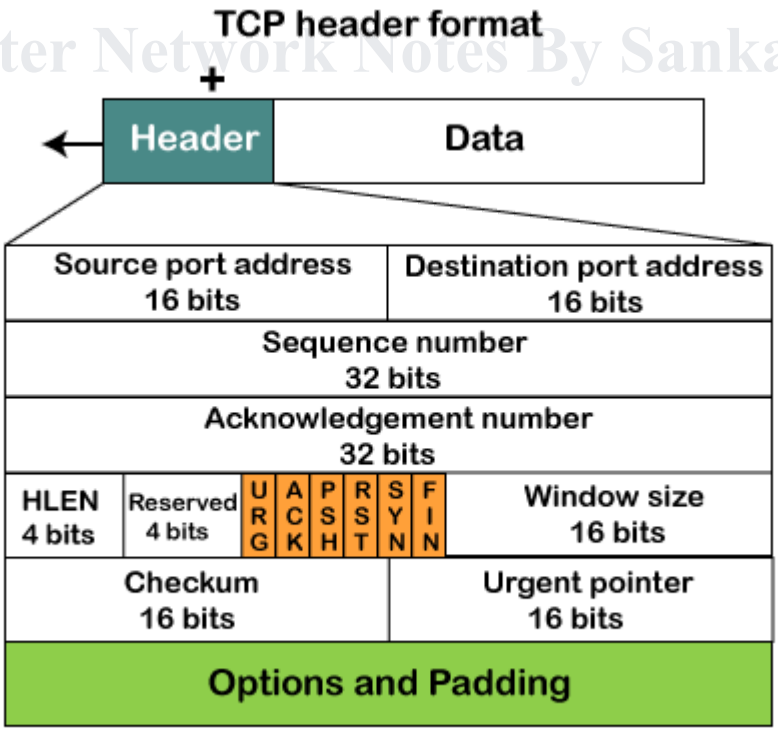
gradually as it confirms that the network can handle more data. This helps avoid congestion during the initial phase of data transfer.

- **Congestion Avoidance:** Once TCP detects the network's capacity, it shifts to a congestion avoidance phase, where the transmission rate increases more slowly to prevent overloading the network.



TCP Segment Format

The TCP segment format consists of a header that ranges from 20 to 60 bytes in length, followed by data from the application program. The header contains several important fields that control and manage the transmission of data across the network. Below is a detailed breakdown of each component of the TCP segment format:



1. Source Port Address

- **Definition:** A 16-bit field that specifies the port number of the application program on the host that is sending the segment.

- **Purpose:** This field identifies the source port, allowing the receiving system to know which application sent the data. It serves a similar function as the source port address in the UDP header.

2. Destination Port Address

- **Definition:** A 16-bit field that specifies the port number of the application program on the host that is receiving the segment.
- **Purpose:** This field identifies the destination port, allowing the segment to be delivered to the correct application on the receiving host. It functions similarly to the destination port address in the UDP header.

3. Sequence Number

- **Definition:** A 32-bit field that indicates the number assigned to the first byte of data in this segment.
- **Purpose:** TCP is a stream-oriented protocol, meaning every byte of data is numbered sequentially. The sequence number helps the receiving system identify the exact order of bytes within the stream. During the connection establishment, each party generates an initial sequence number (ISN) randomly, which is used to synchronize the data flow.
    - **Example:**
        - If a segment contains the first 1000 bytes of data starting with byte number 1, the sequence number field will be set to 1. The next segment, if it contains the following 1000 bytes, will have a sequence number of 1001.

4. Acknowledgment Number

- **Definition:** A 32-bit field that specifies the next byte the receiver expects to receive.
- **Purpose:** This field plays a crucial role in ensuring data integrity and order. It confirms the receipt of bytes up to a certain point in the sequence. If the acknowledgment number is 1001, it means the receiver has successfully received all bytes up to byte 1000 and expects byte 1001 next.
    - **Cumulative Acknowledgment:** TCP uses cumulative acknowledgment, where the acknowledgment number includes all bytes received up to that point.

5. Header Length (Data Offset)

- **Definition:** A 4-bit field indicating the size of the TCP header in 4-bit Long.
- **Purpose:** This field helps in identifying where the header ends and where the data begins. The minimum header size is 20 bytes (value of 5 in this field), and the maximum is 60 bytes (value of 15 in this field).
- The TCP header plays a crucial role in the reliable transmission of data over the network. It is divided into a **fixed part** and an **optional part**.

1. Fixed Part of the TCP Header:

- **Size:** 20 bytes.
- **Includes:** Essential fields such as source port, destination port, sequence number, acknowledgment number, data offset, flags, window size, checksum, and urgent pointer.

2. Optional Part of the TCP Header:

- **Size:** Variable, up to 40 bytes.
- **Purpose:** Contains options that enhance TCP functionality, such as Maximum Segment Size (MSS), window scaling, timestamps, etc.

Header Offset (Data Offset)

- The **Header Offset** (also known as the Data Offset) is a 4-bit field that indicates the size of the TCP header.
- **Measured in:** 32-bit words (4 bytes each).
- **Purpose:** It tells the receiver where the actual data begins in the TCP segment.
    - **Example:** A header offset value of 5 means the TCP header is 20 bytes long (5 x 4 bytes). If there are options included, the header size increases.

Scaling Up and Down by a Factor of 4

Scaling refers to adjusting the size of a value by a specific factor:

1. **Scaling Up by a Factor of 4:**
    - **Meaning:** Multiplying the original value by 4.
    - **Example:** If the initial TCP window size is 10,000 bytes, scaling up by a factor of 4 would increase it to 40,000 bytes.
2. **Scaling Down by a Factor of 4:**
    - **Meaning:** Dividing the original value by 4.
    - **Example:** If the TCP window size is initially 40,000 bytes, scaling down by a factor of 4 would reduce it to 10,000 bytes.

Finding the Last Sequence Number Using the IP Header and TCP Header Length

To determine the last sequence number of a TCP segment, you need to understand the relationship between the IP header and the TCP header:

1. **IP Header Length (IHL)**: This field indicates the size of the IP header in 32-bit words. The minimum length is 20 bytes (5 * 32-bit words). The data offset of the TCP header starts immediately after the IP header.
2. **TCP Header Length (Data Offset)**: This field specifies the length of the TCP header. By combining the IP header length with the TCP header length, you can find the total header length.
3. **Data Size**: The size of the data segment is calculated by subtracting the total header length from the total packet length (found in the IP header's Total Length field).

4. **Last Sequence Number**: The last sequence number can be found by adding the sequence number in the TCP header to the size of the data segment.

In essence, the IP header length helps identify the starting point of the TCP header, and the TCP header length helps pinpoint the beginning of the data. The last sequence number is determined by considering the initial sequence number and the amount of data sent.

Example: Finding the Last Sequence Number Using IP and TCP Header Lengths

Let's assume we have the following details for an IP packet containing a TCP segment:

IP Header Length (IHL): 20 bytes (5 * 32-bit words)

TCP Header Length (Data Offset): 24 bytes (6 * 32-bit words)

Total IP Packet Length: 100 bytes

Initial Sequence Number (ISN): 1000

Steps to Calculate the Last Sequence Number:

1. **Determine the total header length:**
   - IP Header Length = 20 bytes
   - TCP Header Length = 24 bytes
   - Total Header Length = 20 + 24 = **44 bytes**
2. **Calculate the size of the data segment:**
   - Total IP Packet Length = 100 bytes
   - Data Size = Total IP Packet Length - Total Header Length
   - Data Size = 100 - 44 = **56 bytes**
3. **Calculate the last sequence number:**
   - Initial Sequence Number (ISN) = 1000
   - Last Sequence Number = ISN + Data Size
   - Last Sequence Number = 1000 + 56 = **1056**

6. Reserved

- **Definition:** A 6-bit field reserved for future use.
- **Purpose:** This field is kept aside for potential future features or modifications in the TCP protocol. Currently, it should be set to zero.

7. Control Flags

- **Definition:** A set of 6 bits (flags) that control various aspects of the TCP connection, as shown in the figure below.
- **Purpose:** These flags manage the state of the connection and control data flow. Each bit represents a different flag with a specific function:
  - **URG:** Urgent pointer field significant.
  - **ACK:** Acknowledgment field significant.
  - **PSH:** Push function.

- **RST:** Reset the connection.
- **SYN:** Synchronize sequence numbers to initiate a connection.
- **FIN:** No more data from the sender (indicates the end of data).
- **Table: Description of Flags in the Control Field**
  - **URG (Urgent Pointer field significant):** Indicates that the Urgent Pointer field has valid data and should be processed immediately.
  - **ACK (Acknowledgment field significant):** Indicates that the Acknowledgment field contains valid data.
  - **PSH (Push Function):** Requests that the data be pushed to the receiving application immediately.
  - **RST (Reset the connection):** Used to reset a connection in case of an error or when the connection is no longer needed.
  - **SYN (Synchronize sequence numbers):** Used during the connection establishment phase to synchronize sequence numbers.
  - **FIN (No more data from the sender):** Indicates that the sender has finished sending data and wishes to terminate the connection.

8. Window Size

- **Definition:** A 16-bit field that specifies the size of the window, in bytes, that the receiver is willing to accept.
- **Purpose:** The window size controls the flow of data between the sender and receiver. The sender must respect this value to avoid overwhelming the receiver. The maximum window size is 65,535 bytes, which is known as the receiving window (rwnd).

9. Checksum

- **Definition:** A 16-bit field used for error-checking the header and data.
- **Purpose:** The checksum ensures the integrity of the segment during transmission. TCP calculates the checksum using the same algorithm as UDP, but unlike UDP, the inclusion of the checksum is mandatory in TCP. The pseudoheader used in the checksum calculation includes the source and destination IP addresses, the protocol number (6 for TCP), and the segment length.

TCP Header Checksum Calculation

The TCP checksum is a mechanism used to ensure data integrity in a TCP segment. It verifies that the data received is the same as the data sent, without any corruption during transit.

Steps to Calculate the TCP Checksum:

1. **Initialize the Checksum Field:**
   - Start by setting the checksum field in the TCP header to zero.
2. **Construct the Pseudo Header:**
   - Although not included in the actual TCP packet, the pseudo header is essential for checksum calculation. It includes:

        - **Source IP Address:** The IP address of the sender.
        - **Destination IP Address:** The IP address of the receiver.
        - **Protocol Number:** The protocol number for TCP, which is 6.
        - **TCP Length:** The length of the TCP header plus the data.
3. **Calculate the Checksum:**
    - **Sum the 16-bit Words:** The checksum is computed by summing the 16-bit words of the TCP header, the TCP data (if any), and the pseudo header.
    - **Handle Overflow:** If the sum exceeds 16 bits, the overflow (carry) is added back to the sum.
    - **One's Complement:** Finally, the one's complement of the sum is taken, which means flipping all the bits (changing 1s to 0s and 0s to 1s).
4. **Insert the Checksum:**
    - The resulting value is inserted into the checksum field of the TCP header.

Verification: When the receiver calculates the checksum and adds it to the received checksum, the result should be all 1s (0xFFFF). If not, it indicates that the packet is corrupted and needs to be discarded.

- **10. Urgent Pointer**

- **Definition:** A 16-bit field that is valid only if the URG flag is set.
- **Purpose:** It is used when the segment contains urgent data that needs immediate attention. The Urgent Pointer specifies the end of the urgent data within the segment by indicating the offset from the sequence number.
    - **Example:** If the Urgent Pointer is set to 1000 and the sequence number is 5000, the urgent data ends at byte number 6000.

11. Options

- **Definition:** A field that can be up to 40 bytes long and contains optional information.
- **Purpose:** The options field allows for various enhancements and extensions to the TCP protocol. Common options include Maximum Segment Size (MSS), Window Scaling, and Selective Acknowledgment (SACK).
- TCP Options Each SYN can contain TCP options. Commonly used options include the following:
- **1. MSS option.** With this option, the TCP sending the SYN announces its maximum segment size, the maximum amount of data that it is willing to accept in each TCP segment, on this connection. The sending TCP uses the receiver's MSS value as the maximum size of a segment that it sends.
- **2. Window scale option**. The maximum window that either TCP can advertise to the other TCP is 65,535, because the corresponding field in the TCP header occupies 16 bits. But, highspeed connections, common in today's Internet (45 Mbits/sec and faster, as described in RFC 1323 [Jacobson, Braden, and Borman 1992]), or long delay paths (satellite links) require a larger window to obtain the maximum throughput possible. This newer option specifies that the advertised

window in the TCP header must be scaled (left-shifted) by 0–14 bits, providing a maximum window of almost one gigabyte (65,535 x 214). Both end-systems must support this option for the window scale to be used on a connection.

- 3. **Timestamp option**: This option is needed for high-speed connections to prevent possible data corruption caused by old, delayed, or duplicated segments.

Steps and Explanation:

1. **Source Port Number:**
   - **Hexadecimal Value:** 0532
   - Convert 0532 to decimal:
     - 0x0532=1330 (in decimal).
   - **Answer:** The source port number is **one thousand three hundred and thirty (1330)**.
2. **Destination Port Number:**
   - **Hexadecimal Value:** 0021
   - Convert 0021 to decimal:
     - 0x0021= 33 (in decimal).
   - **Answer:** The destination port number is **thirty-three (33)**.
3. **Sequence Number:**
   - **Hexadecimal Value:** 7000 0000
   - Convert 7000 0000 to decimal:
     - 0x70000000 = 1,879,048,192 (in decimal).
   - **Answer:** The sequence number is **one billion eight hundred seventy-nine million forty-eight thousand one hundred ninety-two (1,879,048,192)**.
4. **Acknowledgment Number:**
   - **Hexadecimal Value:** 0100 0000
   - Convert 0100 0000 to decimal:
     - 0x01000000=16,777,216 (in decimal).
   - **Answer:** The acknowledgment number is **sixteen million seven hundred seventy-seven thousand two hundred sixteen (16,777,216)**.
5. **Length of the Header:**
   - The header length is determined by the first 4 bits of the 5th byte (first digit of 50).
   - **Hexadecimal Value:** 5 (from 50)
   - Convert 5 to decimal:
     - 5×4= 20 bytes.
   - **Answer:** The header length is **twenty (20) bytes**.
6. **Type of the Segment:**
   - The type of the segment is indicated by the control flags in the 5th and 6th bytes (50 and 02).
   - **Hexadecimal Value:** 02
   - The 02 indicates that the SYN flag is set, meaning this is a connection establishment segment.
   - **Answer:** The type of the segment is **SYN (synchronize)**.
7. **Window Size:**
   - **Hexadecimal Value:** 07FF

- Convert 07FF to decimal:
  - 0x07FF= 2,047 (in decimal).
- **Answer:** The window size is **two thousand forty-seven (2,047)**.

Summary of Answers:

1. The source port number is **one thousand three hundred thirty (1330)**.
2. The destination port number is **thirty-three (33)**.
3. The sequence number is **one billion eight hundred seventy-nine million forty-eight thousand one hundred ninety-two (1,879,048,192)**.
4. The acknowledgment number is **sixteen million seven hundred seventy-seven thousand two hundred sixteen (16,777,216)**.
5. The header length is **twenty (20) bytes**.
6. The type of the segment is **SYN (synchronize)**.
7. The window size is **two thousand forty-seven (2,047)**.

Problem:A TCP segment is sent with the following details:

- Sequence Number: 5000
- URG Flag: Set (1)
- Urgent Pointer: 1500

Determine the sequence number of the last byte of urgent data in this TCP segment.

Solution: The Urgent Pointer is used when the URG flag is set and helps determine the end of the urgent data by adding its value to the sequence number.

Steps:

1. Starting Sequence Number: 5000
2. Urgent Pointer Value: 1500

To find the sequence number of the last byte of urgent data, add the Urgent Pointer value to the Sequence Number and then subtract 1:

- Last Byte of Urgent Data: Sequence Number plus Urgent Pointer minus 1
- Last Byte of Urgent Data = 5000 plus 1500 minus 1 = 6499

Answer: The last byte of urgent data has a sequence number of six thousand four hundred ninety-nine (6499).

TCP Connection Management

Transmission Control Protocol (TCP) is a connection-oriented transport protocol that requires the establishment, maintenance, and termination of a connection between two devices for reliable communication. TCP connection management is divided into three key phases:

1. **Connection Establishment**

2. **Data Transfer**
3. **Connection Termination**

1. Connection Establishment

TCP uses a method called **Three-Way Handshaking** to establish a connection between a client and a server. This handshake ensures that both sides synchronize their sequence numbers and prepare to exchange data reliably. Here's how it works:

1. **Client Sends SYN:**
    - The client initiates the connection by sending a SYN (synchronize) segment to the server. This segment includes the client's initial sequence number, x.
    - **Segment Flags:** SYN
    - **Sequence Number:** x
2. **Server Responds with SYN + ACK:**
    - The server, upon receiving the SYN, replies with a SYN + ACK segment. This segment serves two purposes: it acknowledges the client's SYN (ACK = x + 1) and synchronizes the server's sequence number by sending its own initial sequence number, y.
    - **Segment Flags:** SYN + ACK
    - **Acknowledgment Number:** x + 1
    - **Sequence Number:** y
3. **Client Sends ACK:**
    - Finally, the client sends an ACK segment to acknowledge the server's sequence number (ACK = y + 1). With this, the connection is established, and data transfer can begin.
    - **Segment Flags:** ACK
    - **Acknowledgment Number:** y + 1

Simultaneous Open: In rare cases, both the client and the server might attempt to open a connection at the same time. This leads to both sides sending SYN segments simultaneously, followed by SYN + ACK segments from each side. TCP handles this situation by establishing a single connection between them.

SYN Flooding Attack: During the connection establishment, TCP is vulnerable to a type of attack known as SYN flooding. In this attack, an attacker sends a large number of SYN segments with spoofed IP addresses, causing the server to allocate resources for connections that are never completed. This can lead to a denial of service. To mitigate this, strategies like SYN cookies and limiting the number of SYN requests are used.

TCP Flow Control: Advertised Window and MSS

- **Advertised Window:** Part of the TCP header that indicates the amount of data (in bytes) that the receiver is willing to accept. It is used for flow control to prevent the sender from overwhelming the receiver with too much data.
- **MSS (Maximum Segment Size):** Defines the largest segment of data that a TCP sender is willing to receive. It is specified during the three-way handshake.

Example: Flow Control with Advertised Window

Scenario:

- The client advertises a window size of 5000 bytes.
- The sender is transmitting segments of 1000 bytes each.

Step 1: The client advertises a window size of 5000 bytes.

Client -> Server: ACK (Advertised Window: 5000 bytes)
Step 2: The server sends 5 segments of 1000 bytes each.
Server -> Client: Data Segment (1000 bytes)
Server -> Client: Data Segment (1000 bytes)
Server -> Client: Data Segment (1000 bytes)
Server -> Client: Data Segment (1000 bytes)
Server -> Client: Data Segment (1000 bytes)

Step 3: The client acknowledges the receipt of all 5 segments and updates the window size accordingly.

Client -> Server: ACK (Advertised Window: 0 bytes)

Now, the sender must wait for the client to update the window size before sending more data.

Example: MSS in Action

Scenario:

- The client and server agree on an MSS of 1460 bytes during the handshake.

Step 1: The client sends a SYN packet with an MSS option of 1460 bytes.

Client -> Server: SYN (MSS: 1460 bytes)

Step 2: The server sends a SYN-ACK packet with an MSS option of 1460 bytes.

Server -> Client: SYN-ACK (MSS: 1460 bytes)

Step 3: The server sends data in segments, each with a maximum size of 1460 bytes.

Server -> Client: Data Segment (1460 bytes)

Numerical Example:

Assume the following:

- Client's Advertised Window = 8000 bytes
- Server's MSS = 2000 bytes

Step 1: The client advertises an 8000-byte window.

Client -> Server: ACK (Advertised Window: 8000 bytes)

Step 2: The server sends four segments of 2000 bytes each.

Server -> Client: Data Segment (2000 bytes) Server -> Client: Data Segment (2000 bytes)
Server -> Client: Data Segment (2000 bytes) Server -> Client: Data Segment (2000 bytes)

The client acknowledges the receipt of these segments and the window size is reduced accordingly.

Client -> Server: ACK (Advertised Window: 0 bytes)

This ensures that the server sends data according to the client's capacity to process the incoming data.

2. Data Transfer

After the connection is established, TCP facilitates **bidirectional data transfer**, allowing both the client and server to send and receive data simultaneously.

- **Full-Duplex Communication:** TCP supports full-duplex communication, which means that data can flow in both directions at the same time. Each segment sent by one side is acknowledged by the other side, ensuring that all data is received correctly.
- **Piggybacking Acknowledgments:** TCP optimizes communication by piggybacking acknowledgments onto data segments that are sent back to the sender. This reduces the overhead of sending separate acknowledgment segments.
- **Pushing Data:** In interactive applications where immediate data transfer is required, the sending application can request TCP to "push" data. This push operation forces TCP to send the data immediately, even if the buffer is not full, ensuring that the data reaches the receiver as soon as possible.
- **Urgent Data:** Sometimes, an application may need to send urgent data that should be processed out of sequence. TCP allows this by using the URG flag and an urgent pointer. The urgent data is delivered immediately to the receiving application, bypassing the usual buffering.

3. Connection Termination

Connection termination in TCP can occur through either a **Four-Way Close** or a **Three-Way Close**, with an additional option for a **Half-Close**.

Four-Way Close

The **Four-Way Close** process ensures that both the client and the server properly close their side of the connection independently. Here’s how it works:

1. **Client Sends FIN:**

    - The client initiates the termination process by sending a FIN (finish) segment to the server, indicating that it has finished sending data.
    - **Segment Flags:** FIN
2. **Server Acknowledges with ACK:**
    - The server responds with an ACK segment, acknowledging the client's FIN.
    - **Segment Flags:** ACK
    - **Acknowledgment Number:** client's FIN sequence number + 1
3. **Server Sends FIN:**
    - After acknowledging the client's FIN, the server sends its own FIN segment, indicating that it has also finished sending data.
    - **Segment Flags:** FIN
4. **Client Acknowledges with ACK:**
    - The client sends a final ACK segment, acknowledging the server's FIN. The connection is now fully terminated.
    - **Segment Flags:** ACK
    - **Acknowledgment Number:** server's FIN sequence number + 1

This four-step process ensures that both parties have had a chance to acknowledge the closure of the connection, preventing any data loss.

Three-Way Close

The **Three-Way Close** is a more efficient termination process that merges the acknowledgment of one party's FIN segment with the sending of the other party's FIN segment. Here's how it works:

1. **Client Sends FIN:**
    - The client sends a FIN segment to the server.
    - **Segment Flags:** FIN
2. **Server Responds with FIN + ACK:**
    - The server acknowledges the client's FIN and simultaneously sends its own FIN.
    - **Segment Flags:** FIN + ACK
3. **Client Sends ACK:**
    - The client sends a final ACK segment to acknowledge the server's FIN. The connection is now terminated.
    - **Segment Flags:** ACK

This method is faster than the Four-Way Close but achieves the same result.

Half-Close

In a **Half-Close** scenario, one side of the connection can stop sending data while still being able to receive data from the other side. This is useful in situations where one party has finished sending data but expects more data from the other side.

- **Initiation by Client:**
    - The client initiates a half-close by sending a FIN segment, indicating that it

will not send more data.
    - **Segment Flags:** FIN
- **Server Acknowledges with ACK:**
    - The server acknowledges this FIN with an ACK but can continue to send data to the client.
- **Server Sends FIN:**
    - Once the server has finished sending data, it sends its own FIN segment.
- **Client Acknowledges with ACK:**
    - The client sends a final ACK, completing the connection termination.

The half-close allows for more flexible communication, particularly in protocols where one side may need to terminate its data stream earlier than the other.

Summary

TCP's connection management is a comprehensive process that ensures reliable communication between two devices. From the three-way handshake for connection establishment to various methods for data transfer and connection termination, TCP employs a range of mechanisms to maintain data integrity, order, and reliability. Whether using a four-way close, three-way close, or half-close, TCP ensures that connections are terminated gracefully without data loss.

Let's go through a detailed example of TCP connection management using specific numerical values. This will help illustrate the process of Connection Establishment, Data Transfer, and Connection Termination, highlighting how sequence numbers and acknowledgments work in a typical TCP session.

1. Connection Establishment (Three-Way Handshake)

TCP is a connection-oriented protocol, which means it requires an initial handshake to establish a connection before any data transfer can occur. The three-way handshake ensures that both the client and server are ready to communicate and agree on initial sequence numbers.

Step 1: Client Sends SYN

- **Client:** Initiates the connection by sending a SYN (synchronize) segment to the server.
    - **Sequence Number (Seq = 1000):** This is the initial sequence number chosen by the client. It represents the starting point for numbering the bytes in the data stream.
    - **Flags:** SYN
- **Explanation:** The client begins by sending a SYN segment with a sequence number of 1000. This sequence number is the first in the client's byte stream. The SYN flag indicates that this segment is attempting to initiate a connection.

Step 2: Server Sends SYN + ACK

- **Server:** Responds with a SYN + ACK segment.
    - **Sequence Number (Seq = 2000):** The server chooses its own initial sequence number (2000) to use for its byte stream.
    - **Acknowledgment Number (ACK = 1001):** The server acknowledges the client's SYN by specifying the next sequence number it expects from the client, which is 1000 + 1.
    - **Flags:** SYN + ACK
- **Explanation:** The server acknowledges the client's SYN segment by setting the ACK flag and sending an acknowledgment number of 1001, which indicates that it successfully received the client's SYN and expects the next byte to start with 1001. The server also sends its own SYN with a sequence number of 2000.

Step 3: Client Sends ACK

- **Client:** Completes the handshake by sending an ACK segment.
    - **Sequence Number (Seq = 1001):** The client's sequence number remains 1001, as it hasn't sent any actual data yet.
    - **Acknowledgment Number (ACK = 2001):** The client acknowledges the server's SYN by indicating the next expected sequence number, which is 2000 + 1.
    - **Flags:** ACK
- **Explanation:** The client confirms receipt of the server's SYN by sending an ACK with an acknowledgment number of 2001, indicating that it's ready to receive data starting from that sequence number. The connection is now fully established, and both parties are synchronized and ready to exchange data.

2. Data Transfer

Once the connection is established, data can flow in both directions between the client and server. Here's how the data transfer might look:

Step 4: Client Sends Data

- **Client:** Sends 2000 bytes of data to the server.
    - **Sequence Number (Seq = 1001):** The sequence number starts from where the last segment left off.
    - **Data Size:** 2000 bytes
    - **Flags:** PSH (Push), ACK
- **Explanation:** The client sends a segment containing 2000 bytes of data, starting from sequence number 1001. The PSH flag is set to indicate that the data should be delivered to the application as soon as possible. This segment is acknowledged implicitly by the server.

Step 5: Server Sends ACK + Data

- **Server:** Acknowledges the client's data and sends its own data back.
    - **Sequence Number (Seq = 2001):** The server sends its own data, starting from its sequence number 2001.

    - **Acknowledgment Number (ACK = 3001):** The server acknowledges the receipt of the 2000 bytes from the client by indicating the next expected sequence number (1001 + 2000).
    - **Data Size:** 1000 bytes
    - **Flags:** PSH, ACK
- **Explanation:** The server confirms that it received the client's 2000 bytes by sending an ACK with acknowledgment number 3001. The server also sends 1000 bytes of data starting from sequence number 2001, pushing the data to the client application immediately due to the PSH flag.

Step 6: Client Sends ACK + Data

- **Client:** Acknowledges the server's data and sends an additional 1000 bytes.
    - **Sequence Number (Seq = 3001):** The sequence number now reflects the data sent by the client.
    - **Acknowledgment Number (ACK = 3001):** The client acknowledges the server's data by sending the next expected sequence number.
    - **Data Size:** 1000 bytes
    - **Flags:** PSH, ACK
- **Explanation:** The client acknowledges the 1000 bytes it received from the server and sends 1000 more bytes of data starting from sequence number 3001. The PSH flag ensures that the data is processed immediately by the server's application.

Step 7: Server Sends ACK

- **Server:** Sends an ACK segment to confirm the receipt of the client's last data segment.
    - **Sequence Number (Seq = 3001):** The sequence number remains unchanged since no new data is being sent.
    - **Acknowledgment Number (ACK = 4001):** The server acknowledges the receipt of the client's last 1000-byte segment.
    - **Flags:** ACK
- **Explanation:** The server acknowledges the client's last segment, confirming that it successfully received the data. The acknowledgment number 4001 indicates that the server expects any further data from the client to start at sequence number 4001.

3. Connection Termination

The connection termination process in TCP is typically initiated by the client, though it can be initiated by either side. It involves a graceful shutdown through a handshake process.

Step 8: Client Sends FIN

- **Client:** Sends a FIN (Finish) segment to signal the end of data transmission.
    - **Sequence Number (Seq = 4001):** The sequence number is set to the last byte sent.
    - **Flags:** FIN, ACK

- **Explanation:** The client sends a FIN segment to indicate that it has finished sending data. This segment consumes one sequence number, which is why the sequence number is still 4001. The client also acknowledges the server's previous data if any were received.

Step 9: Server Sends ACK

- **Server:** Acknowledges the client's FIN.
    - **Sequence Number (Seq = 3001):** No new data is sent, so the sequence number remains unchanged.
    - **Acknowledgment Number (ACK = 4002):** The server acknowledges the client's FIN by indicating the next expected sequence number.
    - **Flags:** ACK
- **Explanation:** The server acknowledges the client's request to close the connection by sending an ACK with acknowledgment number 4002. This means the server expects any further data (if there were any) to start at 4002.

Step 10: Server Sends FIN

- **Server:** Sends its own FIN segment to close the connection from its side.
    - **Sequence Number (Seq = 3001):** The sequence number remains unchanged.
    - **Flags:** FIN, ACK
- **Explanation:** After acknowledging the client's FIN, the server sends a FIN segment to signal that it has also finished sending data. This segment consumes one sequence number.

Step 11: Client Sends ACK

- **Client:** Sends a final ACK segment to complete the connection termination.
    - **Sequence Number (Seq = 4002):** Acknowledges the server's FIN.
    - **Flags:** ACK
- **Explanation:** The client sends an ACK to acknowledge the server's FIN segment, completing the four-way termination process. The connection is now fully closed, and both the client and server can release their resources.

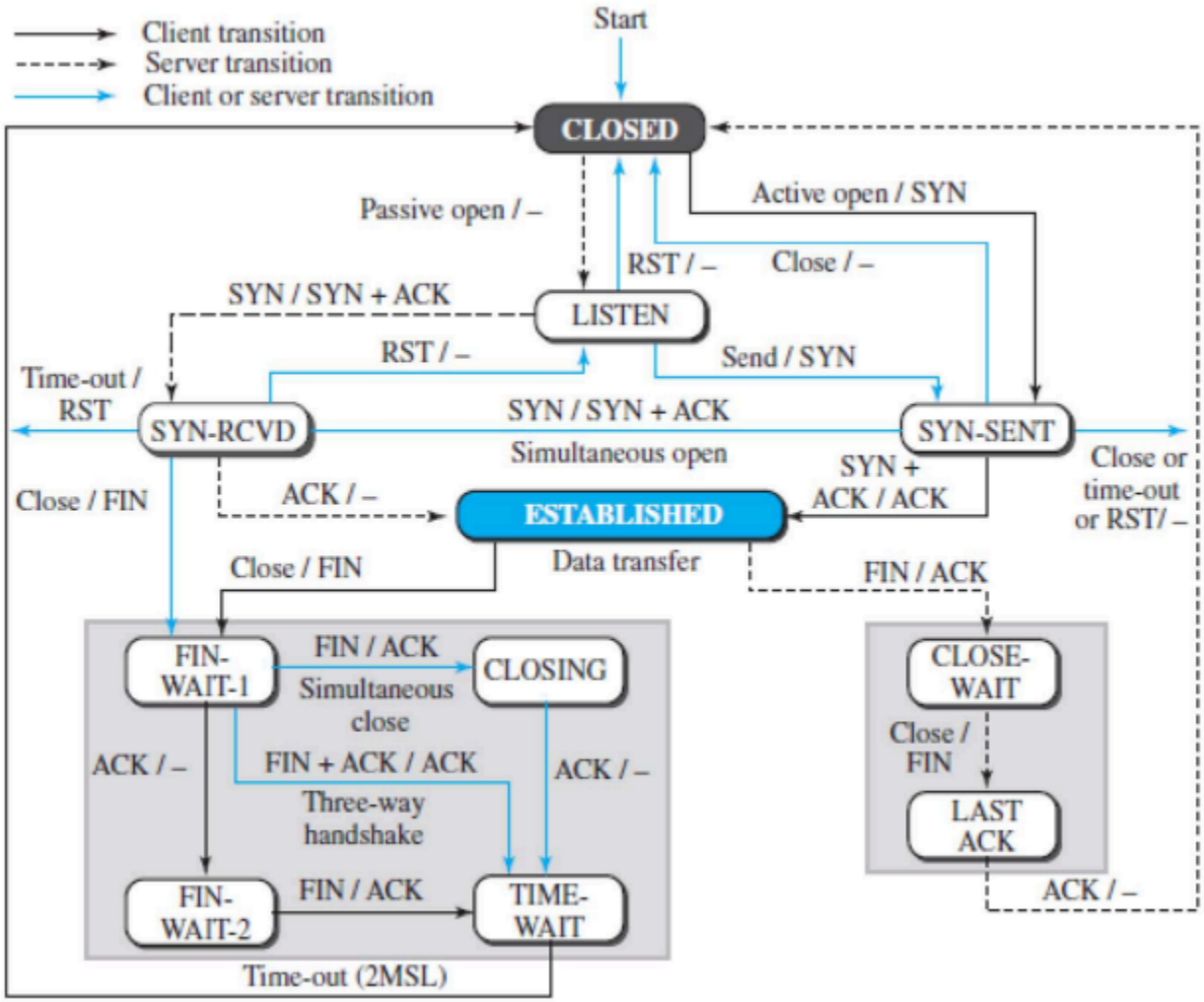
Condition	Consumes Sequence Number?	Explanation
SYN Flag Set	Yes	Marks the start of a connection. Consumes one sequence number.
FIN Flag Set	Yes	Indicates the end of data transmission. Consumes one sequence number.
RST Flag Set	Yes	Resets the connection. Consumes one sequence number.
Data Transmission	Yes	Each byte of data consumes a sequence number.
ACK Flag Set	No	Acknowledges received data, but does not consume a sequence number.
PSH Flag Set	No	Signals immediate data delivery without consuming a sequence number.
URG Flag Set	No	Indicates urgent data, but does not consume a sequence number.

TCP State Transition Diagram: Connection Opening and Closing

State	Description
CLOSED	No connection is active or pending
LISTEN	The server is waiting for an incoming call
SYN RCVD	A connection request has arrived; wait for ACK
SYN SENT	The application has started to open a connection
ESTABLISHED	The normal data transfer state
FIN WAIT 1	The application has said it is finished
FIN WAIT 2	The other side has agreed to release
TIMED WAIT	Wait for all packets to die off
CLOSING	Both sides have tried to close simultaneously
CLOSE WAIT	The other side has initiated a release
LAST ACK	Wait for all packets to die off

TCP connections are managed through a series of well-defined states that ensure reliable data transmission. The state transition diagram represents these states and the transitionsbetween them during connection establishment (opening) and termination

(closing).



1. Opening a TCP Connection

Key States:

1. **LISTEN:**
   - **Description:** The server waits for a connection request from a client.
   - **Transition:** The server enters this state after performing a passive open, signaling its readiness to accept incoming connections.
2. **SYN-SENT:**
   - **Description:** The client has sent a SYN (synchronize) segment to initiate a connection.
   - **Transition:** The client moves to SYN-SENT after an active open, where it sends a SYN to the server to request a connection.
3. **SYN-RECEIVED:**
   - **Description:** The server receives the SYN from the client and responds with a SYN-ACK (synchronize-acknowledge).
   - **Transition:** Upon receiving the SYN, the server transitions to SYN-RECEIVED, indicating it is ready to establish a connection.

4. **ESTABLISHED:**
    - **Description:** The connection is fully established, allowing data transfer between client and server.
    - **Transition:** The client moves to ESTABLISHED after receiving the SYN-ACK and sending an ACK. The server also transitions to ESTABLISHED upon receiving this ACK.

2. Closing a TCP Connection
Key States:

1. **FIN-WAIT-1:**
    - **Description:** One side initiates the connection termination by sending a FIN (finish) segment.
    - **Transition:** The side that wants to close the connection moves from ESTABLISHED to FIN-WAIT-1 after sending a FIN.
2. **FIN-WAIT-2:**
    - **Description:** The initiator waits for the other side to send a FIN after acknowledging the first FIN.
    - **Transition:** The initiator moves to FIN-WAIT-2 after receiving an ACK for its FIN.
3. **TIME-WAIT:**
    - **Description:** The side that initiated the close waits to ensure all packets are received and to handle any delayed segments.
    - **Transition:** After receiving a FIN from the other side, the initiator moves to TIME-WAIT.
4. **CLOSED:**
    - **Description:** The connection is fully terminated, and all resources are released.
    - **Transition:** After the TIME-WAIT period, the connection is officially closed, moving to the CLOSED state.
5. **CLOSE-WAIT:**
    - **Description:** The side that receives the first FIN is in the process of closing its half of the connection.
    - **Transition:** Upon receiving the FIN, the side moves to CLOSE-WAIT, indicating it's preparing to close.
6. **LAST-ACK:**
    - **Description:** After sending its own FIN, the side waits for an ACK from the other side.
    - **Transition:** After sending a FIN from CLOSE-WAIT, it transitions to LAST-ACK, awaiting the final acknowledgment.

3. Half-Close vs. Full Close

Half-Close:

- **Description:** In a half-close scenario, one side of the connection is closed for sending data but remains open for receiving. This allows one direction of data flow to be terminated while the other continues.
- **Process:**
    1. One side sends a FIN, transitioning to FIN-WAIT-1.
    2. Upon receiving the FIN, the other side moves to CLOSE-WAIT but can still send data.
    3. The side that received the FIN eventually sends its own FIN and moves to LAST-ACK.
    4. After receiving the ACK, the connection is fully closed.

Full Close:

- **Description:** In a full close, both sides of the connection are completely closed, and no more data can be sent or received.
- **Process:**
    1. One side initiates the close by sending a FIN and moves through FIN-WAIT-1 and FIN-WAIT-2 states.
    2. The other side responds with its own FIN after acknowledging the first FIN, moving through CLOSE-WAIT and LAST-ACK.
    3. Both sides move to the CLOSED state after completing the handshake, fully terminating the connection.

Key Differences:

- **Data Flow:** In a half-close, data can still be sent in one direction while the other is closed. In a full close, all data flow stops.
- **Use Cases:** Half-close is useful in scenarios where one side needs to finish sending data but is still expecting to receive data, while full close is used when the entire connection needs to be terminated.

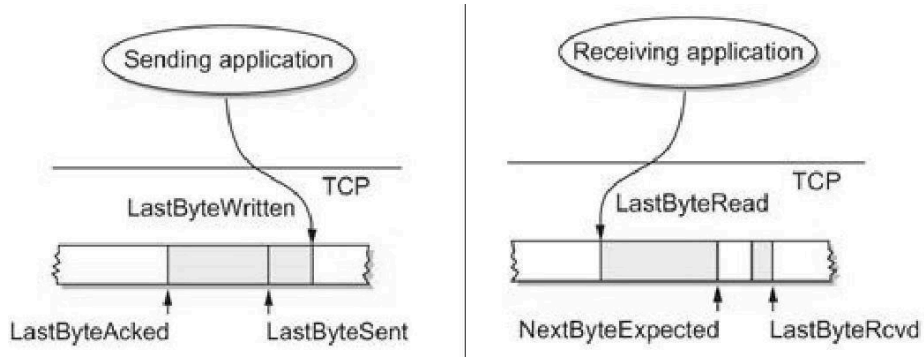
TCP Flow Control and Transmission Mechanisms

TCP Flow Control

TCP uses an adaptive flow control mechanism to ensure that data is transmitted reliably, in order, and without overwhelming the receiver's capacity to process it. This is primarily managed using sliding windows.

Send Buffer

The sending TCP maintains a send buffer containing:



- **Acknowledged Data:** Data that has been acknowledged by the receiver.
- **Unacknowledged Data:** Data that has been sent but not yet acknowledged.
- **Data to be Transmitted:** Data that is ready to be sent but hasn't been transmitted yet.

Three pointers are used to manage the send buffer:

- **LastByteAcked:** The last byte that has been acknowledged.
- **LastByteSent:** The last byte that has been sent.
- **LastByteWritten:** The last byte written into the send buffer.

The relationship among these pointers is:

- **LastByteAcked ≤ LastByteSent ≤ LastByteWritten**

This means a byte must be written before it can be sent, and a byte can only be acknowledged after it has been sent.

Receive Buffer
The receiving TCP maintains a receive buffer to store incoming data, even if it arrives out-of-order.

Three pointers are used to manage the receive buffer:

- **LastByteRead:** The last byte that has been read by the application.
- **NextByteExpected:** The next byte expected by the receiver.
- **LastByteRcvd:** The last byte received.

The relationship among these pointers is:

- **LastByteRead ≤ NextByteExpected ≤ LastByteRcvd + 1**

If data is received in order, the next expected byte is exactly one more than the last byte received.

Flow Control Mechanism

Flow control ensures that the sender does not overwhelm the receiver by sending more data than the receiver can handle.

- **Send Buffer Constraint:**
  - **Condition:** LastByteWritten − LastByteAcked ≤ MaxSendBuffer
  - This ensures that the sender's buffer doesn't overflow.
- **Receive Buffer Constraint:**
  - **Condition:** LastByteRcvd − LastByteRead ≤ MaxRcvBuffer
  - This ensures that the receiver's buffer doesn't overflow.

The **Advertised Window** is calculated by the receiver to inform the sender how much data it can still accept:

- **AdvertisedWindow = MaxRcvBuffer − ((NextByteExpected − 1) – LastByteRead)**

The sender calculates the **Effective Window** to determine how much data it can send:

- **EffectiveWindow = AdvertisedWindow − (LastByteSent − LastByteAcked)**

As data is received, the **LastByteRcvd** pointer moves forward, shrinking the Advertised Window. The window expands again as the application reads data from the buffer.

- **If data is read as fast as it arrives:** The Advertised Window remains at MaxRcvBuffer.
- **If data is read slowly:** The Advertised Window may shrink to 0, pausing the sender.

Here is a comprehensive comparison of TCP and UDP in tabular format:

Parameter	TCP (Transmission Control Protocol)	UDP (User Datagram Protocol)
Name	Transmission Control Protocol	User Datagram Protocol or Universal Datagram Protocol
Connection	Connection-oriented protocol	Connectionless protocol
Usage	Suited for applications requiring high reliability; transmission time is less critical.	Suitable for fast, efficient transmission (e.g., games, VOIP). Useful for stateless servers.
Use by Other Protocols	HTTP, HTTPS, FTP, SMTP, Telnet	DNS, DHCP, TFTP, SNMP, RIP, VOIP
Ordering of Data Packets	Rearranges data packets in the order specified.	No inherent order; packets are independent. Ordering managed by the application layer.
Speed of Transfer	Slower due to error-checking and connection setup.	Faster, as there is no error-checking for packets.
Header Size	20 bytes	8 bytes
Common Header Fields	Source port, Destination port, Checksum	Source port, Destination port, Checksum
Error Checking	Performs error checking and provides recovery options.	Performs error checking but has no recovery options.
Data Flow Control	Provides flow control, congestion control, and requires three packets to set up a connection.	No flow control or congestion management.
Reliability	Guarantees data integrity and ensures packets arrive in the correct order.	No guarantee that packets will arrive or that they will arrive in order.