Introduction to Information Security

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Contents

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The following five sections are from Concise Work Section Modules [67].
Available at: https://github.com/Concise-Works/sect-modules

— 1 —

Networking Fundamentals

1.1 The Internet

Terminology and concepts of the internet, which will be used throughout this text.

Definition 1.1: Protocol

A **protocol** is a set of rules which govern the exchange of data between devices. Protocols define the format, timing, sequencing, and error control of data transmission [57].

Definition 1.2: Internet

The **Internet** is a global network of distributed system communicating over an **Internet Protocol** (IP) [22]. Documents served over the internet are referred to as **webpages** or **websites**.

Definition 1.3: HTTP & HTML

HTTP (HyperText Transfer Protocol), the protocol which transfer data over the internet, distributing **HTML** (HyperText Markup Language) documents. Such documents include **hyperlinks** to other websites, images, and other media [33].

Definition 1.4: RFC (Request for Comments)

RFC (Request for Comments) is a publication from the **Internet Engineering Task Force** (IETF) and the **Internet Society** (ISOC). This body governs the specifications for the internet and its protocols [65].

Definition 1.5: DNS and IP Addresses

An **Internet Protocol address** (IP address) is a unique identifier for a device on a network. The **Domain Name System** (DNS) maps domain names to IP addresses [1].

Definition 1.6: Web Browser

A **web browser** is a software application for accessing the **World Wide Web** (WWW) [66].

Definition 1.7: URL (Uniform Resource Locator)

A **URL** (Uniform Resource Locator) references each webpage, specifying protocol, domain, and path [68]. E.g., `http://www.example.com/path/to/resource`.

- **Protocol**: `http`
- **Domain**: `www.example.com`
- **Path**: `/path/to/resource`

Definition 1.8: Client-Server Model

Most of the internet operates on a **client-server model**, where an agent device–the **client**–requests data from another agent–the **server**–which serves an appropriate response. Clients are not servers and vice versa, as they receive and interpret data differently [19].

Definition 1.9: HTTP Methods

When a client makes a request to a server, they must specify their intent, categorized by **HTTP methods** [31]:

- **GET**: Retrieve data from the server.
- **POST**: Send data to the server.
- **PUT**: Update data on the server.
- **DELETE**: Remove data from the server.

Definition 1.10: HTTP Headers

HTTP headers are key-value pairs sent between the client and server to provide **metadata** about the request or response. **Metadata** is data about the transmitted data, telling the receiver how the incoming data should be interpreted [31].

Tim Berners-Lee and his team at CERN developed the first web server and browser in 1989 [69].

HTTP Version	Description
HTTP/0.9 (1991)	Only supports GET method (retrieving HTML alone).
HTTP/1.0 (1996)	RFC#1945, adding support for metadata in HTTP headers, status codes, and POST and HEAD methods [8].
HTTP/1.1 (1997)	Defined in RFC#2068 and later updated by RFC#2616, introduced persistent connections, chunked transfer encoding, and additional cache control mechanisms [30][31].
HTTP/2 (2015)	RFC#7540, improving performance by enabling request and response multiplexing, header compression, and prioritization [7].
HTTP/3 (2022)	Builds upon HTTP/2's features and uses the QUIC transport protocol to reduce latency and improve security. [10]

Table 1.1: Evolution of HTTP Versions

Note: In short, **Persistent Connections** allow multiple requests and responses to be sent over a single connection, reducing latency and improving performance [31]. **Chunked Transfer Encoding** allows the server to send data in chunks, enabling the client to start processing data before the entire response is received [31]. **Multiplexing**, is the ability to send multiple requests and responses over a single connection, reducing latency and improving performance [29]. **QUIC** will be discussed alter on with other transfer protocols in a later section.

1.2 Data Transmission

This section details how internet traffic is transmitted between devices.

Definition 2.1: ISO Model

The **ISO model** (International Organization for Standardization) is a conceptual framework for transmitted data between devices. It is divided into seven layers of function[13]. Published in 1984 by the International Organization for Standardization (ISO) [41].

Definition 2.2: TCP/IP Model

The **TCP/IP model** (Transmission Control Protocol/Internet Protocol) is a concise representation of the ISO model used in practical settings [70].

Definition 2.3: ISO Layers

1. **Physical**: Converts data into physical signals (e.g., electrical, optical, or radio waves) for transmission across the network medium (e.g., cables, fiber optics, or wireless channels).
2. **Data Link**: local delivery of directly connected devices within the same network.
3. **Network**: Handles addressing, routing, in external networks from source to destination.
4. **Transport**: Ensures end-to-end delivery, via a message delivery protocol.
5. **Session**: Initiates and terminates network connections, ensuring efficient resource usage.
6. **Presentation**: To translate, compress, and encrypt data (e.g., Operating Systems).
7. **Application**: User facing services such as, HTTP , FTP, DNS, SMTP, etc.

[44][60]

Note: Many of the above layers are closely related, if not identical. In practice, layers 5-6 are integrated into layer 7, and layers 1-2 are often combined into a single layer in the TCP/IP model.

Definition 2.4: TCP/IP Layers

1. **Network Interface**: Physical and data link layers from ISO.
2. **Internet**: Attaches IP addresses to data packets for routing across the internet.
3. **Transport**: Defines the delivery protocol, segmenting data into packets.
4. **Application**: The Session, Presentation, and Application layers from ISO.

[60]

Despite the numbering of the layers, the user interacts with the application layer, which communicates down the chain of layers to the physical layer, where the data is transmitted over the network medium. The receiving device then interprets the data, moving back up the chain to the application layer.

To illustrate the contrast between the ISO and TCP/IP models, consider the diagram:

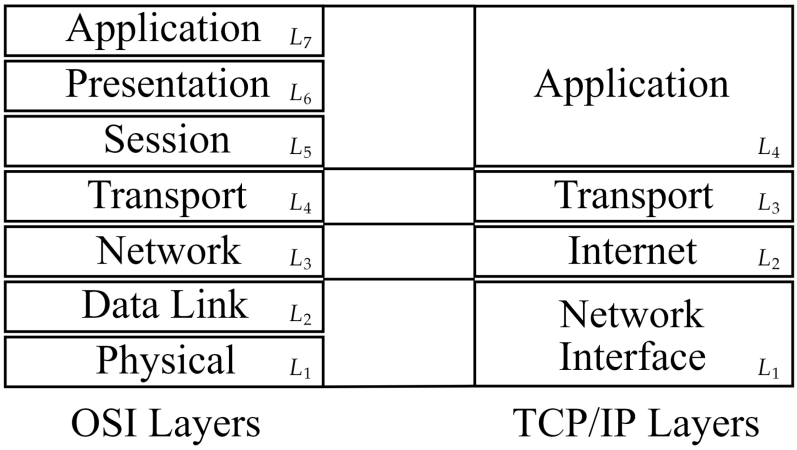


Figure 1.1: ISO vs TCP/IP Model

To illustrate two devices communicating over the internet, consider the diagram:

1.3 Routing Networks

When IP addresses began

Definition 3.1: Routing

Routing is the process of selecting the best path across networks. Data is segmented into packets, each with a destination address. **Routers** are devices which forward this data through the network.

Routers have a **routing table** which maps to other reachable networks. When a packet arrives, the router checks against its routing table to find the best path. [23]

Definition 3.2: Hop-by-Hop & End-to-End Routing

- **Hop-by-Hop Routing**: When a packet of data is forwarded from one router to the next, a forward decision is called a **hop**.
- **End-to-End Routing**: The process of sending data from source to destination without intermediate hops.

It is often rare to see end-to-end routing in modern networks, as data is often forwarded through multiple routers. A target destination may be unreachable from a given router. [36]

Definition 3.3: Router Advertising

When routers inform each other of their existence and the networks they can reach [49].

Definition 3.4: Routing Protocols

- **IP** (Internet Protocol): The primary protocol for routing data across the internet.
- **BGP** (Border Gateway Protocol): The protocol for routing data between **Autonomous Systems** (AS). an AS is a collection of IP networks and routers under the control of a single entity (e.g., an **ISP** (Internet Service Provider)). These may only connect with each other if they have a mutual agreement. ASes identify themselves to external networks using a unique **Autonomous System Number** (ASN). These are unique 16 bit numbers between 1-65534 or 32 bit numbers between 131072-4294967294 (e.g., `AS12345`) [21].
- **OSPF** (Open Shortest Path First): A link-state routing protocol used within an AS. Link-state protocols are a set of algorithms which determine the best path, based on the topology of a network graph [43]. It is also an **IGP** (Interior Gateway Protocol), meaning it operates within a single AS. It does so by sending out **LSAs** (Link State Advertisements) to other routers in the AS. Then routers in the system build a **LSADB** (Link State Advertisement Database) of the network topology. Then a shortest path algorithm is run to determine the best path to each network [11].
- **RIP** (Routing Information Protocol): RIP employs hop count as a routing metric, with a maximum allowable hop count of 15 (network size limitation). It operates as an **IGP** within a single AS, periodically broadcasting the entire routing table to neighboring routers every 30 seconds, which can lead to slower convergence and higher bandwidth usage compared to other protocols. RIP is largely deprecated [40].

Definition 3.5: IP Addressing

IP addresses are unique identifiers for devices on a network. There are two versions of IP addresses, **IPv4** and **IPv6**. IPv4 A 32-bit address (2^{32} addresses), employed since 1983, quickly exhausted all available addresses by the 2010s [45]. IPv6 is a 128-bit address (2^{128} addresses), introduced in 1998 , in an attempt to address this shortage [28][37]. For example,

- **IPv4**: a decimal octet "$x.x.x.x$": $x \in [0, 255]$ (e.g., `192.168.1.1`).
- **IPv6**: a hexadecimal segment "$y:y:y:y:y:y:y:y$": $y \in [0, FFFF]$ (e.g., `2001:0db8:85a3:0000:0000:8a2e:0370:7334`).

Definition 3.6: Subnetting

Instead of a large monolith network of routers, networks can be divided into smaller networks called **subnets**. I.e., Instead of passing data to every device on a network, routers forward data to a representative device on each subnet. [20]

Definition 3.7: Subnet Masking

A **subnet mask** defines which part of an IP address identifies the **network** and which part identifies the **host**.

Definition 3.8: Classful Network

In the beginning, the first octet of an IPv4 address determined the network class—only allowing for 256 networks. The RFC#791 published in 1981 introduced **Classful Networks** [56]. It uses the first three bits of the first octet's binary representation as a subnet mask to determine a class ranging from A-E—D and E were rarely if ever used.

Class	Binary Prefix	Range (Decimal)	Purpose	Details
A	`0xx`	1.0.0.0 to 126.0.0.0	Unicast (large networks)	For large organizations; 8 bits for the network, 24 for hosts.
B	`10x`	128.0.0.0 to 191.255.0.0	Unicast (medium networks)	For medium-sized networks; 16 bits for the network, 16 for hosts.
C	`110`	192.0.0.0 to 223.255.255.0	Unicast (small networks)	For small networks; 24 bits for the network, 8 for hosts.
D	`1110`	224.0.0.0 to 239.255.255.255	Multicast	Reserved for multicast addressing; not for general use.
E	`1111`	240.0.0.0 to 255.255.255.255	Experimental and future use	Reserved for research and development; not assigned for standard use.

Table 1.2: Overview of IPv4 Address Classes

Definition 3.9: Fixed Length Subnet Masking (FLSM)

Fixed Length Subnet Masking (FLSM) is a technique which divides a network into equal-sized subnets. This may lead to inefficient use of IP addresses. [6]

Definition 3.10: Variable Length Subnet Masking (VLSM)

Variable Length Subnet Masking (VLSM) is a technique which allows for the creation of subnets with different sizes. As some ASes may require more IP addresses than others, VLSM allows for more efficient use of IP addresses. [6]

Definition 3.11: Classless Inter-Domain Routing (CIDR)

Classless Inter-Domain Routing (CIDR), introduced in 1993 through RFC#1518 and RFC#1519 to address IPv4 exhaustion. **CIDR replaced classful subnetting** with VLSM. CIDR notation is written as `IP Address/Prefix Length` (e.g., `192.168.1.0/24`), where:

- `IP Address`: Represents the starting address of the network.
- `Prefix Length`: The number of bits used for the **network portion** of the address.

For example:

`255.0.0.0/8`; `255.255.0.0/16`; `255.255.255.0/24`; `255.255.255.192/26`;

[34]

Definition 3.12: Route Aggregation

CIDR introduced **Route Aggregation** also known as **Supernetting**, or **Route Summarization**, is the process of combining multiple routes into a single route advertisement. **Example**: Consider an organization assigned the following contiguous IP address blocks:

`192.168.1.0/24`; `192.168.2.0/24`; `192.168.3.0/24`; `192.168.4.0/24`;

Each block holding 256 IP addresses with a subnet mask of 255.255.255.0, requiring four routing table entries. However, these networks share a common prefix: the first 22 bits (`192.168.0.0/22`), which aggregates to: **`192.168.0.0/22`** [34].

Definition 3.13: IP Address Components

Network Address:

- Identifies the specific network segment to which a device is connected.
- Determined by setting all bits in the host portion to 0.
- Example: For the IP address `192.168.1.10` with a subnet mask of `255.255.255.0` (/24), the network address is `192.168.1.0`.

Host Address:

- Uniquely identifies a device within a network segment.
- The bits in the IP address designated for hosts, specified by the subnet mask.
- Example: In the IP address `192.168.1.10` with a /24 subnet mask, the host portion is the last octet (10).

Broadcast Address:

- Used to communicate with all devices on a specific network segment simultaneously.
- Determined by setting all bits in the host portion to 1.
- Example: For the network `192.168.1.0/24`, the broadcast address is `192.168.1.255`.

[64] [59] [46]

Consider the IP address `192.168.2.12/26` and its binary `11000000.10101000.00000010.00001100`:

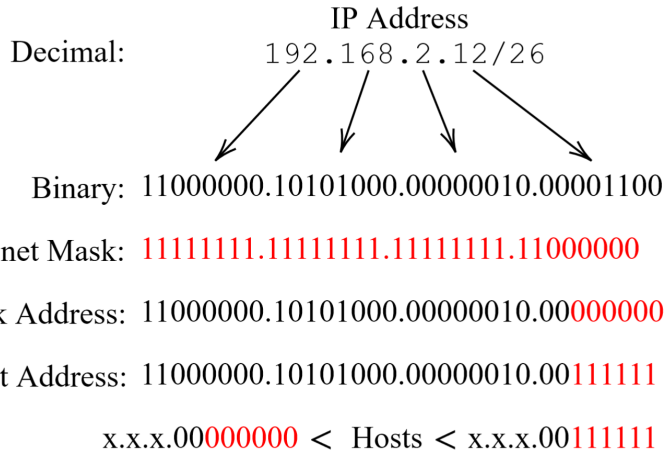


Figure 1.2: Binary Subnetting: Red indicating parts of the IP address identified for each component.

Definition 3.14: Common Types of Area Networks (ANs)

PAN (Personal Area Network): A network for personal devices, such as smartphones, smartwatches, or earbuds, with a short range (typically a few meters) using technologies like Bluetooth or infrared.

LAN (Local Area Network): Connects devices within a small area, such as a home, office, or school, enabling high-speed communication and resource sharing.

WLAN (Wireless Local Area Network): A wireless version of LAN that uses Wi-Fi to connect devices within a localized area like a home or office.

CAN (Campus Area Network): A network that connects multiple LANs across a limited geographical area, such as a university campus or corporate facility, for resource sharing and communication.

MAN (Metropolitan Area Network): Covers a larger area than a LAN, typically a city or metropolitan region, connecting multiple LANs or CANs via high-speed infrastructure like fiber optics.

WAN (Wide Area Network): Connects LANs, MANs, or other networks over large geographical areas, such as countries or continents. The internet is the largest WAN example.

SAN (Storage Area Network): A high-speed network that provides access to storage devices for data centers, ensuring fast and reliable storage management.

EPN (Enterprise Private Network): A private network created by organizations to connect their various locations securely, often including VPNs for remote access.

VPN (Virtual Private Network): Creates a secure, encrypted connection over public networks, like the internet, to allow users to access private networks remotely.

HAN (Home Area Network): A network within a home environment, connecting personal devices like computers, printers, and smart home gadgets.

GAN (Global Area Network): A large-scale network that connects multiple WANs and supports worldwide communication, with the internet as its most prominent example.

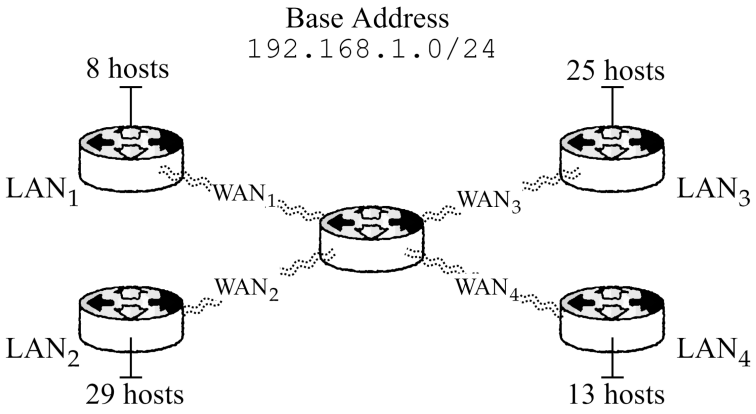
[53]

Example 3.1: Subnetting a Network via VLSM

Consider the FLSM below, which all have 62 hosts per network:

Network Address	Hosts	Broadcast Address
192.168.100.0	.1 – .62	.63
192.168.100.64	.65 – .126	.127
192.168.100.128	.129 – .190	.191
192.168.100.192	.193 – .254	.255

Below illustrates this network, where a router of base address `192.168.1.0/24`, connects four LANs:



Subnetting: Process each LAN from largest to smallest, Select the nearest block size, identify the network, host, and broadcast addresses. Since there is a subnet mask of /24, blocks $[128, 64, 32, 16, 8, 4, 2, 1]$ are available. This is the case as $2^8 = 256$. If a LAN has 129 hosts, that LAN will occupy all 256 addresses.

1. **LAN**$_2$: 29 hosts ⇒ Block size 32. Network: `x.0`, Broadcast: `x.31`, Hosts: `x.1-x.30`.
2. **LAN**$_3$: 25 hosts ⇒ Block size 32. Network: `x.32`, Broadcast: `x.63`, Hosts: `x.33-x.62`.
3. **LAN**$_4$: 13 hosts ⇒ Block size 16. Network: `x.64`, Broadcast: `x.79`, Hosts: `x.65-x.78`.
4. **LAN**$_1$: 8 hosts ⇒ Block size 16. Network: `x.80`, Broadcast: `x.95`, Hosts: `x.81-x.94`.

8 hosts need occupy 16, as a block size of 8 only has 6 usable addresses. The computed subnet now only occupies addresses `x.0-x.95`, leaving room for additional LANs [12].

■

Definition 3.15: Ports

A host may have serve multiple resources, HTTP, FTP, SSH, etc. **Ports** are used to distinguish between these services. Port numbers are managed by the **Internet Assigned Numbers Authority (IANA)**, outlined in RFC#6335. The RFC divides ports into three categories:

- **Well-Known Ports (0–1023)**: Reserved for standardized services (HTTP: port 80).
- **Registered Ports (1024–49151)**: User applications or services upon request.
- **Dynamic/Private Ports (49152–65535)**: Temporary communications. [26]

Which can be found here: IANA Service Names and Port Numbers.

Definition 3.16: Transport Layer Protocols (TCP, UDP, QUIC)

Out of numerous transport layer protocols, there are three primary protocols used to dictate the flow of data between devices:

- **TCP**: A connection-oriented protocol that ensures reliable communication by establishing a connection before transmitting data. TCP guarantees delivery, maintains packet order, and retransmits lost packets. It is ideal for applications like web browsing (HTTP/HTTPS) and file transfers (FTP). [58]
- **UDP**: A connectionless protocol that prioritizes speed by sending data without establishing a connection. It does not guarantee delivery, order, or error correction, making it suitable for time-sensitive applications like video streaming, online gaming, and DNS lookups. [54]
- **QUIC**: A modern, connection-oriented protocol built on UDP that combines speed with reliability. QUIC provides features like multiplexed streams, faster connection establishment, and built-in encryption, addressing TCP's latency issues while retaining UDP's efficiency. It is optimized for HTTP/3 and increasing in use. [39]

Definition 3.17: MAC Address

A **MAC address** (Media Access Control address) is a globally unique identifier assigned to a device's network interface card (NIC) at the **network interface layer** of the TCP/IP model. MAC addresses consist of 48 bits, typically represented as six pairs of hexadecimal digits (e.g., `00:1A:2B:3C:4D:5E`).

The first 24 bits represent the **Organizationally Unique Identifier (OUI)**, assigned to manufacturers by the **Institute of Electrical and Electronics Engineers (IEEE)**. The remaining 24 bits are left to the manufacturer to ensure device uniqueness [38].

Definition 3.18: Ethernet

Ethernet is a protocol used at the **network interface layer** of the TCP/IP model for communication within local area networks (LANs). If a network is communicating at these layers—such as in homes, offices, or data centers—Ethernet provides the rules for framing, addressing, and transmitting data between devices using **MAC addresses**. Ethernet is the dominant standard for wired LAN communication. [3]

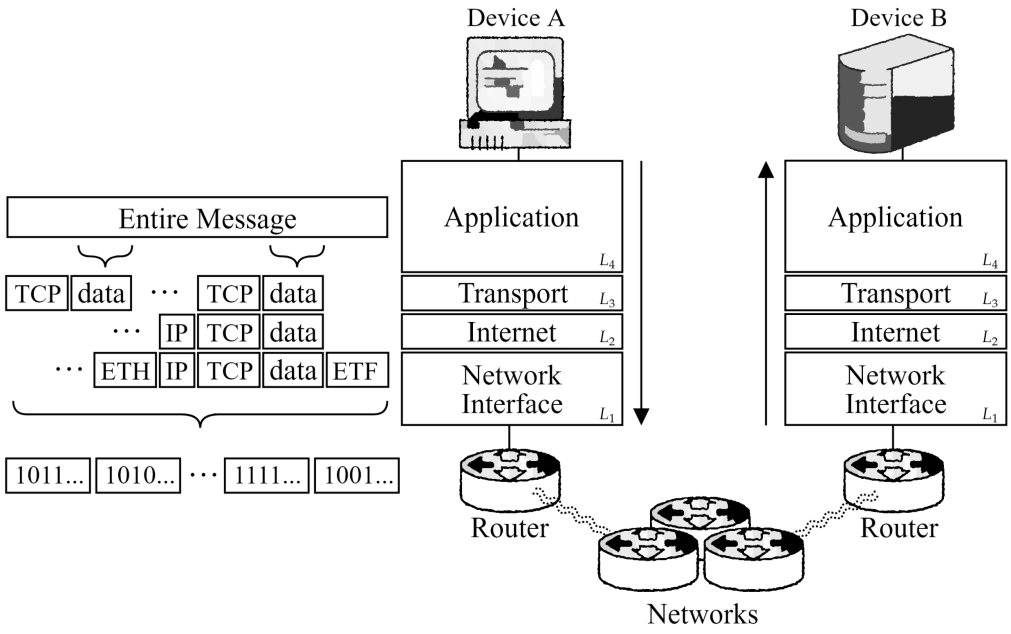


Figure 1.3: Data transmission between devices from application to physical layer and back.

1. **Transport Layer (L3)**: Data is segmented and encapsulated by a protocol like TCP, UDP, or QUIC. Headers with source and destination port numbers are added to enable communication with the correct application.
2. **Network Layer (L2)**: Data is encapsulated into an IP packet, including the source and destination IP addresses. The router uses the destination IP to determine if the packet should be sent locally or to a remote network.
3. **Data Link Layer (L1)**: For local delivery, the packet is encapsulated into an Ethernet frame with source and destination MAC addresses. If the packet is leaving the local network, it is sent to the router. Data is wrapped with a **Ethernet Header and Trailer**.
4. **Routing Across Networks**: If the destination is on another network, routing protocols like **BGP** or **OSPF** determine the optimal path. The packet is forwarded across multiple routers, each stripping the current Ethernet frame and applying a new one for the next hop.

Definition 3.19: TCP Header

A **TCP header**, as defined in RFC#793, is a component of a TCP segment that contains essential information for reliable data delivery between devices. Minimum size of 20 bytes and a max 60 bytes with options. It's called a header as it sits *ahead* of the **payload** (data) in the segment. Eg., [TCP Header (20–60 bytes), Payload (0-65,495 bytes)]. [58]

Field	Size (bits)	Description
Source Port	16	Identifies the sending application on the source device.
Destination Port	16	Identifies the receiving application on the destination device.
Sequence Number	32	Specifies the position of the first byte of data in the current segment relative to the start of the data stream.
Acknowledgment Number	32	Used to confirm receipt of data by specifying the next expected byte.
Data Offset	4	Indicates the size of the TCP header in 32-bit words.
Reserved	6	Reserved for future use; must be set to 0.
Flags (Control Bits)	6	Includes control flags (e.g., SYN, ACK, FIN) for managing connections and flow.
Window Size	16	Specifies the size of the sender's receive window for flow control.
Checksum	16	Ensures the integrity of the TCP header and payload.
Urgent Pointer	16	Points to urgent data within the segment, if the URG flag is set.
Options	Variable	Optional fields for additional settings (e.g., Maximum Segment Size).
Padding	Variable	Ensures the header is a multiple of 32 bits.

Table 1.3: Fields of the TCP Header

Definition 3.20: Maximum Transmission Unit (MTU)

The **Maximum Transmission Unit (MTU)** is the maximum size of a packet, in bytes, that a network can receive before requiring further fragmentation. Theoretically, a payload of 65,535 bytes can be sent, but in practice, are much lower (e.g., Ethernet 1,500 bytes). [35][48]

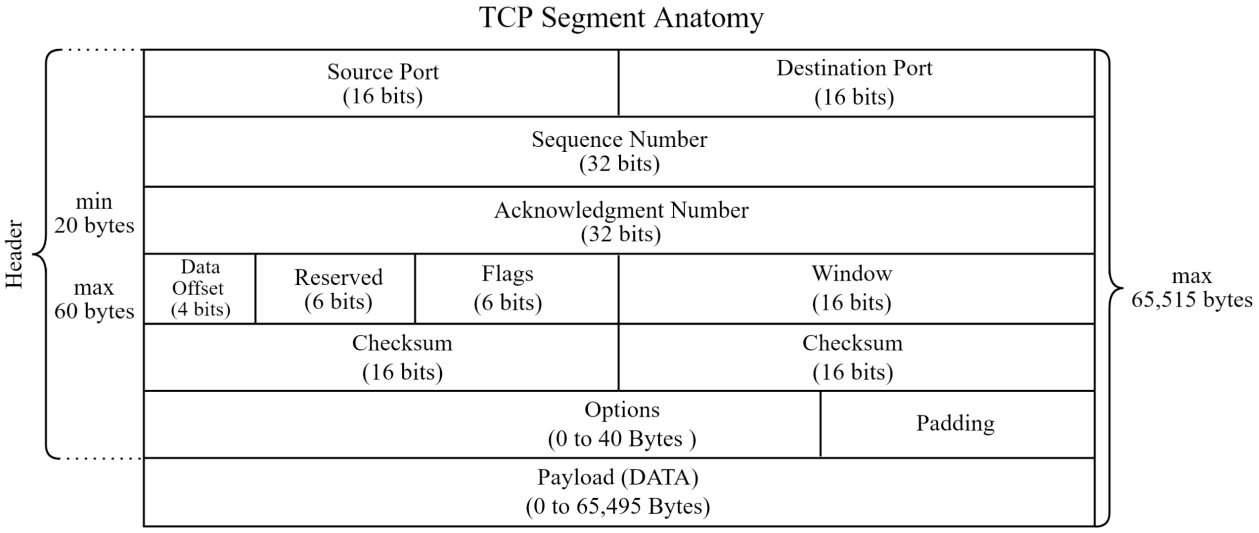


Figure 1.4: TCP Header

Definition 3.21: Flags (Control Bits) in TCP Header

The **Flags (Control Bits)** in the TCP header are a 6-bit field used to control and manage the state of a TCP connection. Each bit represents a specific flag, and one or more flags can be set simultaneously to define the segment's purpose.

List of Control Bits:

- **URG (Urgent Pointer)**: Indicates that the Urgent Pointer field is significant.
- **ACK (Acknowledgment)**: Confirms receipt of data; the Acknowledgment Number field is valid.
- **PSH (Push Function)**: Requests the receiver to pass the data to the application immediately.
- **RST (Reset)**: Resets the connection due to errors or unexpected conditions.
- **SYN (Synchronize)**: Initiates a connection by synchronizing sequence numbers.
- **FIN (Finish)**: Signals the sender's intention to terminate the connection.

[58]

Definition 3.22: TCP Options

- **Maximum Segment Size (MSS)**: Specifies the largest segment size the sender is willing to accept (4 bytes).
- **Window Scale**: Extends the window size field to support larger flow control (3 bytes).
- **Selective Acknowledgment (SACK)**: Allows acknowledgment of specific data blocks, improving performance in packet loss scenarios (variable size).
- **Timestamps**: Provides timing information for round-trip time measurement and protection against wrapped sequence numbers (10 bytes).
- **NOP (No Operation)**: Used for padding to ensure proper alignment (1 byte).
- **End of Option List (EOL)**: Marks the end of the options field (1 byte). [58]

Definition 3.23: SYN-ACK Handshake

The **SYN-ACK Handshake** is a three-step process used to establish a TCP connection between two devices. After the handshake, data is exchanged bidirectionally via ACKs receipts. Connection termination follows a similar process **FIN-ACK**.

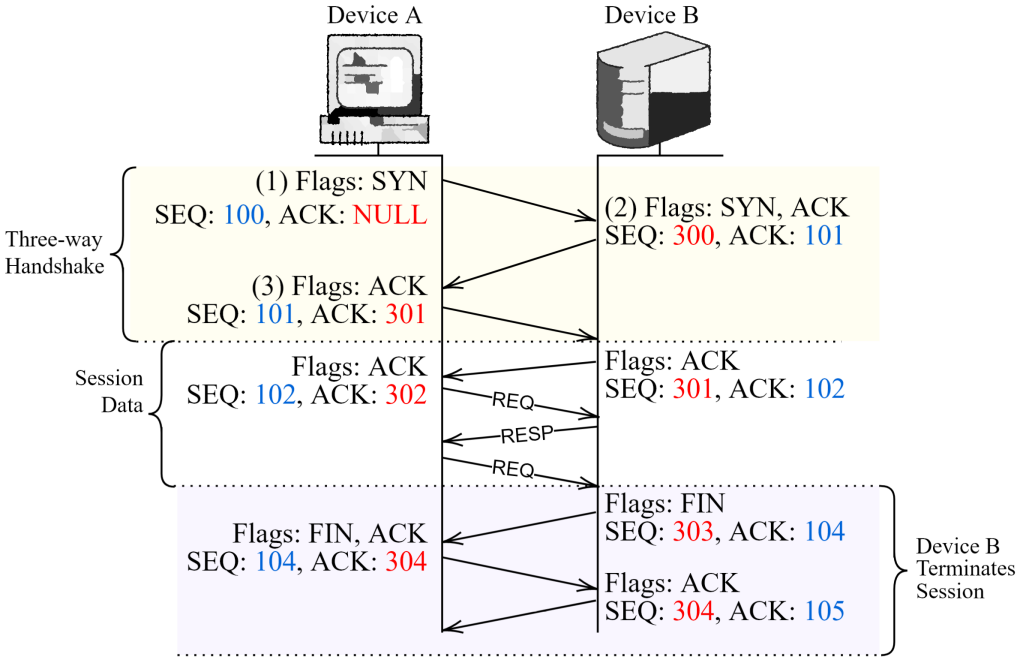


Figure 1.5: SYN-ACK Handshake, showing Sequence (SEQ) and Acknowledgment (ACK) Numbers.

Definition 3.24: TCP Windows

The **TCP Window** is a flow control mechanism that determines how much data can be sent before receiving an acknowledgment from the receiver. The size of the window is specified by the **Window Size** field in the TCP header and can dynamically adjust during the connection.

E.g., Consider a window allowance of 10 packets. If the sender is still waiting on an ACK for packet 1 while it has sent out packets 2-10, the window size reduces momentarily waiting for the receiver to acknowledge the first packet before sending more. [58]

Definition 3.25: UDP Header

The **UDP (User Datagram Protocol) Header** is a fixed-size, lightweight header. It consists of only 8 bytes, containing only essential information. [54]

Field	Size (bits)	Description
Source Port	16	Identifies the sending application. This field is optional and may be set to zero if not used.
Destination Port	16	Identifies the receiving application.
Length	16	Specifies the total length of the UDP packet, including the header and payload, in bytes.
Checksum	16	Provides basic error-checking for the header and payload. If not used, it can be set to zero.

Table 1.4: Fields of the UDP Header

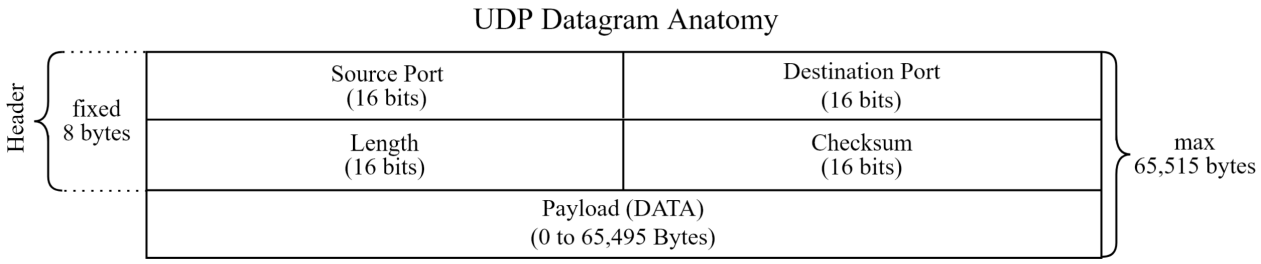


Figure 1.6: UDP Header

Definition 3.26: IPv4 Packet Header

An **IPv4 packet header** as outline in RFC#791, contains essential information for routing and delivering data across networks. The header consists of several fields, each serving a specific purpose. Eg., [IP Header (20–60 bytes), Transport Header, Payload]. in a stream of bits. [57]

Field	Size (bits)	Description
Version	4	Specifies the IP version; for IPv4, this value is 4.
Internet Header Length (IHL)	4	Indicates the header length in 32-bit words; minimum value is 5 (20 bytes).
Type of Service (ToS)	8	Defines packet priority and request for specific handling, such as low delay or high throughput.
Total Length	16	Total size of the packet (header and data) in bytes; minimum is 20 bytes, maximum is 65,535 bytes.
Identification	16	Unique identifier for fragmenting and reassembling packets.
Flags	3	Control flags for fragmentation: Reserved (1 bit), Don't Fragment (1 bit), More Fragments (1 bit).
Fragment Offset	13	Specifies the position of this fragment in the original packet; measured in 8-byte blocks.
Time to Live (TTL)	8	Limits the packet's lifespan; decremented by each router, and discarded when reaching zero to prevent infinite loops.
Protocol	8	Indicates the encapsulated protocol (e.g., 6 for TCP, 17 for UDP).
Header Checksum	16	Error-checking of the header; recalculated at each hop.
Source Address	32	IP address of the sender.
Destination Address	32	IP address of the receiver.
Options	0-320	Optional settings for control, routing, or security; length varies and is not commonly used.
Padding	Variable	Added to ensure the header length is a multiple of 32 bits.

Figure 1.7: IPv4 Packet Header Fields

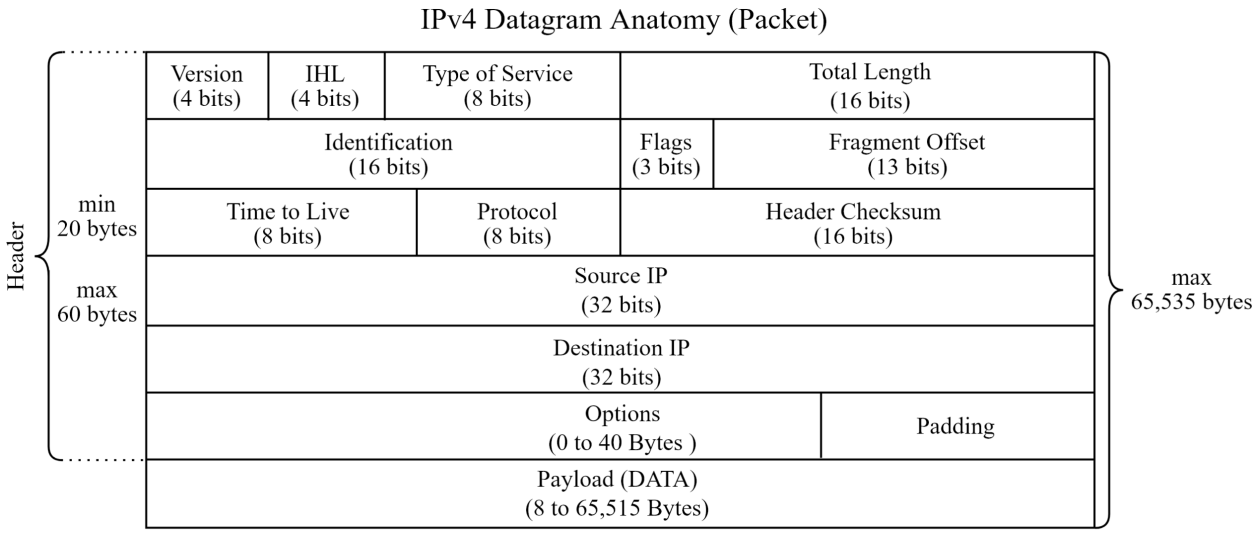


Figure 1.8: IPv4 Packet Header.

Payload is possibly 8-65,515 bytes, because of UDP's 8-byte header. Normally the size is variable, and much more in the ball park of 1,500 bytes.

Definition 3.27: IPv4 Flags

Reserved (Bit 0): Reserved for future use, must be set to `0`.
Don't Fragment (DF, Bit 1): `0`: Fragmenting allowed. `1`: Fragmented prohibited; if required, the packet is discarded, and an ICMP error (next definition) is sent to the sender.
More Fragments (MF, Bit 2): `0`: Last fragment. `1`: More fragments are expected. [57]

Definition 3.28: Internet Control Message Protocol (ICMP)

Internet Control Message Protocol (ICMP) is a supporting protocol used by network devices to communicate error messages and operational information. To name a few:

- **Destination Unreachable**: Indicates that a packet could not reach its destination.
- **Time Exceeded**: Signals that the packet's **Time to Live (TTL)** has expired.
- **Fragmentation Needed**: Informs the sender the packet is too large without fragmenting.
- **Echo Request and Reply (Ping)**: Tests connectivity between devices. [55]

For full specifications visit: ICMP Parameters. Note viewing their reference RFCs may be more informative.

Definition 3.29: IPv4 Options

The **IPv4 Options** field is an optional. Every options occupies 1 byte regardless do data (var = variable, '-' = none).

Common IPv4 Options (class, number, data length (bytes)):

- **End of Option List (0, 0, -)**: Marks the end of the options field.
- **No Operation (0, 1, -)**: Used for padding.
- **Security (0, 2, 11)**: Includes security and compartmentalization details.
- **Loose Source Routing (0, 3, var)**: Specifies a loose route for pathing.
- **Internet Timestamp (2, 4, var)**: Records timestamps at each hop.
- **Strict Source Routing (0, 9, var)**: Specifies an exact route for pathing.
- **Record Route (0, 7, var)**: Records the route taken by the datagram.
- **Stream ID (0, 8, 4)**: Identifies the stream of communication.

Classes: 0: Control. **1**: Reserved for future use. **2**: Debugging and Measurement. **3**: Reserved for future use. [57]

QUIC Headers will be introduced later, as it incorporates uncovered content. The following solution was implemented to address the exhaustion of IPv4 addresses:

Definition 3.30: Private and Public IP Addresses

IP addresses are classified as **private** or **public** based on their scope and accessibility:

- **Private IP Addresses**: Reserved for use within private networks (e.g., home or corporate networks). These addresses cannot communicate directly over the internet and include ranges like:
  - $10.0.0.0 - 10.255.255.255$
  - $172.16.0.0 - 172.31.255.255$
  - $192.168.0.0 - 192.168.255.255$
- **Public IP Addresses**: Globally unique addresses assigned by the Internet Assigned Numbers Authority (IANA) for communication over the internet.

Devices on a private network can communicate internally using private IPs, while a public IP is needed to access external networks like the internet. Communication between these address types is facilitated by **Network Address Translation (NAT)**. [61]

Definition 3.31: Network Address Translation (NAT)

Network Address Translation (NAT) is a networking technique that translates private IP addresses within a local network to a public IP address for communication over external networks, such as the internet. NAT modifies the source IP address in outbound packets and reverses the process for inbound packets, ensuring data is correctly routed to devices within the private network.

NAT enables multiple devices to share a single public IP address, facilitating efficient communication while keeping private IP addresses hidden from external networks. [61][63]

Definition 3.32: Dynamic & Static NATs and PATs

When a device crosses a router into an external network, the router replaces parts of the packet with a public translation. There are **NATs** and **Port Address Translations (PATs)**:

- **NAT**: Only translates the IP address, leaving the port unchanged.
- **PAT**: Translates both the IP address and port number (rarely, only the port).

There are two types of configurations for NAT and PAT:

- **Static:** The administrator explicitly defines the translations of IP addresses and ports.
- **Dynamic:** The administrator defines a pool of public IP addresses and ports, allowing the router to assign them dynamically.

PATs are referred to in RFC#2663 as **Network Address Port Translation (NAPT)**. This overall process is also known as **Overloading** or **IP Masquerading**. [63]

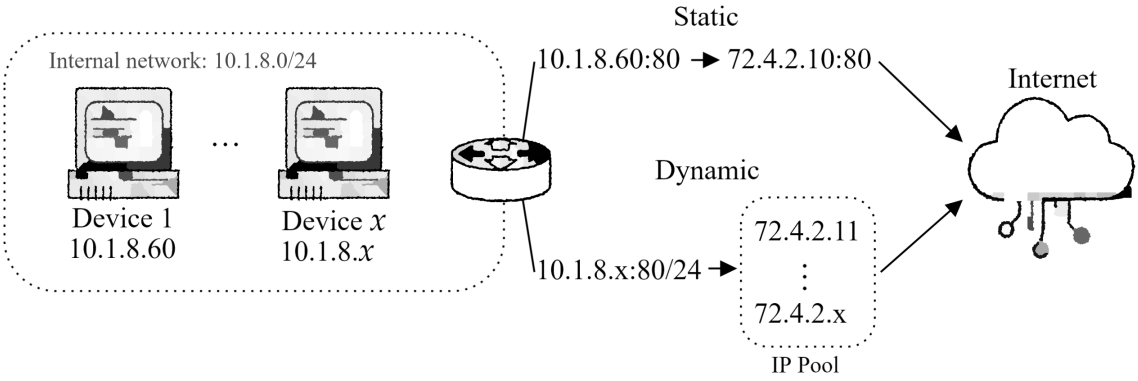


Figure 1.9: Static and Dynamic NATs from an internal network to the internet.

Incoming traffic will reverse the process, translating the public IP back into its private mapping. In many cases, an administrator would be an ISP, who distributes public IPs to clients.

Definition 3.33: Regional Internet Registries (RIRs)

Regional Internet Registries (RIRs) are non-profit organizations responsible for the allocation, distribution, and management of Internet number resources, including **IPv4 and IPv6 addresses** and **Autonomous System Numbers (ASNs)**, within specific geographic regions.

Key Functions of RIRs:

- **Database Management**: Maintain public records documenting the allocation and assignment of Internet number resources.
- **Policy Development**: Facilitate community-driven processes for creating policies on resource management.

The Five RIRs and Their Regions:

- **ARIN**: North America, Canada, parts of the Caribbean.
- **RIPE NCC**: Europe, the Middle East, and Central Asia.
- **APNIC**: Asia and the Pacific region.
- **LACNIC**: Latin America and parts of the Caribbean.
- **AFRINIC**: Africa and the Indian Ocean region.

[50]

Definition 3.34: Carrier-Grade NAT (CGNAT/NAT444)

Carrier-Grade NAT (CGNAT), also known as **NAT444**, is a network translation mechanism used by Internet Service Providers (ISPs) to address IPv4 address exhaustion. It refers to three sets of IPv4 addresses:

- **Customer Private**: IPv4 addresses within the customer's local network.
- **ISP Private**: IPv4 addresses used internally within the ISP's network.
- **Public Internet**: IPv4 addresses used for external communication.

Network Address Translation occurs in two stages:

- **Customer Private → ISP Private**: Translation by the customer's router—**Customer Premises Equipment (CPE)**.
- **ISP Private → Public Internet**: Translation by the ISP's CGNAT device.

[63][62]

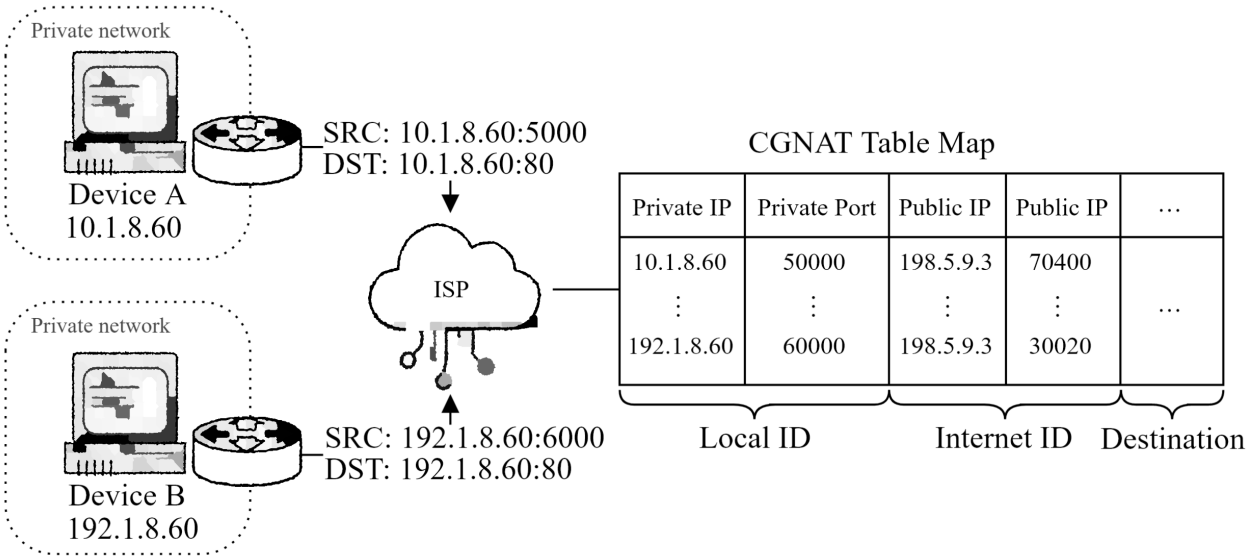


Figure 1.10: Carrier-Grade NAT (CGNAT) Translation Process

Definition 3.35: DNS Servers

Domain Name System (DNS) Servers are specialized servers responsible for translating human-readable domain names (e.g., `example.com`) into machine-readable IP addresses (e.g., `192.0.2.1`), a process known as a **DNS Lookup**. Retrieving a website involves:

- Querying DNS servers to resolve a domain name into its corresponding IP address.
- Traversing a hierarchical network of DNS servers: starting from **root servers**, through **Top-Level Domain (TLD) servers** (e.g., `.com`), to the **authoritative DNS server** for the domain.

Control and Operation:

- **Root DNS Servers** are managed by independent organizations under the coordination of the **Internet Corporation for Assigned Names and Numbers (ICANN)**.
- **TLD DNS Servers** manage domains under specific extensions like `.com`, `.org`, and country-specific domains like `.uk`.
- **Authoritative DNS Servers** are controlled by entities that manage specific domain names, including private companies, governments, or educational institutions.

Caching: Devices (e.g., computers, routers) and services (e.g., ISPs) may store previously resolved domain names in a **DNS cache**, reducing the need for repeated lookups and improving connection speed. [47]

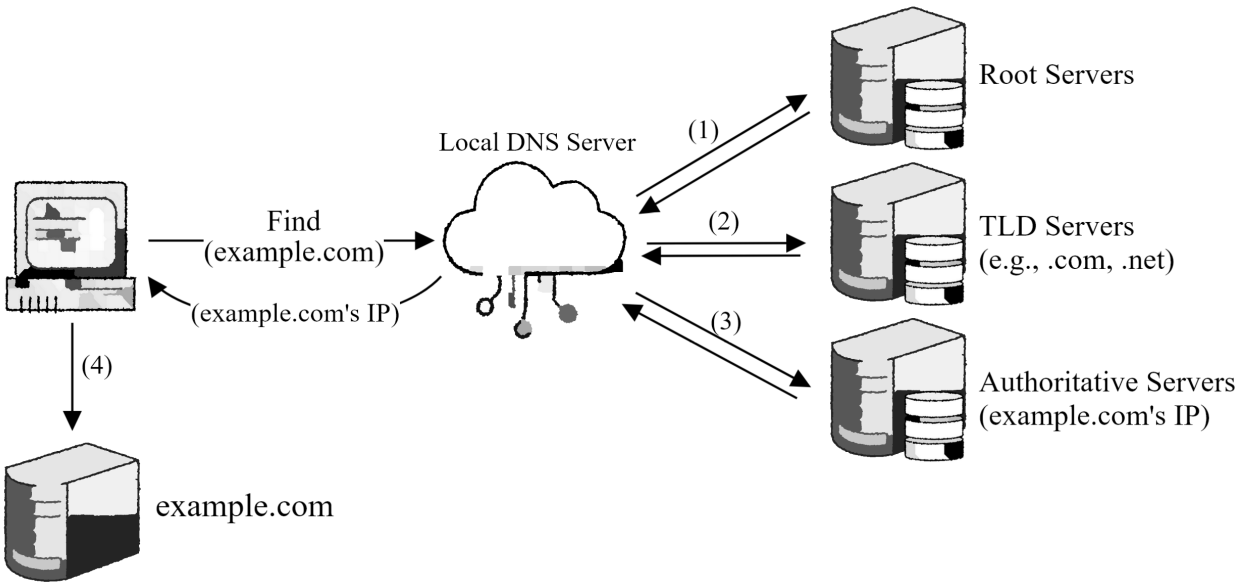


Figure 1.11: DNS Lookup Process: (1). Query root server for (`.com`), (2). Query TLD for (`example.com`), (3). Query Authority for (`example.com's IP`).

Definition 3.36: DNS Hierarchy: Root, TLD, and Authoritative Servers

- **Root Servers**: Only provide references to the appropriate **TLD servers** based on the queried domain extension (e.g., `.com`, `.org`).
  - Operated by organizations like VeriSign, USC, and ICANN.
  - Example: The `A` Root Server is managed by VeriSign.
  - View the full list at: https://root-servers.org/.
- **TLD Servers**: Manages **Top-Level Domains (TLDs)** such as `.com`, `.org`, and `.uk`. They direct queries to the **authoritative servers** for the requested domain.
  - Example: VeriSign manages TLD servers for `.com` and `.net`.
  - Often operated by private companies or regional internet registries.
- **Authoritative Servers**: These servers store DNS records for specific domain names, responding with the IP address of the queried domain.
  - Example: A hosting provider like AWS or Google Cloud might manage the authoritative server for `example.com`.
  - Businesses, ISPs, or hosting services typically operate these servers.

[5][14]

Definition 3.37: HTTP Messages

When communicating with a web server, a client establishes an **HTTP session** to exchange data. The client sends an **HTTP request** to the server, which processes the request and responds with an **HTTP response**. The HTTP header and Response consists of:

1. **Request Line**: Contains the request method (e.g., GET, POST), URL, and HTTP version.
2. **Request Headers**: Include additional information such as DNS and client software.
3. **Empty Line**: Separates the header from the body.
4. **Request Body**: Contains data sent to the server (e.g., form data). Optional for some requests (e.g., GET).

Messages are sent over **TCP** or **UDP** stored in the **Payload** of the datagram. [32]

Definition 3.38: Uniform Resource Identifier (URI) & URLs

A **Uniform Resource Identifier (URI)**: a string which identifies resources on the web. A **Uniform Resource Locator (URL)** a subset of URI that specifies the resource and its location. A **Uniform Resource Name (URN)** is a URI under a different schema, a unique global identifier of a resource even after it is no longer available (e.g., a book isbn, urn:isbn:0451450523). [9]

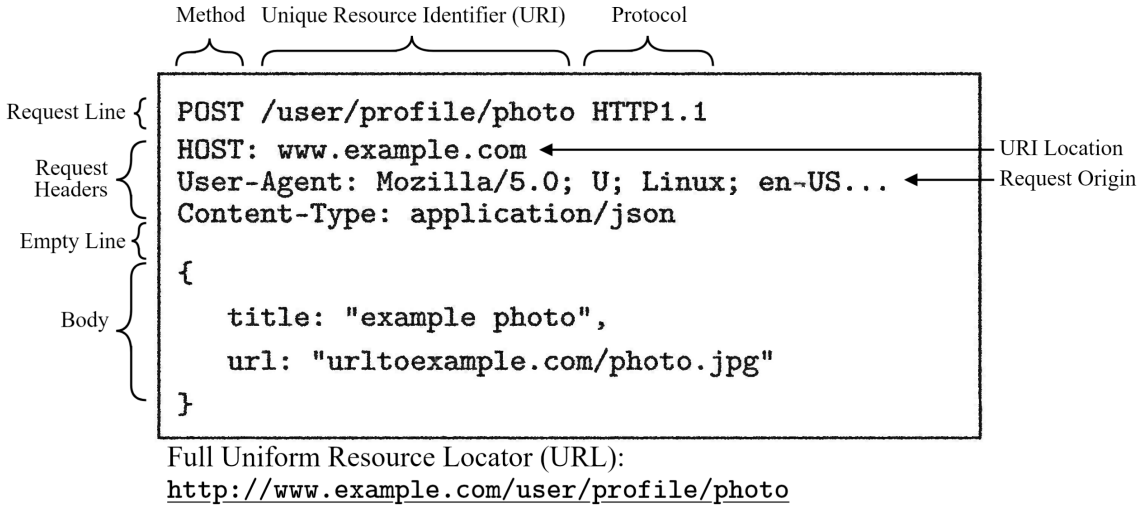


Figure 1.12: HTTP Request and Response Structure

Definition 3.39: Ethernet Frame

Ethernet Frames at the **Data Link Layer** (ISO model), encapsulate IP packets for transmission over a local network. The specifications for Ethernet, including frame structure and operational parameters, are defined by the **Institute of Electrical and Electronics Engineers (IEEE)** in the **IEEE 802.3** standard. [2]

Field	Size (bytes)	Description
Preamble	7	A sequence of alternating 1s and 0s (10101010) used for synchronization between the sending and receiving devices.
Start Frame Delimiter (SFD)	1	Indicates the start of the frame; typically has the bit pattern 10101011.
Destination MAC Address	6	The hardware address of the intended recipient.
Source MAC Address	6	The hardware address of the sender.
EtherType/Length	2	Specifies either the protocol type encapsulated in the payload (if ≥ 1536) or the length of the payload in bytes (if ≤ 1500).
VLAN Tag (optional)	4	Present if IEEE 802.1Q tagging is used; includes Priority Code Point (PCP), Drop Eligible Indicator (DEI), and VLAN Identifier (VID).
Payload	46–1500	The encapsulated data from higher network layers. If the payload is less than 46 bytes, padding is added to meet the minimum frame size requirement.
Frame Check Sequence (FCS)	4	A cyclic redundancy check (CRC) value used to detect errors in the transmitted frame.

Table 1.5: Structure of an Ethernet Frame

Theorem 3.1: Establishing a Website Connection

1. **Application Layer (DNS Request)**: The browser initiates a DNS query to resolve the website's domain name (e.g., `example.com`) into an IP address. The DNS query traverses:

   - **Root DNS Server→TLD Server→Authoritative DNS Server**. (e.g., `.com`→`example.com`→`example.com's IP`).

   If the IP address is cached locally or by the ISP, the query resolves faster.

2. **Transport Layer (Connection Establishment)**: After the IP address is resolved, the browser establishes a connection to the server. If using **TCP**, the connection involves a **three-way handshake**:

   - The browser sends a **SYN** packet to the server.
   - The server responds with a **SYN-ACK** packet.
   - The browser completes the handshake by sending an **ACK** packet.

   For protocols like **UDP**, no handshake occurs, and packets are sent directly without connection establishment.

3. **Network Layer (Routing)**: Packets, regardless of protocol (e.g., TCP, UDP, or ICMP), are encapsulated within IP datagrams and routed to the destination. Routers along the path forward the packets based on the destination IP address in the IP header. The routing process is agnostic to the transport protocol and works universally across all IP-based communication.

4. **Data Link Layer (Frame Transmission)**: If connection is within a local network (e.g., LAN), IP packets incur Ethernet frame encapsulation (or equivalent, depending on the network).

5. **Physical Layer (Transmission)**: Frames are transmitted as electrical signals, light pulses, or radio waves, depending on the physical medium used. **Inter-domain routing protocols**, such as **OSPF** or **BGP**, facilitate the transfer of packets through **AS**es.

6. **Application Layer (HTTP Request)**: Once the connection is established, the browser sends an **HTTP request** to the server via datagram **Payload**:

   - The browser requests the document.
   - The server responds with the HTML content, which is sent back over the established connection.

7. **Response and Rendering**: The server's response is segmented into TCP packets (if applicable) and reassembled by the browser. The browser processes the HTML and renders the webpage for the user.

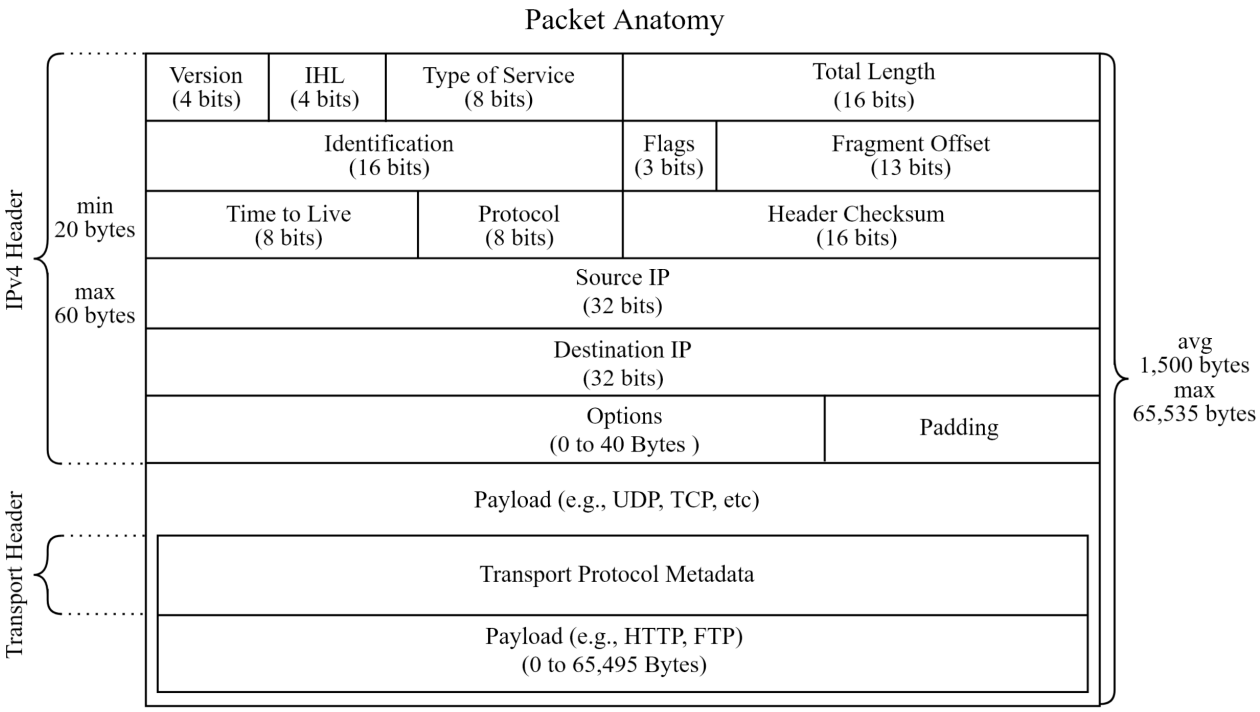


Figure 1.13: Anatomy of a packet, from IPv4[TCP/UDP[Data]]

— 2 —

Network Security

2.1 Transport Layer Security & Certificates

Before, all communication sent "**over the wire**" (from device to device), was sent "**in the clear**" (unencrypted). This means that anyone could view data sent between devices in plain text. This is a problem when setting up infrastructure such as banking, e-commerce, or any other service that requires sensitive information to be sent over the internet.

Definition 1.1: Integrity & Authenticity

Integrity is the assurance that data has not been altered in transit.
Authenticity is the assurance that the data is coming from the correct source.

Definition 1.2: Transport Layer Security (TLS)

TLS is a protocol providing end-to-end encryption of data. It authenticates the server via **TLS certificates** to ensure the client is connecting to the correct host. It also ensures integrity of the data.

The Engineering Task Force (IETF) published the first version of TLS in 1999. As of today the most recent version is TLS 1.3. (2018). [17]

Definition 1.3: Secure Sockets Layer (SSL) [Deprecated

SSL is the predecessor to TLS. It was developed by Netscape in the 1990s. SSL 3.0 was released in 1996. SSL 3.0 was found to be insecure and was replaced by TLS 1.0 in 1999. [17]

Definition 1.4: Certificate Authority (CA)

A CA is a third-party entity that issues digital certificates. Often called **SSL certificates** or TLS certificates. The protocol supports both SSL and TLS. Despite SSL's deprecation the name stuck due branding issues. Browsers and Operating systems have a list of trusted CAs called the **root store**. A full list of Microsoft's trusted CAs can be found here:
https://ccadb.my.salesforce-sites.com/microsoft/... [42]

Definition 1.5: Encryption

Encryption is the process of converting plaintext into ciphertext (indiscernible text).
Decryption is the process of converting ciphertext back into plaintext.

Definition 1.6: Symmetric & Asymmetric Encryption

Key: is a seed/piece of information used to encrypt or decrypt data.
Symmetric Encryption: uses the same key for both encryption and decryption.
Asymmetric Encryption: uses a public key for encryption and a private key for decryption. [4]

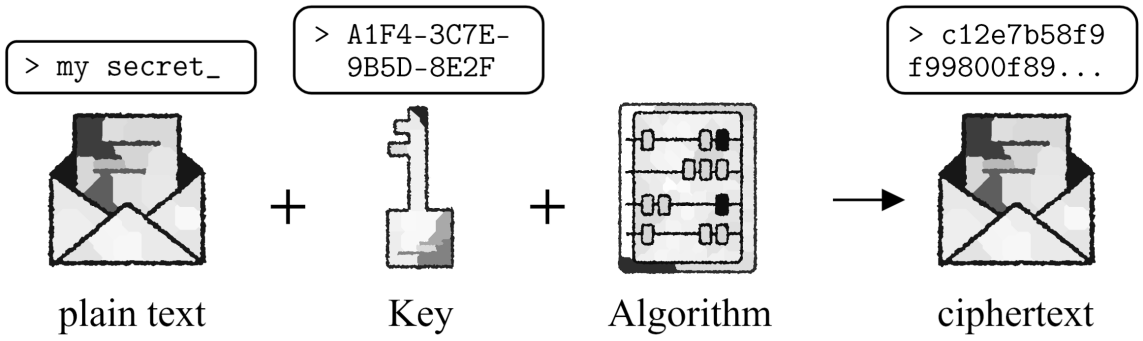


Figure 2.1: High-level depiction of encryption.

Encryption takes a key, data, and an algorithm to produce ciphertext. Decryption takes the same key, ciphertext, and algorithm to produce the original data.

Definition 1.7: Hashing

Hashing is the process of converting data into a fixed-length string of characters. Hashing is a one-way function, meaning it cannot be reversed (theoretically). In practice, it is computationally infeasible to reverse a hash without brute force (trying all possible inputs) or exploiting weaknesses in the hashing algorithm. Some hash algorithms use the text itself as input, while others may incorporate a separate key (e.g., HMAC). [24]

Definition 1.8: Hypertext Transfer Protocol Secure (HTTPS)

A version of HTTP that uses TLS to encrypt data. [18]

Definition 1.9: SSL/TLS Certificate Specifications

- **Common Name (CN)**: The domain name the certificate is issued for.
- **Subject Alternative Name (SAN)**: Additional domain names or subdomains covered by the certificate.
- **Key Length**: A minimum of 2048 bits, ensuring strong encryption.
- **Hashing Algorithm**: Typically SHA-256 for secure data integrity.
- **Valid From/To**: The validity period, usually up to 397 days.
- **Issuer**: The trusted Certificate Authority (CA) that issued the certificate.
- **Extended Key Usage**: Specifies purposes like server authentication or client authentication.

[42]

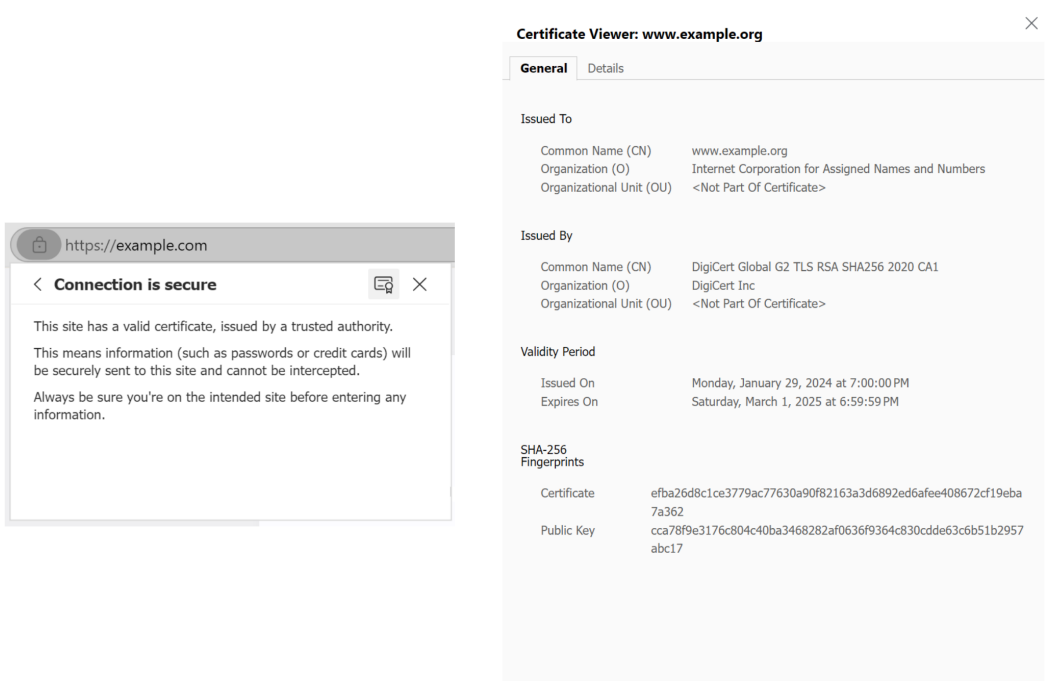


Figure 2.2: SSL certificate obtained through the Edge browser on example.com

Definition 1.10: Public Key Infrastructure (PKI)

PKI is a system for managing digital certificates. It includes the creation, distribution, and revocation of certificates. PKI is used to secure data transmission over the internet such as secure email, VPNs, and other services. [52]

Definition 1.11: Digtial & Authority Certificates

Digital Certificate: An electronic document binding and proving ownership of a public key. **Authority Certificate**: or **Root Certificate** issued by a CA, signs other certificates. it is **self-signed** and is the top of the certificate chain.

This establishes layers of trust and distance between the root certificate and the end-user certificates. If the root certificate is compromised, all certificates through the chain are compromised. [71]

Definition 1.12: Digital Signatures

To verify a source, a **digital signature** is used.

- **Key Generation**: A private and public key pair is generated beforehand.
- **Hashing**: A cryptographic hash of the data is created (e.g., SHA-256).
- **Encryption**: The private key encrypts the hash, creating the digital signature through an algorithm (e.g., RSA).
- **Verification**: The recipient decrypts the signature with the public key and compares the result to their own hash of the data. [27]

Definition 1.13: Certificate Signing Request (CSR)

To obtain a digital certificate, a client generates a CSR, which involves the following steps:

1. **Generate Key Pair**: Create a private key (kept secret) and a public key (shared).
2. **Produce CSR Data**: Include identifying information (e.g., Organization (O), Common Name (CN)), the public key, and other details in a standardized format such as X.509.
3. **Sign the CSR**: Hash the CSR data and sign it using the private key to prove ownership.
4. **Submit and Issue Certificate**: Submit the CSR to a CA, which validates the signature, signs the certificate with its own private key, and issues the certificate. [51]

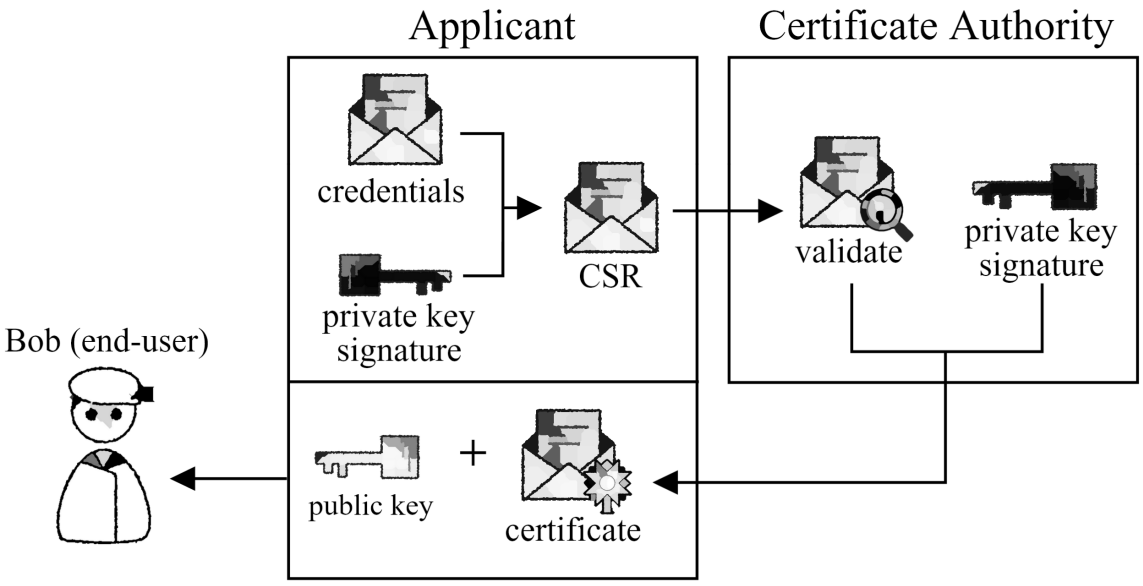


Figure 2.3: Example of a Certificate Signing Request (CSR)

Definition 1.14: Certificate Revocation List (CRL)

A CRL is a list of certificates that have been revoked by the CA before their expiration date. This is used to prevent the use of compromised certificates. [25]

Definition 1.15: Chain of Trust

A **Chain of Trust** is a hierarchical sequence of certificates used in PKI to establish trust between entities. It consists of:

- **Root Certificates**: Self-signed certificates at the top of the trust chain, trusted directly by operating systems and browsers.
- **Intermediate Certificates**: Issued by the root CA to delegate trust, adding a layer of security by isolating the root CA from direct interactions.
- **End-Entity Certificates**: Issued to users, servers, or devices to authenticate their identity and enable secure communications.

Each certificate is digitally signed by the private key of the certificate authority above it in the chain, with the root certificate serving as the ultimate trust anchor. Certified issuers are preferred over self-signed certificates because they undergo rigorous external validation, creating a verifiable path of trust. [25]

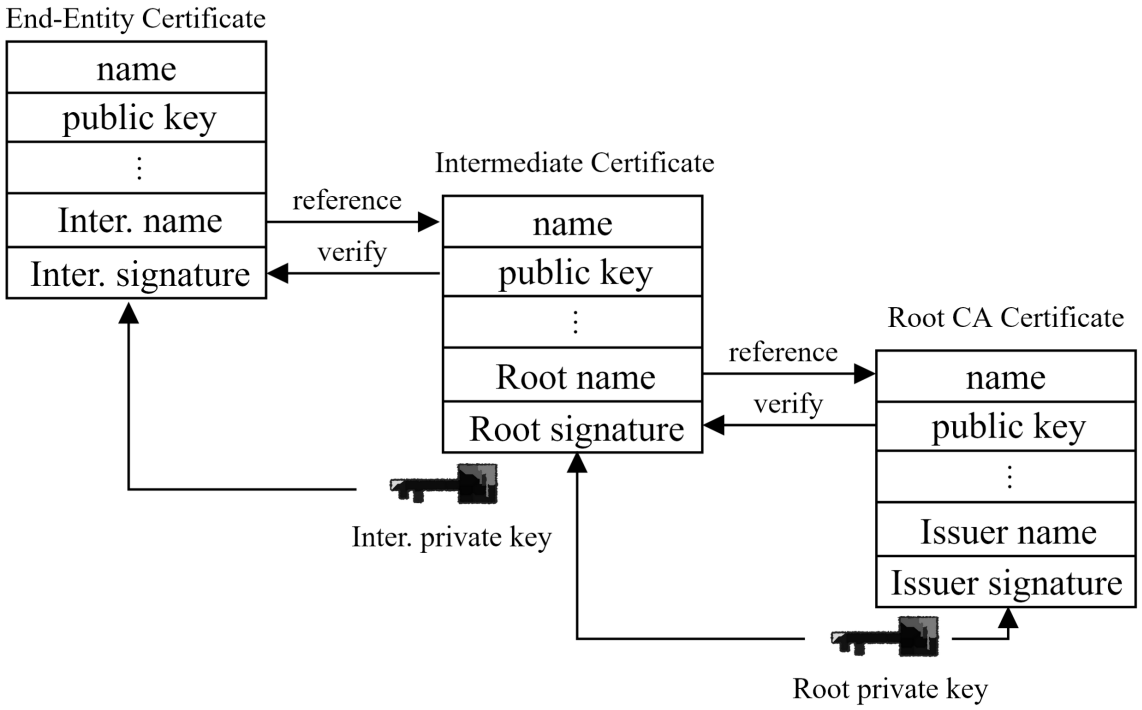


Figure 2.4: A Chain of Trust from the Root Certificate to the End-Entity Certificate.

Definition 1.16: Root Certificate Authority (CA) Signing Ceremonies

A **Root Certificate Authority (CA) Signing Ceremony** is a highly secure process in which a Root CA's private key is used to sign subordinate certificates, establishing trust within a Public Key Infrastructure (PKI). Key characteristics include:

- **Rigorous Security**: Conducted in offline, access-controlled environments with multiple layers of physical and procedural security. Entry requires the presence of multiple trusted individuals simultaneously.
- **Defined Roles**: Roles such as Crypto Officers, Witnesses, and Administrators are assigned to ensure transparency and accountability.
- **Global Trust Anchors**: Managed by organizations like ICANN for DNSSEC, these ceremonies protect the integrity of critical internet infrastructure.
- **Independent Operations**: Root CAs are typically independent from government oversight, though some, like the U.S. Department of Defense, manage government-affiliated Root CAs.

Learn More: https://cloudflare.com/learning/dns/dnssec/root-signing-ceremony/ [16]

Definition 1.17: DNS over HTTPS (DoH) and DNS over TLS (DoT)

DNS over HTTPS (DoH) and **DNS over TLS (DoT)** are protocols designed to encrypt DNS queries, improving privacy and security:

- **DoH**: Encrypts DNS queries over the HTTPS protocol (port 443), making them indistinguishable from regular HTTPS traffic.
- **DoT**: Encrypts DNS queries using the TLS protocol (port 853), ensuring DNS requests are secure and tamper-proof. Though because of its use of port 853, traffic is more easily identifiable as DNS, making DoH the preferred method.

Both protocols prevent DNS queries from being visible in plaintext, mitigating risks like eavesdropping and DNS spoofing. DNS security is known as **DNSSEC**. [15]

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