

CS 250: FOUNDATIONS OF COMPUTER SYSTEMS

[NETWORKING]

Encapsulation and Layering

Packets grow with headers and trailers
As they trickle down successive layers

A small price to pay
To keep complexity at bay

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Frequently asked questions from the previous class survey

- Do you typically put a lot of logic in the while(true) loop for the ServerSocket?
- Routers vs Switches
 - ▣ Router connects different networks together and directs data traffic
 - ▣ switch connects multiple devices (computers, printers, servers) within a LAN



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Topics covered in this lecture

- Delay x Bandwidth product
- Support for Common Services
- Encapsulation
- Internet Architecture



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Network performance is measured in two fundamental ways

□ **Bandwidth**

- Number of bits transmitted over the network in a given time (e.g., 10 million bits per seconds 10 Mbps)
- Also called *throughput*

□ **Latency**

- How long it takes for message to go from one end of the network to another?



Components of latency

□ Speed-of-light **propagation** delay

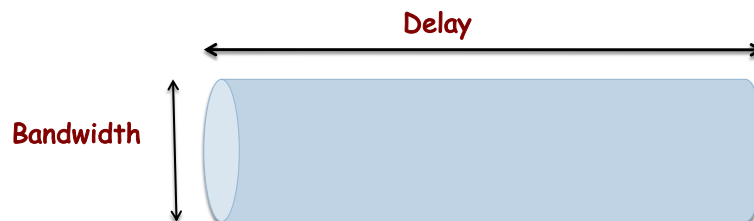
- 3×10^8 m/sec in vacuum
- 2.3×10^8 m/sec in cable

□ Amount of time to **transmit** a unit of data

□ **Queuing** delays



The Delay x Bandwidth product



Viewing the Network as a pipe



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The Delay x Bandwidth product

- The product gives us information about *how many bits fit* in the pipe
- Transcontinental channel
 - 50 ms one-way latency
 - Bandwidth: 45 Mbps
 - Can hold: 50×10^{-3} seconds \times 45×10^6 bits/second
 - 2.25×10^6 bits = 280 KB



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The Delay x Bandwidth product

- Corresponds to how many bits the sender must send
 - ▣ Before first bit arrives at the receiver
- Bits in the pipe are said to be **in flight**



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Bandwidth and latency improvements are not in lockstep

- Over past 45 years approximately
 - ▣ Bandwidth improvements: 220-1200 times
 - ▣ Latency improvements: 4-20 times
- Ethernet 802.3 (1978)
 - ▣ 10 Mbps
 - ▣ Latency 3 millisecond
- Ethernet 802.3ae (2003)
 - ▣ 10,000 Mbps (1000 times)
 - ▣ Latency 0.19 millisecond (15 times)
- Ethernet 802.3ck and 802.3db standards [100 Gbps] approved 9/21/23



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What does not change as the bandwidth increases?

- Speed of light
- High-speed **does not** mean that latency improves at the same rate as bandwidth
 - Transcontinental delays of 100 ms for
 - 1-Mbps/1-Gbps link



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Sending 1 MB data over a cross-country link. Delay 100 ms

- 1 Mbps link
 - Pipe: $100 \times 10^{-3} \times 10^6 = 100 \text{ Kb} = 0.1 \text{ Mb}$
 - So, you need 80 pipes to transmit 1 MB (8 Mb)
 - $8 \text{ Mb} / 0.1 \text{ Mb} = 80$
- 1 Gbps
 - Pipe: $100 \times 10^{-3} \times 10^9 = 100 \text{ Mb}$
 - So, you need $8 \text{ Mb} / 100 \text{ Mb} = \text{approx } 1/12^{\text{th}}$ of the pipe is utilized



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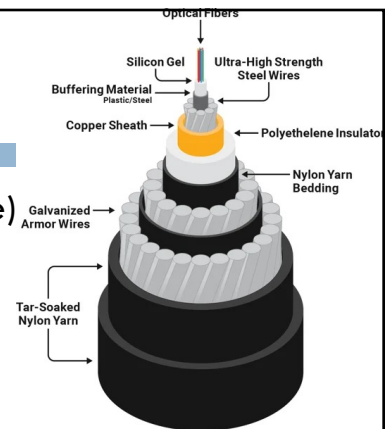
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A recent underwater cable [Marea]

- Transatlantic cable (6km under the ocean's surface)
 - ▣ Reefs, earthquake zones, etc.
- About the width of a garden hose (1.5x)
- 4000 miles long
 - ▣ Virginia Beach, US to Bilboa, Spain
- Transfer rate: 160 Tbps
 - ▣ 6000 HiDef Movies
 - ▣ The entire catalog of the US Library of Congress
 - ~38 million books; medium novel is about 1 MB



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Come as you are, as you were
As I want you to be
As a friend, as a friend
As an old enemy
Take your time, hurry up
Choice is yours, don't be late
Take a rest as a friend
As an old memoria

Come as you are; Kurt Cobain, Nirvana

WIRELESS TRANSMISSIONS

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How to move data wirelessly

- Optical connections use light beams as the data-carrying energy
 - ▣ Wired connections use electric pulses
- Wireless connections need an *electromagnetic* energy wave (called a **carrier wave**) to carry data



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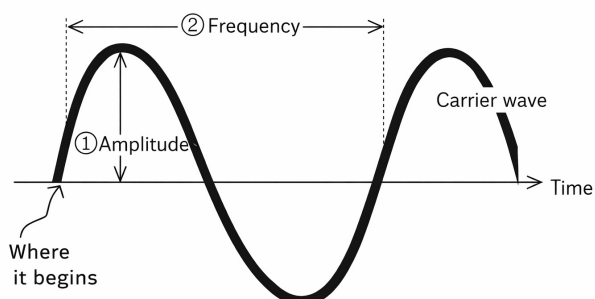
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Any carrier wave has three key properties:

- Its **height** (**amplitude** or strength)
- How often it oscillates up and down in 1 second (**frequency** measured in waves produced per second or hertz)
 - ▣ The frequency of a wave is *inversely* related to the length of each wave
 - So lower frequencies have lengthier waves and higher frequencies have shorter wavelengths
- The point at which each wave begins (**phase**)



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To **encode** data onto this carrier wave

- We can **tweak** the wave's
 - Amplitude
 - E.g., squishing it down to signal a zero; unsquished is a one
 - Or its frequency
 - E.g., squeezing the waves closer together to signal a one; otherwise a zero



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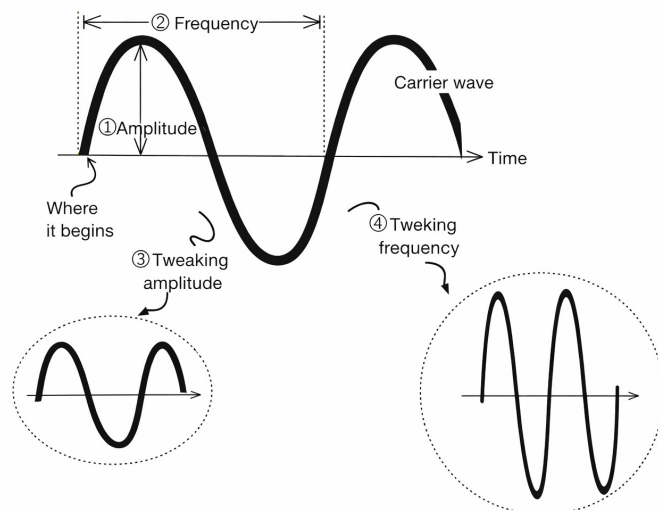
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Carrier Wave

- Components
- Tweaking to encode data



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Modulation

- We create a signal by adding data to a raw carrier wave
- We add data onto a raw carrier wave by *altering* one of the carrier wave's three properties
 - ▣ Amplitude, frequency, and, less commonly, its phase
- The stream of ones and zeroes representing the data is sent as a series of *changes in the carrier wave*
 - ▣ A process called **modulation**



Modulation

- We call the first strategy **amplitude modulation** (AM)
 - ▣ We can alter its **height**, saying that when it's full height, it means one, and when it's a lower height, it means zero
- The second strategy is **frequency modulation**
 - ▣ We can say that leaving a carrier wave's frequency untouched means zero, but increasing it to a specific different frequency means one



A visual depiction

- Encoding data
 - Amplitude modulation
 - Frequency modulation

Time → Block #1 | Block #2 | Block #3 →

Data 1 0 1

+ Carrier wave

= Amplitude-modulated signal

or Frequency-modulated signal

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Carrier frequency is a trade-off between range and capacity

- The frequency of a carrier wave (a **choice** we make) can range from very low to very high
 - Like all choices, it has consequences
- Carrier frequency carries a **trade-off** between its data-carrying **capacity** (bandwidth, measured in bps) and **how far** it can travel (range)
- Lower carrier frequencies can travel longer distances but can carry little data
 - Higher frequencies can carry more data but travel shorter distances

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You've intuitively experienced this trade-off with your car radio

- FM radio stations (which use higher frequencies) sound better but are lost after driving about 50 miles,
 - But AM radio stations (which use lower frequencies) sound noisier but are easily picked up even 500 miles away
- Similarly, higher-frequency 5G networks on our phones are much faster than lower-frequency 4G networks but have one-tenth their range
 - This is why 5G networks require a lot more cell towers and are prone to interference from buildings and trees



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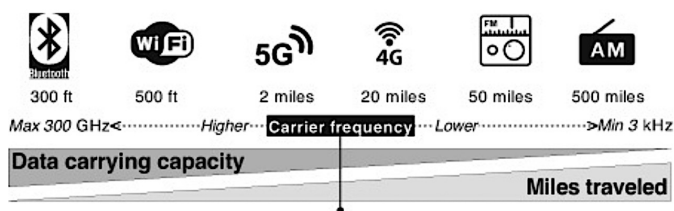
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Let's look at the spectrum of wireless transmissions



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All communications in networked systems are based on sending and receiving messages

- **No shared memory**
- Sending message from **A** to **B**
 - **Build message** in **A**'s address space
 - **Send message** over the network
 - **Reconstruct** message at **B**

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But A and B must agree on the *meaning* of the bits

- Signaling 1's and 0's
- What is the *last bit* of the message?
- Detect if the message is lost or damaged
 - Respond to problems
- Representation of data types



Layering and Protocols

- Start with services provided by hardware
- Add a **sequence** of layers
 - Each providing higher level of service
- Services at higher layers implemented **in terms of** lower layers



Advantages of layering

- Decomposes problem into **manageable** components
- Provides **modular** design
 - Adding functionality may result only in minor modifications



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Advantages of layering

- Each layer can be changed **independently** of the other
 - Change as technology improves



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Layered Architectures: Requests go down the hierarchy; results flow upward

The diagram illustrates a layered architecture with four layers: Layer N, Layer N - 1, Layer 2, and Layer 1. Request flow is shown as a solid black arrow pointing down from Layer N to Layer 1. Response flow is shown as a solid black arrow pointing up from Layer 1 to Layer N. Additionally, dashed red arrows indicate bidirectional communication between Layer N and Layer N - 1, and between Layer 2 and Layer 1. A text box on the right states: "Component at layer L_i can call components at layer L_{i-1} ".

Request flow ↓

Response flow ↑

Component at layer L_i can call components at layer L_{i-1}

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Example of a layered network system

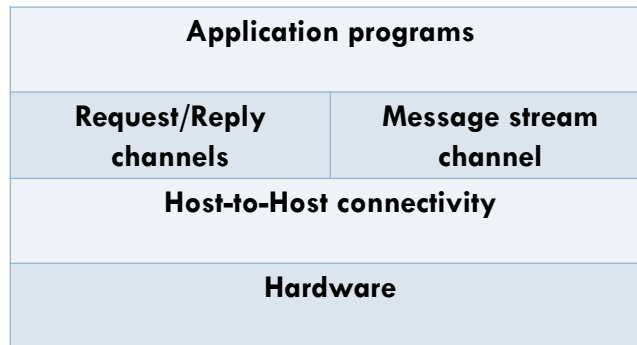
The diagram shows a layered network system with four distinct layers stacked vertically:

- Application programs
- Process-to-process channels
- Host-to-Host connectivity
- Hardware

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Layered system with alternative abstractions at a given layer



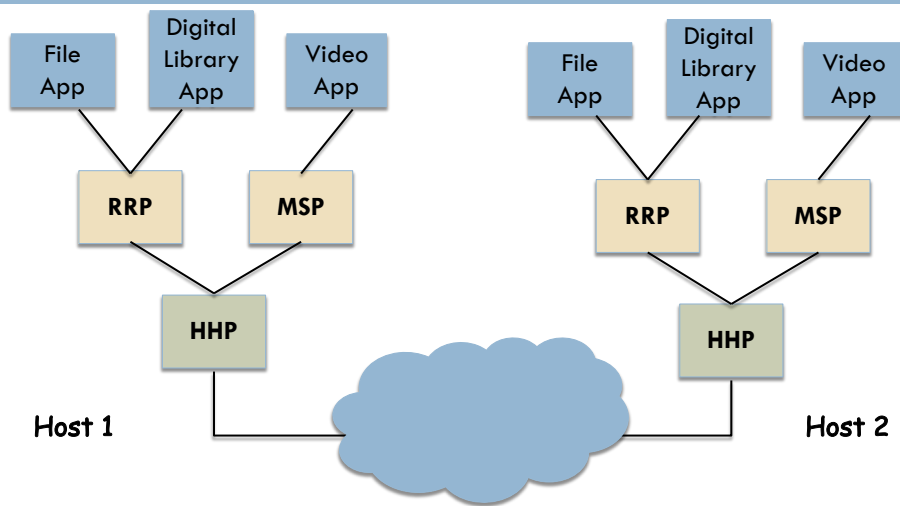
Abstract objects that comprise layers of a network system are called **protocols**

- Provides a **service interface** to other objects on the same computer
 - Wishing to use its communication services
- Defines the **form** and **meaning of messages** exchanged by protocol peers
- Protocol also refers to modules that implement a specification



ENCAPSULATION

Example of a protocol graph



Encapsulation

- RRP receives a set of bytes to transmit from the application
 - ▣ E-mail, integers, images etc
- RRP is responsible for sending this data to its peer at the other end
 - ▣ Must communicate **control information** to its peer
 - ▣ Instruct how to **handle** the message

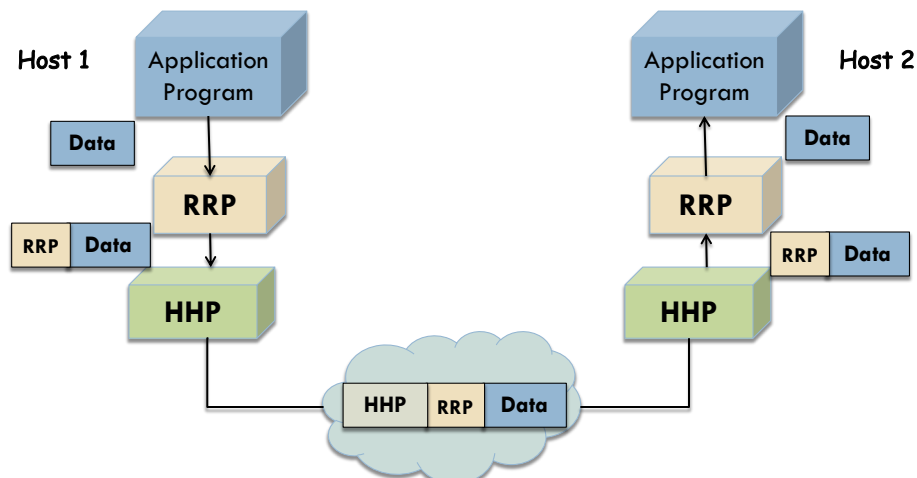


When asked to transmit info, lower-level layers add information to the message

- Attach a **header** to the message
 - ▣ Small data structure
 - ▣ Few bytes to several dozen bytes
- Control info at the end of message: **trailer**
- Format is specific to the protocol
- Data being transmitted: body or **payload**
- Application data is said to be **encapsulated**



Encapsulating high-level messages inside low-level messages



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Encapsulation: Some more info

- Low-level protocol does not **interpret** message given to it by high-level protocol
 - *Cannot extract* meaning
- Low-level protocol may apply simple **transformations** to the data it is given
 - Compress
 - Encrypt



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Multiplexing is applicable up-and-down the protocol graph too

- RRP attaches header to every message that goes through it
 - ▣ Header includes information to identify the application
 - Called demultiplexing key or **demux key**
- At the destination host, RRP strips its header
 - ▣ Examines demux key
 - ▣ Demultiplexes message to correct application



Demux key is used at all levels of the protocol stack

- Some use an 8-bit field {TCP (6), UDP (17)}
 - ▣ Can support only 2^8 (256) high level protocols
 - ▣ Can also be 16/32-bits
- There could be a **single** demultiplexing field
 - ▣ Same demux key used at both ends
- There could be a **pair** of demultiplexing fields
 - ▣ Each side uses different key to identify high-level protocol






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A computer network is a system that allows computing devices to **communicate** with each other

- Networks can be connected wirelessly, using technologies like Wi-Fi
 - ▣ Transmit data using radio waves
- Networks can also be connected with cables
 - ▣ Such as copper wiring or fiber optics

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A 30,000 foot view of the internet

- The internet is a globally connected set of computer networks that all use a **suite of common protocols**
- The internet is a **network of networks**
 - Connecting networks from various organizations all around the world



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Does physical connectivity equate with communications?

[1/2]

- Physically connecting the networks of the world *isn't enough* to allow the devices on those networks to communicate with each other
- All participating computers need to **communicate in the same way**



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Does physical connectivity equate with communications?

[2/2]

- The internet protocol suite **standardizes** the method of communication on the internet
 - ▣ Ensuring that all devices on the network speak the same language
- The two foundational protocols in the internet protocol suite are
 - ▣ Transmission Control Protocol (TCP) and Internet Protocol (IP)
 - ▣ Collectively known as **TCP/IP**



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THE LAYERED MODEL

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Network protocols operate in a layered model [1/2]

- An implementation of such a model is referred to as a **network stack**
- The protocols at the lowest layer
 - ▣ Interact with the underlying networking hardware
- Applications interact with protocols in the upper layers



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Network protocols operate in a layered model [2/2]

- Protocols in the intermediate layers provide services such as addressing and reliable delivery of data
- A protocol at a certain layer doesn't have to concern itself with the entire networking stack
 - ▣ **Only the layers with which it interfaces**, simplifying the overall design
 - ▣ This is another example of encapsulation



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The internet protocol suite is designed around a four-layer model

- This is sometimes called the **TCP/IP model**
- The four layers of the protocol suite:
 - The link layer
 - The internet layer
 - The transport layer
 - The application layer



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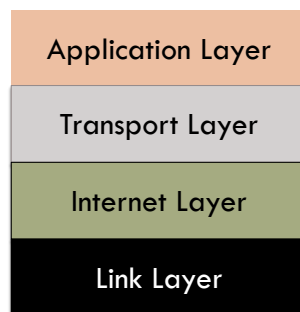
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The Internet Layered Protocol Stack



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Networking layers

- Networking layers represent an **abstraction**
 - A model for us to use when discussing the operation of the internet
- In practice, each layer is realized with specific networking protocols
- Each network layer **represents a scope of responsibilities**
 - Protocols must fulfill the responsibilities of their assigned layer



LOOKING AT THE INDIVIDUAL LAYERS



Application Layer

- Protocols that operate at the application layer provide **application-specific functionality**
 - Sending an email, retrieving a web page, transferring a file, etc.
 - E.g.: SMTP (Simple Mail Transfer Protocol), HTTP (Hypertext Transfer Protocol) , SSH (Secure Shell)
- These protocols accomplish tasks that end users (or backend services) wish to complete
- Application layer protocols structure the data used in process-to-process communication across a network
- All lower layer protocols exist as “plumbing” to support the application layer



An application ...

- **Structures data** according to an application layer protocol and ...
- **Hands off that data** to a transport layer protocol for delivery to a remote host



Transport Layer

- Transport layer protocols provide a **communications channel** for applications to send and receive data between hosts
 - E.g., TCP and UDP



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Internet Layer

- Internet layer protocols provide a mechanism for **communicating across networks**
- Responsible for identifying hosts with addresses and enabling the routing of data from network to network across the internet
- The transport layer relies on the internet layer for **addressing and routing**



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Link Layer

- Link layer protocols provide a way to **communicate on a local network**
- Protocols at this layer are closely associated with the type of networking hardware on a local network
 - E.g., Wi-Fi, Ethernet, FDDI, etc.
- Protocols at the internet layer rely on link layer protocols to communicate on a local network



Not every device is interested in using all 4 layers

- Network hosts (such as a client or server) make use of protocols from all four layers
- Other types of networking hardware (such as switches and routers) only use protocols associated with lower layers
 - Such devices can perform their jobs without bothering to examine the higher layer protocol data contained in a network transmission



The contents of this slide-set are based on the following references

- *Computer Networks: A Systems Approach*. Larry Peterson and Bruce Davie. 4th edition. Morgan Kaufmann. ISBN: 978-0-12-370548-8. [Chapter 1, 2]
- Amrit Tiwana. *The Internet Stack*. MIT Press. [Chapter 1,2].
- Matthew Justice. *How Computers Really Work: A Hands-On Guide to the Inner Workings of the Machine*. ISBN-10/ISBN-13 : 1718500661/ 978-1718500662. No Starch Press. 2020. [Chapter 11]

