# Wireless Communications

## 1. Introduction

Elvio J. Leonardo

DIN/CTC/UEM

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# First networks

- Postal Network
  - Global delivery of different types of objects (letters, packages, etc.)
  - Differentiated treatment by object class
  - High delay but low cost
  - Recipient and sender identified by postal address (name, street and number, city, etc.)
- Telephone Network
  - Global voice delivery in real time
  - Low delay but higher cost
  - Users identified by phone number
  - High reliability
  - Moderate fidelity

# Telephone Network

- 1876: Phone was patented by Graham Bell
- In order for communication to be possible, a direct connection between the two devices is necessary
  - A wire mess
- 1878: first telephone exchange
  - User connects to central
  - The call was switched manually by operators in the central
- Exchanges were connected to each other to allow long distance calls
- Trunks between exchanges allowed for several connections occurring at the same time
- Number of trunks has increased too much and a new hierarchical level was added
- Current telephone system has 5 hierarchical levels

# Communication Networks

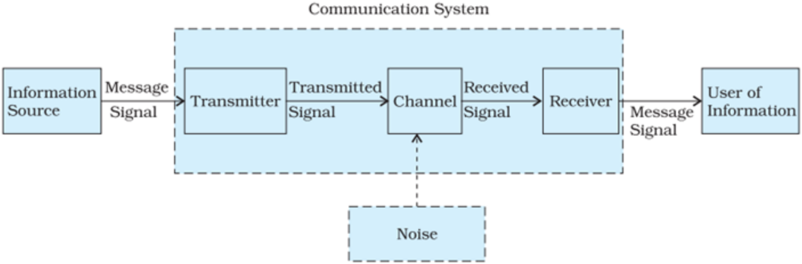
- 1800s: Telegraph network
- 1900s: Public Switched Telephone Network (PSTN)
- Data networks
  - 1956: Telex network (Canada)
  - Packet switched data networks
    - 1969: ARPANET: first operational network
    - 1976: Datapac (Canada): first network using X.25
- Integrated Services Digital Network (ISDN)
  - Motivation: Integrate voice and data
  - 1984: Publication of specifications
  - Basic subscriber access with 128 Kbps over 2x64 Kbps lines
- Internet
  - Attempt to integrate services, for example Voice over IP (VoIP)

# Internet

- ARPANET
  - 1969: ARPANET is established, connecting the universities UCLA, UCSB, U-Utah and Stanford
  - 1969: Specification of the Telnet service
  - 1971: Specification of the File Transfer Protocol (FTP)
  - 1972: E-mail service created by Ray Tomlinson
  - 1973: ARPANET becomes international
- 1981: The term **internet** is created
  - Designates a set of interconnected networks
- 1982: Open System Interconnect (OSI) Reference Model
- 1990: ARPANET becomes Internet
- 1991: Hypertext concept proposed by Tim Berners-Lee
  - WWW (World Wide Web) established
  - 1993: Mosaic, the first web browser is launched
- 2000s: Number of users doubles every 6 months
- 2017: Internet has over 1 million hosts in the Domain Name System (DNS)

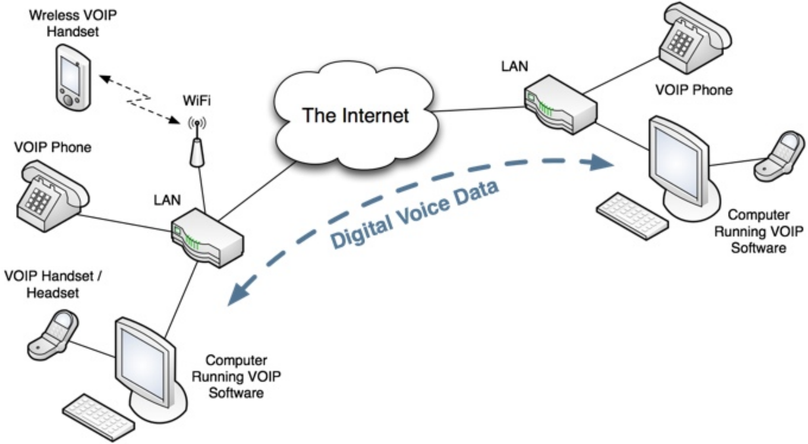
# Communication System

- Source: Produces the data to be transmitted (mostly digital)
- Transmitter: converts bits into signals
- Channel: carry the data signals
- Receiver: converts signals to bits
- User (Destination): consumes incoming data



# Communication System

- Example:



# Main Tasks

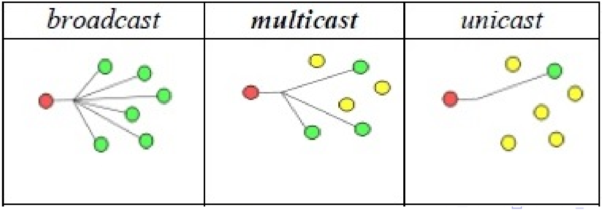
- Transmission
- Signal generation
- Synchronization
- Detection and correction of errors
- Routing and addressing
- Recovering from errors (end-to-end)
- Security

# Some Characteristics

- Message destination
- Type of link
- Geographic range
- Physical topology
- Data flow
- Connected or non-connected service
- Reception confirmed or not
- Communication alternation
- Switching method
- Bandwidth and throughput

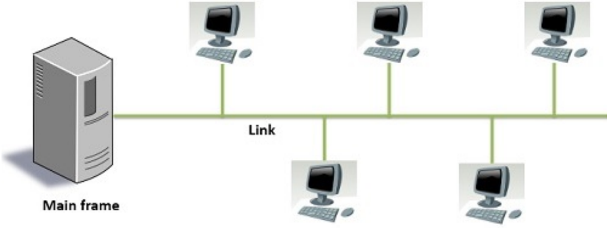
# Message Destination

- *Unicast*
  - Message addressed to only one destination
- *Multicast*
  - Message addressed to a group of destinations
- *Broadcast*
  - Message addressed to all network devices
  - In practice the scope of the broadcast is limited to one domain



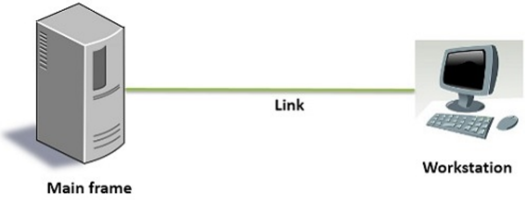
# Link Types

- Shared Medium
  - Medium (medium or communication channel) is shared by all nodes in the network
  - Each message (packet) has the recipient's address (in addition to other information)
  - Easy implementation of broadcast and multicast
  - Small geographic scale networks



# Link Types

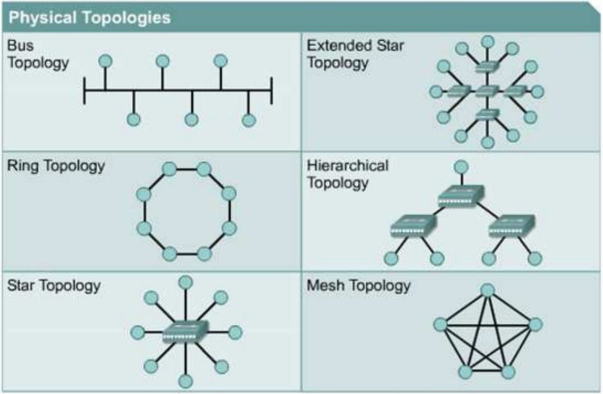
- Point-to-Point Link
  - Connect individual machines
  - Origin-destination connection may require use of intermediary nodes
    - In this case the determination of the route is an important question



# Geographical Scale

| Interprocessor distance | Processors located in same | Example |
|---|---|---|
| 1 m | Square meter | Personal area network |
| 10 m | Room | Local area network |
| 100 m | Building | |
| 1 km | Campus | |
| 10 km | City | Metropolitan area network |
| 100 km | Country | Wide area network |
| 1000 km | Continent | |
| 10,000 km | Planet | The Internet |

# Physical topology



# Data Flow

- Synchronous
  - Traffic appears as a continuous stream
  - In general it requires fixed and limited delays
  - Examples: voice, video
- Asynchronous
  - Traffic appears as an irregular sequence of messages
  - Traffic in bursts
  - Examples: file transfer, e-mail, etc.

# Connected or Non-Connected Service

- Connection-oriented service
  - It requires the establishment of a connection (session) between the nodes before the transmission of data can start
  - During connection establishment, link parameters or route can be negotiated
  - Flow of rhythmic and ordered data, generally reliable (with guarantee of delivery)
  - Packets always follow the same route and arrive at the same sequence in which they were transmitted
  - Each packet carries an abbreviated address: only the route or connection number
  - Easy to offer quality of service and flow control
  - Overhead for session establishment should be less than the benefits of the session
  - Examples: Telnet, FTP

# Connected or Non-Connected Service

- Connectionless services
  - Data flow can begin without any preliminary negotiation or warranty that the recipient is able to receive the data
  - Initially used for sporadic traffic, which does not justify the establishment of a session
  - Packets are routed individually and can arrive at destination out of order
  - Each packet carries the recipient's full address
  - There is no flow control
  - Quality of service is difficult to implement
  - Example: Internet Protocol (IP)

# Reception Confirmed or Not

- Recipient confirms the receipt of the message or packet by returning a positive acknowledgment (ACK)
  - Example: registered mail
- Recipient confirms the lack of reception by returning a negative acknowledgment (NACK)
- There is no acknowledgment of receipt
  - Example: voice in the telephone network

# Communication Alternation

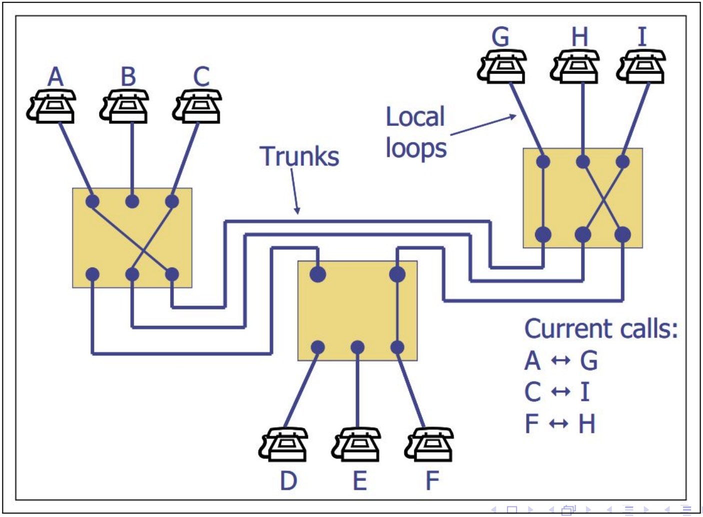
- Simplex: communication exists only in one direction
  - Example: broadcast radio
- Half-Duplex: communication in both directions but not at the same time
  - Example: amateur radio
- Full-Duplex: communication in both directions all the time
  - Example: telephone network

# Switching Method

- Circuit Switching
  - Used by the traditional (old) telephone network to handle voice traffic
  - Once the connection is established, all traffic follows a fixed path (circuit) through the network
  - Source and destination are physically linked by the connection that exists between them
  - Simple: once the connection is established, there is no need to worry about traffic
  - Network resources are dedicated to a particular call
  - Sequence of establishment:
    - Control messages establish the route between source and destination
    - Source is informed of the establishment and transmission can begin
    - Data transmission happens
    - Route remains dedicated to transmission, whether used or not
    - When transmission completes, the connection is released

# Switching Method

- Circuit Switching



# Switching Method

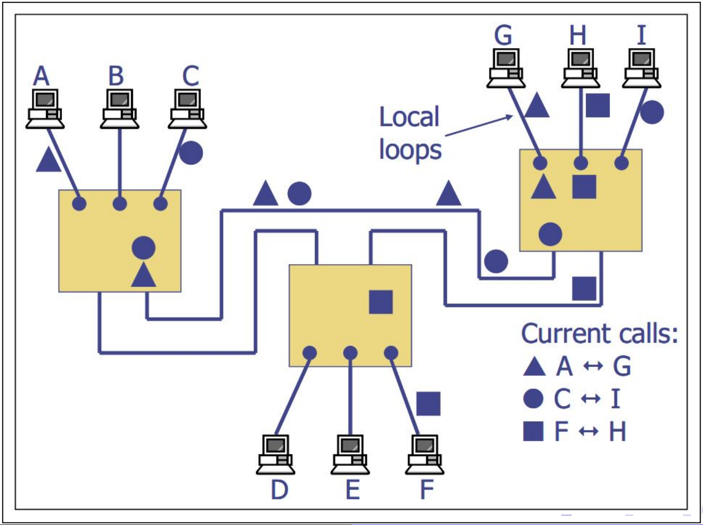
- Circuit Switching
  - However, as the circuit-switching network began to be used increasingly for data connections, two shortcomings became apparent:
    - In a typical user host data connection (e.g., personal computer user logged on to a database server), much of the time the line is idle. Thus, with data connections, a circuit-switching approach is inefficient.
    - In a circuit-switching network, the connection provides for transmission at constant data rate. Thus, each of the two devices that are connected must transmit and receive at the same data rate as the other; this limits the utility of the network in interconnecting a variety of host computers and terminals

# Switching Method

- Packet Switching
  - Messages are divided into small pieces called packets
    - A typical upper bound on packet length is 1000 octets (bytes)
    - If a source has a longer message to send, the message is broken up into a series of packets
  - Packets are numbered and placed for transmission one at a time
    - Each packet contains a portion of the user's data plus some control information
    - The control information, at a minimum, includes the information that the network requires in order to be able to route the packet through the network
  - Different conversation packets may share the same physical link
  - At each node en route, the packet is received, stored briefly, and passed on to the next node

# Switching Method

- Packet Switching

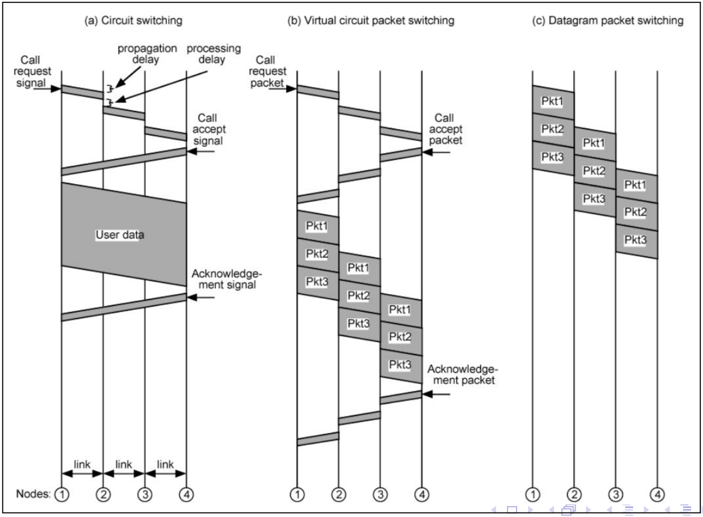


# Switching Method

- Packet Switching (Datagram)
  - Each packet is treated independently, with no reference to packets that have gone before
  - Some implication of this approach:
    - Data packets might take different routes to destination
    - There is no garantee that packets will arrive in order
    - Receiver should detect packet loss and recovers from it
- Packet Switching (Virtual Circuit)
  - A preplanned route is established before any packets are sent
  - It first sends a special control packet (Call-Request)
  - Nodes decides to route the request and all subsequent packets to other nodes
  - If Station is prepared to accept the connection, it sends Call-Accept back
  - Stations can then exchange data over the route that has been established
  - As route is fixed for the duration of the logical connection, it is somewhat similar to a circuit-switching network

# Switching Method

- Message sequency



# Switching Method

- Coarse comparison

| Circuit Switching | Packet Switching (Datagram) | Packet Switching (Virtual Circuit) |
|---|---|---|
| Dedicated path | No dedicated path | No dedicated path |
| Route established for entire conversation | Route established for each packet | Route established for entire conversation |
| Call setup delay | Packet transmission delay | Call setup and packet transmission delays |
| Overload may block call setup | Overload increases packet delay | Overload may block call setup and increases packet delay |
| Fixed bandwidth | Dynamic bandwidth | Dynamic bandwidth |
| No overhead after call setup | Overhead in each packet | Overhead in each packet |

# Bandwidth

- Analog Bandwidth: is the difference between the lower and top cut-off frequencies of a communication channel, or filter, or electric signal, and is expressed in Hertz [Hz]
- For bandabase signals, that is, where the lower cut-off frequency is zero, the bandwidth is equal to the upper cut-off frequency
- Digital Bandwidth: In computer networks, it is the capacity (maximum amount of information that can flow) in a link or network connection per unit of time
- Analogies
  - Bandwidth is like the gauge of a water pipe
  - Bandwidth is like the width of a road

# Bandwidth

- Bandwidth is finite
  - Regardless of the medium (wire, fiber optic, air), the network's ability to carry information is limited for physical and technological reasons
- Bandwidth is not for free
- The demand for bandwidth is growing
  - New applications, particularly those involving streaming of video and audio in real time, require large amounts of bandwidth
- Units
  - bps = bits per segundo
  - kbps = kilobits per segundo = 1000 bps
  - Mbps = megabits per segundo = 1000 kbps
  - Gbps = gigabits per segundo = 1000 Mbps
  - Tbps = terabits per segundo = 1000 Gbps

# Bandwidth (Examples - Physical Media)

| Medium | Maximum Theoretical Bandwidth | Maximum Physical Distance |
|---|---|---|
| coaxial cable (50 Ω) (10BASE2 Ethernet, Thinnet) | 10 Mbps | 185 m |
| coaxial cable (50 Ω) (10BASE5 Ethernet, Thicknet) | 10 Mbps | 500 m |
| UTP category 5 (10BASE-T Ethernet) | 10 Mbps | 100 m |
| multimode optic fiber (100BASE-FX Ethernet) | 100 Mbps | 2000 m |
| single-mode optic fiber (1000BASE-LX Ethernet) | 1 Gbps | 5000 m |

# Bandwidth (Examples - Services)

| Service | Typical User | Bandwidth |
|---|---|---|
| dial-up modem | individuals | 56 kbps |
| DSL | individuals,<br>small companies | 12 kbps to<br>6,1 Mbps |
| RDSI (IDSN) | individuals,<br>small companies | 128 kbps |
| Frame Relay | medium companies | 56 kbps to<br>40 Mbps |
| T1 | large companies | 1,544 Mbps |
| T3 | large companies | 44,736 Mbps |

# Throughput

- Amount of data flowing through a physical or logical link or passing through a network node per unit of time
- Must always be less than the bandwidth of the link
- Must be monitored frequently in order to detect changes in network behavior
- Estimated flow can be obtained by:

$$\text{Throughput [bits/s=bps]} = \frac{\text{file size [bits]}}{\text{transfer time [s]}}$$

# Communication Protocol

- What do we need to communicate with each other?
  - A common language (syntax and semantics)
  - A structured exchange of sentences (questions and answers, commands and confirmations, etc.)
  - A means of communication (voice over the air, pen on paper, electrical signals on a wire, etc.)
- Protocol
  - Rules for communication between two or more parties
  - For computers, set of rules that specifies communication:
    - language and encoding
    - structure of the information exchange
    - physical communication medium

# Standardization of Protocols

- Initial development of networks (1980s) was chaotic, with accentuated growth in the network size in the demand for services
- Many products used proprietary solutions (when one or few companies control the use of technology)
  - Problems of interconnection of products from different manufacturers
  - Dependent on a single vendor
  - Increase in cost
- Solution: implementation of **open systems** with well defined, public interfaces
- International Organization for Standardization (ISO) analyzed several existing networks and proposed a **Reference Model** for the specification of protocols:
  - Open Systems Interconnection (OSI) published in 1984

# Protocol Layers

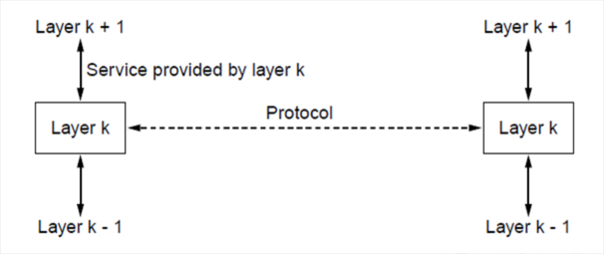
- A way of organizing the structure of the network...
- ... or at least our discussion of networks
- Approach: "divide and conquer"
  - Split the work (protocol) into smaller and simpler parts (layers)
  - Analogous to tasks in other fields:
    - Building a house: sticking, laying foundation, erecting walls, etc.
    - Assembly line of a car ...
- Standardizes network components and allows purchase from multiple vendors
- Allows interconnection of different types of hardware and software
- Prevents changes in one layer from affecting other layers
- Facilitates learning (network components are smaller)

# Protocol Layers

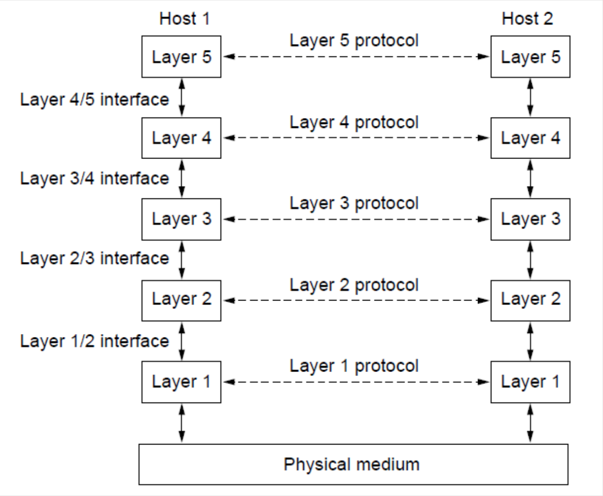
- Example: sending a parcel
  - User: wants to send a parcel to another user
  - Postman: collects parcel for shipping
  - Post office: accepts parcel and does handling
  - Ground transfer: loading on trucks
  - Airport transfer: loading on airplane
  - Airplane routing from source to destination
- Each layer implements a service
  - Either with its own internal-layer actions
  - Or using services provided by layer below

# Protocol Layers

- Layers offer services to the upper layers, isolating these layers from the details of the implementation
- Layer $k$ of a machine communicates with layer $k$ of another machine
- Rules and conventions used are known as layer $k$ protocol
- Interface defined between layers
- Volume of information between layers should be minimized
- Modularity: Layers can be replaced without harming protocol operation

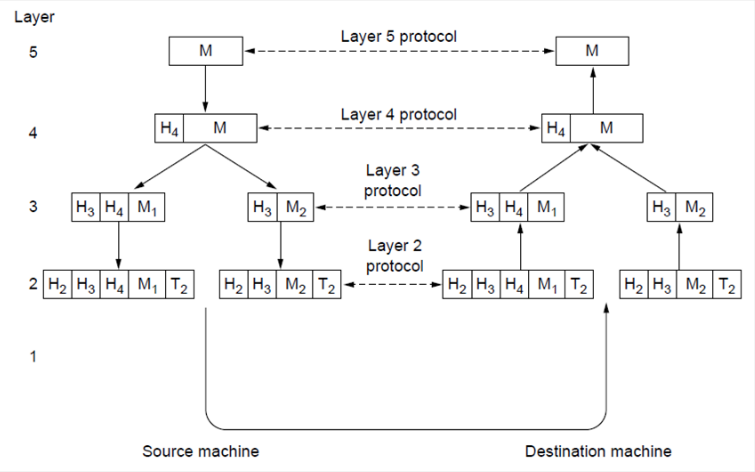


# Protocol Layers



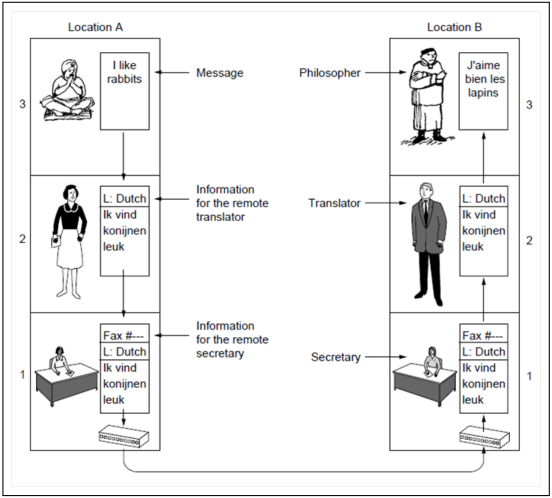

Layer 1 connects the physical medium.

# Encapsulation



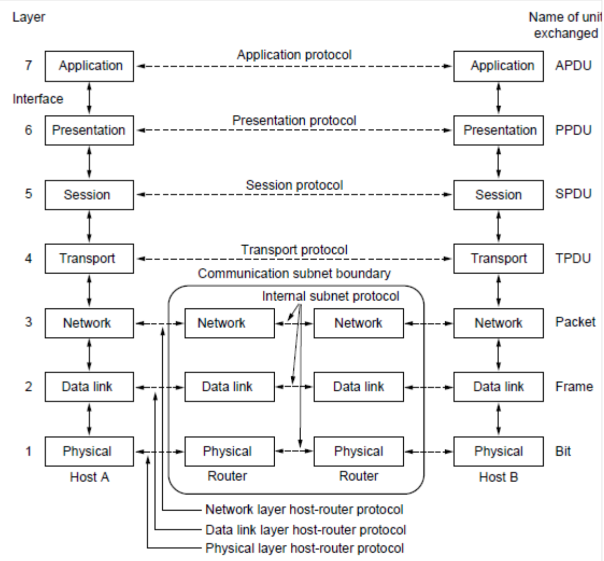

M = Message (original information), segmented in $M_1$ e $M_2$; H = header; e T = tail

# The philosopher-translator-secretary architecture




- Translators can be replaced without affecting communication (for example, using another language at level 2)
- Secretaries can send message by mail (instead of fax)
- These changes need not be reported to philosophers
- Header contains specific information for each layer

# The OSI Reference Model



# Layers of the OSI Reference Model

- Physical Layer
  - PDU: bit
  - Transmission and reception of raw bit streams over a physical medium
  - Method of representing the bits in the medium
  - Format and size of the connectors
  - Wire size, frequency, bandwidth
- Data Link Layer
  - PDU: frame
  - Reliable transmission of data frames between two nodes connected by a physical layer
  - Delimitation of frames (sequence of bits that determine beginning and end of frames)
  - Physical address (hardware address)
  - Error control (channel) and flow control (at link level)

# Layers of the OSI Reference Model

- Network Layer
  - PDU: packet
  - Structuring and managing a multi-node network, including addressing, routing and traffic control
  - Responsible for the route connecting source and destination through network of switches (routing)
  - Fragmentation and reassembly: when the packet size exceeds that allowed by the data link layer
  - Addressing: Provides a unique address for each network node
  - Responsible for internetworking (connection of different networks)
  - Concatenation of data links to form a single end-to-end link
  - Examples: Internet Protocol (IP) and Internetwork Packet Exchange (IPX)

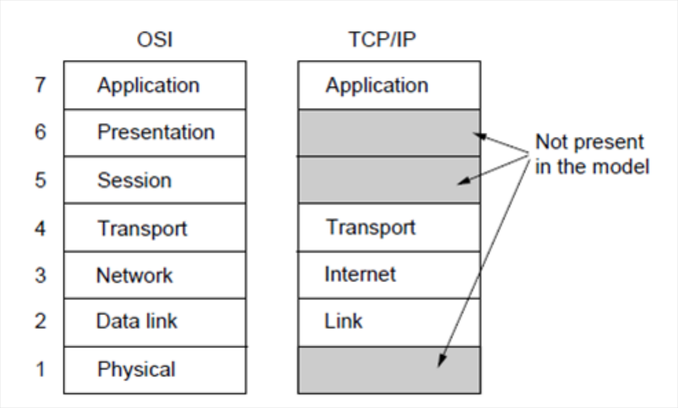
# Layers of the OSI Reference Model

- Transport Layer
  - PDU: segment or datagram
  - Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
  - Detection and error correction end-to-end
  - Examples: Transmission Control Protocol (TCP), User Datagram Protocol (UDP) and Sequenced Packet Exchange (SPX)
- Session Layer
  - PDU: data
  - Managing communication sessions, i.e. continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
  - Who should transmit when
  - If previous requests have been answered before a new one can be accepted
  - In case of an exception, allowing long transmissions to continue from the point of failure
  - Exemples: Network File System (NFS) and AppleTalk Session Protocol (ASP)

# Layers of the OSI Reference Model

- Presentation Layer
  - PDU: data
  - Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
  - Controls translation between structures or data formats used by the application
    - Example: Conversion between different formats for graphic content
  - Usually not implemented
- Application Layer
  - PDU: data
  - High-level APIs, including resource sharing, remote file access
  - Examples: Telnet, Hypertext Transfer Protocol (HTTP)

# The TCP/IP Reference Model



# The TCP/IP Reference Model

- Host-to-network Layer
  - Corresponds to the Physical and Data Link layers in the OSI Model
  - Not specified in detail
- Internet Layer
  - Corresponds to the Network Layer in the OSI Model
  - Packet switching (no connection)
  - Protocol: Internet Protocol (IP)
- Transport Layer
  - Corresponds to the Transport Layer in the OSI Model
  - Protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP)
- Application Layer
  - Corresponds to the Application Layer in the OSI Model
  - Protocols: Telnet, File Transfer Protocol (FTP), Simple Mail Transfer Protocol (SMTP), Domain Name System (DNS), etc.

# Comparison between OSI and TCP/IP Models

- OSI
  - Developed in the 1980s by an international organization (ISO)
  - Success turns out less than expected
  - Almost unused Session and Presentation Layers
- TCP/IP
  - Origins goes back to 1950s
  - Protocols developed first, model coming subsequently
  - Internet Basis
  - Widely used

# Standards

- For systems to communicate successfully they need to follow a common set of protocols
- There is a wide range of protocol specifications that have developed over the years
  - Connectors
  - Electrical signals
  - Frame and packet formats
  - Coding rules
  - Etc.
- The specifications are written in natural language (English in general) and therefore are subject to misinterpretation
- Where possible, formal techniques should be used to specify protocols and services
  - State transition diagrams
  - Event/message sequence diagrams
  - Data types using some formal notation

# Publishing of Specifications

- Many entities publish specifications
  - International Entities
    - International Organization for Standardization (ISO)
    - International Telecommunication Union (ITU), formerly the *Commité Consultatif International de Telegraphique et Telephonique* (CCITT)
  - National Entities
    - American National Standards Institute (ANSI)
    - *Associação Brasileira de Normas Técnicas* (ABNT)
  - Business or Class Entities
    - Institute of Electrical and Electronics Engineers (IEEE)
    - Electronic Industries Alliance (EIA)
  - Companies
    - Ethernet
    - Bluetooth Special Interest Group
- Market determines what specifications survive

# ITU

- Main sectors
  - Radiocommunications
  - Telecommunications

- Members
  - National governments
  - Regulatory agencies
  - Sector members (private companies)
  - Associated Members (telecommunications entities)

# IETF

- Internet Engineering Task Force (IETF)
  - Contribution process that seeks to stimulate openness and participation
  - Specifications are opened in **Request for Comment** (RFC)
  - Example of success (in contrast to many initiatives of more traditional organizations)

# IEEE

| Number | Topic |
|---|---|
| 802.1 | Overview and architecture of LANs |
| 802.2 ↓ | Logical link control |
| 802.3 * | Ethernet |
| 802.4 ↓ | Token bus (was briefly used in manufacturing plants) |
| 802.5 | Token ring (IBM's entry into the LAN world) |
| 802.6 ↓ | Dual queue dual bus (early metropolitan area network) |
| 802.7 ↓ | Technical advisory group on broadband technologies |
| 802.8 † | Technical advisory group on fiber optic technologies |
| 802.9 ↓ | Isochronous LANs (for real-time applications) |
| 802.10 ↓ | Virtual LANs and security |
| 802.11 * | Wireless LANs (WiFi) |
| 802.12 ↓ | Demand priority (Hewlett-Packard's AnyLAN) |
| 802.13 | Unlucky number; nobody wanted it |
| 802.14 ↓ | Cable modems (defunct: an industry consortium got there first) |
| 802.15 * | Personal area networks (Bluetooth, Zigbee) |
| 802.16 * | Broadband wireless (WiMAX) |
| 802.17 | Resilient packet ring |
| 802.18 | Technical advisory group on radio regulatory issues |
| 802.19 | Technical advisory group on coexistence of all these standards |
| 802.20 | Mobile broadband wireless (similar to 802.16e) |
| 802.21 | Media independent handoff (for roaming over technologies) |
| 802.22 | Wireless regional area network |

IEEE

Marked groups:

* (active),

↓ (hibernating) and

†(disbanded)