Reti di Calcolatori

Università degli Studi di Napoli Federico II

Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione
Corso di Laurea in Ingegneria Informatica

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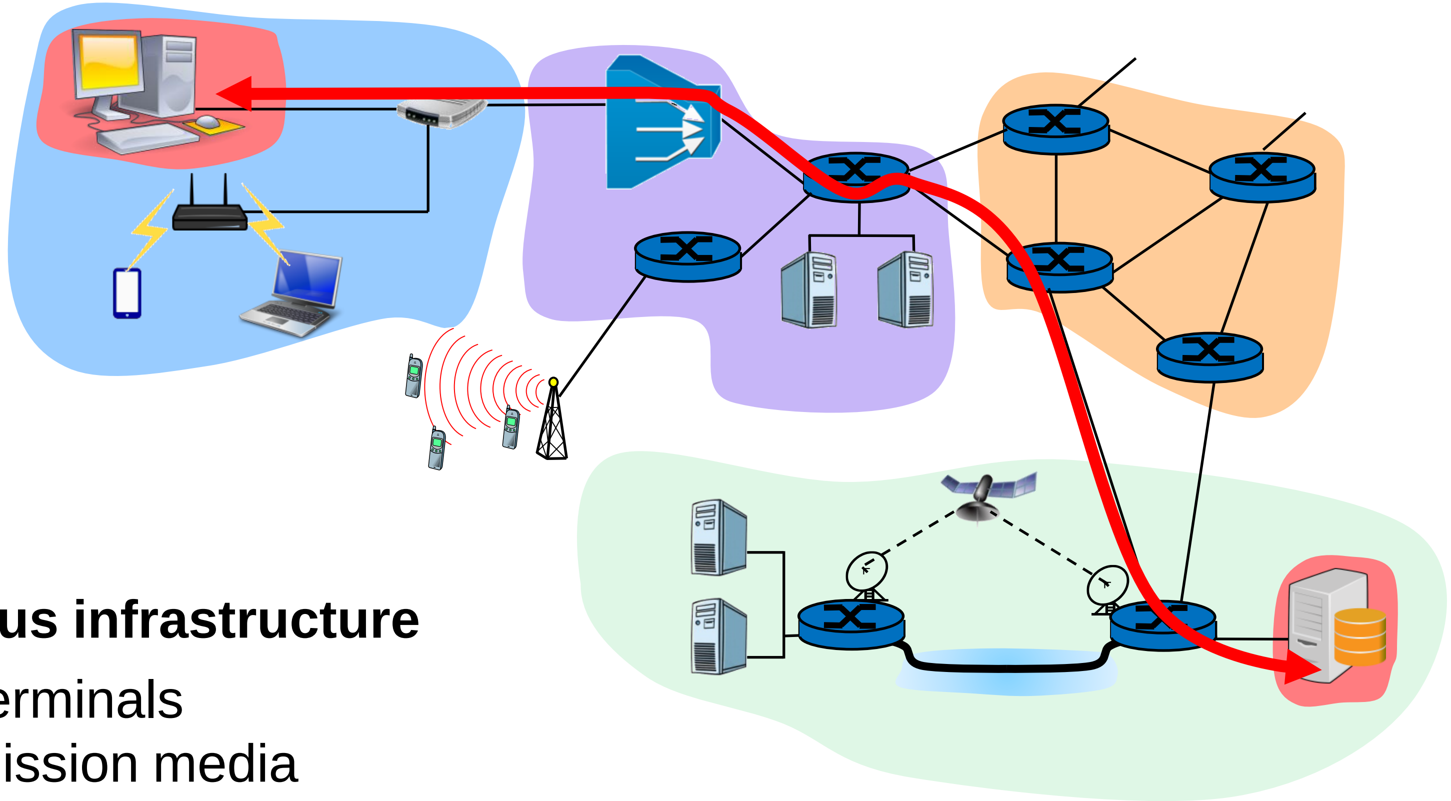
An introduction to Computer Networks

What is a computer network ?

A collection of **computing devices** connected in various ways
in order to communicate and share resources



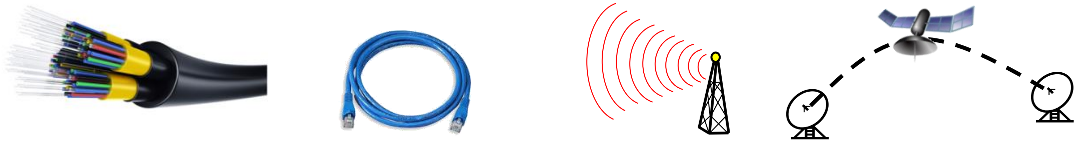
Heterogeneous infrastructure

- Many kinds of terminals
- Different transmission media
- Multiple communication technologies
- Several owners
- A number of different services

Computer network components

- **Terminals (*a.k.a. hosts or end-systems*)**
  - personal computers, servers, computer peripherals (printers, scanners, …), smartphones, sensors, “connected things”, …

- **Intermediate devices**
  - perform various communication tasks and are placed “in the middle” while terminals are “at the edges” of the network
  - take different names according to the main function they perform
    - hub, switches, routers, modems, access points, firewalls, …



- **Connections (*a.k.a. links*)**
  - ***physical wires*** or cables
  - ***wireless connections***, using radio waves or infrared signals

Digital transmission basics: bit rate

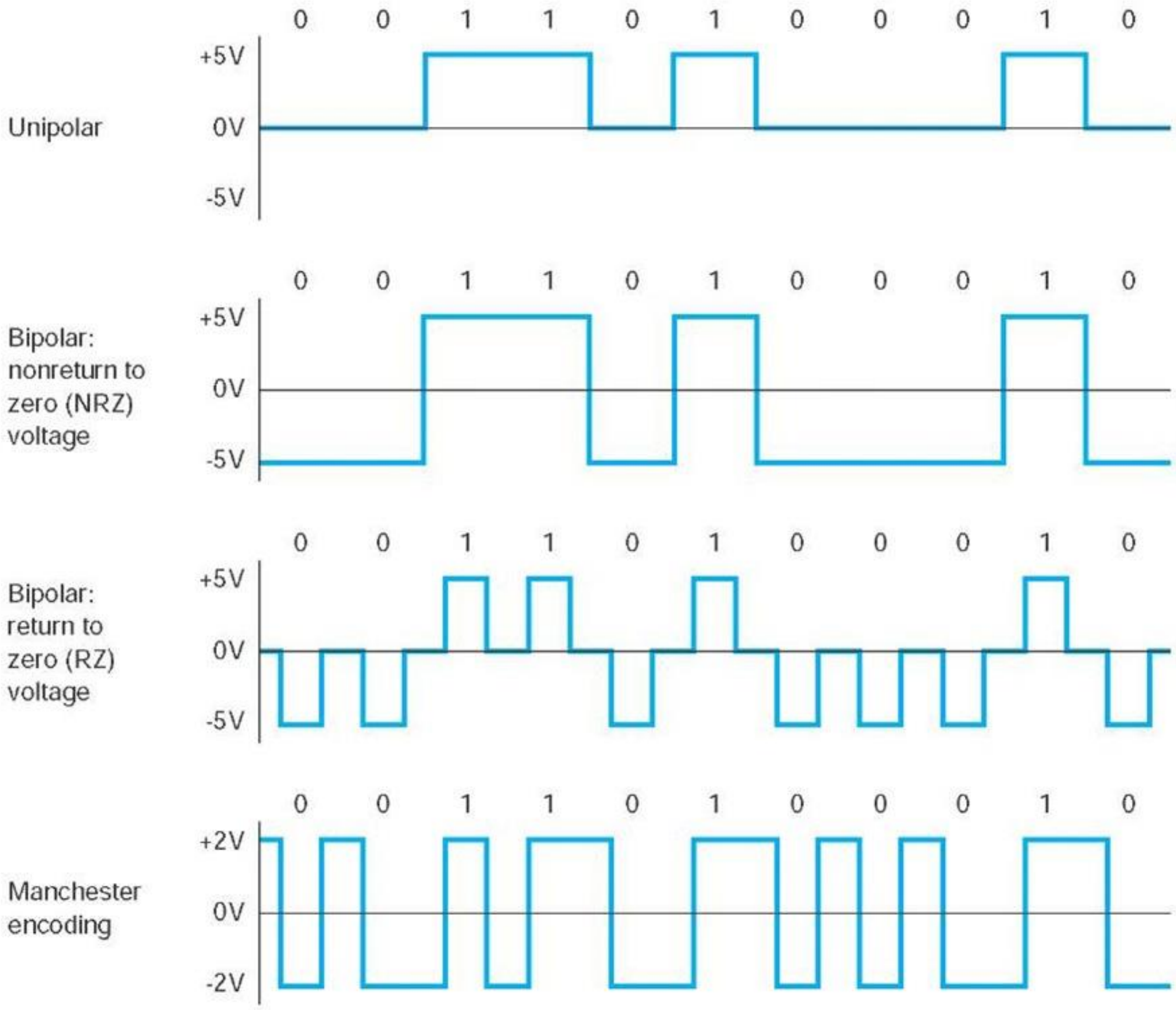
- Computers are complex programmable digital systems
- Computer networks use digital transmission techniques to let computers send and receive sequence of bits (0 and 1) over digital links
- A **digital transmission technique** allows sequence of binary symbols (**bits**) to be transmitted and received on a communication channel
- Different ***modulation techniques*** are possible to transmit a binary symbol (0 or 1) by associating its value to a signal level or to a variation (edge) of a signal level

- A digital transmission is characterized by the **bit rate** (or **data rate**), i.e. the number of bits that can be transmitted in a time unit (1 second)

- Early days' links had a data rate of 56-64 kbps
- Today's links have a data rate in the order of:
  - 1 Mb/s = 10^6 bits per second
  - 1 Gb/s = 10^9 bits per second
  - 1 Tb/s = 10^{12} bits per second

- **Time needed to transmit L bits at data rate R =** $\dfrac{\boldsymbol{L}\ \textbf{(bits)}}{\boldsymbol{R}\ \textbf{(bits/sec)}}$

Digital transmission basics: baseband digital modulation



Communication links: wired vs wireless

- Communication links connecting end systems and intermediate devices may be of two different categories:
  1. **wired communication links** – involve transmission of digital signals in a physical medium
     - Twisted pairs
     - Coaxial cables
     - Optical fibers
     - …

UTP cable with RJ-45 connector

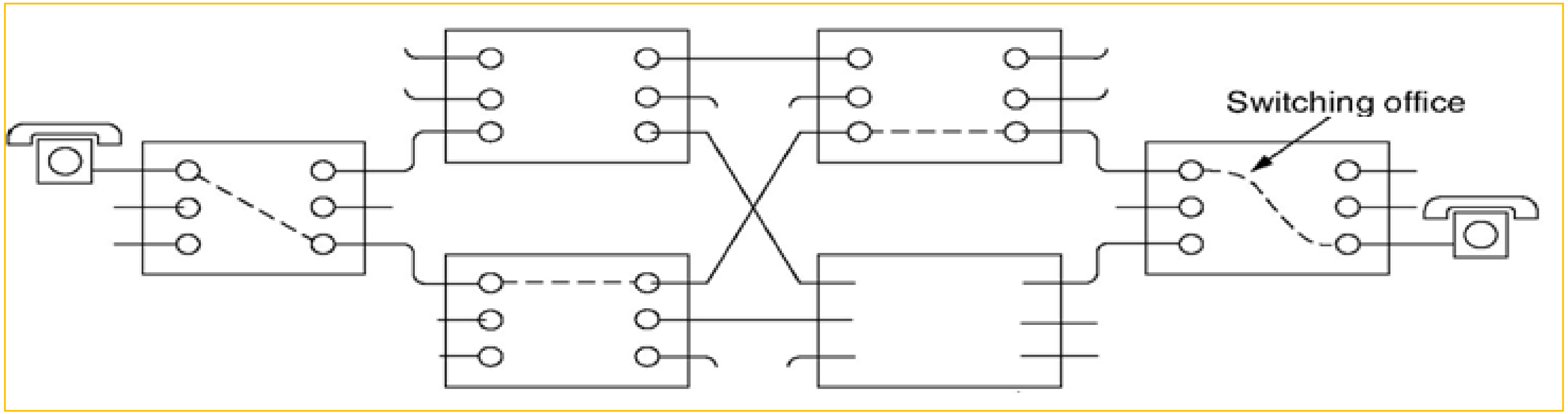
Coaxial cable
with BNC connectors

Optical cable

  2. **wireless communication links** – involve transmission of digital signals modulating a radio wave (in the range of GHz or in the infrared spectrum) propagating in the air
     - **Licensed spectrum** – transmission only allowed to licensed entities
     - **Unlicensed spectrum** – transmission allowed to anyone in specific portions of the radio spectrum without any license under power constraints

PSTN and circuit switching (1/2)

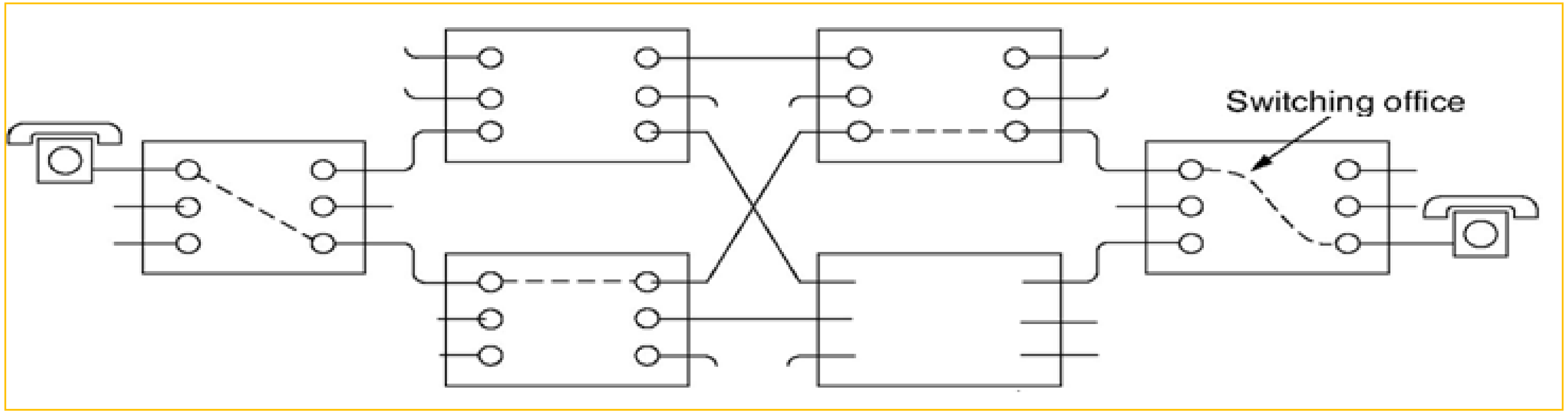
- Computer networks operate according to the ***packet switching model***, while the traditional telephone system operates according to the ***circuit switching model***
- In the PSTN (*Public Switched Telephone Network*), communicating terminals (*phones*) are connected through switching offices
  - The PSTN service is also referred to as POTS (*Plain Old Telephone System*)
- When a phone call is made, a ***circuit*** is established between the two phones as a concatenation of links along a fixed path
  - A circuit is dedicated to a single phone call, i.e. its transmission capacity is assigned to a call even when none of the two communicating persons is talking



PSTN and circuit switching (1/2)

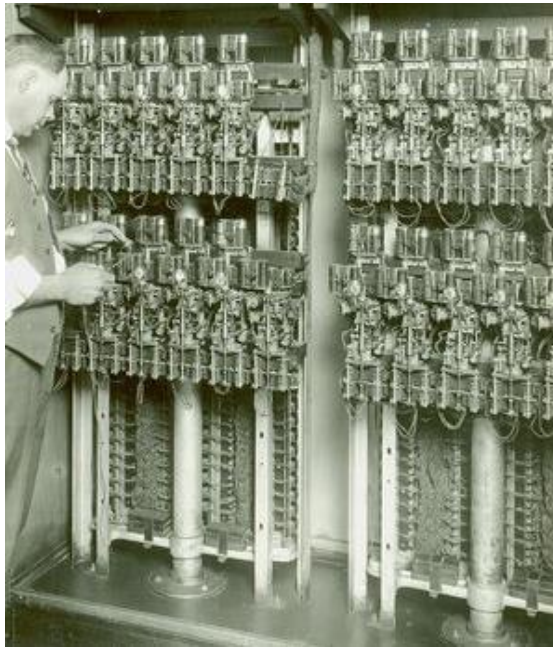
- Establishing a communication in a circuit switching network involves 3 phases:
  1) Circuit establishment
     - Route selection and link by link resource allocation
  2) Call or data transfer
  3) Circuit tear-down
     - Resource deallocation

- Phases 1) and 3) involve exchange of ***signalling*** information both
  - between terminals and switching offices
  - and between switching offices among themselves



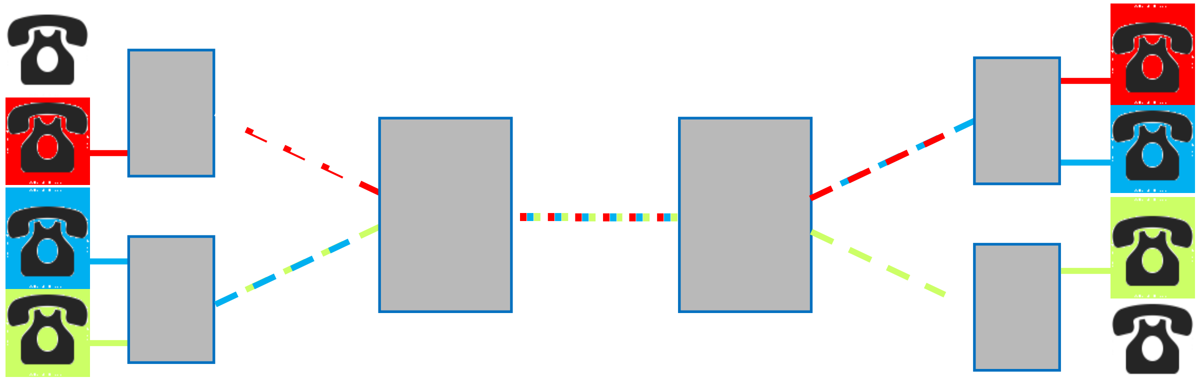
Switching in the old telephone system

- First telephone systems used manually-operated switchboards to establish circuits in Central Offices
- Being in complete control of the call, the operator was in a position to listen in on private conversations at all times
- In 1889, A. Strowger applied for a U.S. patent for a device that served as the basis for the first automatic telephone switch.
- In the Strowger switch, pulses generated at a subscriber's telephone directly moved electromagnetic contacts in a stack of rotary contacts, thus selecting a telephone number, one digit at a time, without operator intervention
- In November 1891, the first automatic telephone switchboard for 99 subscribers was installed in Indiana, USA



Link multiplexing in PSTN

- Switching offices in the PSTN network are hierarchically organized
- Links connecting switches need to carry several phone calls at the same time
- The transmission capacity of such links must be split in multiple ***channels*** to accommodate this ***aggregate traffic***
- Different multiplexing techniques may be adopted
    - time-division multiplexing (TDM) vs. frequency-division multiplexing (FDM)



- Both TDM and FDM partition a link capacity in channels of fixed capacity
    - A single phone call is typically transmitted over a 64 kb/s channel
    - A channel is associated to a specific call during the circuit establishment phase

Computer networks and packet switching

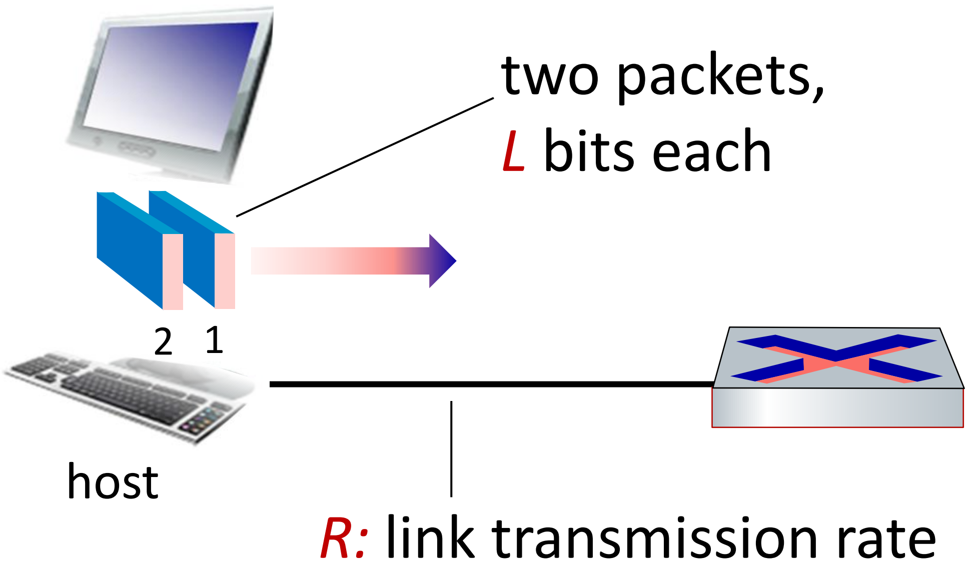
- Computer networks operate according to the ***packet switching model (*)***
- In a packet switched network, information is transmitted in ***packets*** formed by a ***header*** and a ***payload***
  - the header contains control information including a destination ***address*** identifying the terminal to which the information must be delivered

- Intermediate systems typically operate in a way called ***store-and-forward***
  - each packet is received in its entirety, inspected for errors, and retransmitted along the path to the destination
  - this implies buffering and enqueueing of packets at these intermediate systems
  - a channel is occupied only during the transmission of a packet, and upon completion of the transmission the channel is made available for the transfer of other traffic

(*) The packet switching concept was first proposed in early 1960s by Paul Baran (1926-2011)

Packet transmission by an end system

- Host takes application message
- breaks into smaller chunks, known as *packets*, of length *L* bits
- transmits packet into access network at *transmission rate R*
  - link transmission rate, aka link *capacity, aka link bandwidth*

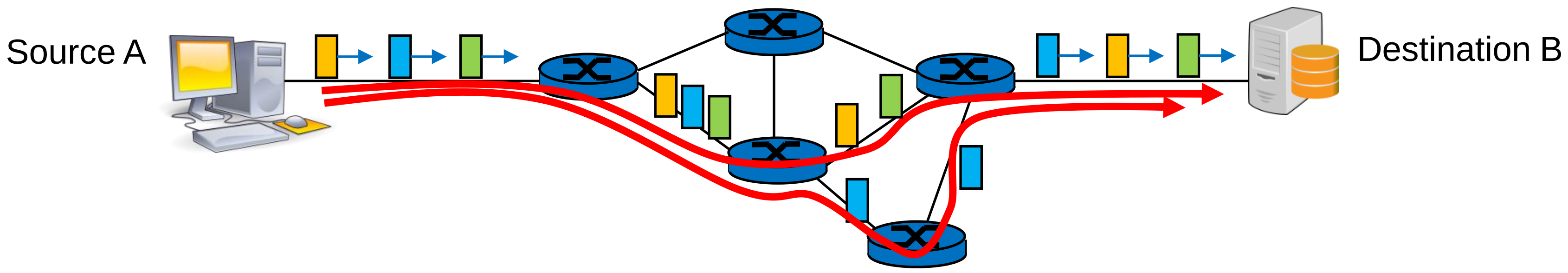


$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Packet switching: datagram networks

The packet switching model has two possible incarnations:
- Datagram networks
- Virtual circuit networks

- In a ***datagram network***, each packet is independently routed toward its destination
  - Packets ***do not*** follow a pre-established route
  - Each time a packet arrives to an intermediate device operating at network layer (i.e. a ***router***), the device decides what is next hop device to which the packet is to be transmitted
  - Subsequent packets sent from the same source A to the same destination B may be routed along different paths
  - Packets may arrive to destination with a different order
  - No need for connection setup

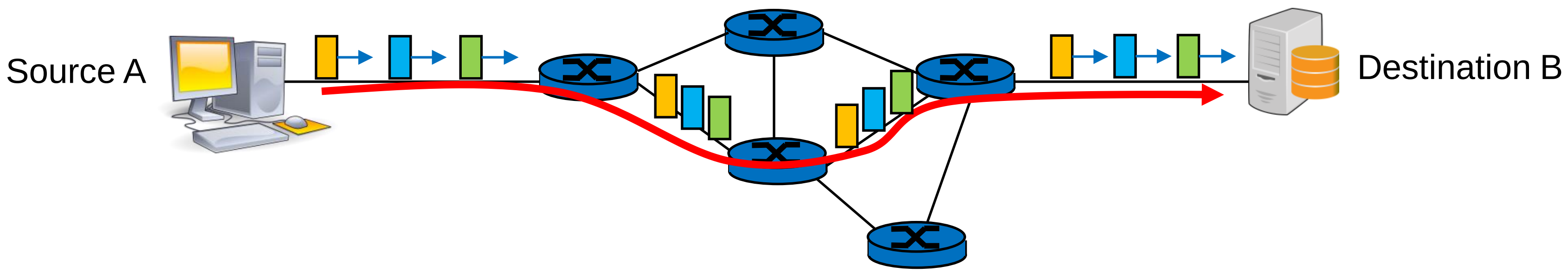


Beware: packets may get lost during their journey from A to B

Packet switching: virtual circuit networks

The packet switching model has two possible incarnations:
- Datagram networks
- Virtual circuit networks

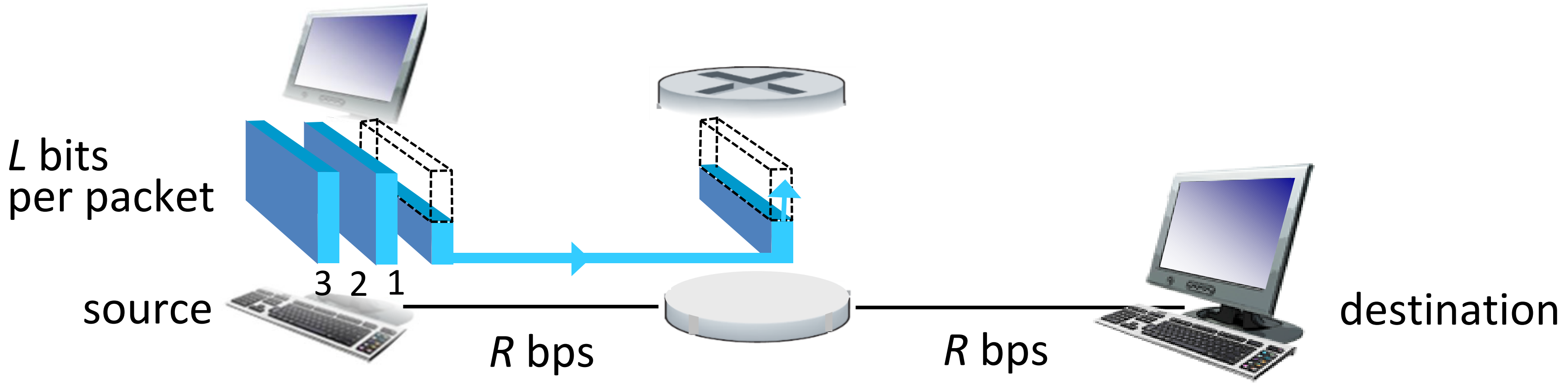
- In a ***virtual circuit network***, a path from source A to destination B is computed and pinned down before communication begins
  - Packets from A to B follow a pre-established route
  - Packets arrive in the same order in which they have been transmitted
  - A connection setup phase is needed (***signalling***)
  - Resources may be set aside for the A→B stream in each intermediate device



Analogies with circuit switching (<u>but this is packet switching</u>!)

Beware: packets may get lost during their journey from A to B

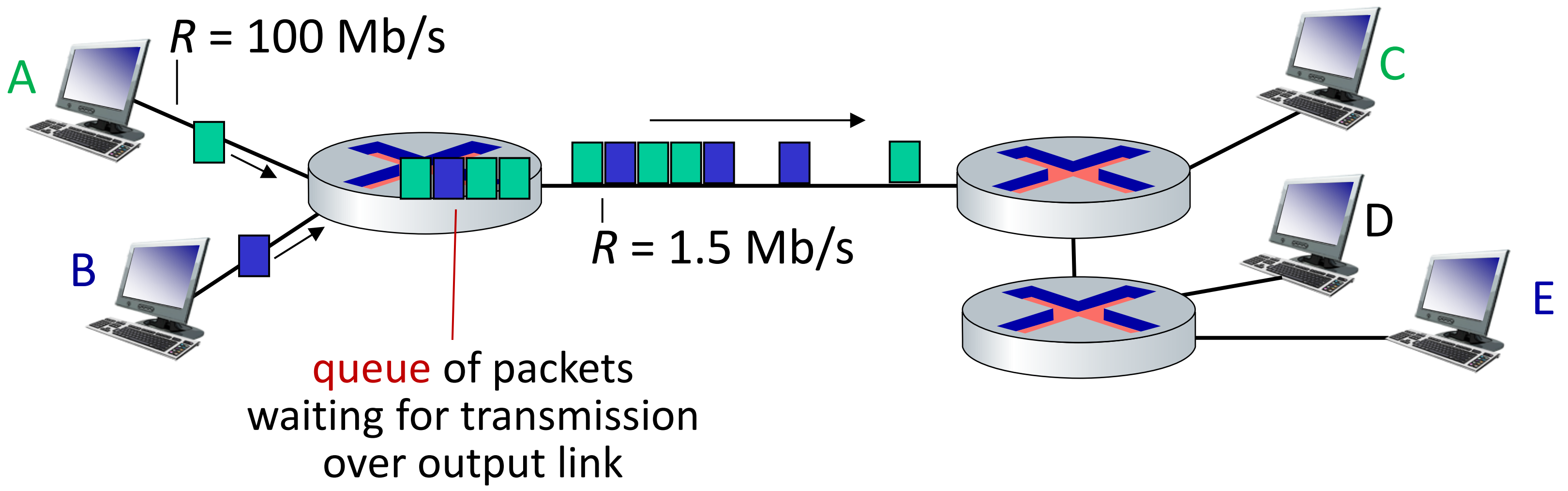
Packet switching: store and forward



- **packet transmission delay:** takes ***L*/*R*** **seconds to transmit (push out)** ***L*-bit packet into link at *R* bps**
- ***store and forward: entire*** **packet must arrive at router before it can be transmitted on next link**

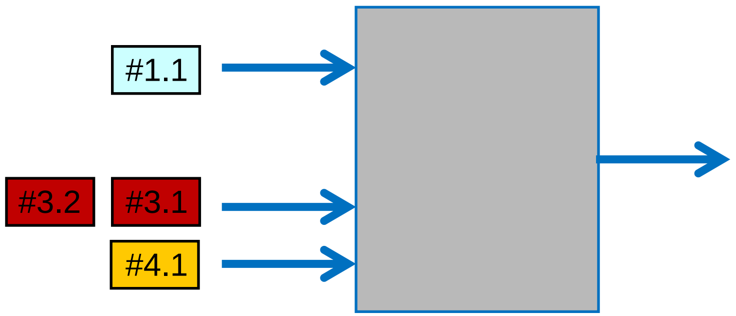
One-hop numerical example:
- *L* = 10 Kbits
- *R* = 100 Mbps
- one-hop transmission delay = 0.1 msec

Packet switching: queueing

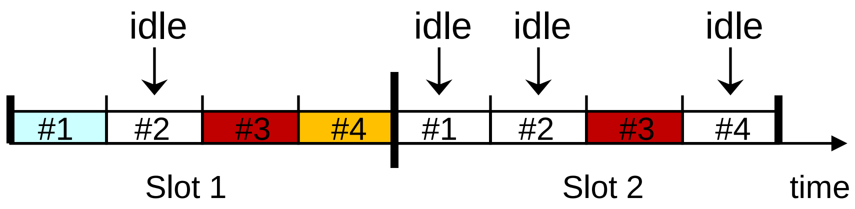


Queueing occurs when work arrives faster than it can be serviced:

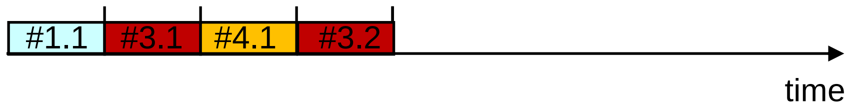
Packet switching and statistical multiplexing



Circuit switching with TDM: each slot may be uniquely assigned to a flow



Packet switching: packets are transmitted as soon as it is possible



Packet switching allows ***statistical multiplexing*** of packets

Type of networks by geographic extension

Local-area network (LAN)
Connects a relatively small number of terminals in a relatively close geographical area

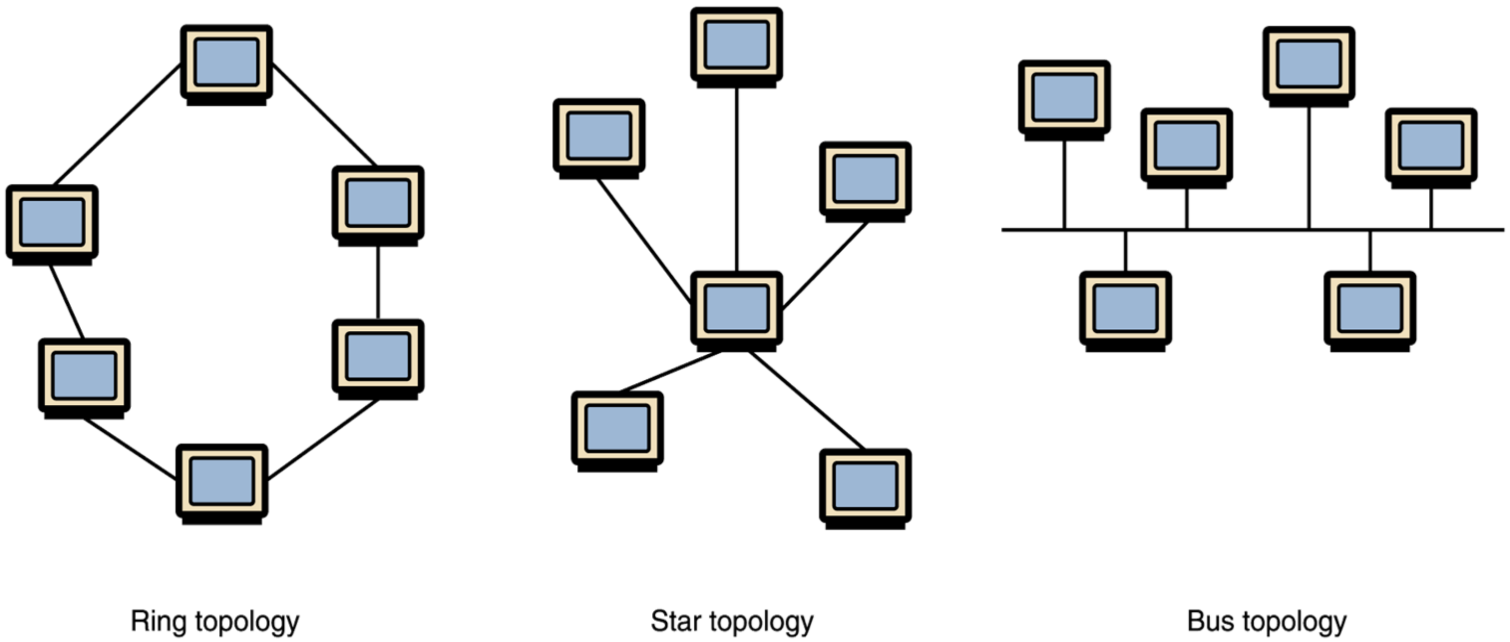
Wide-area network (WAN)
Connects two or more local-area networks over a potentially large geographic distance

Metropolitan-area network (MAN)
Communication infrastructures spanning large cities

The Internet, as we know it today, is essentially the ultimate wide-area network, spanning the entire globe

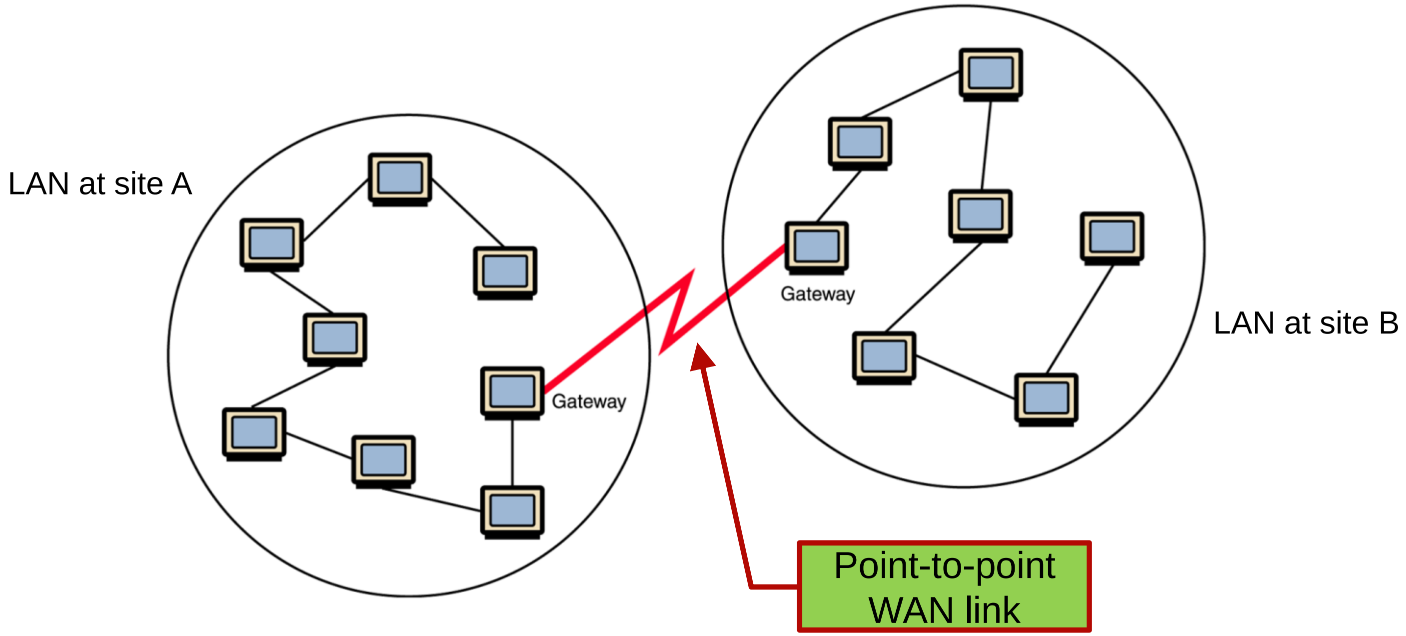
WANs are typically created by LAN interconnections
Communication between networks is called ***internetworking***

LAN topologies



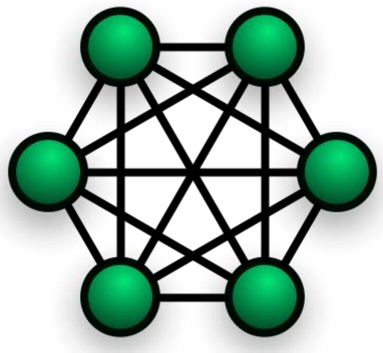
Internetworking

- When two or more LANs, located at different sites, are to be interconnected, a particular node at each LAN is set up to serve as a ***gateway*** to handle all communication going between that LAN and other networks
- In the Internet, gateways are also referred to as ***routers***



Full mesh topology

- Consider an internetwork of N sites in which any site is connected to all other N-1 sites according to a full mesh topology
- Number of bidirectional links is N*(N-1)/2

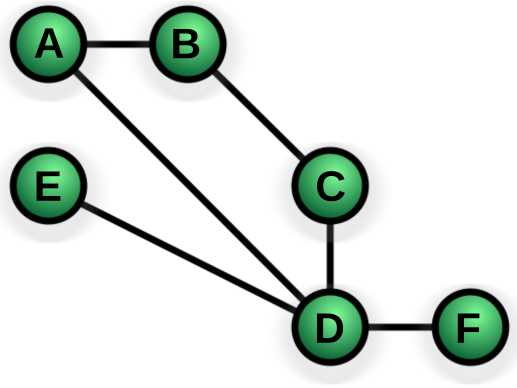


- Large scale internetworks (such as the Internet) cannot have a full mesh topology for scalability reasons
  - Most of the links would be rarely used anyway

Typical WAN topologies

- Large scale WAN internetworks (such as the Internet) typically have a partially connected mesh topology
- Not all the links are equal: some have great ***capacity*** than others, i.e. are able to carry a larger amount of information per time unit

If not directly connected, two nodes may communicate along a **path** traversing other intermediate nodes



A may communicate with F along the paths:

a) A ↔ D ↔ F
b) A ↔ B ↔ C ↔ D ↔ F

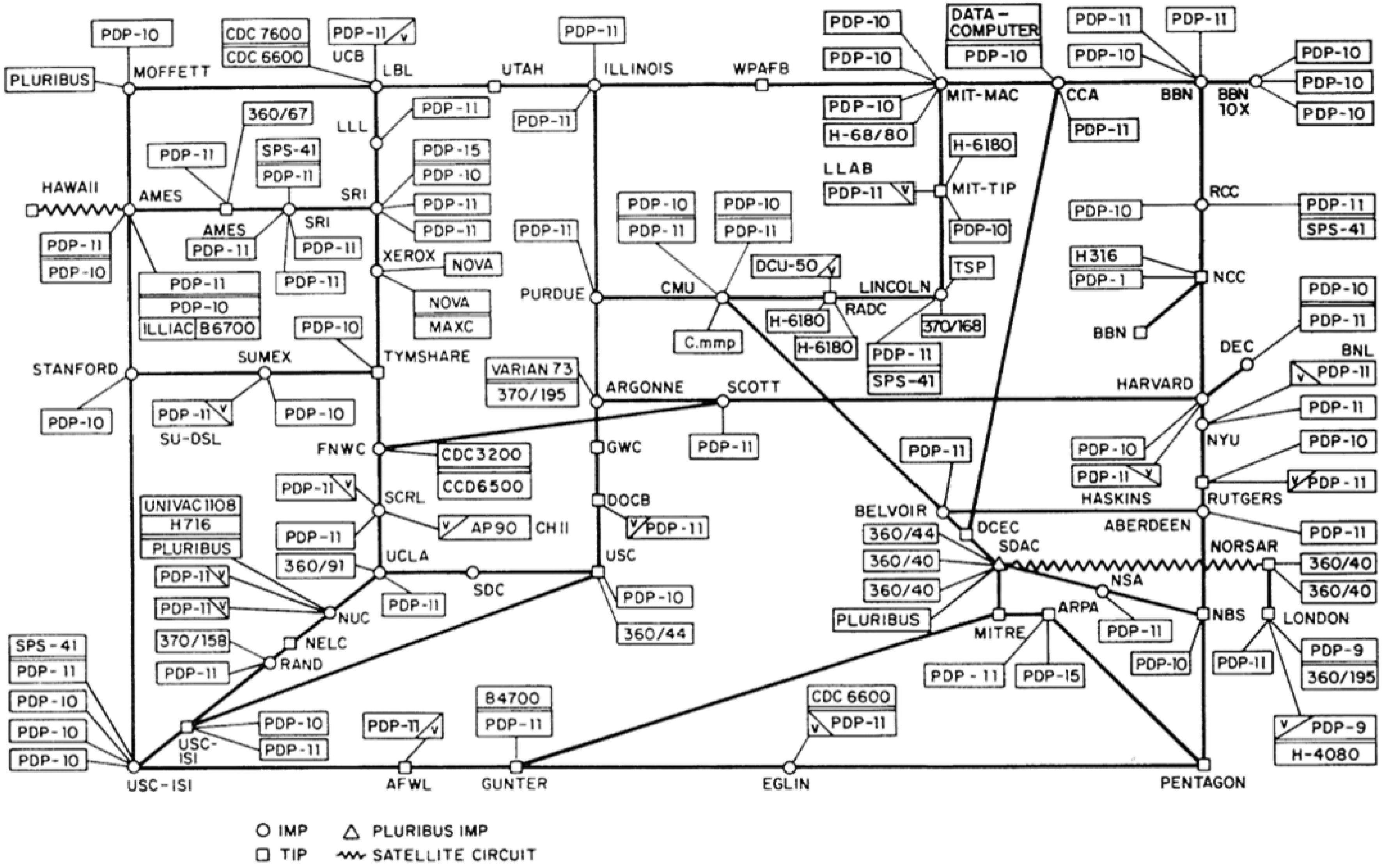
The Internet

- The largest WAN is "the Internet"
- Initially created as DARPANET by initiative of DARPA
  Defense Advanced Research Projects Agency Network
  funded in the 1960s by the US Department of Defense (DoD)
  with the aimed to share research and computing resources
  among government and academic institutions

Leonard Kleinrock

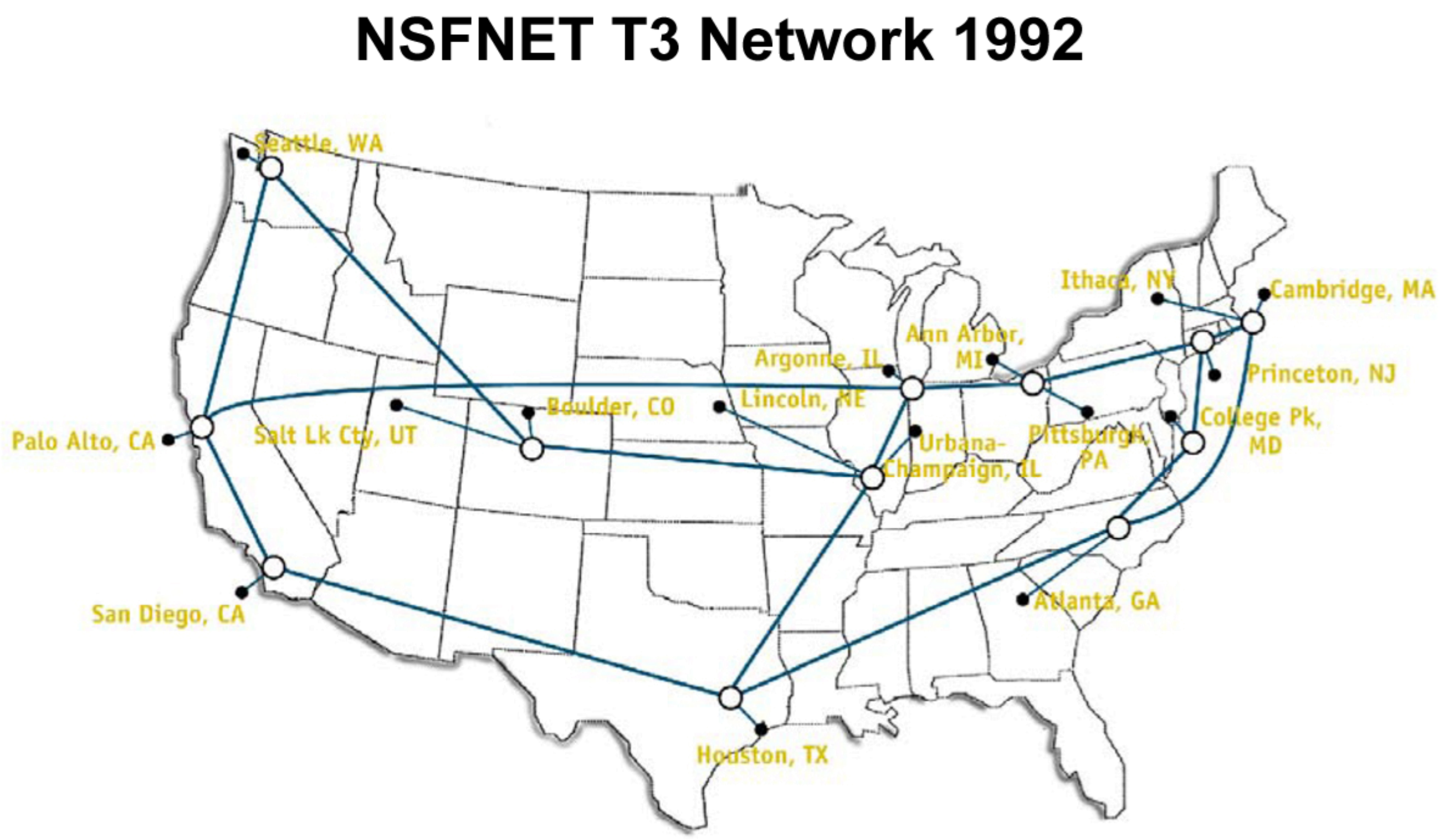
- The name Internet recalls that it is an inter-network,
  i.e. a "network of networks" singularly managed by independent institutions and companies
- The name DARPANET was later on replaced by the names ARPANET and NSFNET
- DARPANET was the first the first network to implement the TCP/IP protocol suite
- The first message sent over DARPANET was on October 29, 1969, between computers at the University of California, Los Angeles (UCLA), and Stanford Research Institute (SRI)
  - The UCLA team was led by prof. Leonard Kleinrock who had previously laid the ground for a mathematical theory describing the behavior of packet switched networks and similar systems (*queueing theory*)
  - The message was intended to be the word "login," but the system crashed after the first two characters were sent - The full message was successfully transmitted an hour later after fixing the issue

Arpanet – August 1976



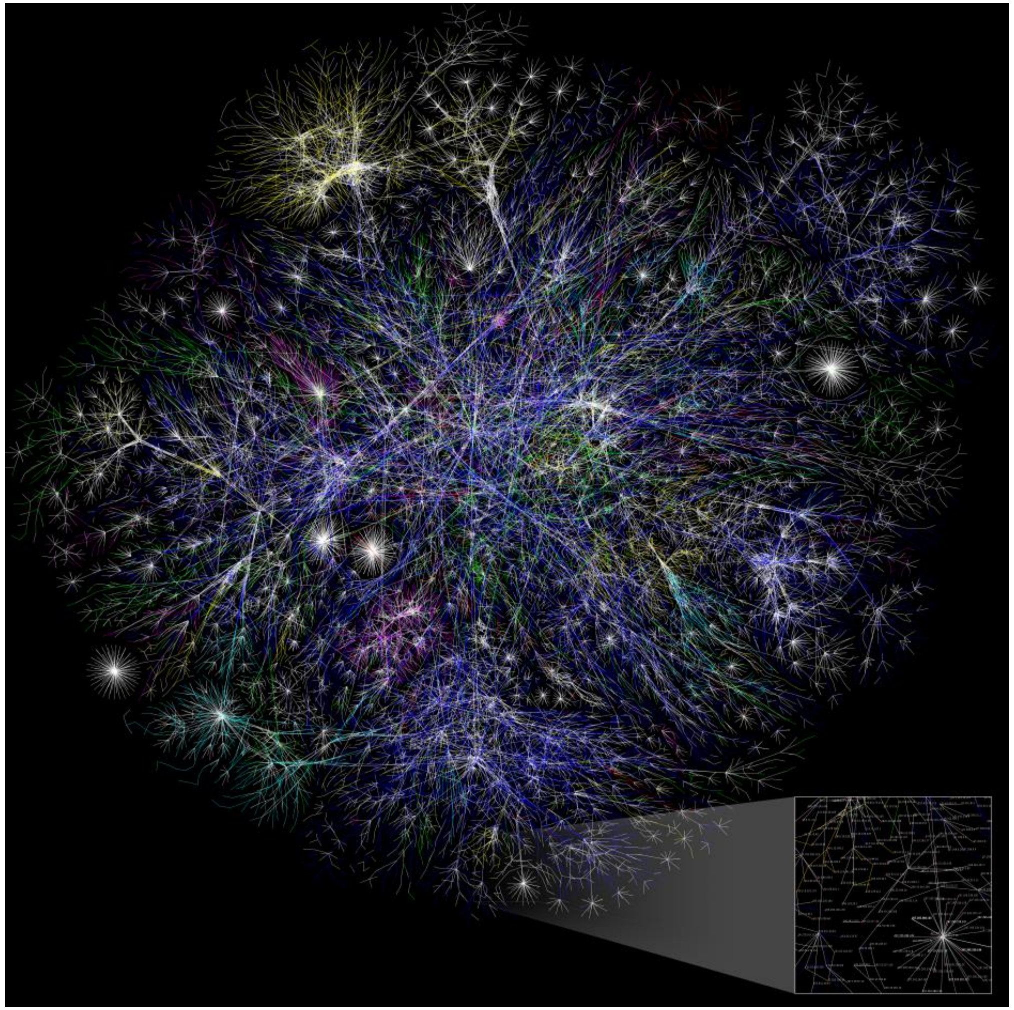
(PLEASE NOTE THAT WHILE THIS MAP SHOWS THE HOST POPULATION OF THE NETWORK ACCORDING TO THE BEST INFORMATION OBTAINABLE, NO CLAIM CAN BE MADE FOR ITS ACCURACY)

NSFNET map - 1992



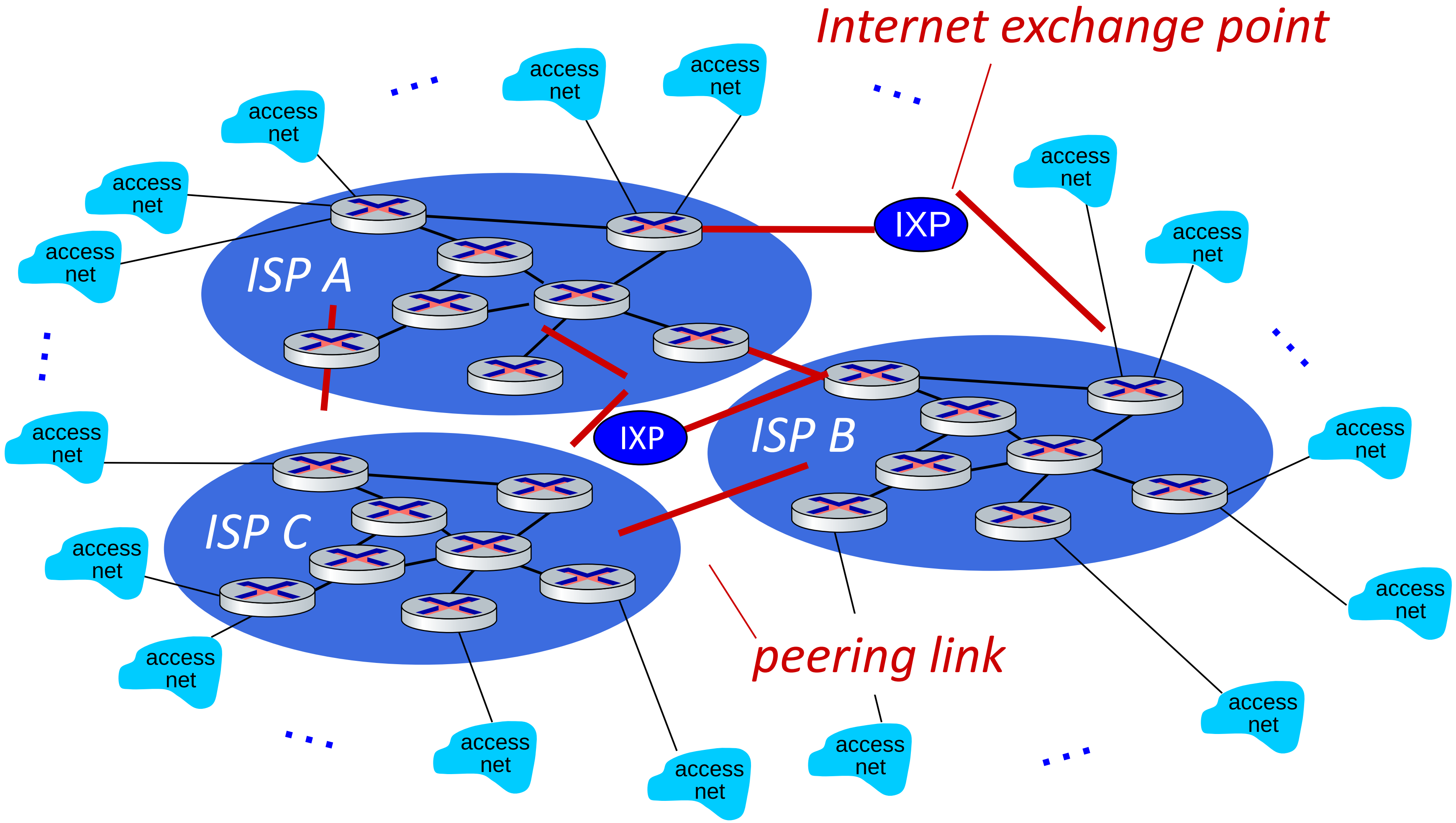
An Internet map - 2015

- Partial map of the Internet based on data found on https://www.opte.org/the-internet

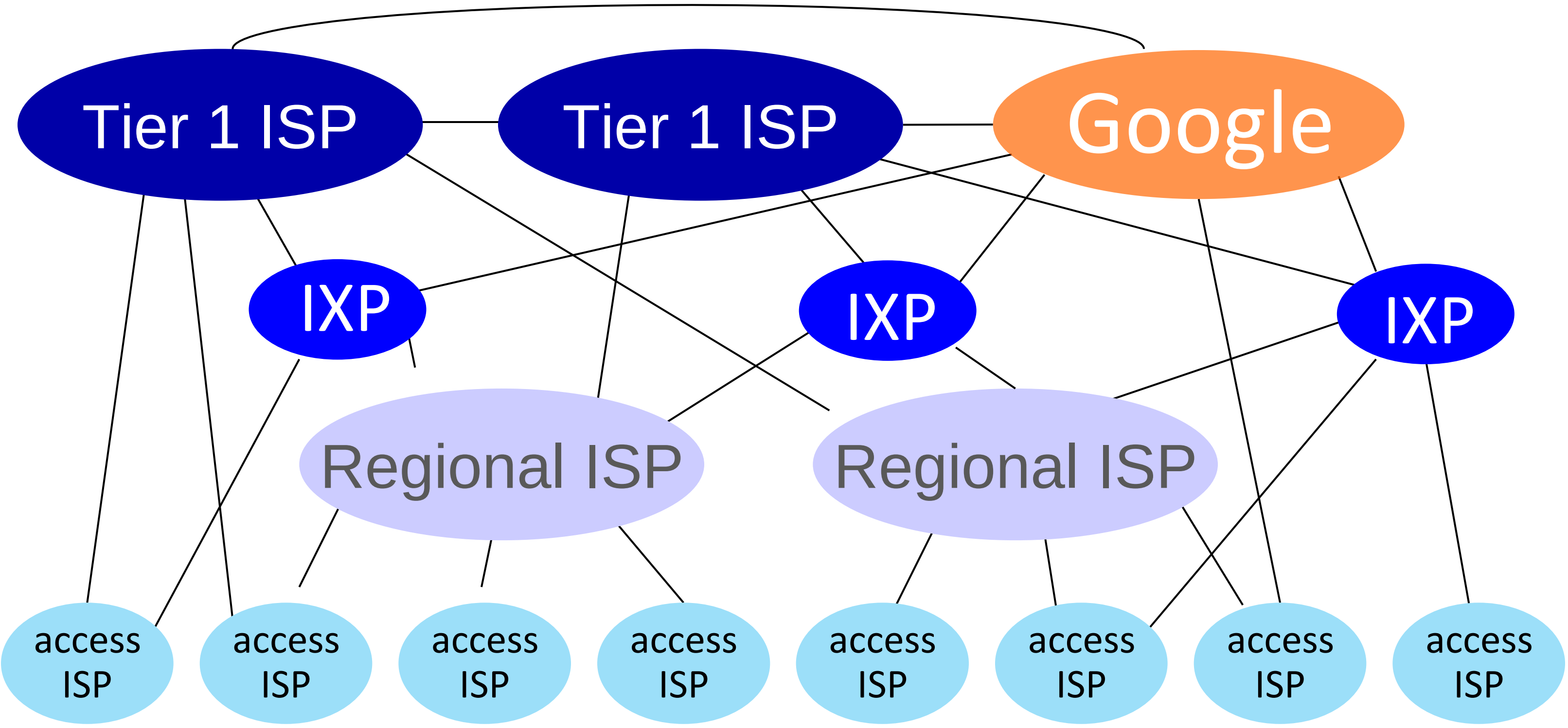


Internet is a network of networks operated by ISPs

- ISP stands for Internet Service Provides
- An ISP operates a portion of the network



Hierarchy of ISPs

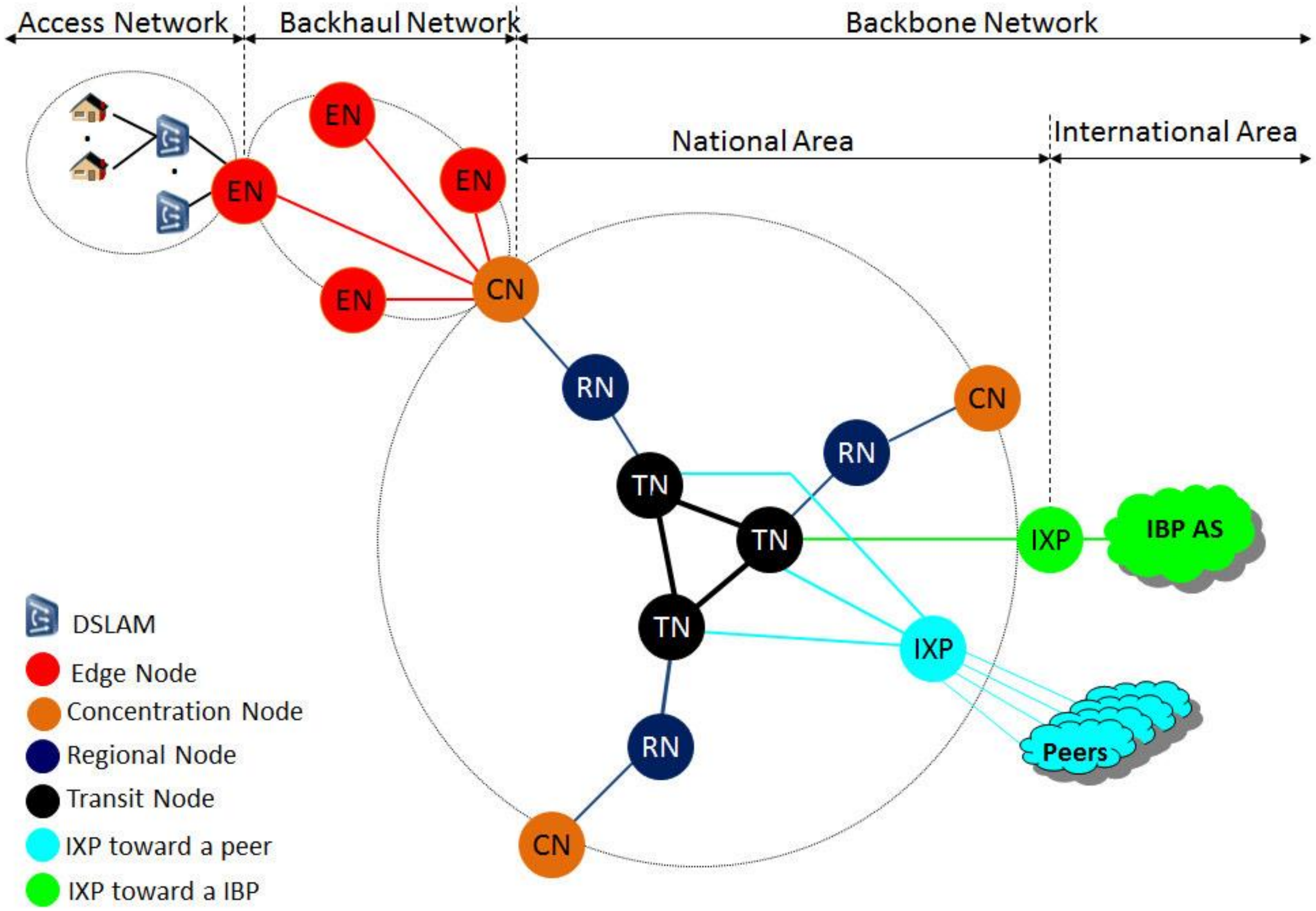


At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

A typical regional ISP network

Connectivity to the Internet is provided to end-users by regional ***Internet Service Providers*** (ISPs)

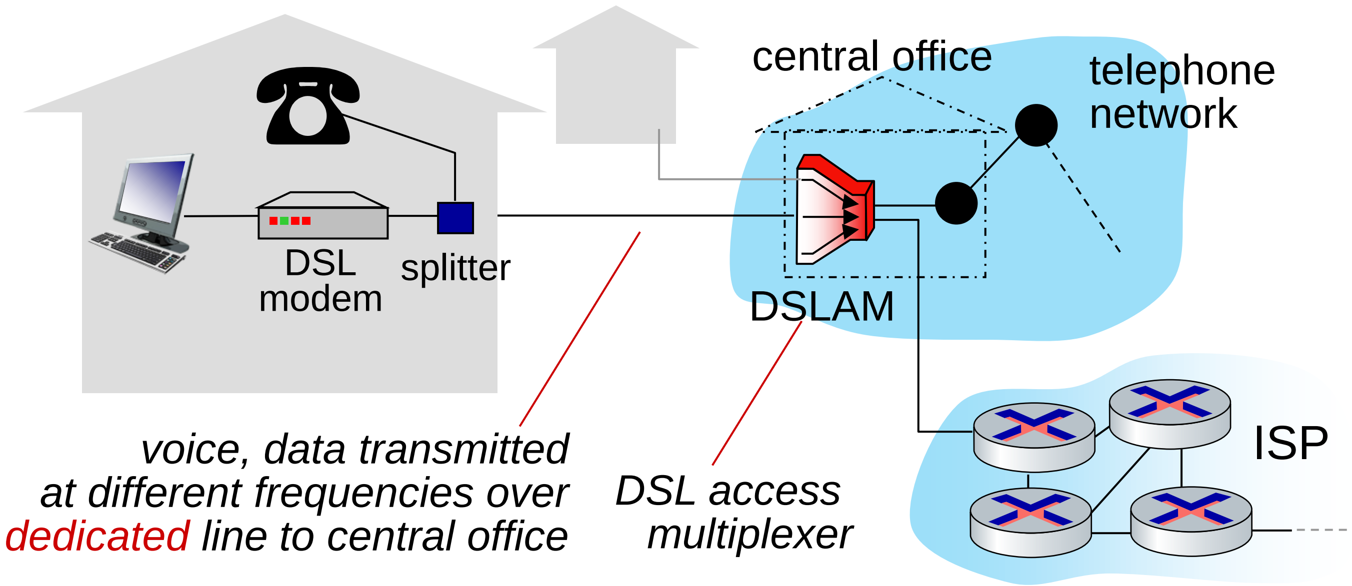


Copper-based broadband Internet access: ADSL and xDSL

- Regional ISPs bring Internet connectivity to end users
- Over the years different technologies have been adopted
- Until the end of '90s, Internet access was based on **dial-up connections** using the existing copper cabling used by the POTS (*Plain Old Telephone Service*)
  - A modem (Modulator/Demodulator) was used to transmit binary data streams on the ordinary telephone line using the same frequencies used by the phone service
    - This technology allowed a typical data-rate of 56 kbps (*kilo bit per second*)
- By the end of the '90s, **ADSL** technology (*Asymmetric Digital Subscriber Line*) allowed special modems to transmit over the ordinary telephone line a digital data stream by using different frequencies than those used by ordinary phone service
    - ADSL evolved over the years in different variants (hence the term xDSL) supporting higher data rates
    - xDSL allowed data-rates of up to 24 Mbps in downstream and 1 Mbps in upstream

xDSL Internet access

- xDSL relies on the telephone infrastructure to reach millions of houses
- A splitter is used at the subscriber premises to separate phone voice signal and modulated data signals



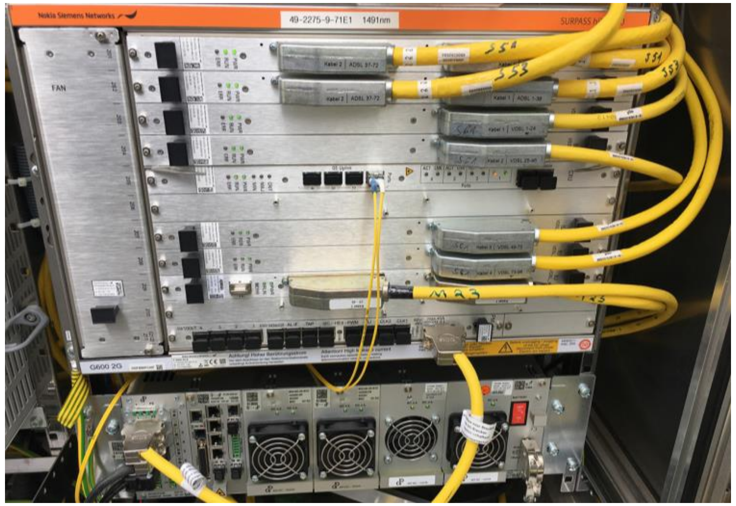
Fiber-based broadband Internet access

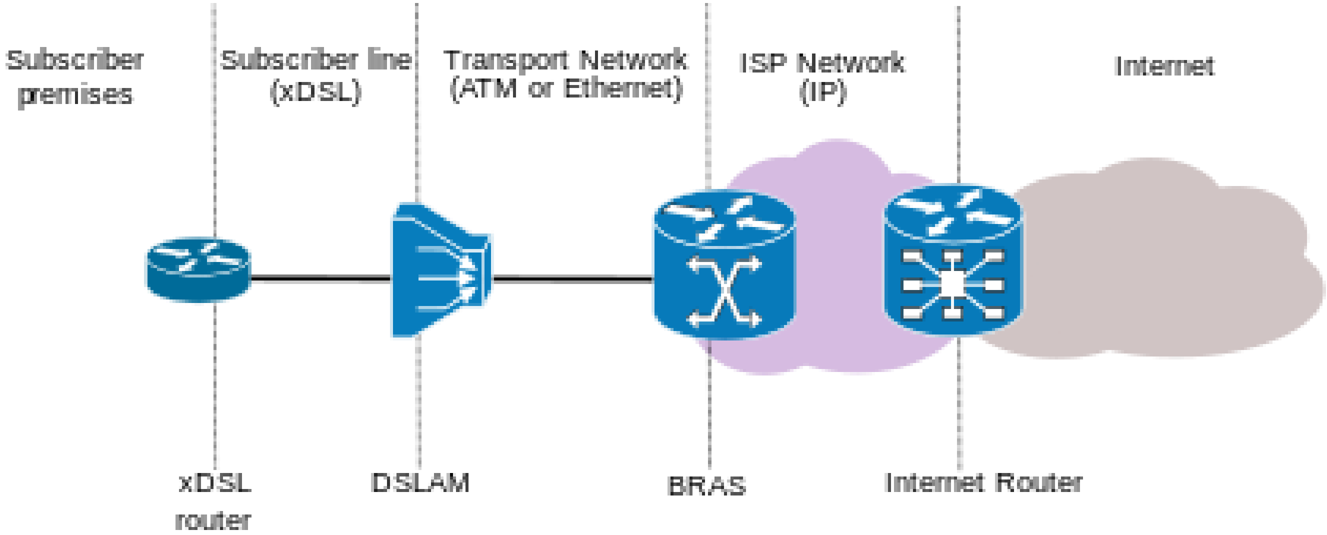
- To achieve higher data rates, optical fibers have been introduced in the ISPs access networks
- Different fiber deployment models have been implemented from 2010 onward
  - Fiber to the Cabinet - FTTC
  - Fiber to the Building - FTTB
  - Fiber to the Home - FTTH
- The FTTC model uses copper from subscribers' premises until a cabinet in the street and optical fiber from the cabinet to the Central Office
  - FTTC is also referred to as "mixed copper"
  - FTTC uses advanced modulation, such as VDSL and VDSL2 to achieve high data rates
  - VSDL (*Very-high-bit-rate Digital Subscriber Loop*) supports 55 Mbps in downstream and 3 Mbps in upstream
  - VSDL2 supports up to 200 Mbps in downstream and 100 Mbps in upstream
- The FTTB model brings fiber connectivity until the basement of a building
- The FTTH model brings fiber connectivity within the user's premises and terminates it to a CPE (*Customer Premises Equipment*) router

A VDSL2 cabinet on top of a copper cabling cabinet in Italy

DSLAM and BRAS

- DSLAM stands for *Digital Subscriber Line Access Multiplexer*
- The DSLAM collects the data streams from subscriber lines and aggregates them via multiplexing
- Depending on its device architecture and setup, a DSLAM aggregates the DSL lines over Asynchronous Transfer Mode (ATM), other circuit-oriented technologies or packet-based Ethernet
- The DSLAM traffic is switched to a *Broadband Remote Access Server* (BRAS) where the end-user traffic is then routed across the ISP network to the Internet





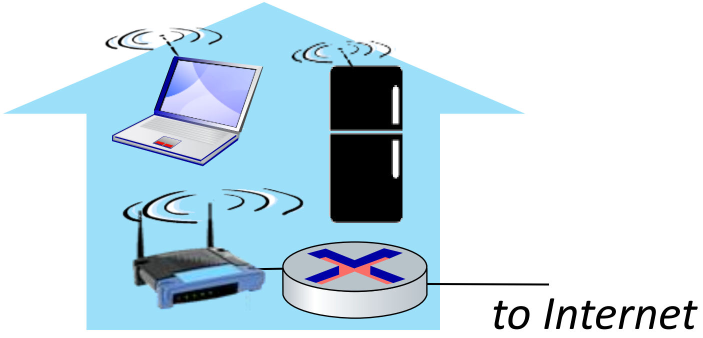
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

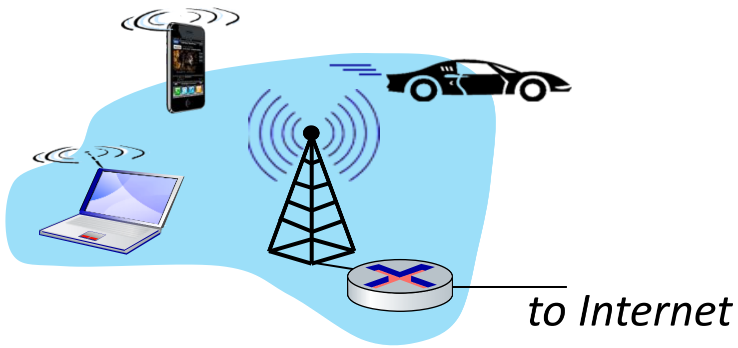
Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



Wide-area cellular access networks

- provided by mobile, cellular network operator (10’s km)
- 10’s Mbps
- 4G/5G cellular networks



Layered models of computer networks

- Computer networks are engineered according to layered conceptual models
    - Each layer deals with a particular aspect of network communication
- *Fundamental Truths of Networking* (RFC 1925): ***It is always possible to aglutenate multiple separate problems into a single complex interdependent solution.***

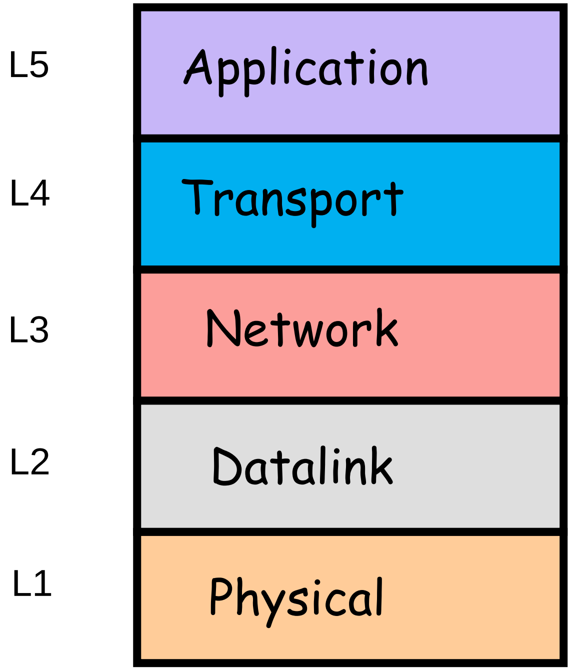
  In most cases this is a bad idea. ☺
- Historically, the **International Organization for Standardization** (ISO) established the **Open Systems Interconnection** (OSI) Reference Model, based on seven layers
    - Today used almost exclusively for teaching purposes
    - Layers 1 to 3 are implemented in both terminals and gateways
    - Layers 4 to 7 are implemented in end systems (terminals)

7	Application layer
6	Presentation layer
5	Session layer
4	Transport layer
3	Network layer
2	Data Link layer
1	Physical layer

Names of the seven layers in the ISO-OSI reference model

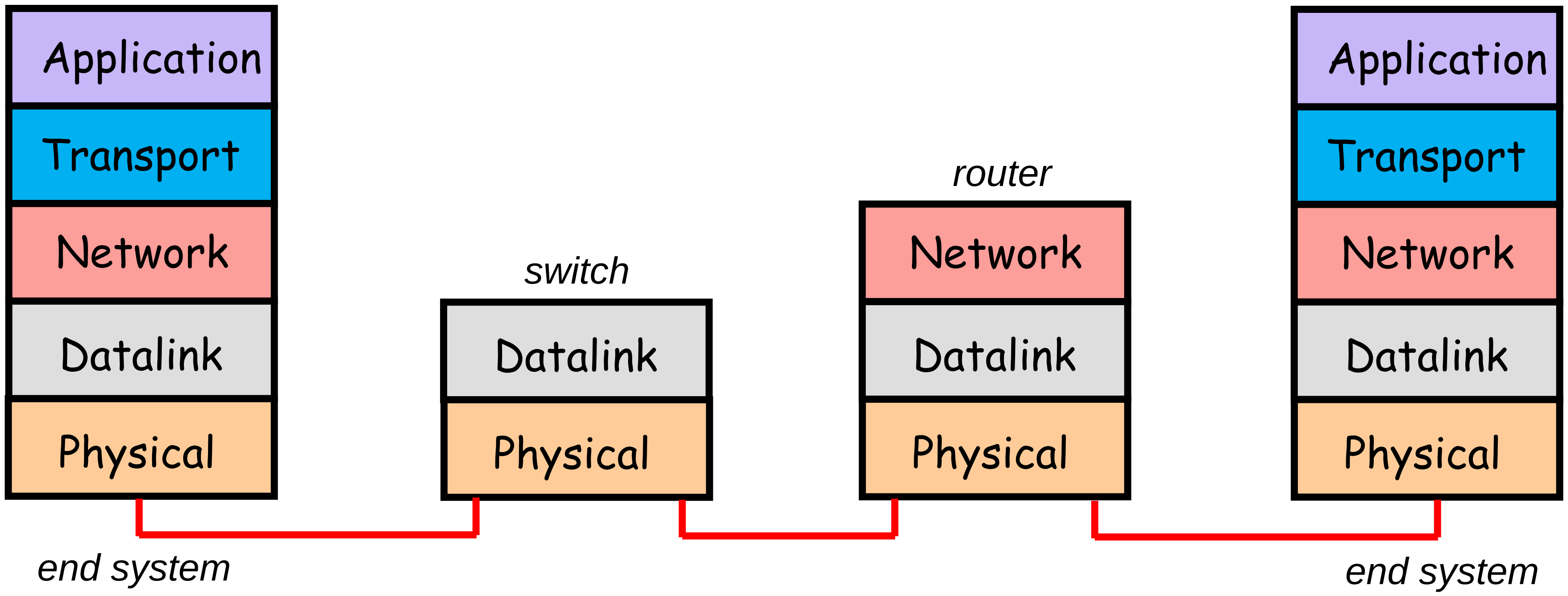
Five layers model of the Internet

- The Internet has been designed according to a five layers stack model
- With respect to the ISO/OSI model, L5 and L6 functions have not been explicitly assigned to specific layers
  - If needed, they are implemented at the upmost level, the Application layer
  - The Application layer is sometimes still referred to as L7, as in OSI/ISO



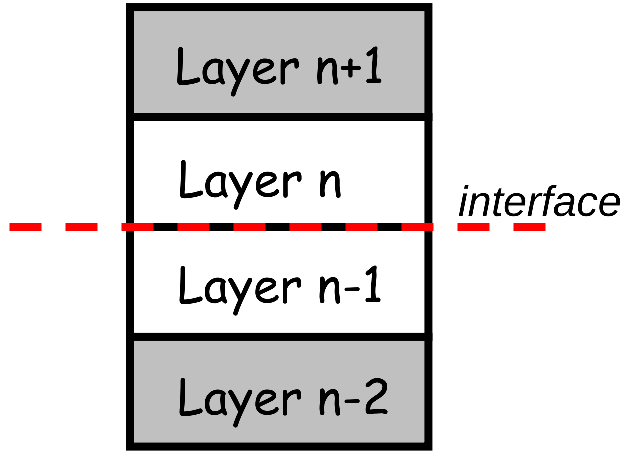
Layers and intermediate devices

- In most networks, two interacting end systems (terminals) are interconnected by a number of ***intermediate devices***
- An intermediate device implements only the lowest layers
- The upmost layer implemented in a device is related to the device specific function
  - ***Repeaters*** and hubs implement only L1
  - ***Switches*** implement layers up to L2
  - ***Routers*** implement layers up to L3



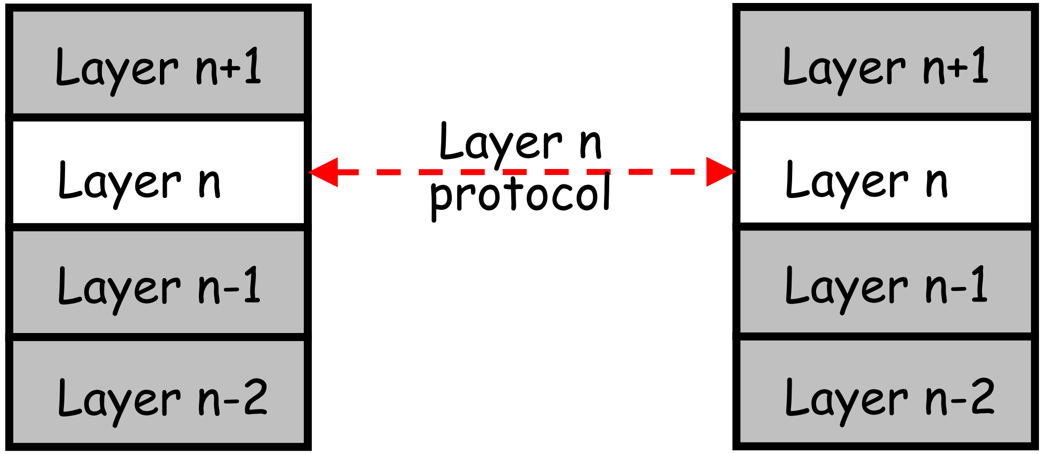
Layers: roles and interactions

- A ***layer located*** is responsible of performing specific tasks
- In a layered model, each layer is located at a level identified by an integer number
- Layer 1 is the lowest
  - L1 usually referred to as the **physical layer**
  - **L1** responsible of transmitting sequence of bits on a digital link
- Lower layers are implemented in hardware, upper layers in software
- Layer *n* provides a ***service*** to layer *n+1*
- Layer *n* (for *n* > 1) uses services provided by layer *n-1*
- The service provided by a layer to the upper layer is accessed through an ***interface***
- Each layer should interact only with adjacent layers

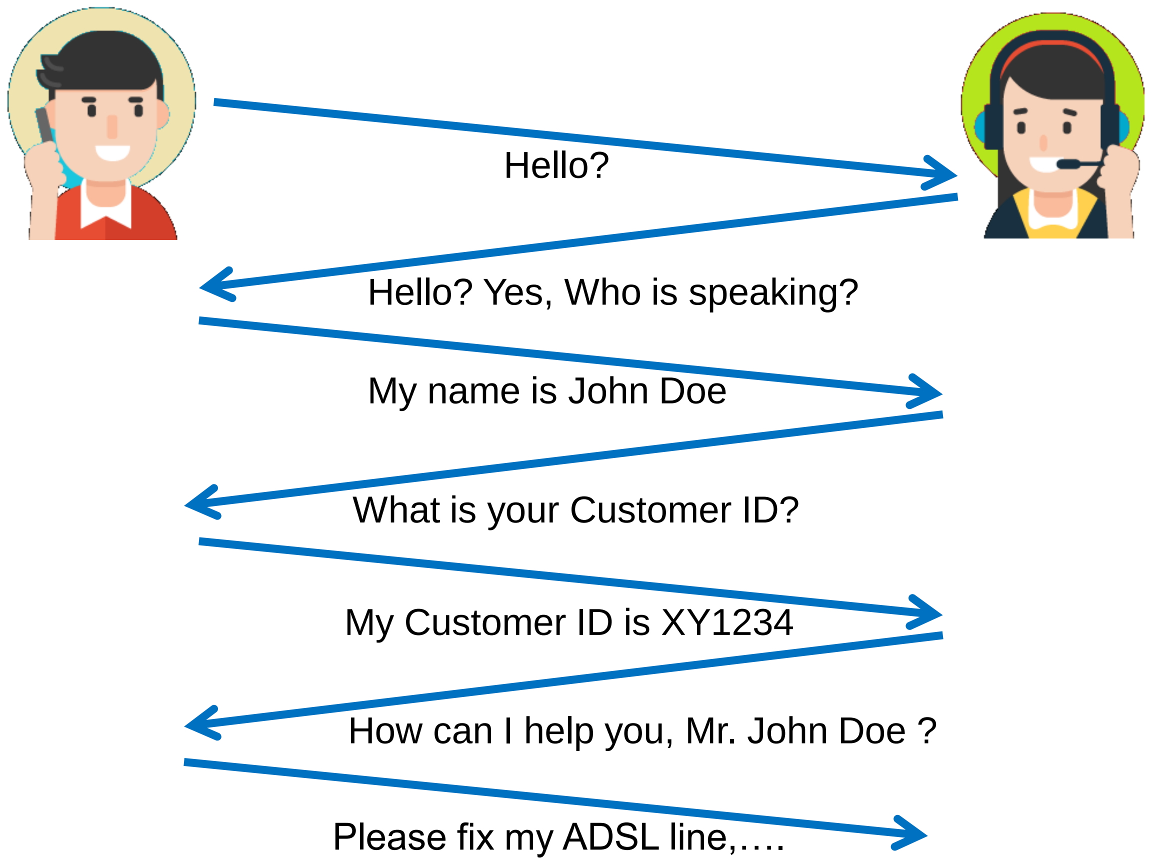


Protocols

- A ***network protocol*** is a set of rules and formats that govern the communication between communicating peers <u>operating at the same layer</u>
- It specifies:
  - format and order of messages sent and received among communicating entities
  - actions to be taken on message transmission or receipt
- Since each layer has its own protocol(s), the term ***protocol stack*** is often used



Protocols in real life



What is a network protocol?

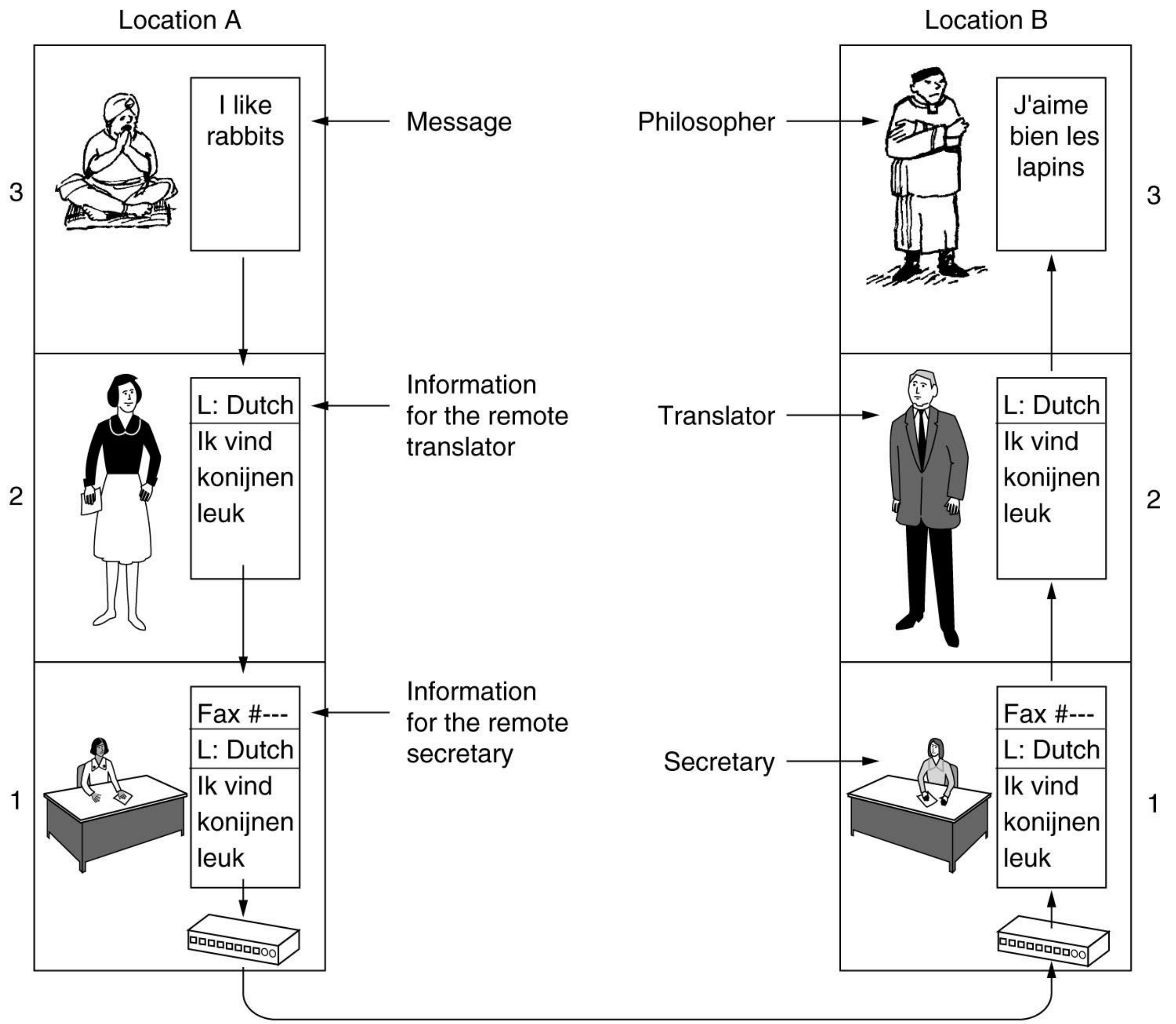
***Network protocols* define the *format*, *order* of *messages sent and received* among network entities, and *actions taken* on message transmission, receipt**

Network protocols define rules for:

- specific messages sent
- specific actions taken when message received, or other events

Message format (syntax) described by formal notations such as ABNF (*Augmented Backus-Naur Form*)

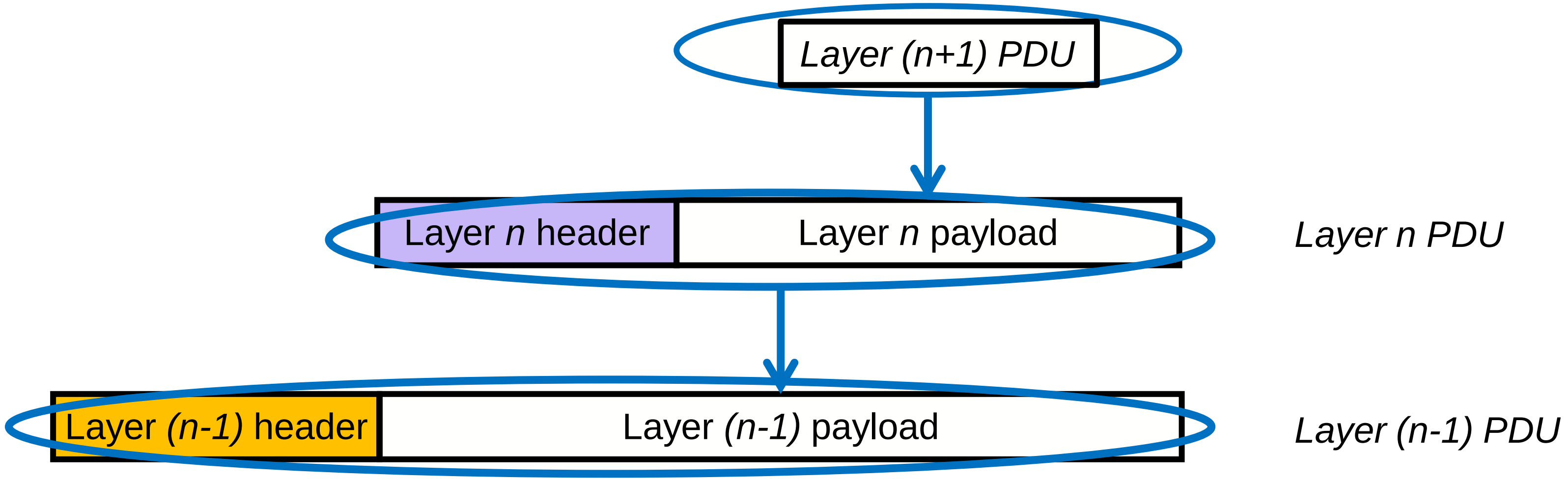
Layering: the two philosophers example



Source: A. S. Tanenbaum. Computer Networks (4 ed.). Prentice Hall, 2003. (Chapter 1, Figure 1.14)

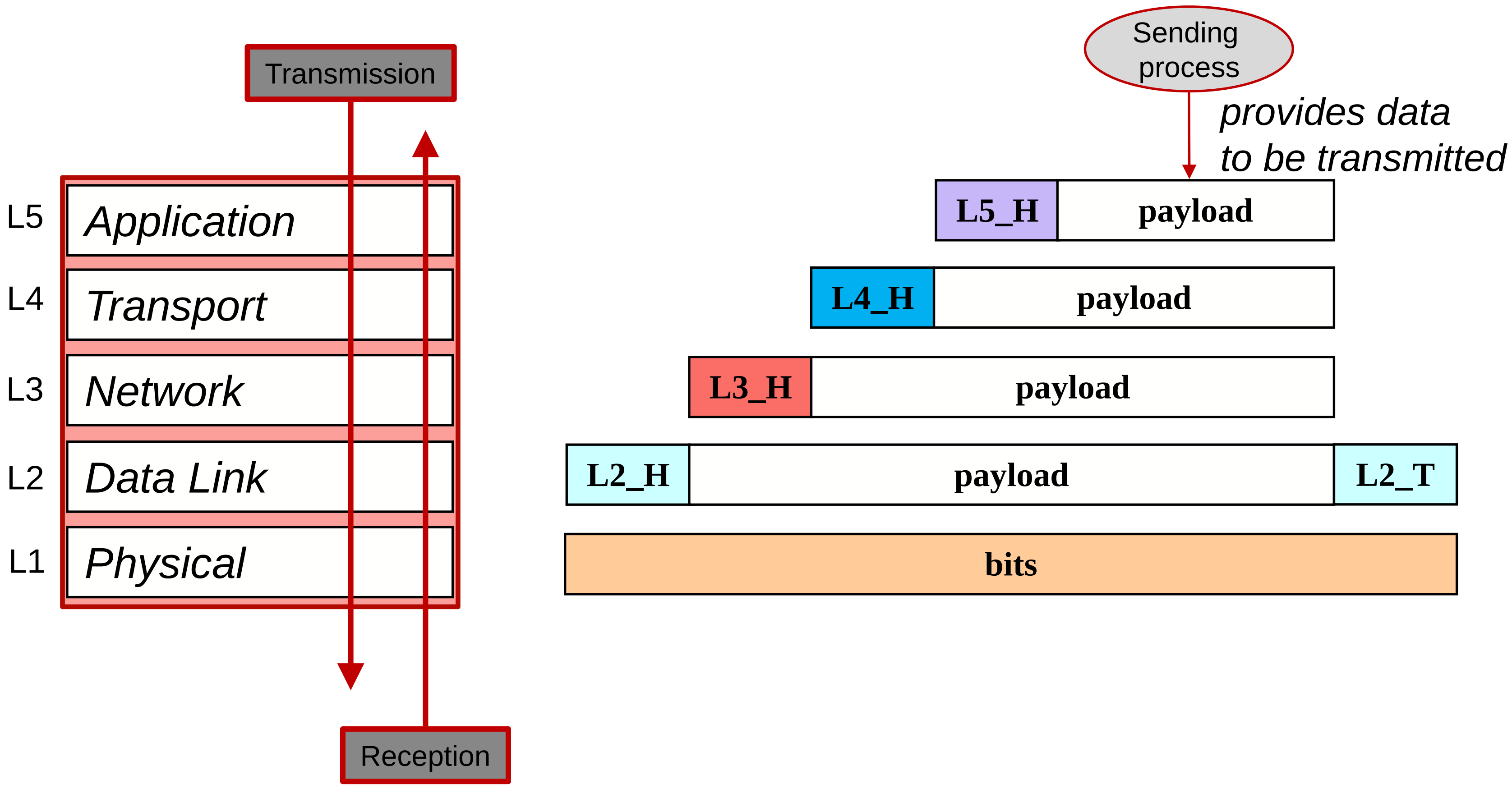
Protocols: PDUs handling (1/2)

- In a layered stack of protocols, each layer receives a payload from the upper layer and forms a ***Protocol Data Unit*** (PDU) made of a ***header*** and a ***payload***



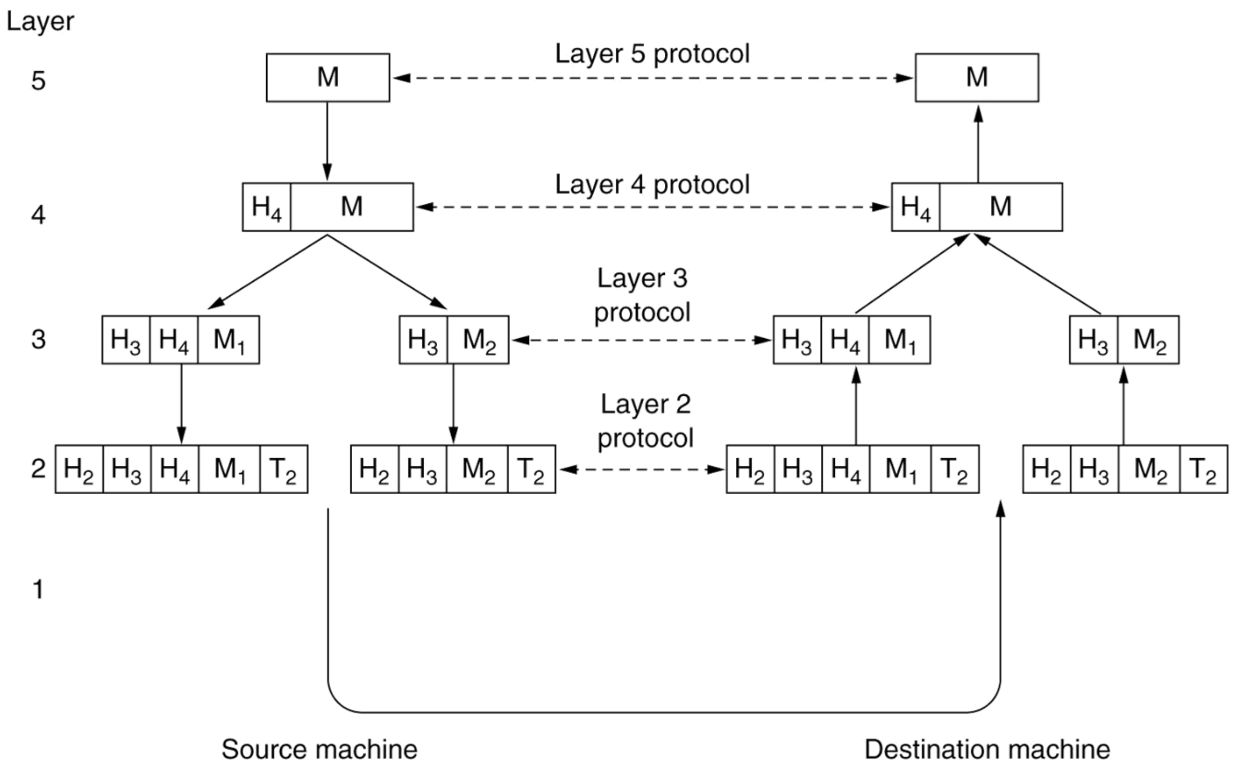
- Such PDU, in turn, is passed to the lower layer as a payload
- Just as with the postal system, the “content” to be sent must be put into an envelope and the envelope must be addressed
  - The PDU header contains control information such as the destination address
- When a PDU is received, the payload is extracted and passed to the upper layer

Protocols: PDUs handling (2/2)



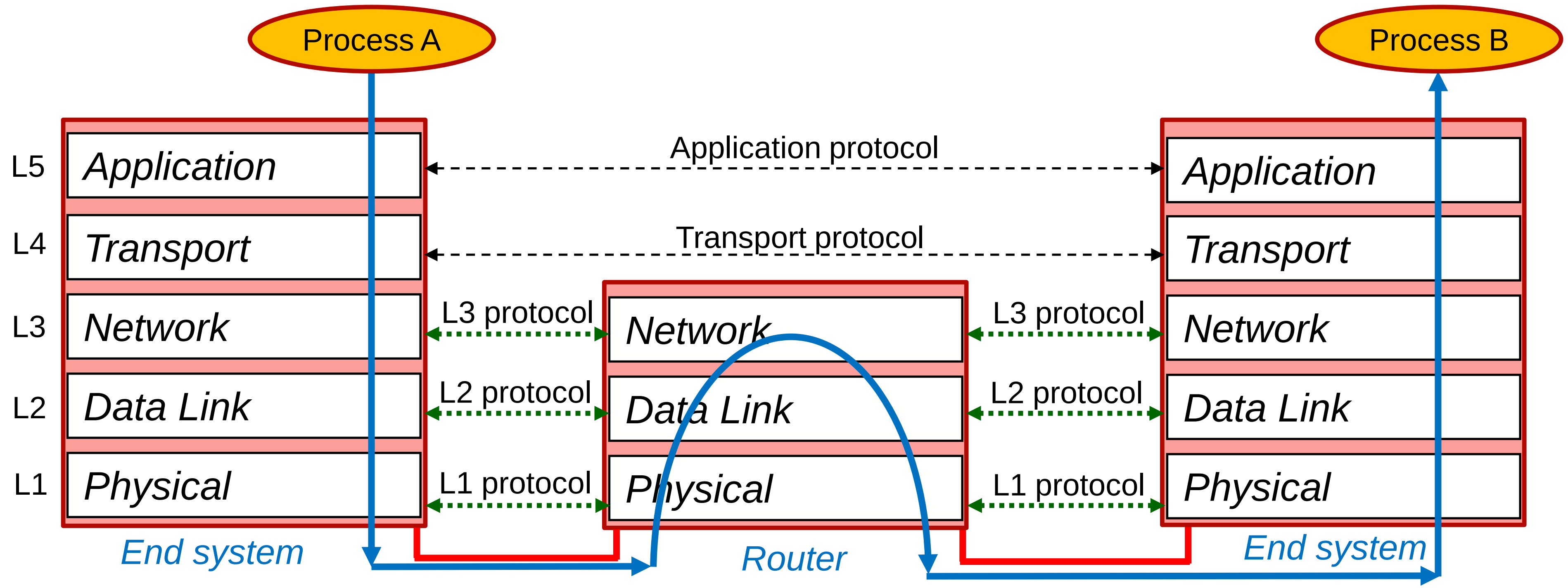
Message fragmentation

- At any layer of a stack it may occur that the payload is too large to fit in a single PDU
- In this event, the payload is split into a sequence of packets → ***fragmentation***
- The original payload is reconstructed at the receiving entity → ***reassembly***

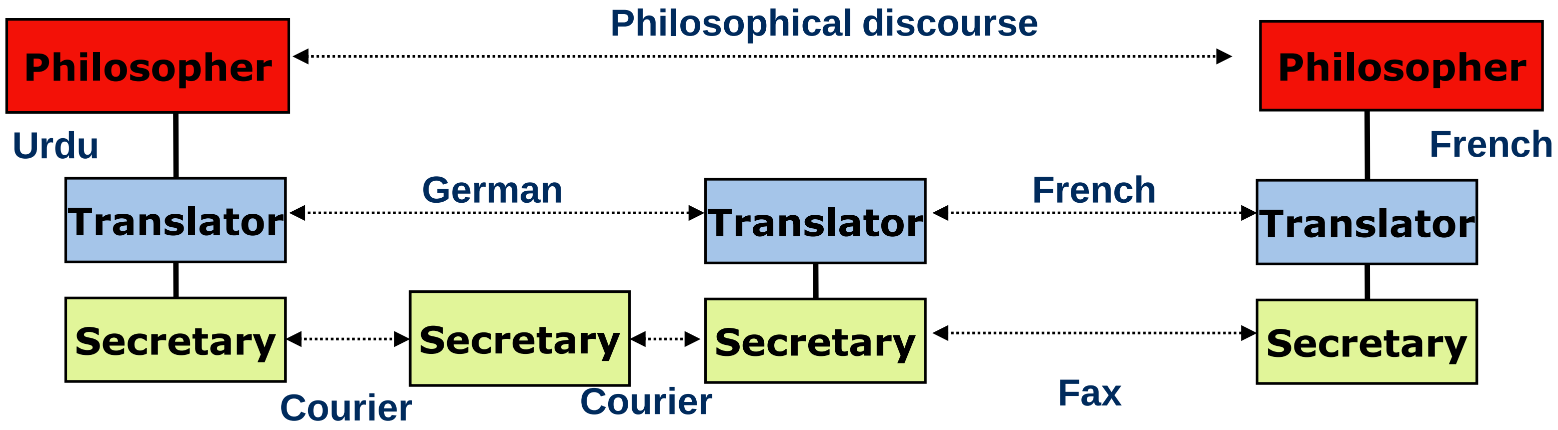


Source: A. S. Tanenbaum. Computer Networks (4 ed.). Prentice Hall, 2003. (Chapter 1, Figure 1.15)

End-to-end communication through an intermediate system



The two philosophers example with intermediaries

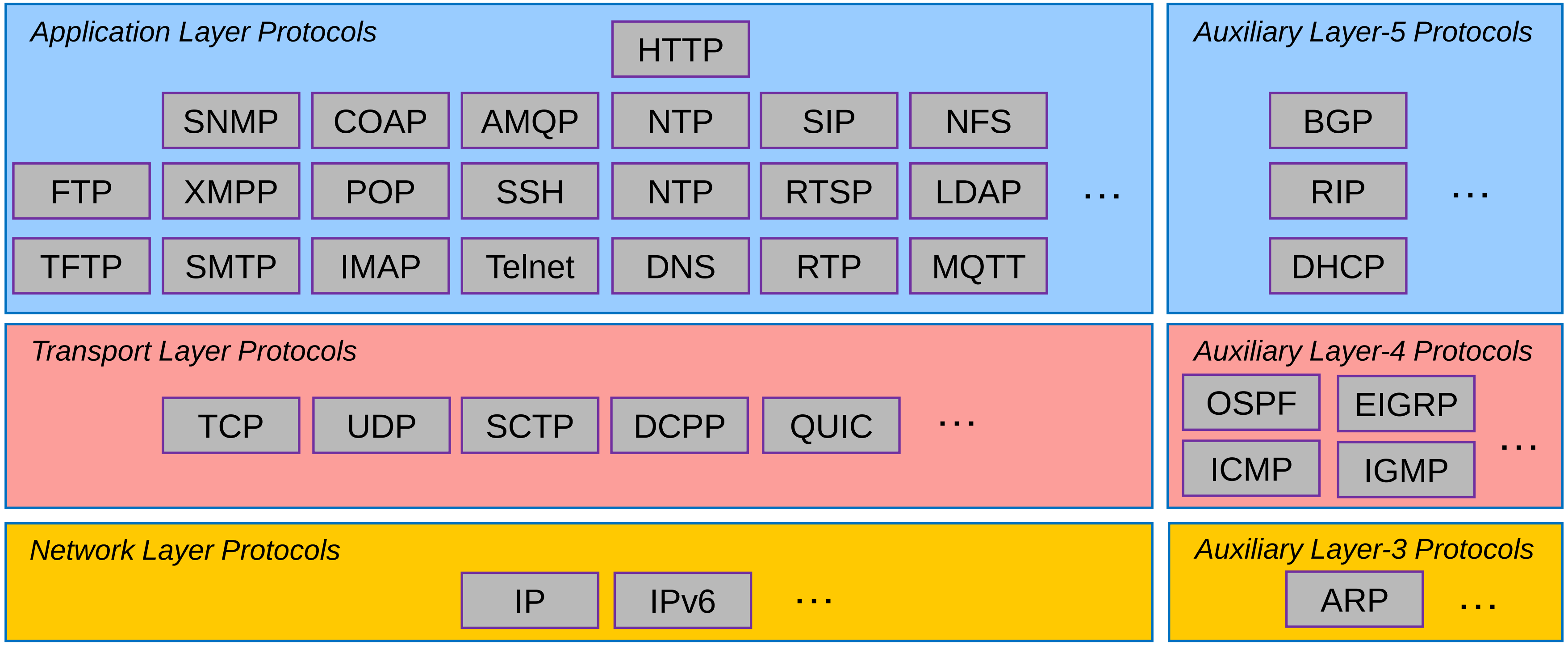


PDU names according to layers

- Generally speaking, a PDU is a ***packet***, made of a ***header***, a ***payload*** and, optionally, of a ***trailer***
- PDUs are usually referred to with different names according to the layer

Layer	PDU name
Application	Message
Transport	Segment
Network	Datagram
Data Link	Frame
Physical	Bit

Internet Protocol suite



- The **Internet Protocol Suite** is the term used to refer to the whole set of protocols today used in the Internet
- Also known as the ***TCP/IP protocol stack***
- Most of these protocols are defined by the ***Internet Engineering Task Force*** (IETF)
- These protocols are "*open standards*"
- The Internet Protocol Suite does not consider layers below the Network layer
  - This is because the IP protocol may be adapted to any layer 2 technology

IETF mission

- The **Internet Engineering Task Force (IETF)** is an open standards organization, which develops and promotes voluntary Internet standards, in particular the standards that comprise the Internet protocol suite (TCP/IP)
- The IETF started out in January 1986 as an activity supported by the federal government of the United States
- Since 1993, the IETF operates as a standards-development function under the auspices of the **Internet Society (ISOC)**, an international membership-based non-profit organization
- The primary mission of IETF is to produce high quality, relevant technical documents, called ***Request for Comments*** **(*RFC*)**, that influence the way people design, use, and manage the Internet in such a way as to make the Internet work better
    - RFC 3935: *A Mission Statement for the IETF* (October 2004)
- More specifically, the IETF mission includes:
  - Identifying and proposing solutions to pressing operational and technical problems in the Internet
  - Specifying the development or usage of protocols and the near-term architecture, to solve technical problems for the Internet
  - Facilitating technology transfer from the *Internet Research Task Force* (IRTF) to the wider Internet community
  - Providing a forum for the exchange of relevant information within the Internet community between vendors, users, researchers, agency contractors, and network managers

IETF organization

- Participation to the IETF does not require the payment of membership fees
- IETF takes decisions "***by rough consensus and running code***" rather than by either individual or organization voting
- Technical activities in the IETF are addressed within **working groups**
  - All working groups are organized roughly by function into **seven areas**
  - Each area is led by one or more Area Directors who have primary responsibility for that area of IETF activity
  - Together with the Chair of the IETF/IESG, these Area Directors comprise the *Internet Engineering Steering Group* (IESG)
- The working groups conduct their business during the tri-annual IETF meetings, at interim working group meetings, and via electronic mail on mailing lists established for each group
  - The tri-annual IETF meetings are 4.5 days in duration, and consist of working group sessions, training sessions, and plenary sessions
  - Following each meeting, the IETF Secretariat publishes meeting proceedings, which contain reports from all of the groups that met, as well as presentation slides, where available
  - The proceedings also include a summary of the standards-related activities that took place since the previous IETF meeting
- Meeting minutes, working group charters (including information about the working group mailing lists), and general information on current IETF activities are available on the IETF Web site at https://www.ietf.org

The importance of standards for ICT

- A **standard** is a framework of specifications that:
  - either has been approved by a recognized organization (*de-jure*),
  - or is generally accepted and widely used throughout by the industry (*de-facto*)

- Following standard specifications is required to obtain **interoperability** between products of different producers
  - *This practice fosters global competition and drives innovation which, in turn, contributes to the creation of new markets and the growth and expansion of existing markets*

- A particular relevance for the development of ICT has been played by ***open standards***
  - There are a number of definitions of open standards which emphasize different aspects of openness
  - Non-open standards are also referred to as ***closed standards***

- In general, it is widely agreed that an ***open standard*** must satisfy at least the following characteristics:
  - easy accessibility for all readers and users
  - developed by a collaborative open process

- It is not generally agreed whether a truly open standard should be royalty-free or not
  - A *royalty* is a sum to be paid to a patent holder for using it in a product

Open standards

- A definition of Open Standards given by Bruce Perens can be found here in
  - Open Standards: Principles and Practice

- The process of creating RFCs in the IETF is described in RFC 2026
  - RFC 2026: *The Internet Standards Process -- Revision 3*
  - In RFC 2026, the IETF classifies specifications that have been developed in a manner similar to that of the IETF itself as being "open standards" and lists the standards produced by ANSI, ISO, IEEE, and ITU-T as examples

- In August 2012, the leaders of the IETF, the *Institute of Electrical and Electronics Engineers* Standards Association (IEEE), the *Internet Architecture Board* (IAB), the *Internet Society* (ISOC), and the *World Wide Web Consortium* (W3C), signed a statement affirming the importance of a jointly developed set of principles establishing a modern paradigm for global open standards
  - These principles have become known as the "OpenStand" principles
    - https://open-stand.org/about-us/principles/
  - The IETF published the OpenStand declaration in the form of RFC 6852 in January 2013
    - RFC 6852: *Affirmation of the Modern Paradigm for Standards*