Computer Communication Networks

Chapter 1: Network Services, Applications Architecture, and Layers

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Communication Services and Applications

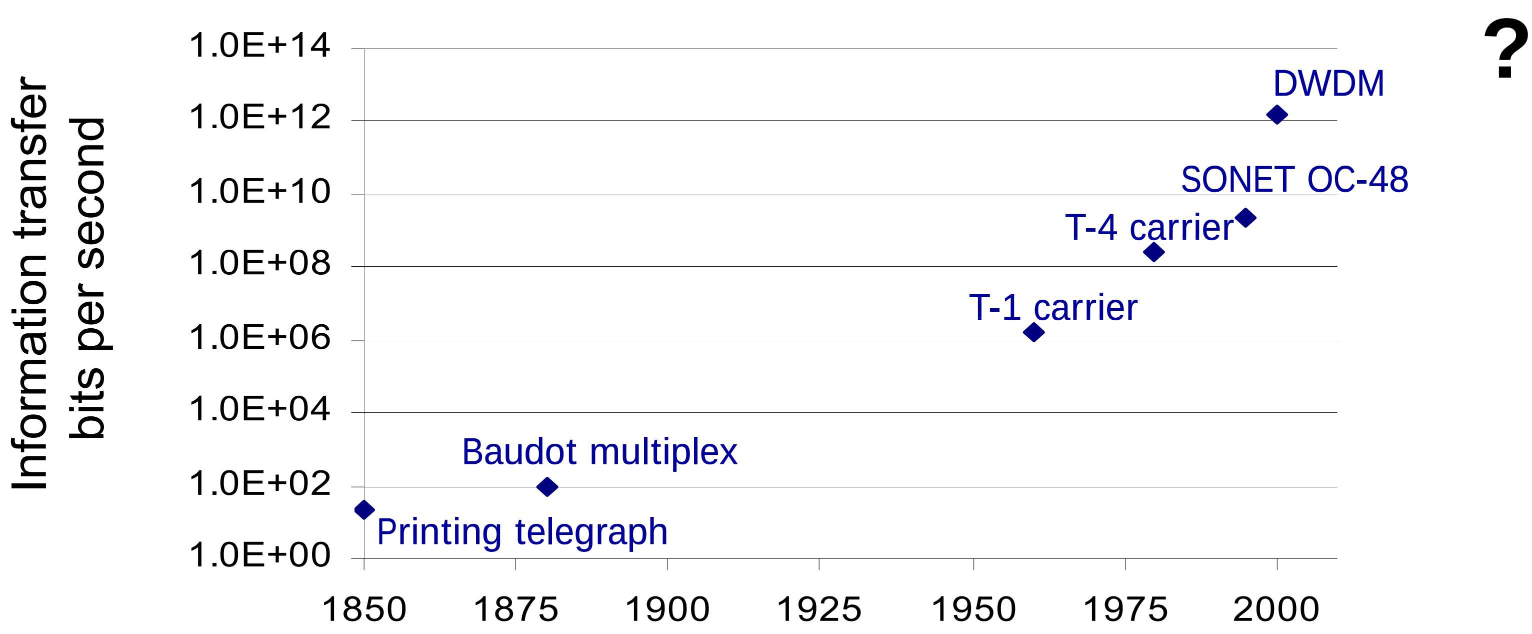
- Purpose
  - A communication service enables the exchange of information between users at different locations
- Examples
  - Courier: USPS, Fedex, UPS, Netflix, etc.
  - Telegraph
  - Telephone
  - Cell phone: voice, VoIP, video streaming, SMS, etc.
  - Internet based services: web-browsing, email, instant messaging, VoIP, video, IPTV, social networking, etc.

What is a Communication Network?

- The equipment (hardware & software) and facilities that provide the basic communication service
- Virtually invisible to the user; Usually represented by a cloud

- Equipment
  - Routers, servers, switches, multiplexers, hubs, modems, …
- Facilities
  - Copper wires, coaxial cables, optical fiber
  - Ducts, conduits, telephone poles …

History of Communication Networks



Telegraph networks

Telephone networks

Internet, Optical & Wireless networks

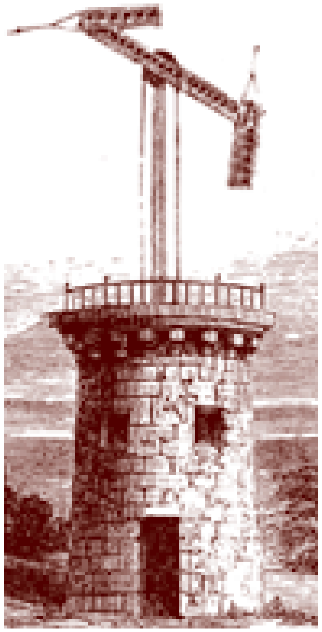
Next Generation Internet

Network Evolution

- Telegraph Networks
  - Message switching & digital transmission
- Telephone Networks
  - Circuit Switching
  - Analog transmission → digital transmission
  - Mobile communications
- Internet
  - Packet switching & computer applications
- Next-Generation Internet
  - Multiservice packet switching network

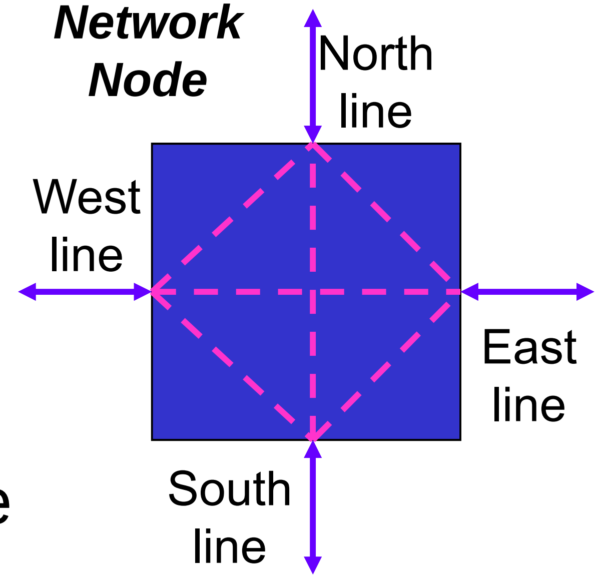
Telegraph (Visual Telegraph)

- Claude Chappe invented optical telegraph in the 1790's
- Semaphore mimicked a person with outstretched arms with flags in each hand
- Different angle combinations of arms & hands generated hundreds of possible signals
- Code for enciphering messages kept secret
- Signal could propagate 800 km in 3 minutes!



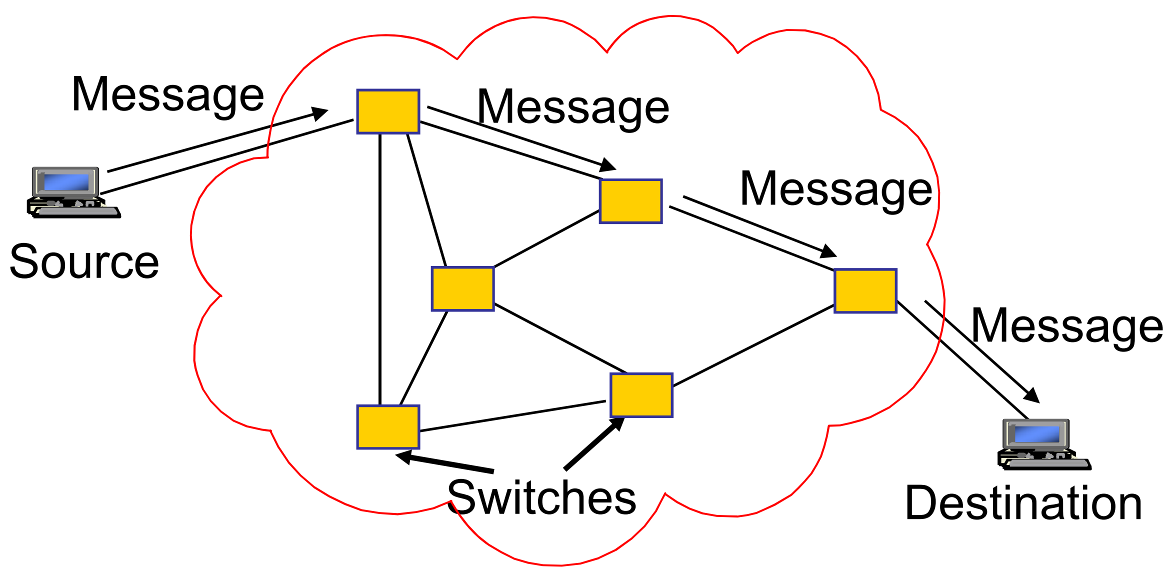
Telegraph (key concept)

- Network nodes were created where several visual telegraph lines met (Paris and other sites)
- *Store-and-Forward* Operation:
  - Messages arriving on each line were decoded
  - Next-hop in ***route*** determined by destination ***address*** of a message
  - Each message was carried by hand to next line, and stored until operator became available for next transmission



Telegraph (Electric Telegraph)

- Architecture
  - Message switching & Store-and-Forward operation
  - Key elements: Addressing, Routing, Forwarding
- Signal propagates at the speed of light
  - Approximately 2 x 10^8 meters/second in cable



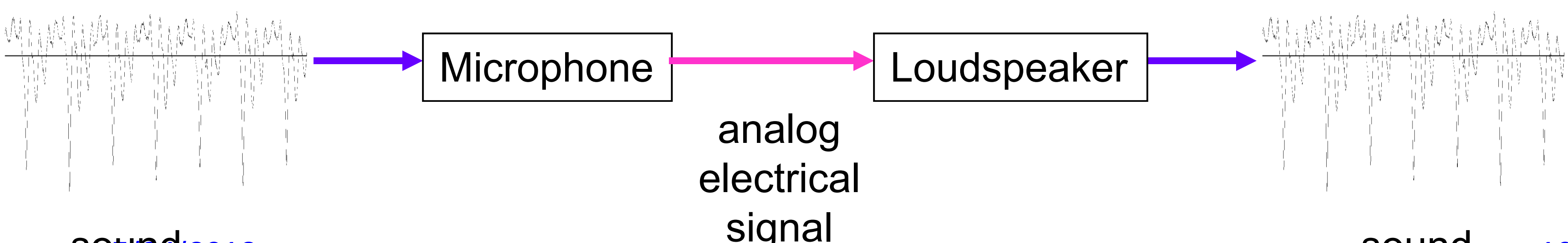
Telegraph (Key Elements)

- Digital transmission
  - Text messages converted into symbols (dots/dashes, zeros/ones) → a simple version of modulation and coding, e.g., Morse code
  - Transmission system designed to convey symbols
- Multiplexing
  - *Framing* needed to recover text characters
- Message Switching
  - Messages contain source & destination *addresses*
  - *Store-and-Forward:* Messages forwarded hop-by-hop across network
  - *Routing* according to destination address

Telephone (Bell’s Telephone)

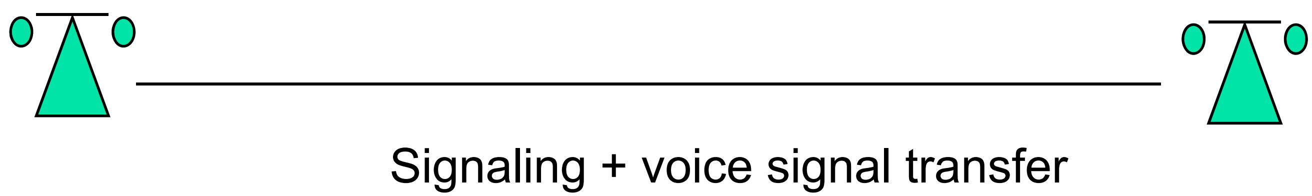
- Alexander Graham Bell (1875) working on harmonic telegraph to multiplex telegraph signals
- Discovered voice signals can be transmitted directly
  - Microphone converts voice pressure variation (sound) into *analogous* electrical signal
  - Loudspeaker converts electrical signal back into sound
- Telephone patent granted in 1876
- Bell Telephone Company founded in 1877

Signal for “ae” as in cat



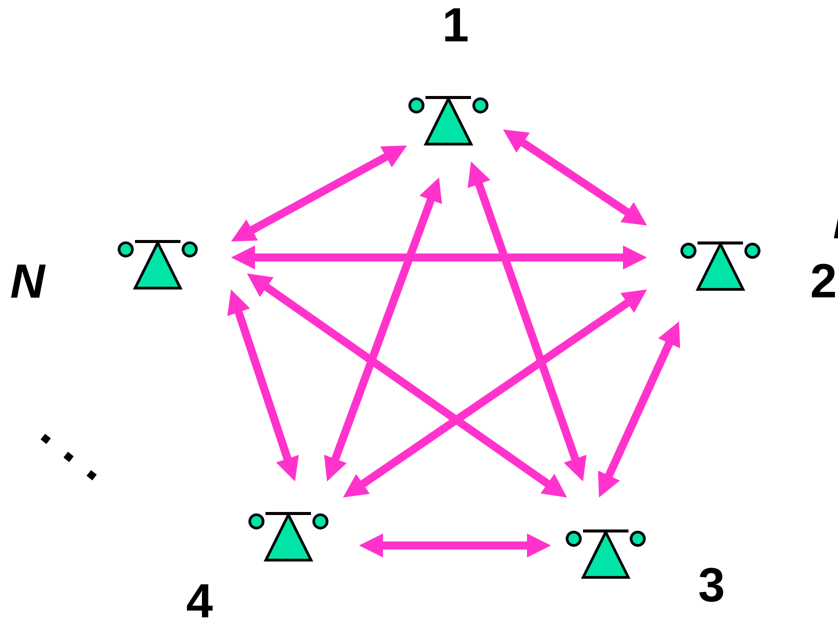
Telephone (Signaling)

- Signaling required to establish a call
  - Flashing light and ringing devices to alert the called party
  - Called party information for operator to establish calls



Telephone (The N^2 Problem)

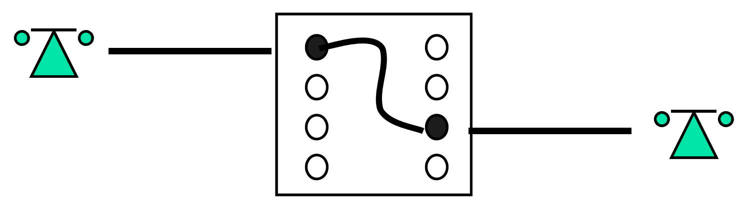
- For N users to be fully connected *directly*
- Requires $N(N-1)/2$ connections
- Requires too much space for cables
- Inefficient & costly since connections not always on



$$N = 1000$$
$$N(N-1)/2 = 499500$$

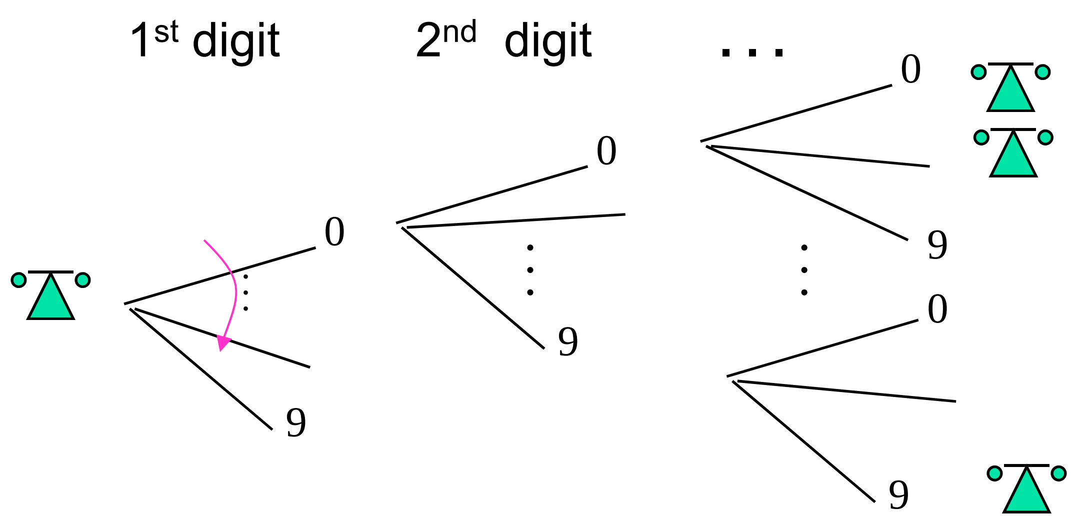
Telephone (Circuit Switching)

- Patchcord panel switch invented in 1877
- Operators connect users on demand
  - Establish *circuit* to allow electrical current to flow from inlet to outlet
- Only *N* connections required to central office

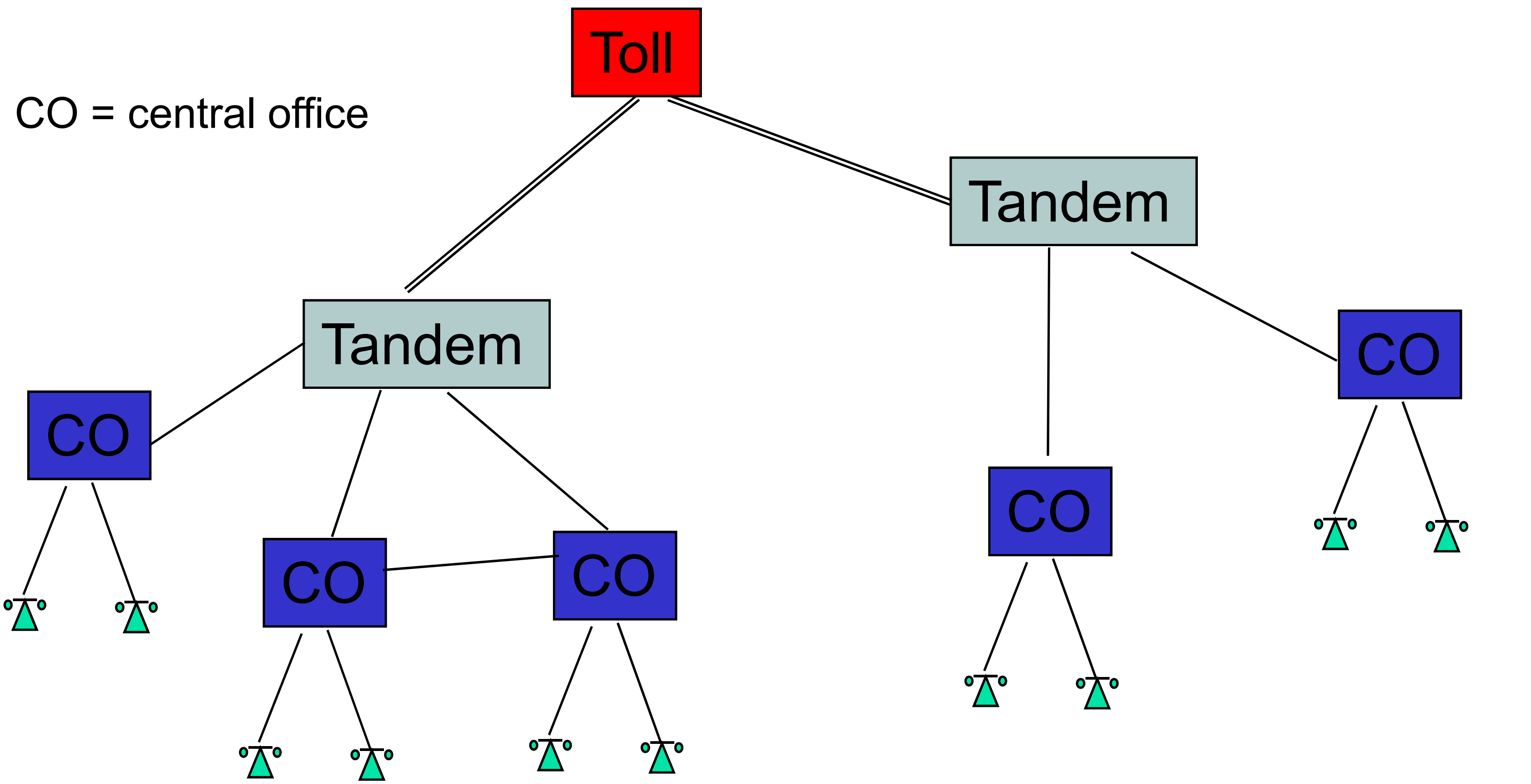


Telephone (Manual versus Automatic Circuit Switching)

- Human operators intelligent & flexible
  - But expensive and not always discreet
- Strowger invented automated switch in 1888
  - Each current pulse advances wiper by 1 position
  - User dialing controls connection setup
- Decimal telephone numbering system
- Hierarchical network structure simplifies routing
  - Area code, exchange (CO), station number



Telephone (Hierarchical Network Architecture)



Telephone subscribers connected to local CO (central office)

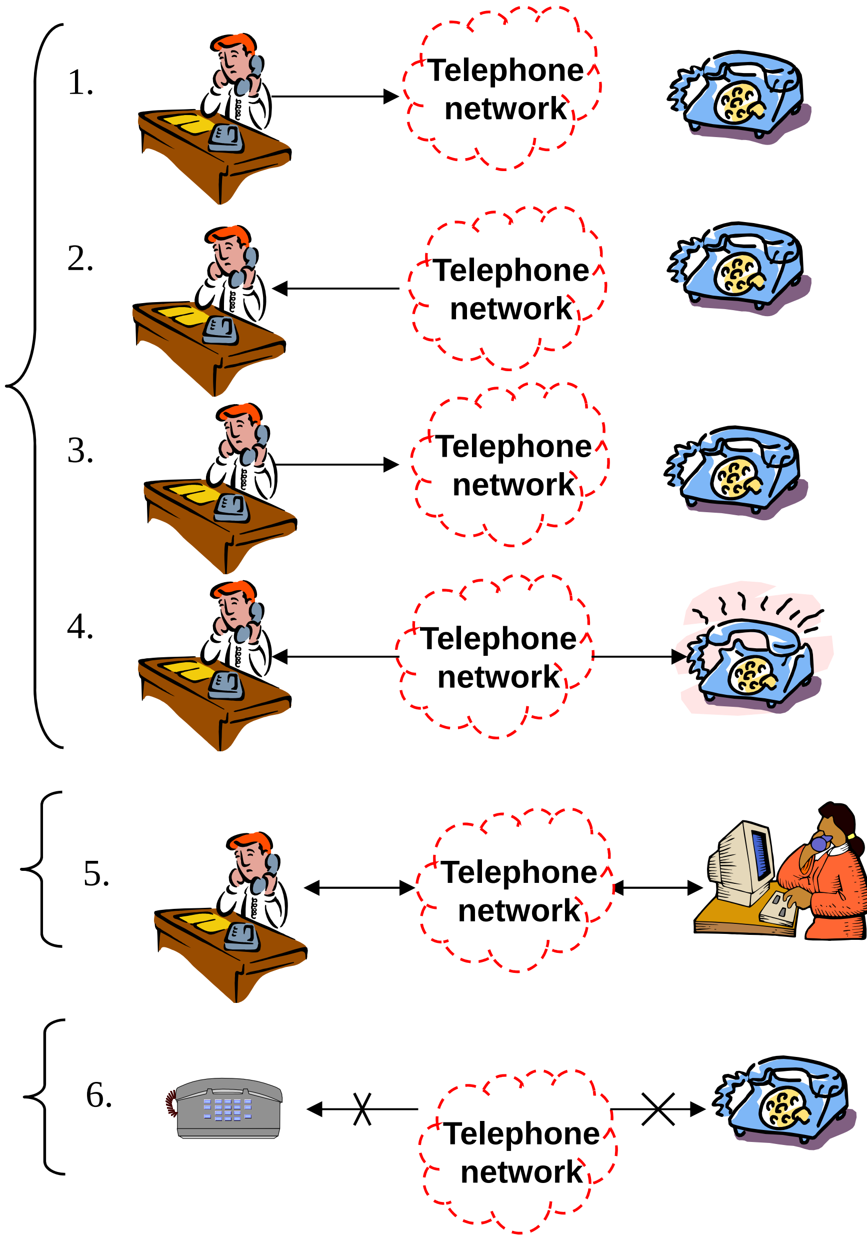
Tandem & Toll switches connect CO's

Telephone (3 Phases of a Call)

Connection set up

Information transfer

Connection release



Pick up phone

Dial tone.

Dial number

Network selects route;

Sets up connection;

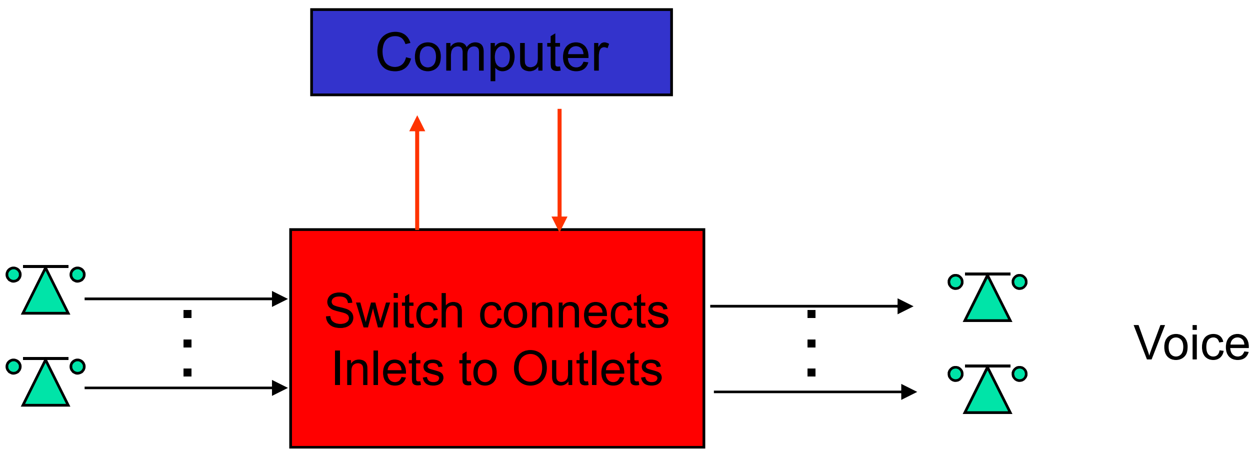
Called party alerted

Exchange voice signals

Hang up.

Telephone (Computer Connection Control)

- A computer controls connection in telephone switch
- Computers exchange *signaling messages* to:
  - Coordinate set up of telephone connections
  - To implement new services such as caller ID, voice mail, . . .
  - To enable *mobility and roaming in* cellular networks
- "Intelligence" inside the network
- A separate *signaling network* is required



Telephone (Digitization)

- Pulse Code Modulation digital voice signal
  - Voice gives 8 bits/sample x 8000 samples/sec = 64×10^3 bps
- Time Division Multiplexing for digital voice
  - T-1 multiplexing (1961): 24 voice signals = 1.544×10^6 bps
- Digital Switching (1980s)
  - Switch TDM signals without conversion to analog form
- Digital Cellular Telephony (1990s)
- Optical Digital Transmission (1990s)
  - One OC-192 optical signal = 10×10^9 bps
  - One optical fiber carries 160 OC-192 signals = 1.6×10^{12} bps!

All digital transmission, switching, and control

Key Elements of Today's Telephone

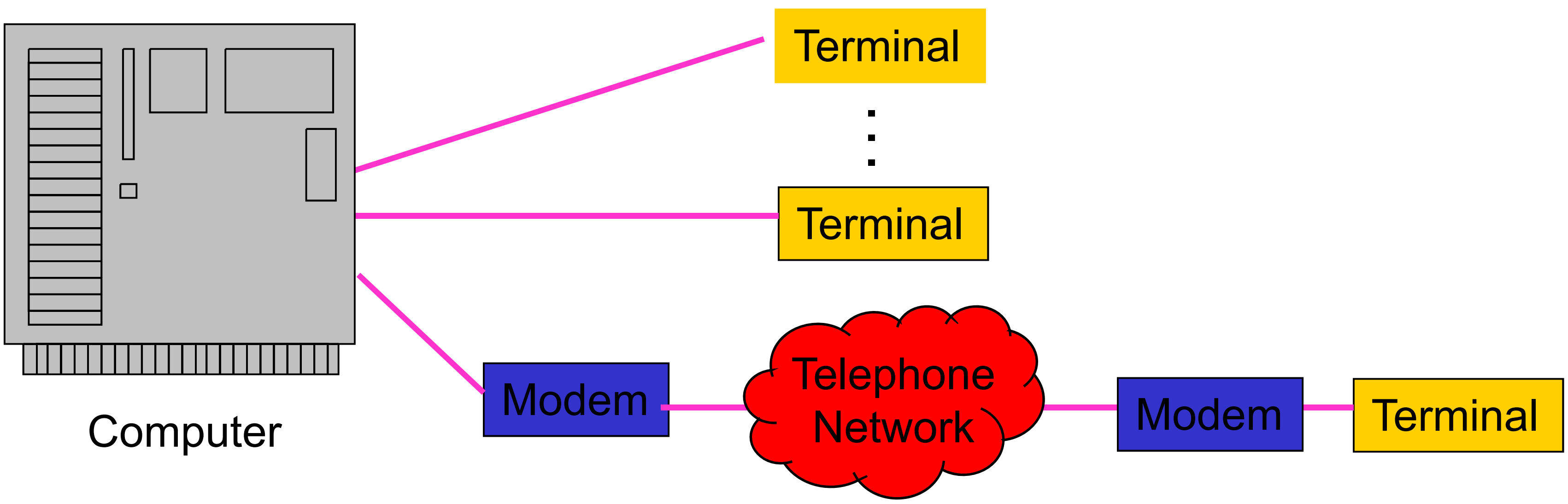
- Digital transmission & switching
  - Digital voice; Time Division Multiplexing
- Circuit switching
  - User signals for call setup and tear-down
  - Route selected during connection setup
  - End-to-end connection across network
  - Signaling coordinates connection setup
- Hierarchical Network
  - Decimal numbering system
  - Hierarchical structure; simplified routing; scalability
- Signaling Network
  - Intelligence inside the network

Computer Network Evolution

- *1950s*: Telegraph technology adapted to computers
- *1960s*: Dumb terminals access shared host computer
  - SABRE airline reservation system
- *1970s*: Computers connect directly to each other
  - ARPANET packet switching network
  - TCP/IP internet protocols
  - Ethernet local area network
- *1980s & 1990s*: New applications and Internet growth
  - Commercialization of Internet
  - E-mail, file transfer, web, P2P, . . .
  - Internet traffic surpasses voice traffic
- Today's computer networks
  - Hybrid of different wired and wireless networks

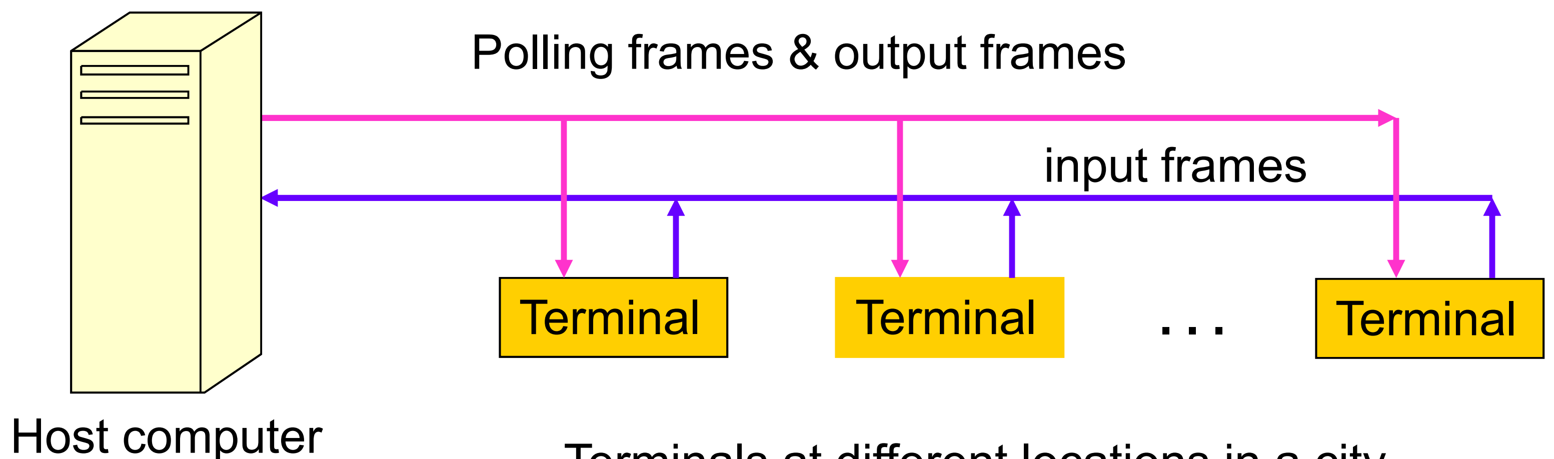
Example 1: Terminal-Oriented Networks

- Early computer systems very expensive
- Time-sharing methods allowed multiple terminals to share local computer
- Remote access via telephone modems



Example 1: Medium Access Control

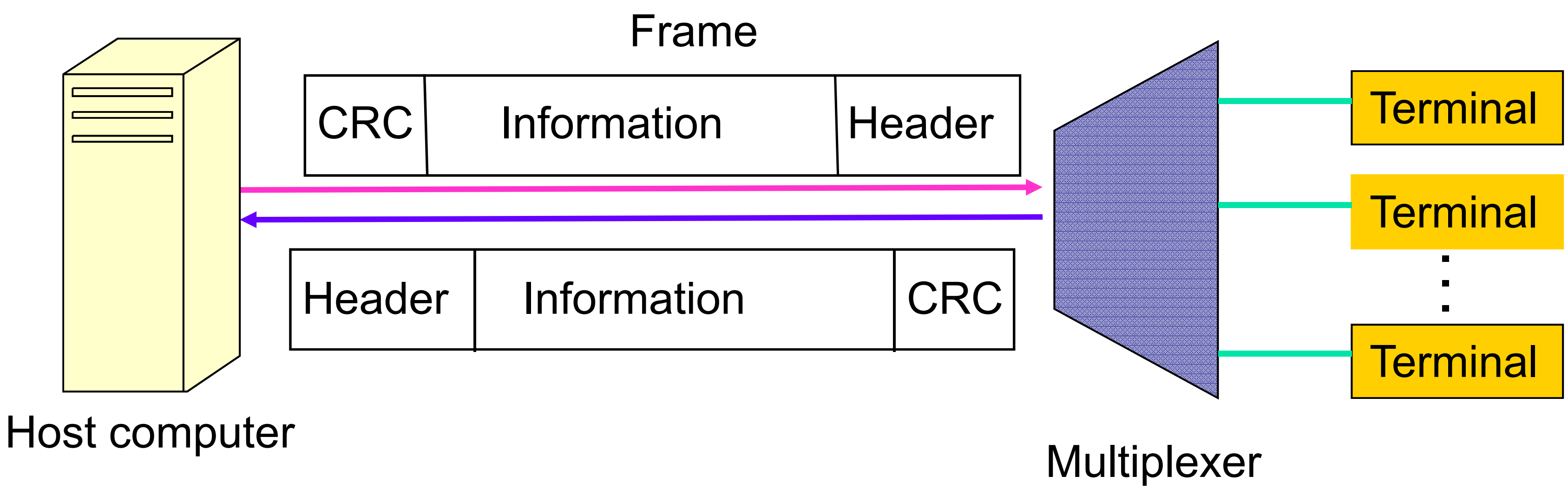
- Terminals generated messages sporadically
- Frames carried messages to/from attached terminals
- Address in frame header identified terminal
- Terminals need to be coordinated to access the same medium (the communication line to the computer)
- *Medium Access Controls* were developed to coordinate access by multiple terminals
- Example: Polling protocol on a multidrop line



Terminals at different locations in a city
Must avoid collisions on inbound line

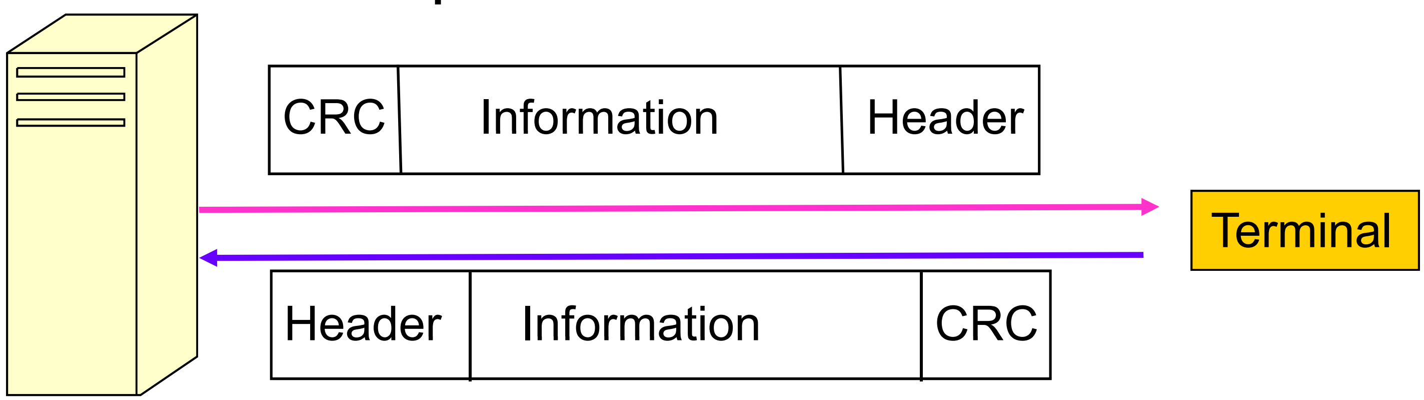
Example 1: Multiplexing

- Dedicated communication lines were expensive
- Statistical multiplexer allows a line to carry *frames* that contain messages to/from multiple terminals
- Frames are buffered at *multiplexer* until line becomes available, i.e. store-and-forward
- *Address* in frame header identifies terminal
- Header carries other *control* information



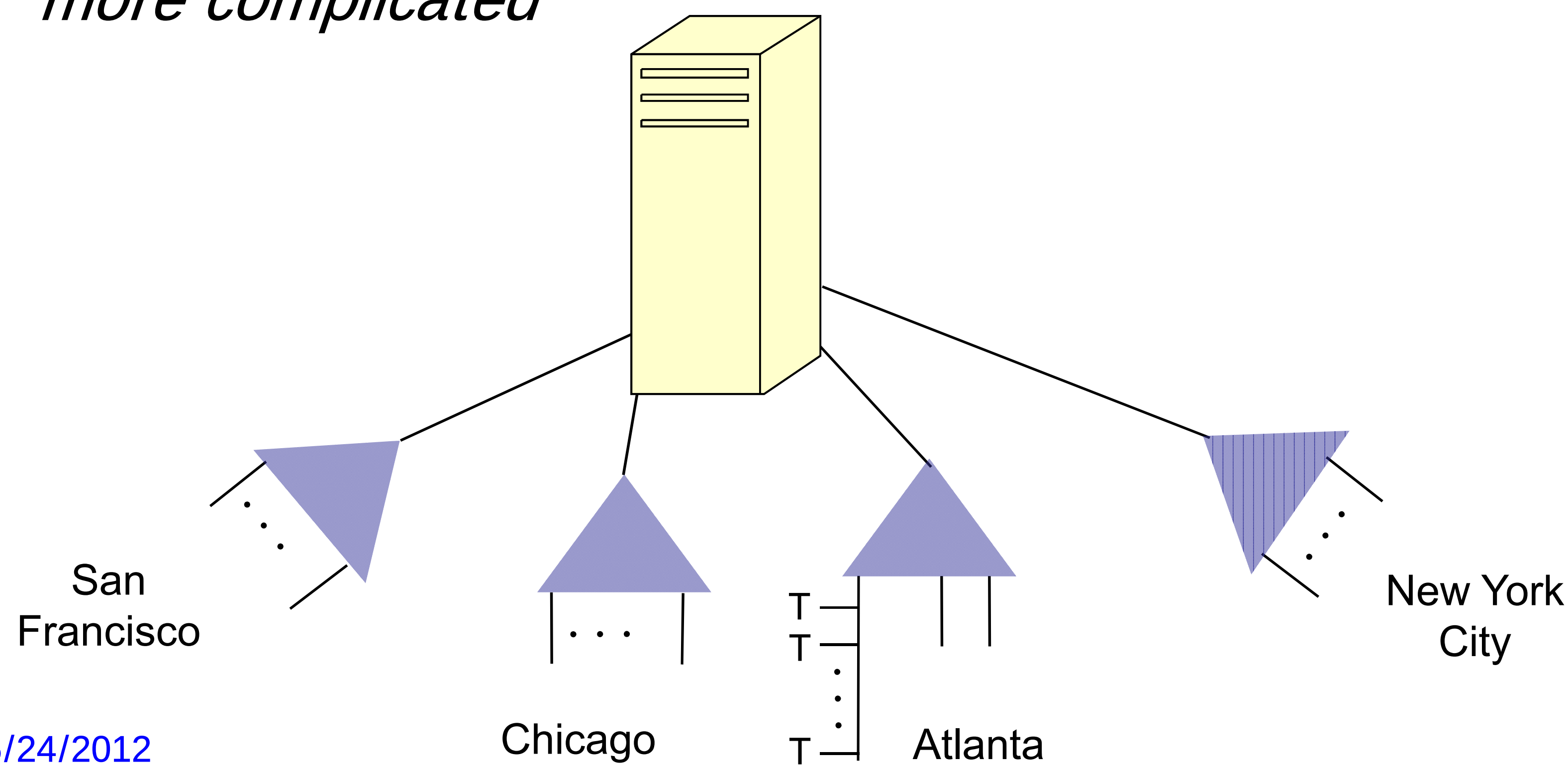
Example 1: Error Control

- Communication lines introduce errors
- Error checking codes used on frames
  - "Cyclic Redundancy Check" (CRC) calculated based on frame header and information payload
    - for *forward error control*
  - Header also carries ACK/NAK control information
    - for *ARQ (auto-repeat-request)*
- Retransmission requested when errors detected



Example 2: Tree-Topology Networks

- National & international terminal-oriented networks
- Routing is very simple (to/from host)
- Each network typically handles a single application
- *Mobility or roaming makes the problem become much more complicated*



Example 3: Computer-to-Computer Networks

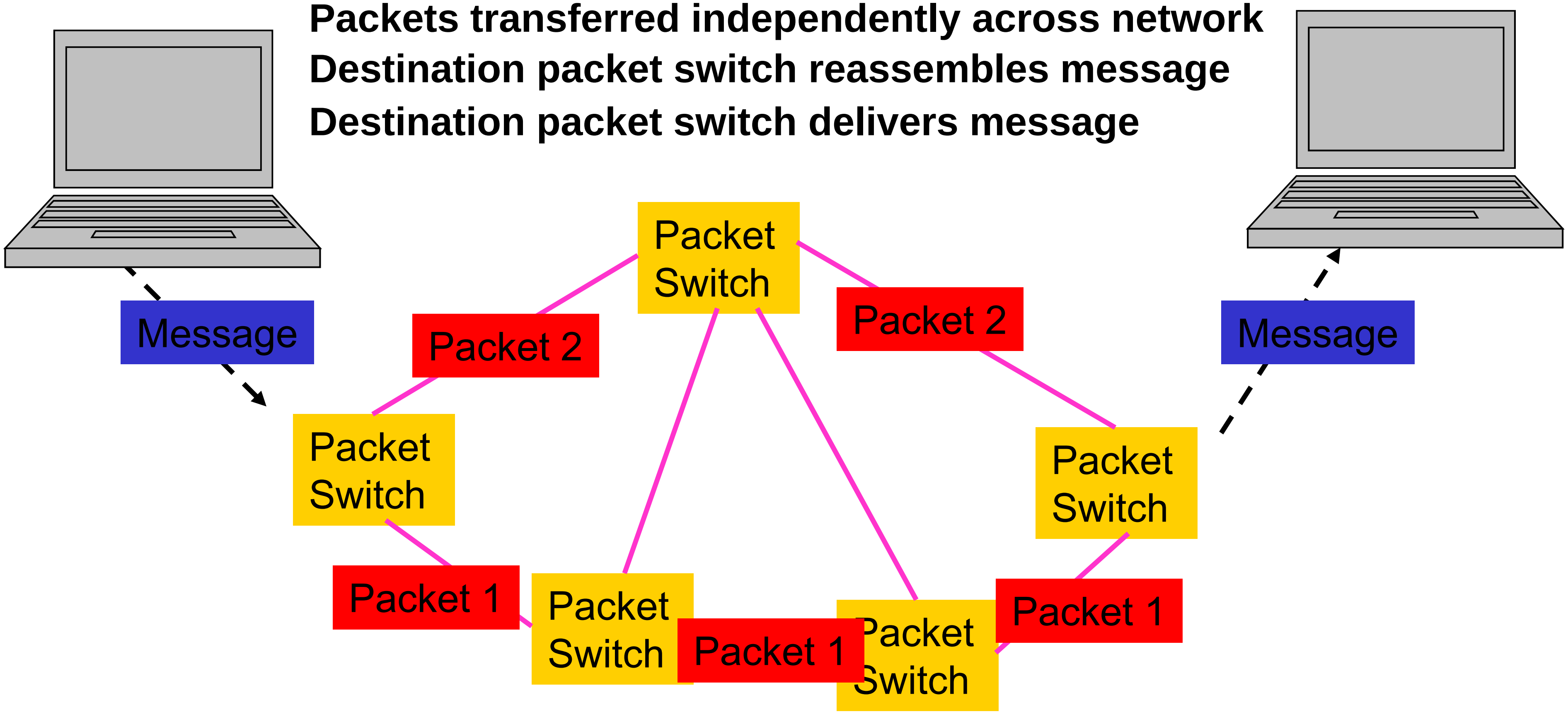
- As cost of computing dropped, terminal-oriented networks viewed as too inflexible and costly
- Need to develop flexible computer networks
  - Interconnect computers as required
  - Support many applications
- Application Examples
  - File transfer between arbitrary computers
  - Execution of a program on another computer
  - Multiprocess operation over multiple computers

Example 3: The Need of Packet Switching

- Network should support multiple applications
  - Transfer arbitrary message size
  - Low delay for interactive applications
  - But in traditional store-and-forward operation, long messages induce high delay on interactive messages
- Packet switching introduced
  - Network transfers packets using store-and-forward
  - Packets have maximum length
  - Break long messages into multiple packets
- ARPANET (Advanced Research Projects Agency) testbed led to many innovations

Example 3: ARPANET Packet Switching

- Host generates message
- Source packet switch converts message to packet(s)
- Packets transferred independently across network
- Destination packet switch reassembles message
- Destination packet switch delivers message



Example 3: ARPANET Routing

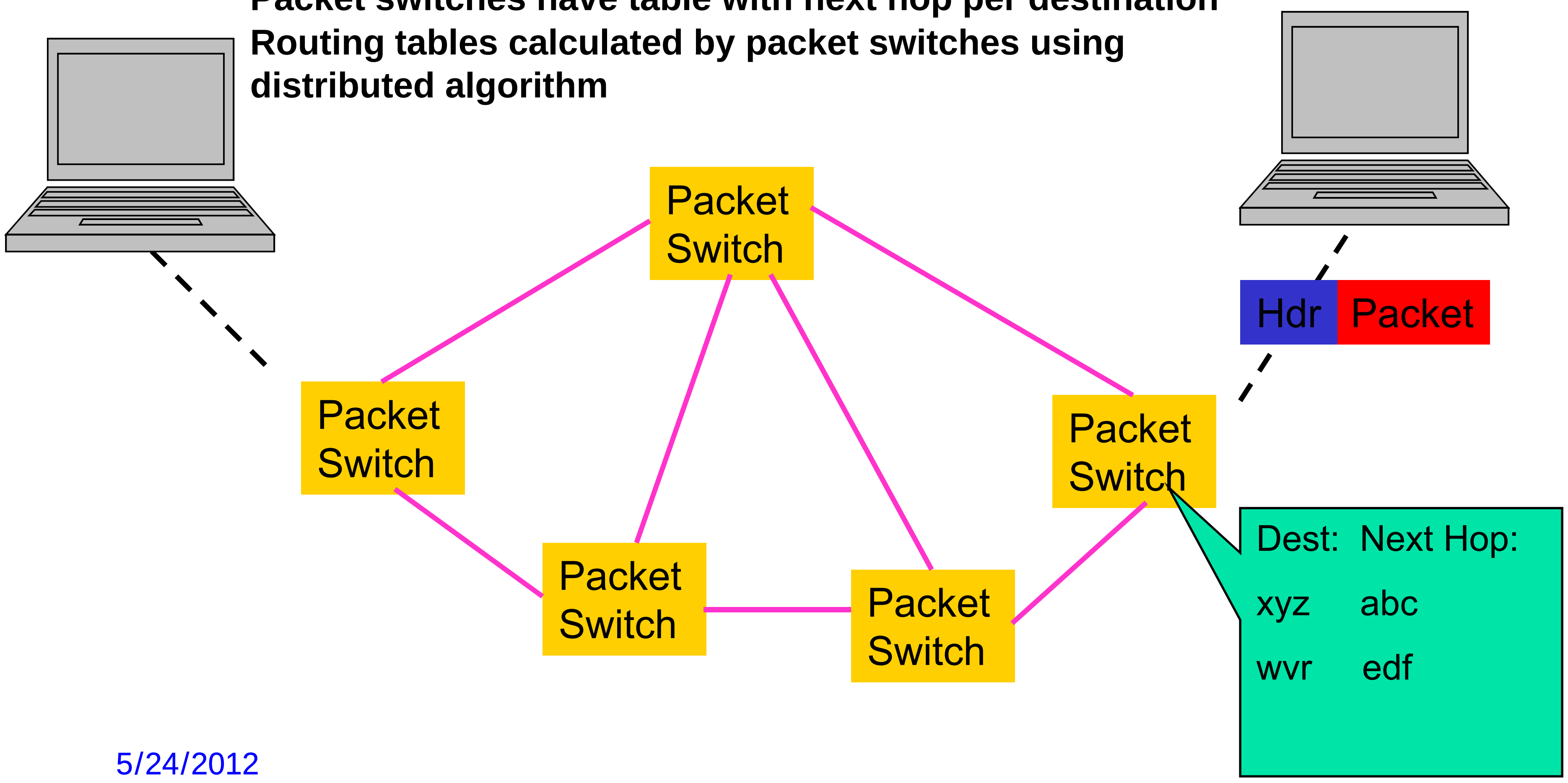
Routing is highly nontrivial in computer networks

No connection setup prior to packet transmission

Packets header includes source & destination addresses

Packet switches have table with next hop per destination

Routing tables calculated by packet switches using distributed algorithm

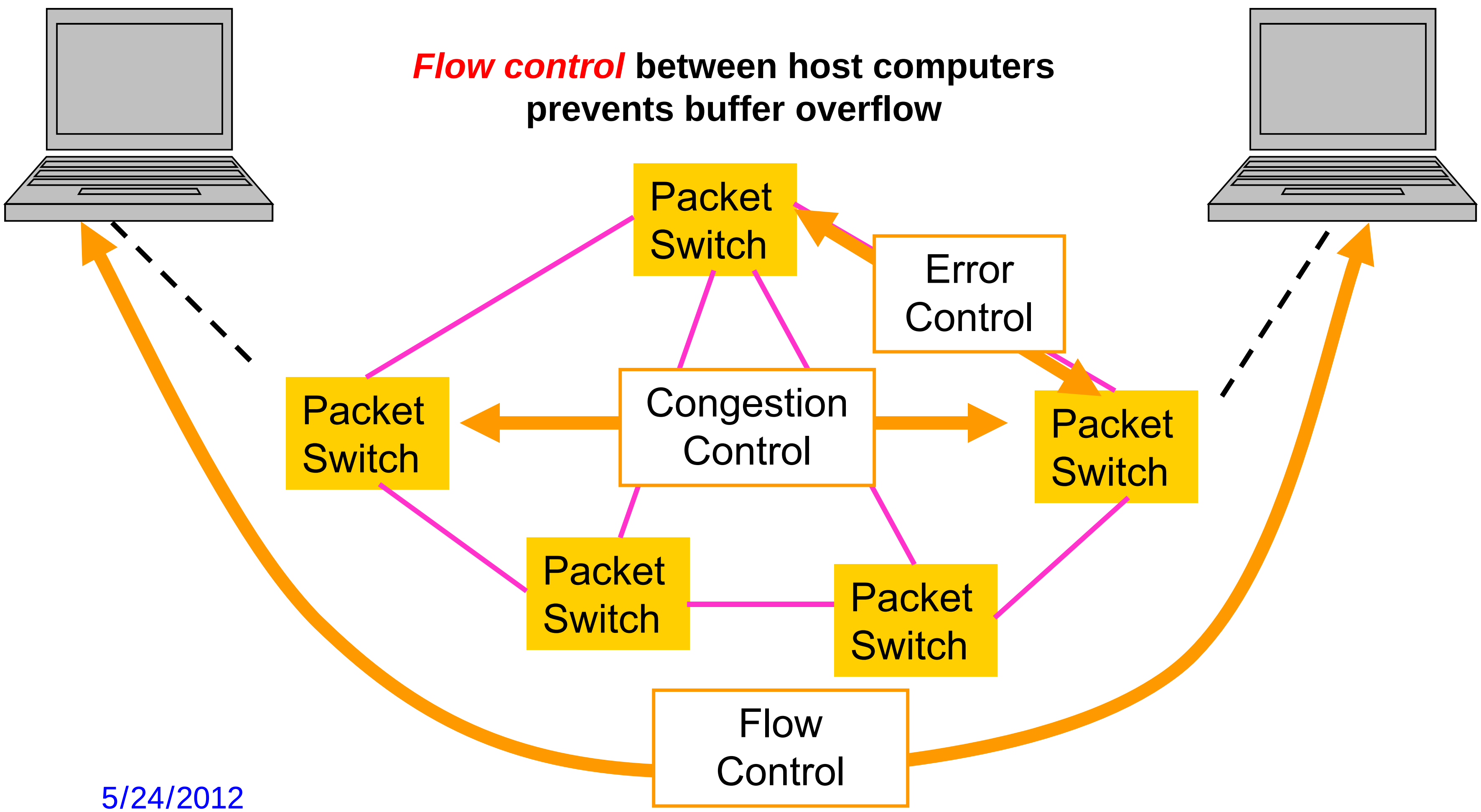


Example 3: Other ARPANET Networking Functions

Error control **between adjacent packet switches**

Congestion control **between source & destination packet switches limit number of packets in transit**

Flow control **between host computers prevents buffer overflow**

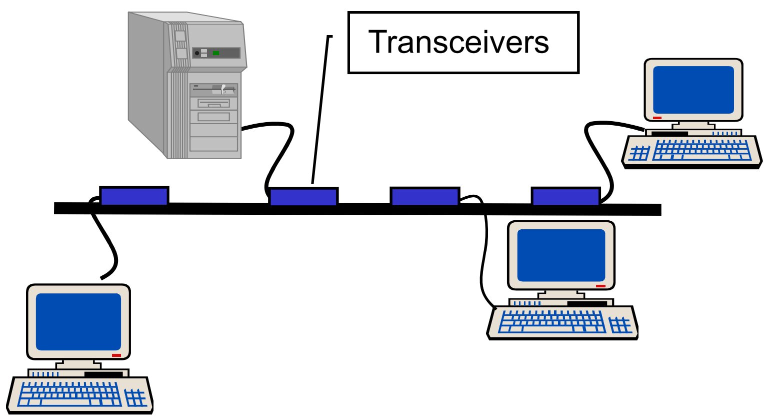


Example 4: Ethernet

- In 1980s, affordable workstations available
- Need for low-cost, high-speed networks
  - To interconnect local workstations
  - To access local shared resources (printers, storage, servers)
- Low cost, high-speed communications with low error rate possible using coaxial cable
- Ethernet is the standard for high-speed wired access to computer networks

Example 4: Ethernet MAC

- Network interface card (NIC) connects workstation to LAN
- Each NIC has globally unique address
- Frames are broadcast into coaxial cable
- NICs listen to medium for frames with their address
- Transmitting NICs listen for collisions with other stations, and abort or reschedule retransmissions

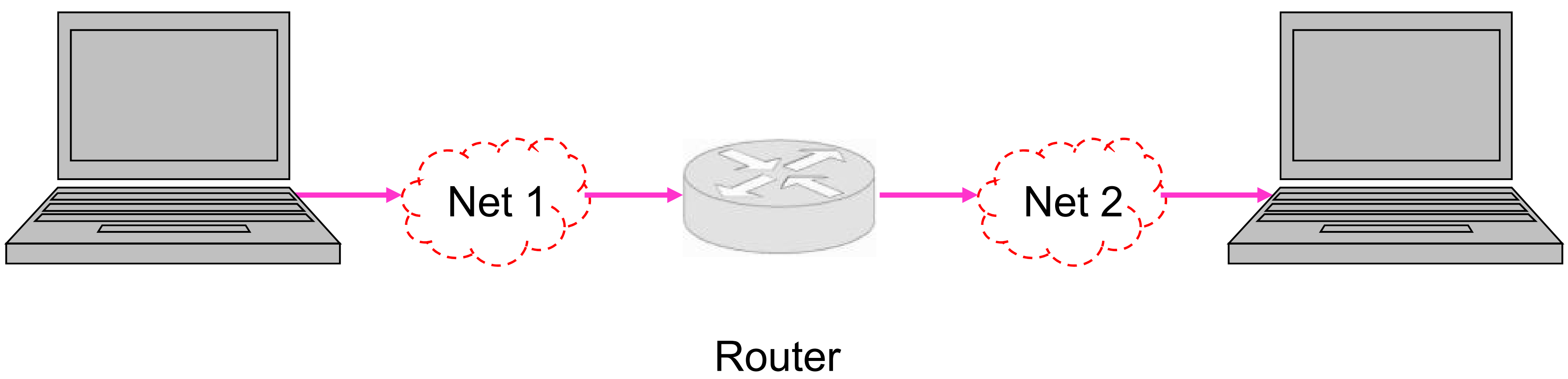


Example 5: Internet

- Different network types emerged for data transfer between computers
- ARPA also explored packet switching using satellite and packet radio networks
- Each network has its protocols and is possibly built on different technologies
- *Internetworking protocols* required to enable communications between computers attached to *different* networks
- ***Internet***: a network of networks

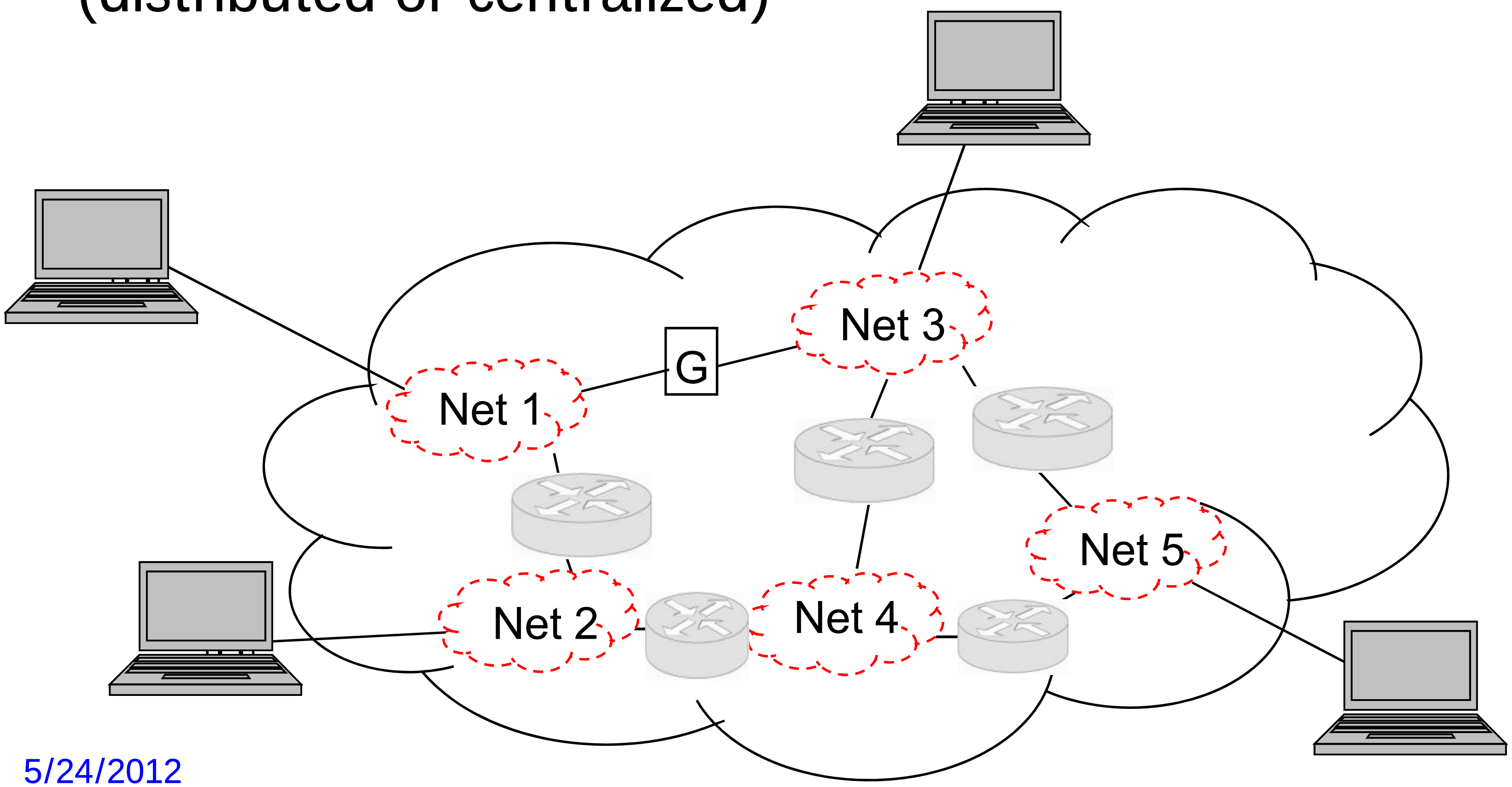
Example 5: IP

- *Routers (gateways)* interconnect different networks
- Host computers prepare IP packets and transmit them over their attached network
- Routers forward IP packets across networks
- *Best-effort* IP transfer service, no retransmission



Example 5: Internet Addressing & Routing

- Hierarchical address: Net ID + Host ID
- IP packets routed according to Net ID
- Routers compute routing tables using certain algorithms (distributed or centralized)

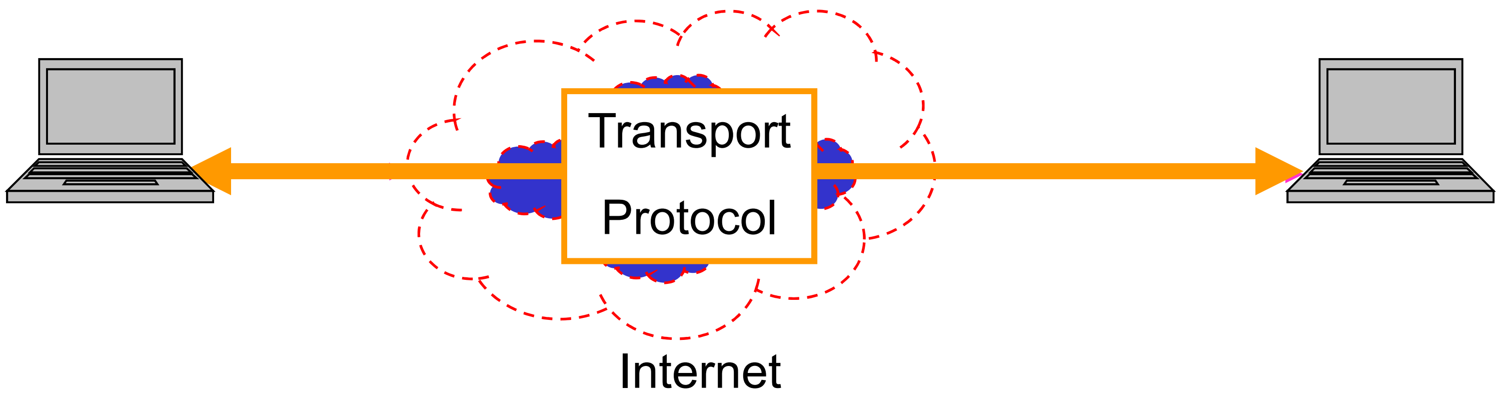


Example 5: Internet Names and IP Addresses

- Routing is done based on 32-bit IP addresses
- Dotted-decimal notation
  - 125.85.30.154
- Hosts are also identified by name
  - Easier to remember
  - Hierarchical name structure
  - E.g.: www.umji.sjtu.edu.cn
  - Domain Name System (DNS) provided conversion between names and addresses

Example 5: Transport IP Packets

- Host computers run two transport protocols on top of IP to enable process-to-process communications
- *User Datagram Protocol* (UDP) enables best-effort transfer of individual block of information
- *Transmission Control Protocol* (TCP) enables reliable transfer of a stream of bytes



Example 5: More Info on Internet

- All Internet applications run on TCP or UDP
- TCP: HTTP (web), SMTP (e-mail), FTP (file transfer, telnet (remote terminal)
- UDP: DNS, RTP (voice & multimedia)
- TCP & UDP incorporated into computer operating systems
- Any application designed to operate over TCP or UDP will run over the Internet

Elements of Computer Networks

- *Digital transmission* involves a lot of digital communication technologies
- Exchange of *frames* between adjacent equipment
  - Framing and error control
- *Medium access control* regulates sharing of broadcast medium.
- *Addresses* identify attachment to network or internet.
- Transfer of *packets* across a packet network
- *Internetworking* across multiple networks using routers
- Distributed calculation of *routing tables*

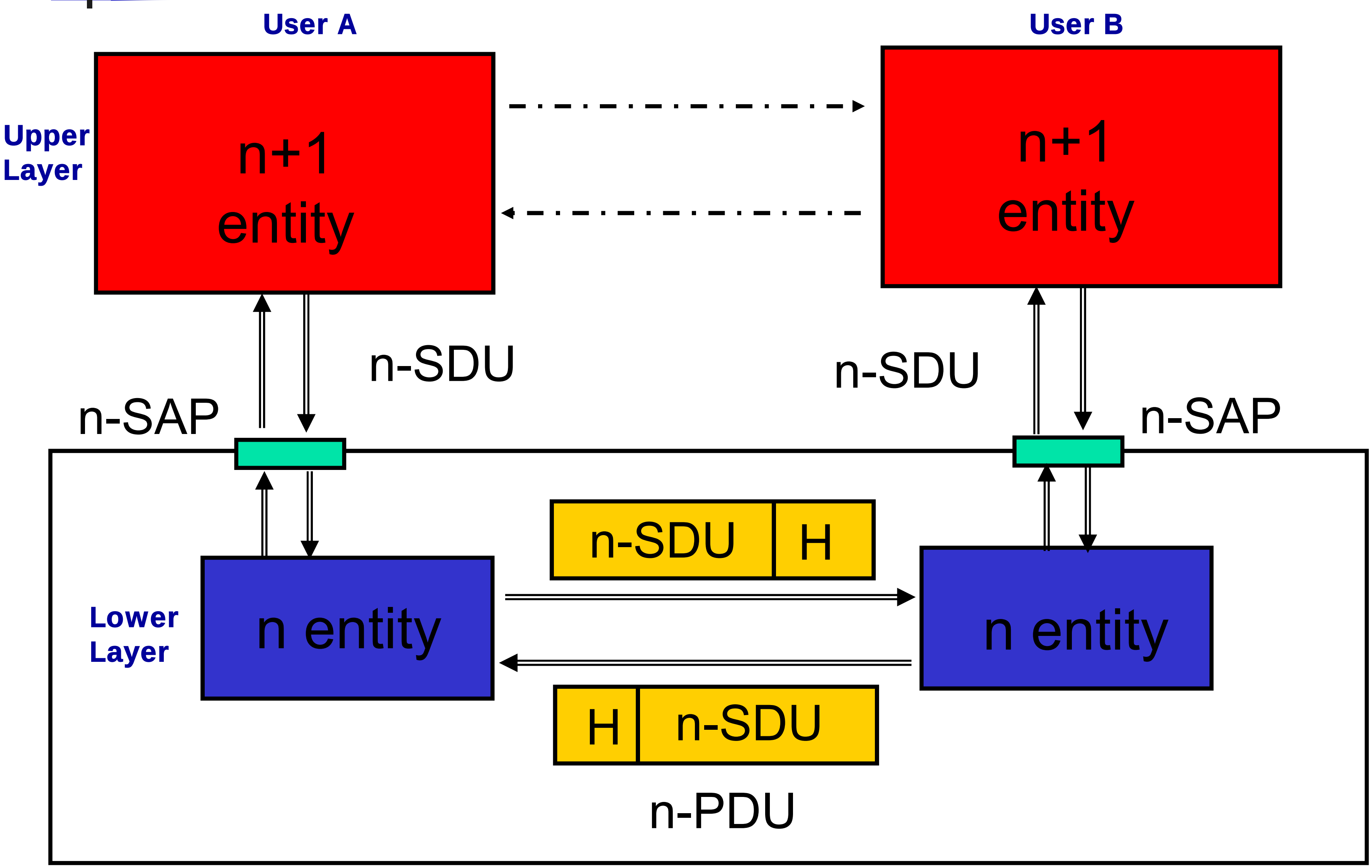
Elements of Computer Networks (continued)

- *Congestion control* inside the network
- *Segmentation and reassembly* of messages into packets at the ingress to and egress from a network or internetwork
- *End-to-end transport protocols* for process-to-process communications
- *Applications* that build on the transfer of messages between computers.
- *Intelligence is needed at the edge of the network.*

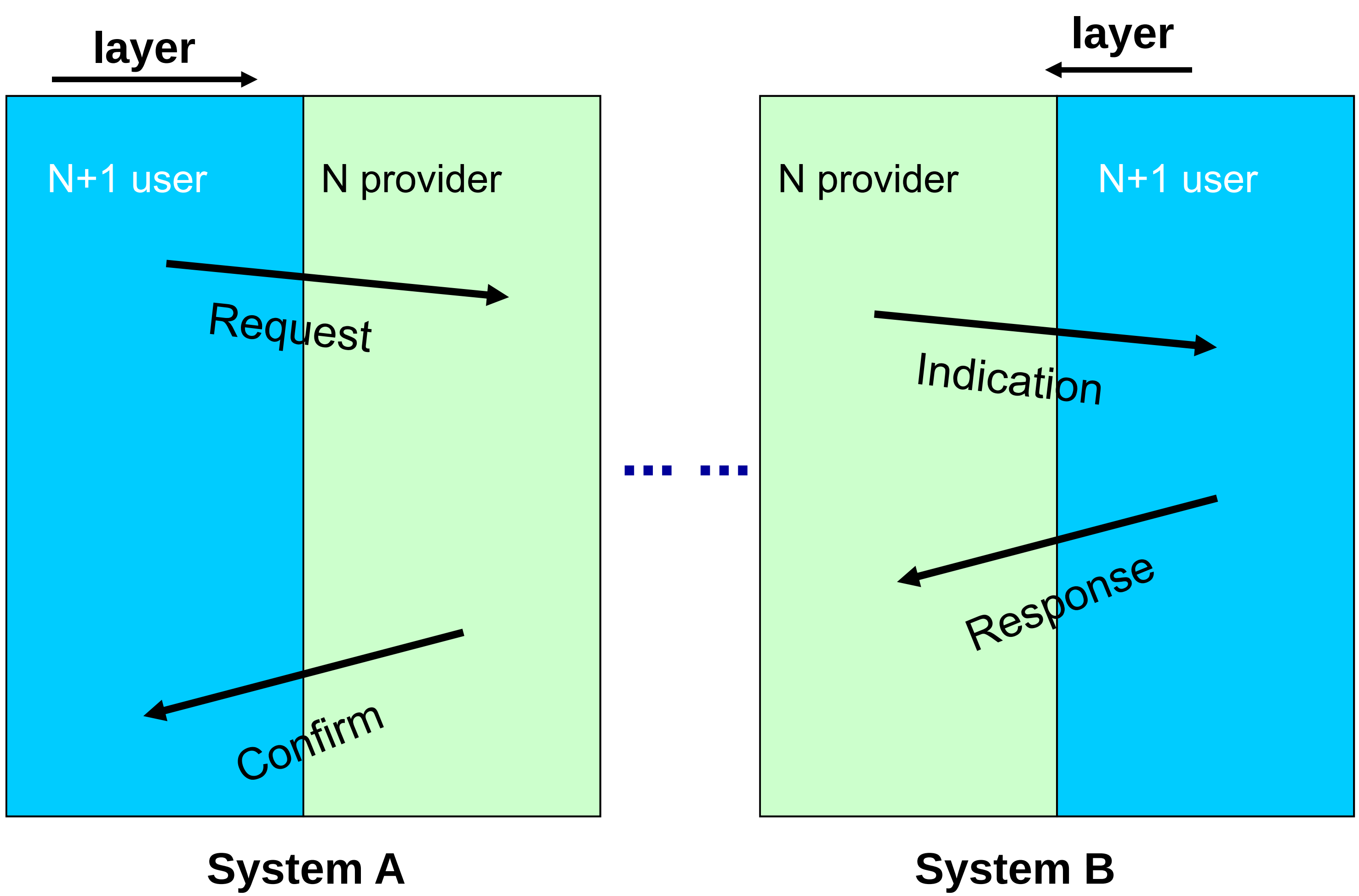
Layers, Services, and Protocols

- The overall communications process between two or more machines connected across one or more networks is very complex
- ***Layering*** partitions related communications functions into groups that are manageable
- Each layer provides a ***service*** to the layer above
- Each layer operates according to a ***protocol***

Information Flow between Two Layers



Interactions between Layers



Why Layering?

- Layering simplifies design, implementation, and testing by partitioning overall communications process into parts
- Protocol in each layer can be designed separately from those in other layers
- Protocol makes “calls” for services from layer below
- Layering provides flexibility for modifying and evolving protocols and services without having to change layers below
- Monolithic non-layered architectures are costly and inflexible

Is Layering always Good?

Protocols

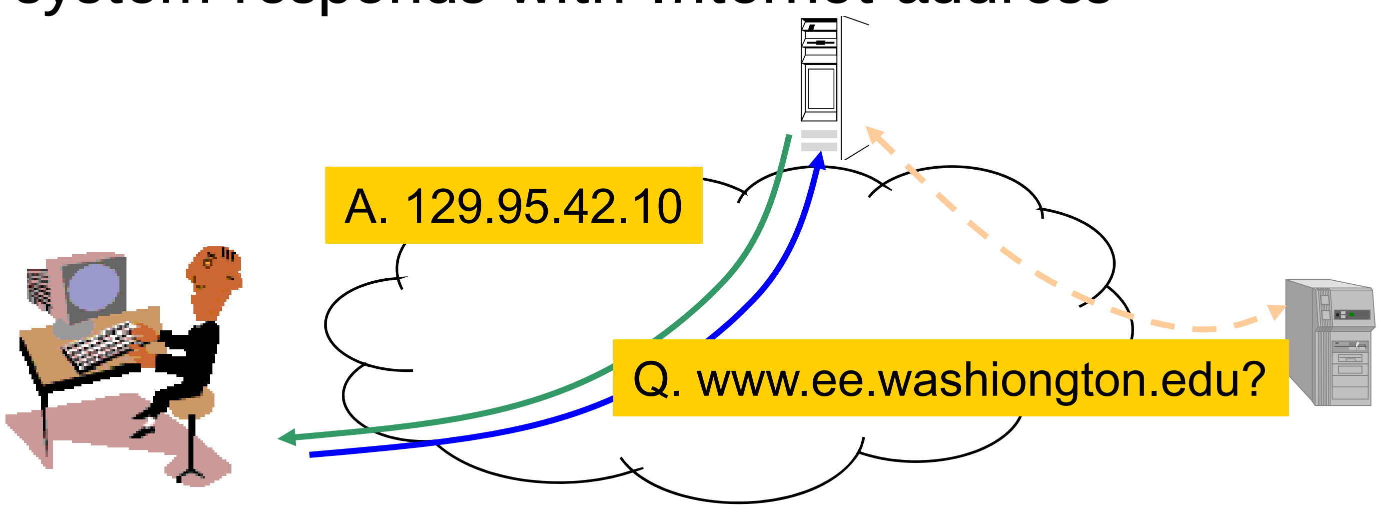
- Communications between different communication entities requires very specific unambiguous rules
- A protocol is a set of rules that governs how two or more communicating parties are to interact
- Examples
  - Internet Protocol (IP)
  - Transmission Control Protocol (TCP)
  - HyperText Transfer Protocol (HTTP)
  - Simple Mail Transfer Protocol (SMTP)

An Example on Interactions between Layers: Web Browsing

- World Wide Web allows users to access resources (i.e. documents) located in computers connected to the Internet
- Documents are prepared using HyperText Markup Language (HTML)
- A browser application program is used to access the web
- The browser displays HTML documents that include *links* to other documents
- Each link references a *Uniform Resource Locator* (URL) that gives the name of the machine and the location of the given document

Step 1: Get the IP Address of the Link

- User clicks on http://www.ee.washington.edu/
- URL contains Internet name of machine (www.ee.washiongton.edu), but not Internet address
- Internet needs Internet address to send information to a machine
- Browser software uses Domain Name System (DNS) protocol to send query for Internet address
- DNS system responds with Internet address



DNS Protocol

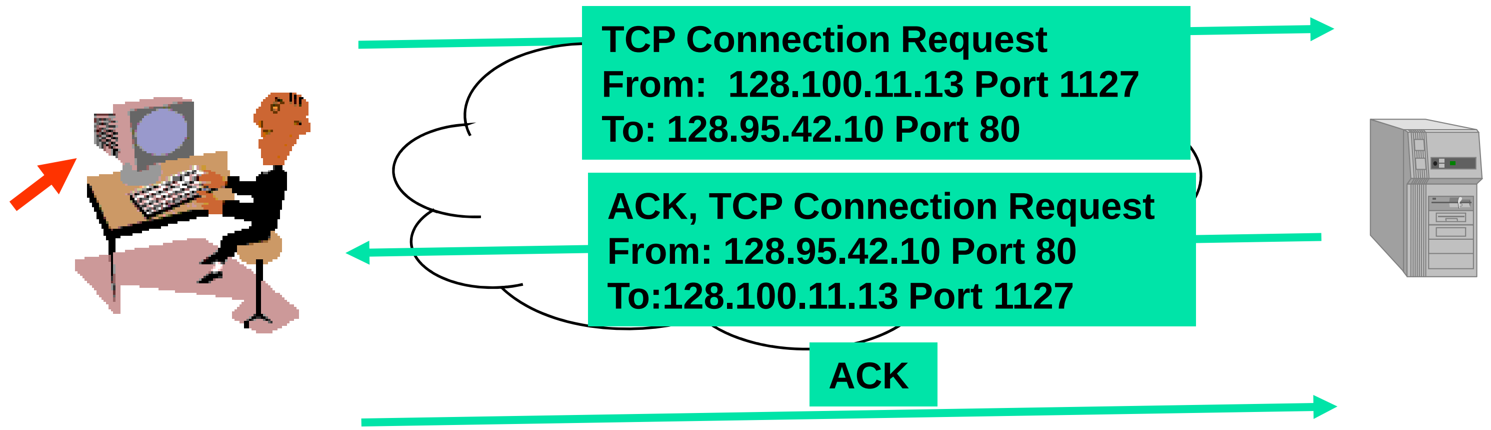
- DNS protocol is an application layer protocol
- DNS is a distributed database that resides in multiple machines in the Internet
- DNS protocol allows queries of different types
  - Name-to-address or Address-to-name
  - Mail exchange
- DNS usually involves short messages and so uses service provided by UDP
- Well-known port 53

UDP Protocol

- UDP is a transport layer protocol
- Provides *best-effort datagram service* between two processes in two computers across the Internet
- Port numbers distinguish various processes in the same machine
- UDP is *connectionless*
- Datagram is sent immediately
- Quick, simple, but not reliable

Step 2: Access the Link, but setup the link first

- Browser software uses HyperText Transfer Protocol (HTTP) to send request for document
- HTTP server waits for requests by listening to a well-known port number (80 for HTTP)
- HTTP client sends request messages through an “ephemeral port number,” e.g. 1127
- HTTP needs a Transmission Control Protocol (TCP) connection between the HTTP client and the HTTP server to transfer messages reliably



TCP Protocol

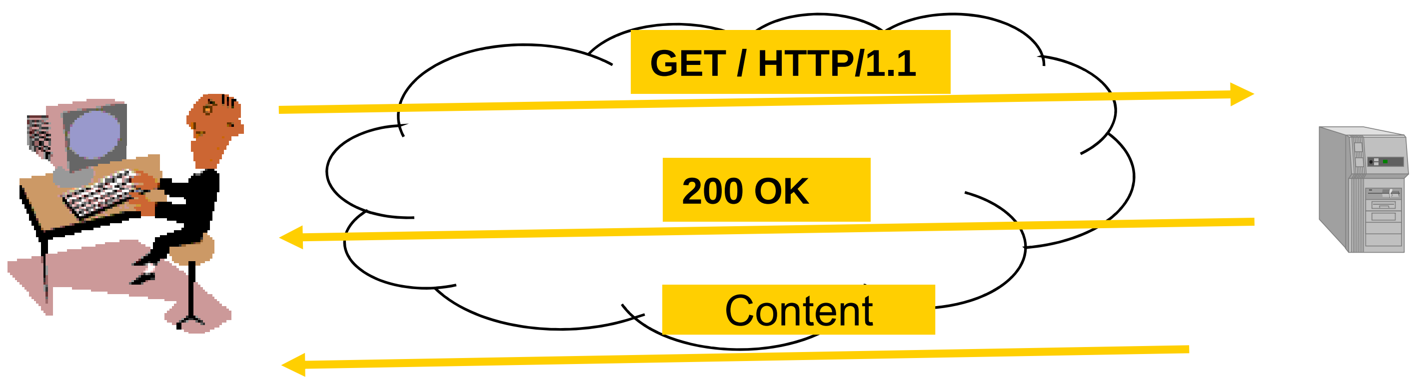
- TCP is a transport layer protocol
- Provides *reliable byte stream service* between two processes in two computers across the Internet
- Sequence numbers keep track of the bytes that have been transmitted and received
- Error detection and retransmission used to recover from transmission errors and losses
- TCP is *connection-oriented*: the sender and receiver must first establish an association and set initial sequence numbers before data is transferred
- Connection ID is specified uniquely by

(send port #, send IP address, receive port #, receiver IP address)

HTTP for Accessing the Web

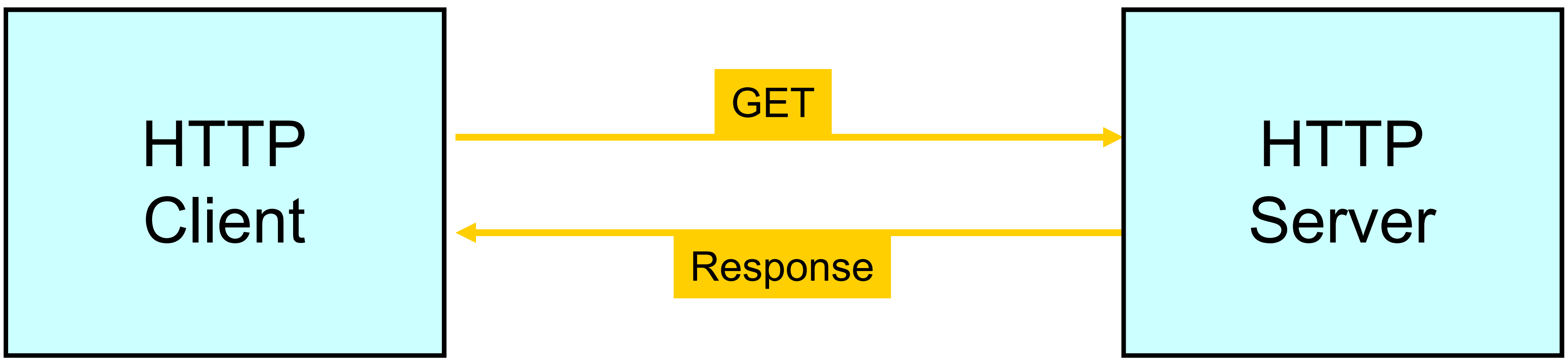
- HTTP client sends its request message: “GET ...”
- HTTP server sends a standard status response: “200 OK”
- HTTP server sends requested file
- Browser displays document

- *Clicking a link sets off a chain of events across the Internet!*

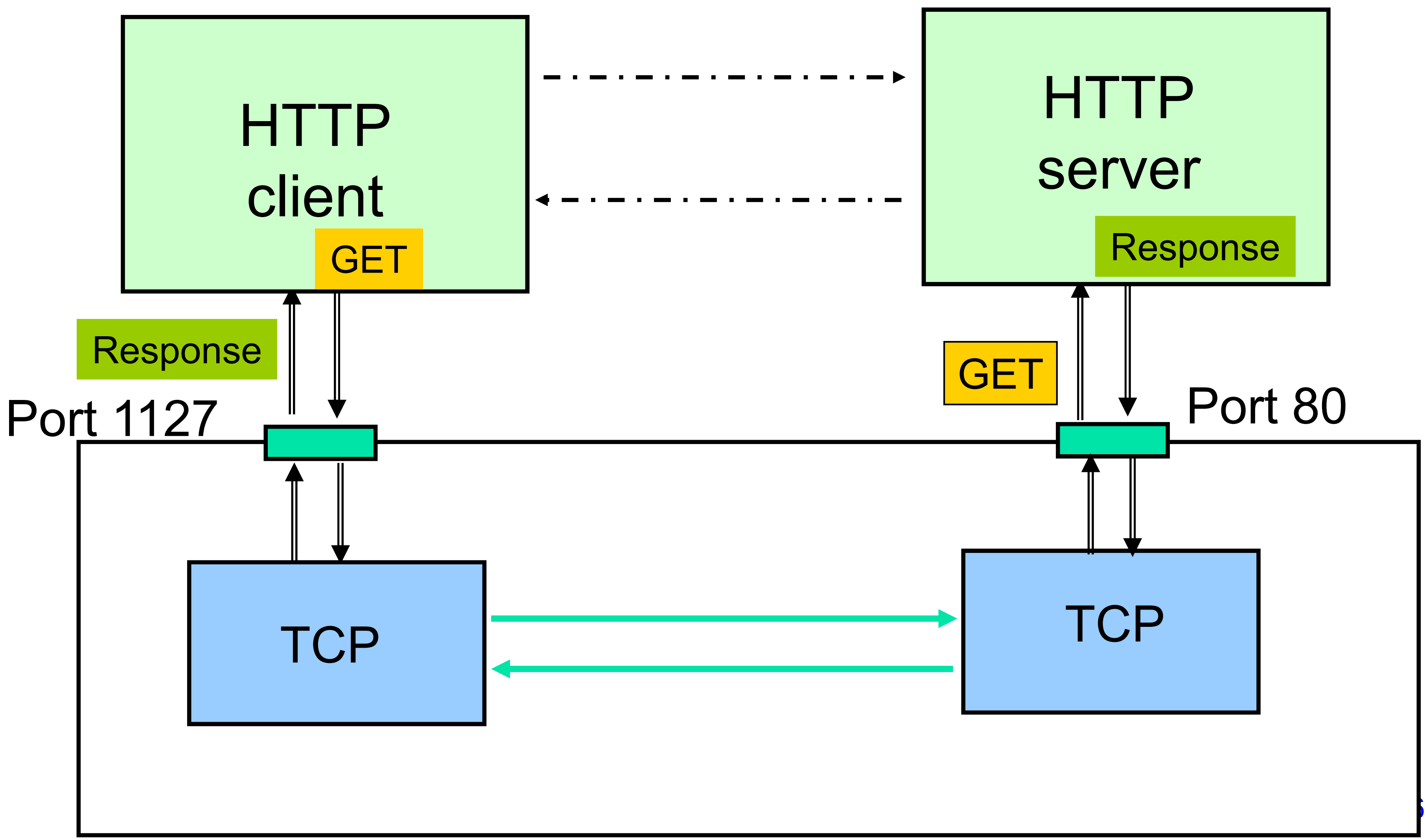


More Details on HTTP

- HTTP assumes messages can be exchanged directly between HTTP client and HTTP server
- In fact, HTTP client and server are processes running in two different machines across the Internet
- HTTP uses the reliable stream transfer service provided by TCP



HTTP/TCP Interactions



Well-Known Protocol Reference Models

- OSI 7-Layer Model
- LAN Model
- Internet Model
- Hybrid Model
- ATM Model
- Other Models

- Question:
  - 1. Why do we need a protocol model?
  - 2. Why are there so many different models?

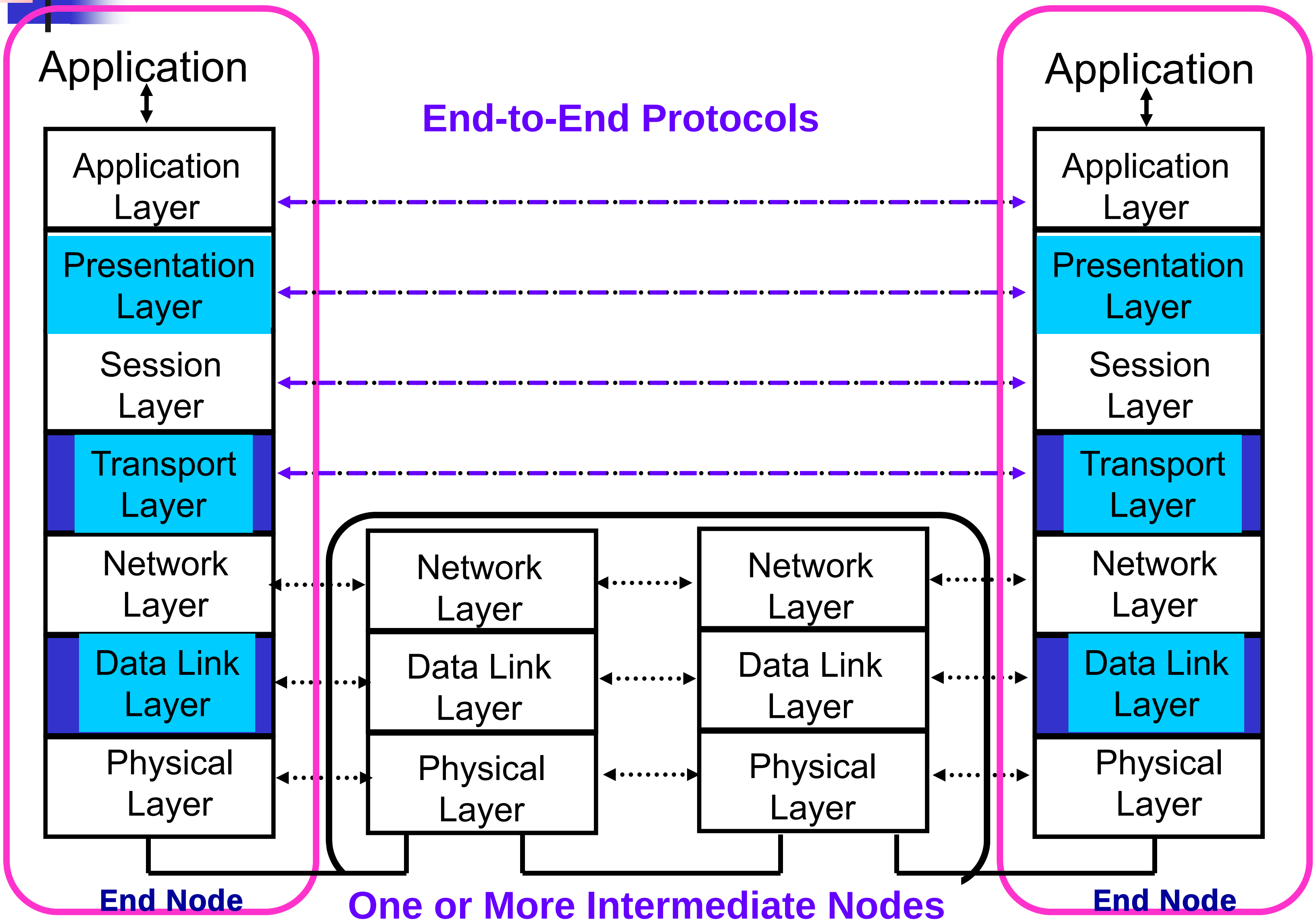
Open System Interconnection (OSI)

- By the 1970s every computer vendor had developed its own proprietary layered network architecture
- Problem: computers from different vendors could not be networked together
- Network architecture:
  - Definition of all the layers
  - Design of protocols for every layer
- Open Systems Interconnection (OSI) was an international effort by the International Organization for Standardization (ISO) to enable multivendor computer interconnection

OSI Protocol Model

- Describes a seven-layer abstract reference model for a network architecture
- Purpose of the reference model was to provide a framework for the development of protocols
- OSI also provided a unified view of layers, protocols, and services, which is still in use in the development of new protocols
- Detailed standards were developed for each layer, but most of these are not in use
- TCP/IP protocols preempted deployment of OSI protocols

The Architecture of the OSI Model



OSI Layers: Physical

- Transfers bits across link
- Definition & specification of the physical aspects of a communications link
  - Mechanical: cable, plugs, pins...
  - Electrical/optical: modulation, signal strength, voltage levels, bit times, ...
  - Functional/procedural: how to activate, maintain, and deactivate physical links...
- Examples: Ethernet, DSL, cable modem, telephone modems...
- Media: Twisted-pair cable, coaxial cable optical fiber, radio, infrared,

OSI Layers: Data Link

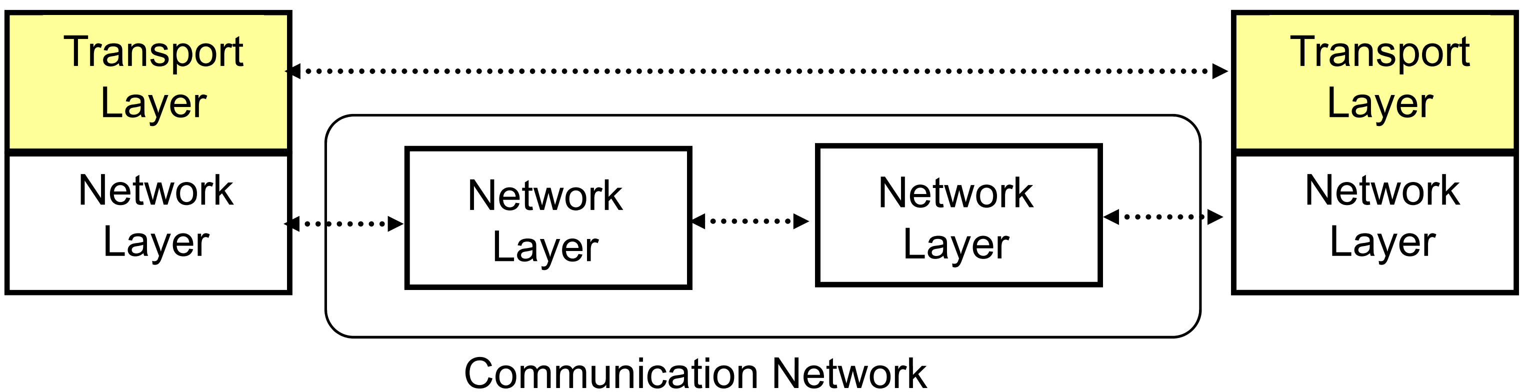
- Groups bits into frames
- Transfers *frames* across *direct* connections
- Detection of bit errors; Retransmission of frames
- Activation, maintenance, & deactivation of data link connections
- Medium access control for local area networks
- Flow control
- Buffer management

OSI Layers: Network

- Transfers *packets* across multiple links and/or multiple networks
- *Addressing* must scale to large networks
- Nodes *jointly* execute *routing* algorithm to determine paths across the network
- *Forwarding* transfers packet across a node
- *Congestion control* to deal with traffic surges
- Connection setup, maintenance, and teardown when connection-based (Optional)

OSI Layers: Transport

- Transfers data end-to-end from process in a machine to process in another machine
- Reliable stream transfer or quick-and-simple single-block transfer
- Port numbers enable multiplexing
- Message segmentation and reassembly
- Connection setup, maintenance, and release or simply connectionless

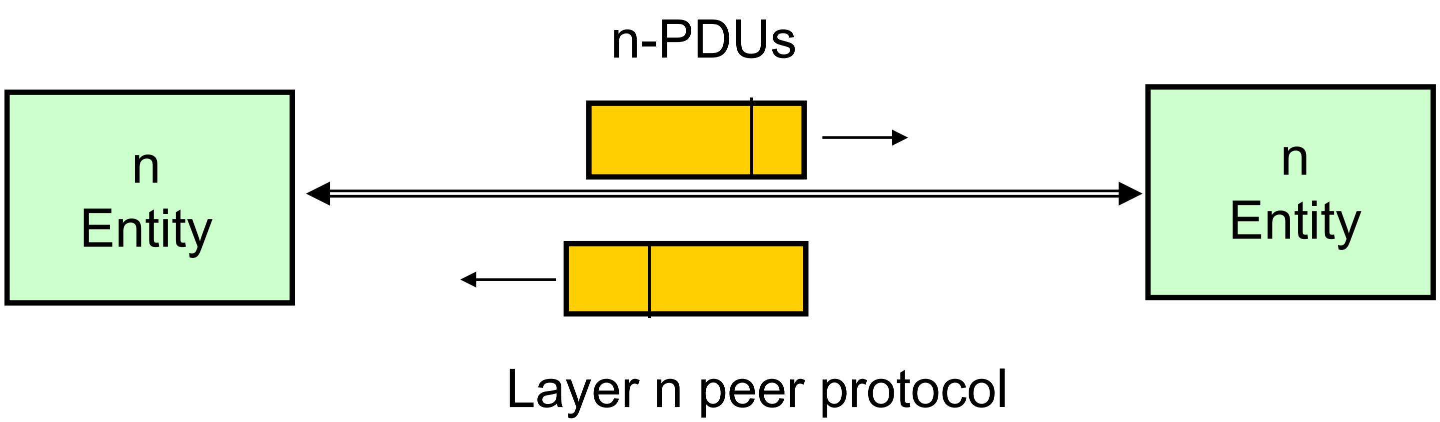


OSI Layers: Session, Presentation, Application

- Presentation Layer: machine-independent representation of data...
- Session Layer: dialog management, recovery from errors, ...
- Application Layer: Provides services that are frequently required by applications: DNS, web acess, file transfer, email...

OSI Unified View on Protocols

- Layer n in one machine interacts with layer n in another machine to provide a service to layer n +1
- The entities comprising the corresponding layers on different machines are called *peer processes.*
- The machines use a set of rules and conventions called the *layer-n protocol*.
- Layer-n peer processes communicate by exchanging *Protocol Data Units* (PDUs)

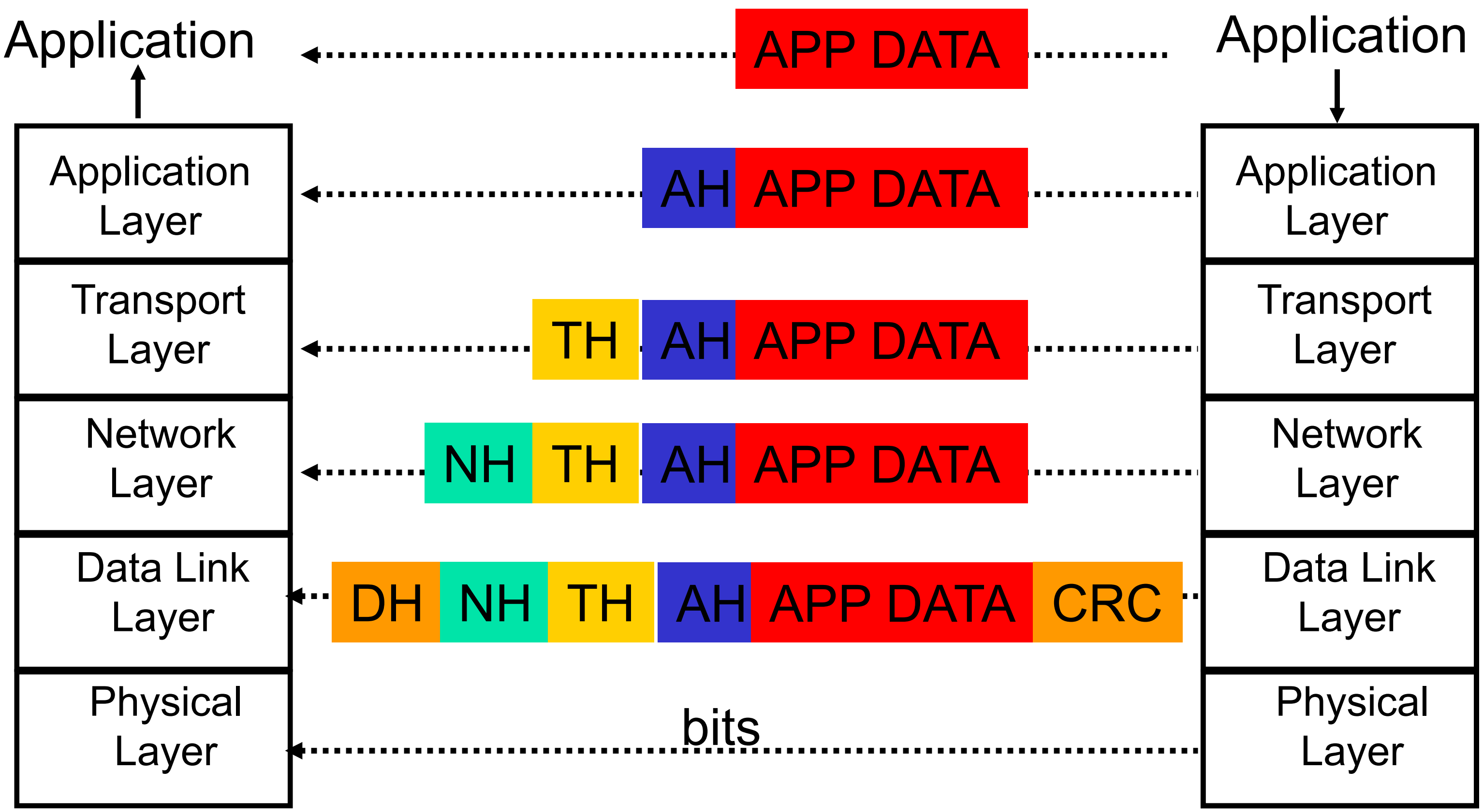


OSI Unified View on Services

- Communication between peer processes is virtual and actually indirect
- Layer n+1 transfers information by invoking the services provided by layer n
- Services are available at *Service Access Points* (SAP's)
- Each layer passes data & control information to the layer below it until the physical layer is reached and transfer occurs
- The data passed to the layer below is called a *Service Data Unit* (SDU)
- SDU's are *encapsulated* in PDU's

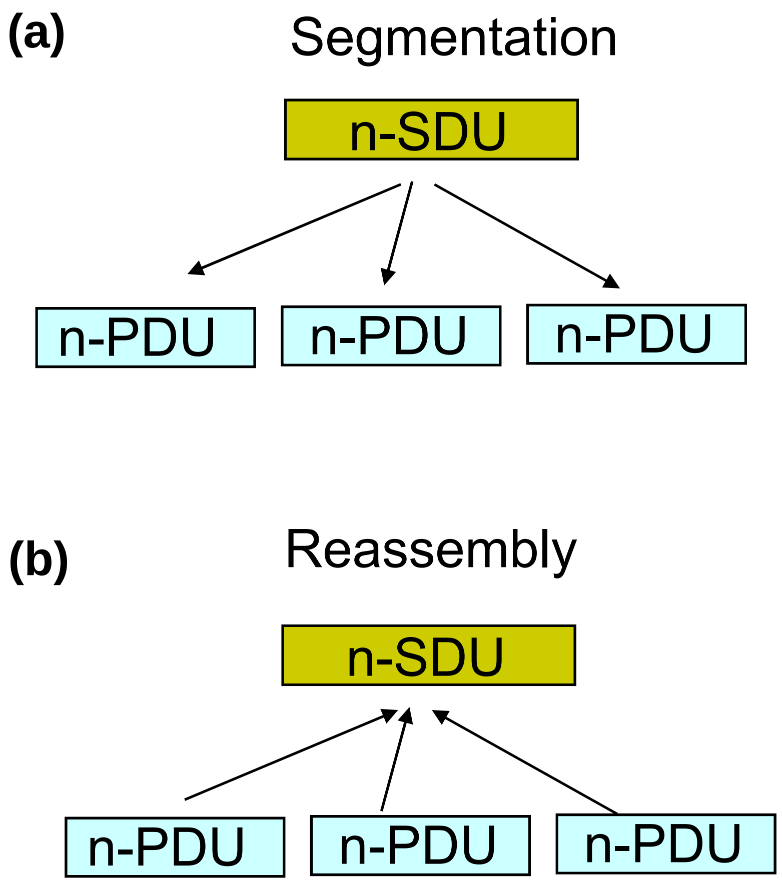
Headers & Trailers

- Each protocol uses a header that carries addresses, sequence numbers, flag bits, length indicators, etc...
- Error detection bits , e.g., CRC check bits, may be appended for error detection



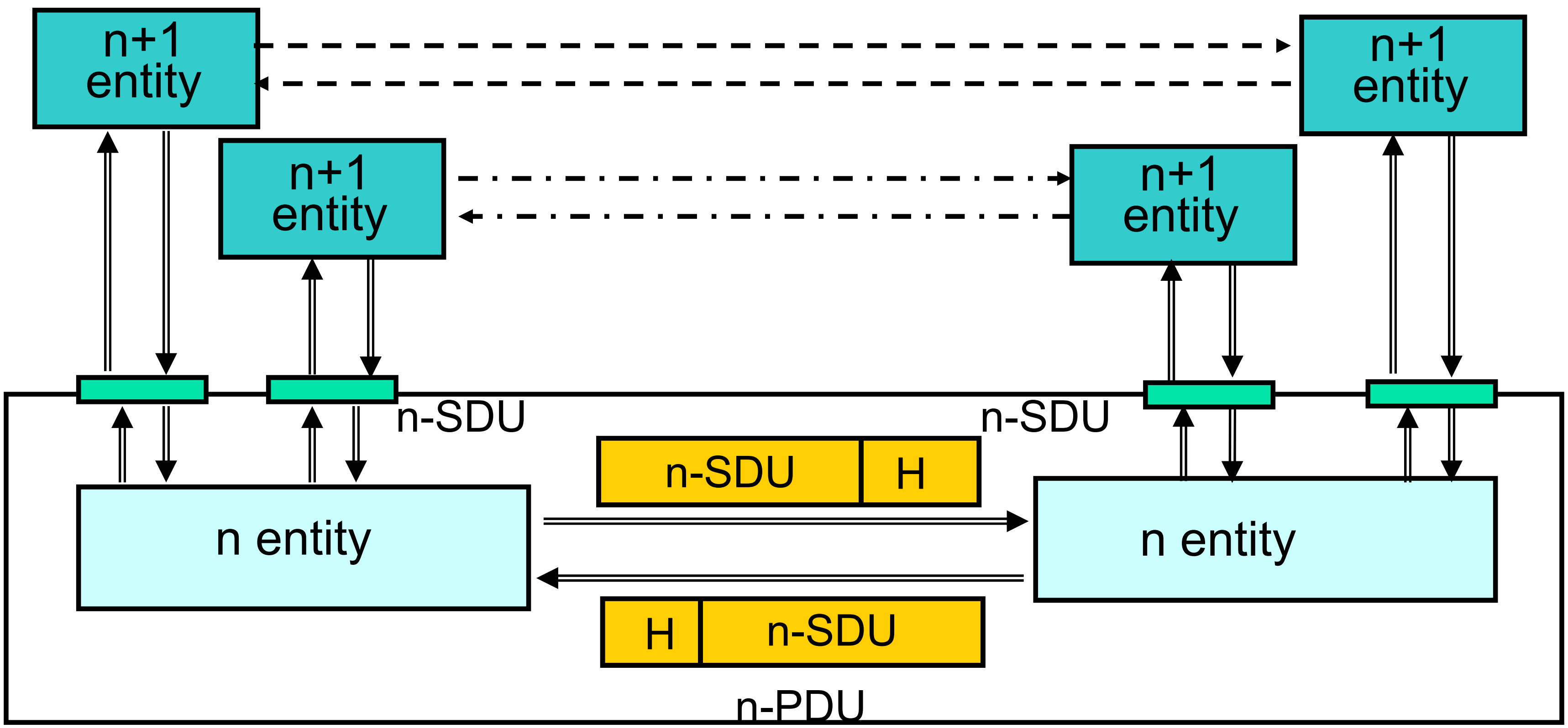
Segmentation & Reassembly

- A layer may impose a limit on the size of a data block that it can transfer for implementation or other reasons
- Thus a layer-n SDU may be too large to be handled as a single unit by layer-(n-1)
- Sender side: SDU is segmented into multiple PDUs
- Receiver side: SDU is reassembled from sequence of PDUs



Multiplexing

- Sharing of layer n service by *multiple* layer n+1 users
- Multiplexing tag or ID required in each PDU to determine which users an SDU belongs to

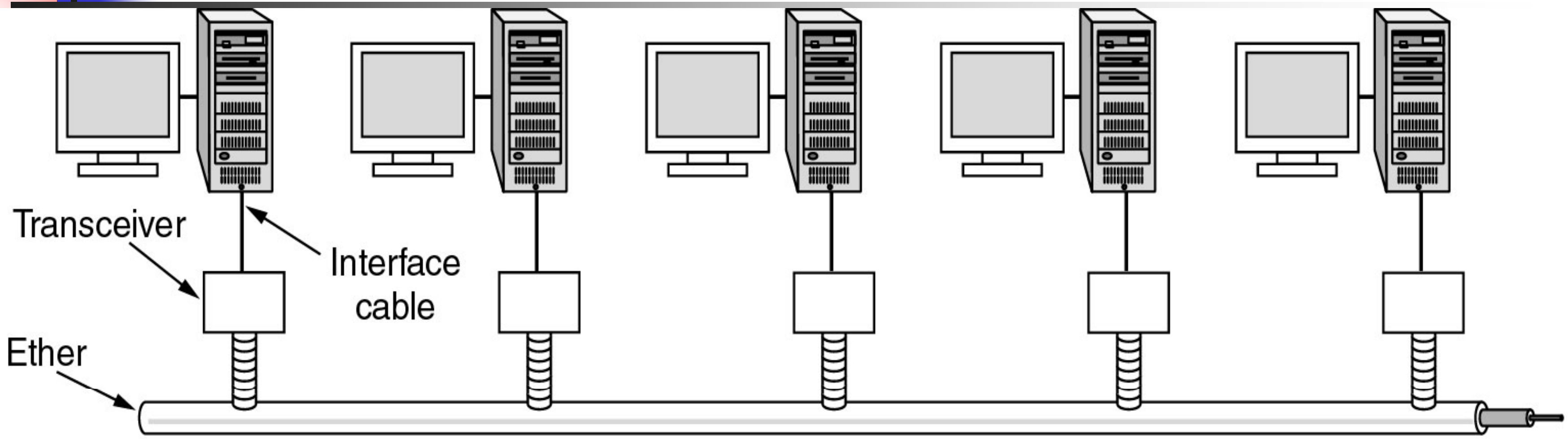


A Critique of the OSI Model and Protocols

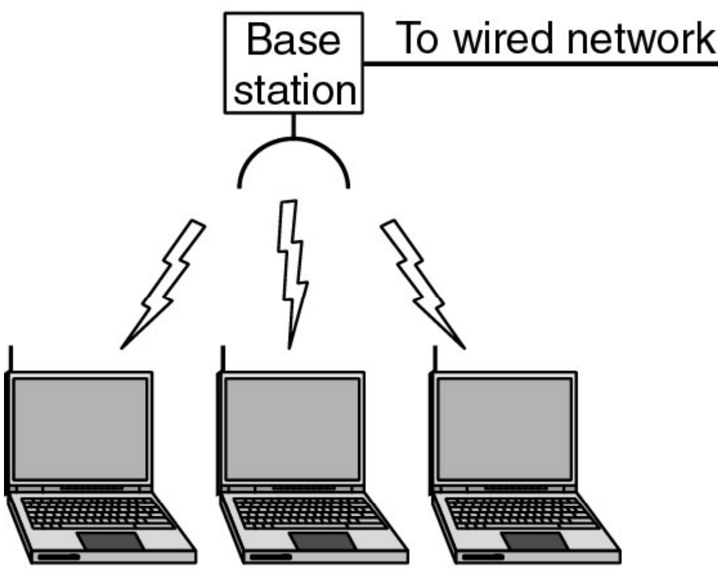
- Why OSI did not take over the world
  - Bad timing
  - Bad politics

  - Bad technology ?
  - Bad implementations ?

Local Area Networks

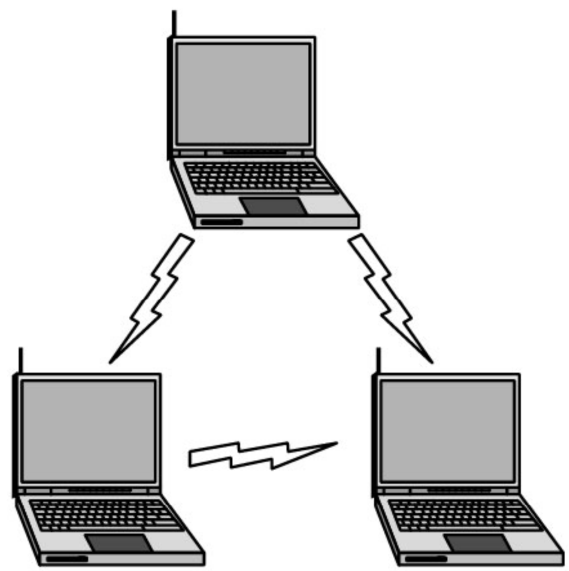


Wired LANs, e.g., Ethernet



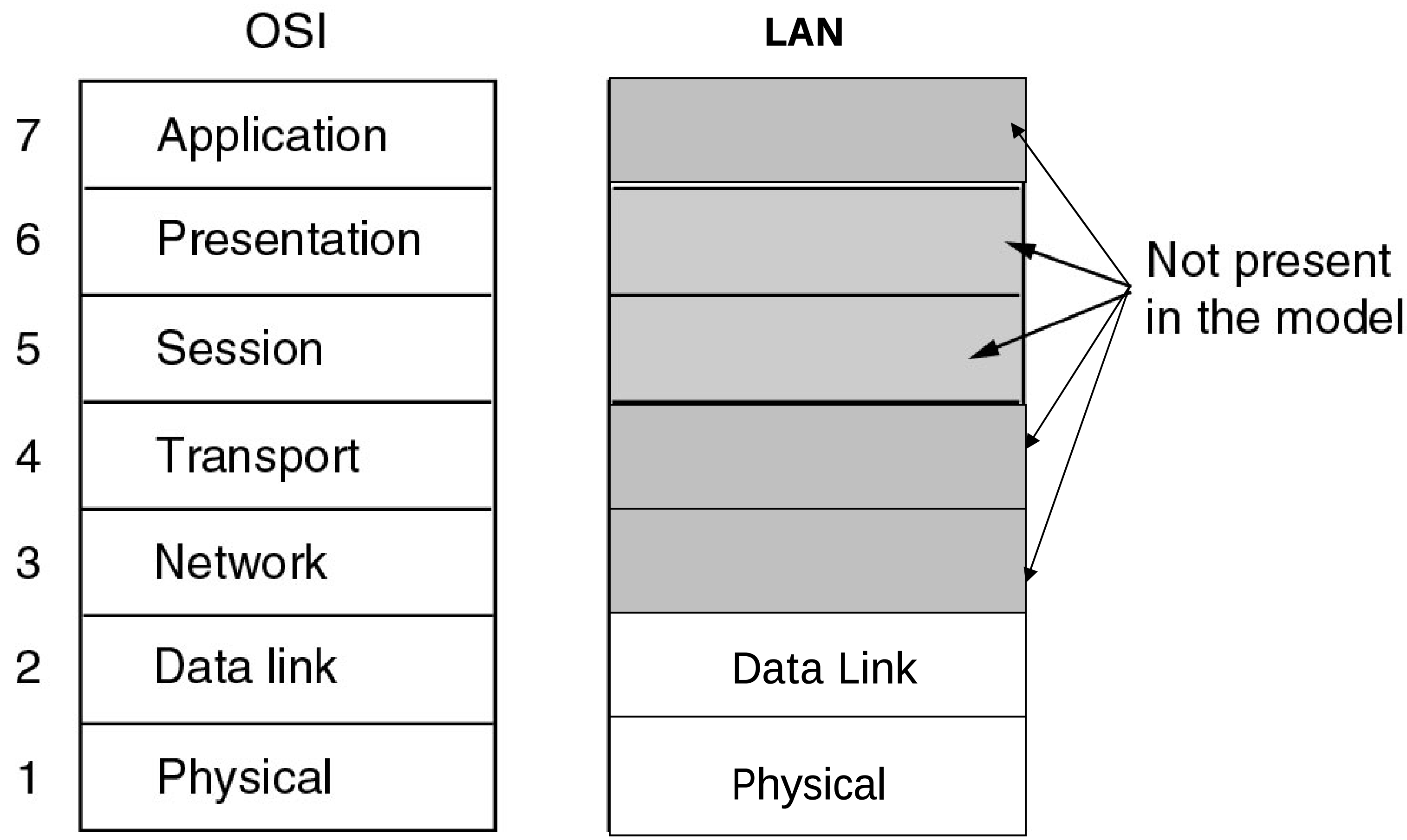
(a)

Wireless LANs



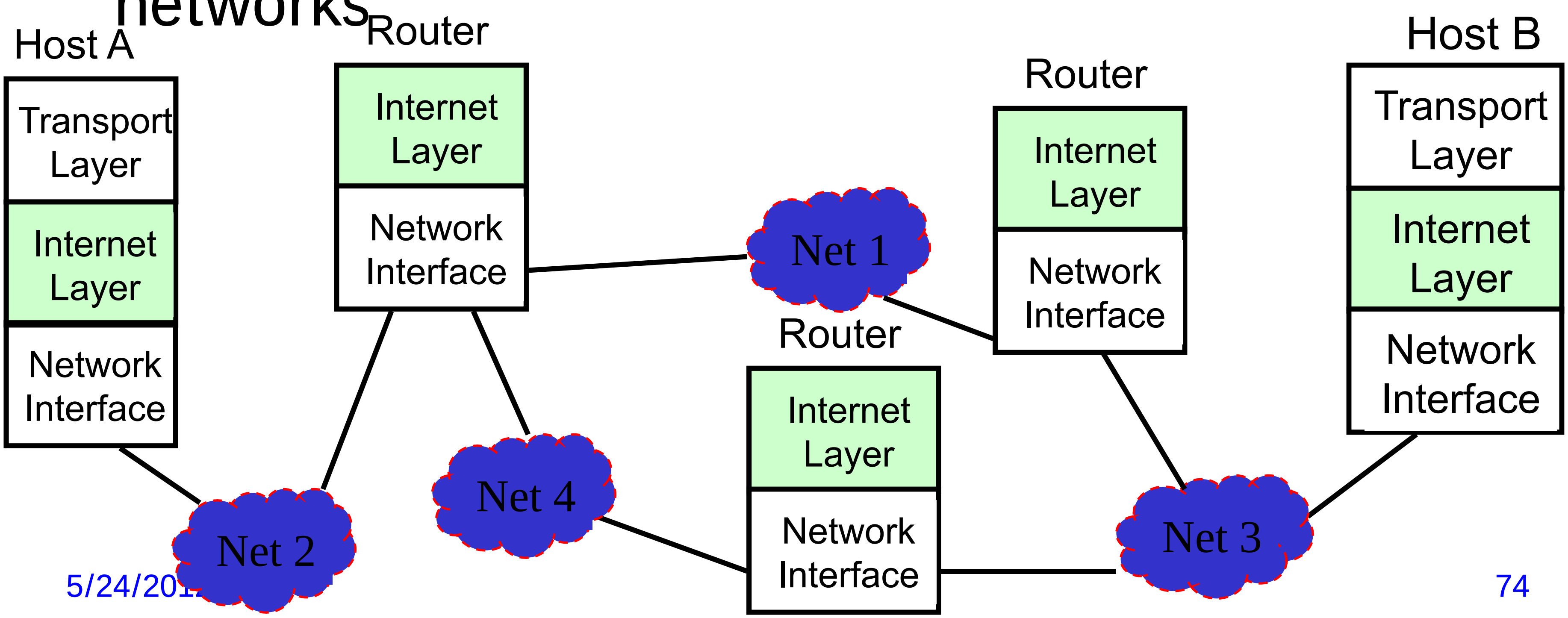
(b)

LAN Protocol Reference Model

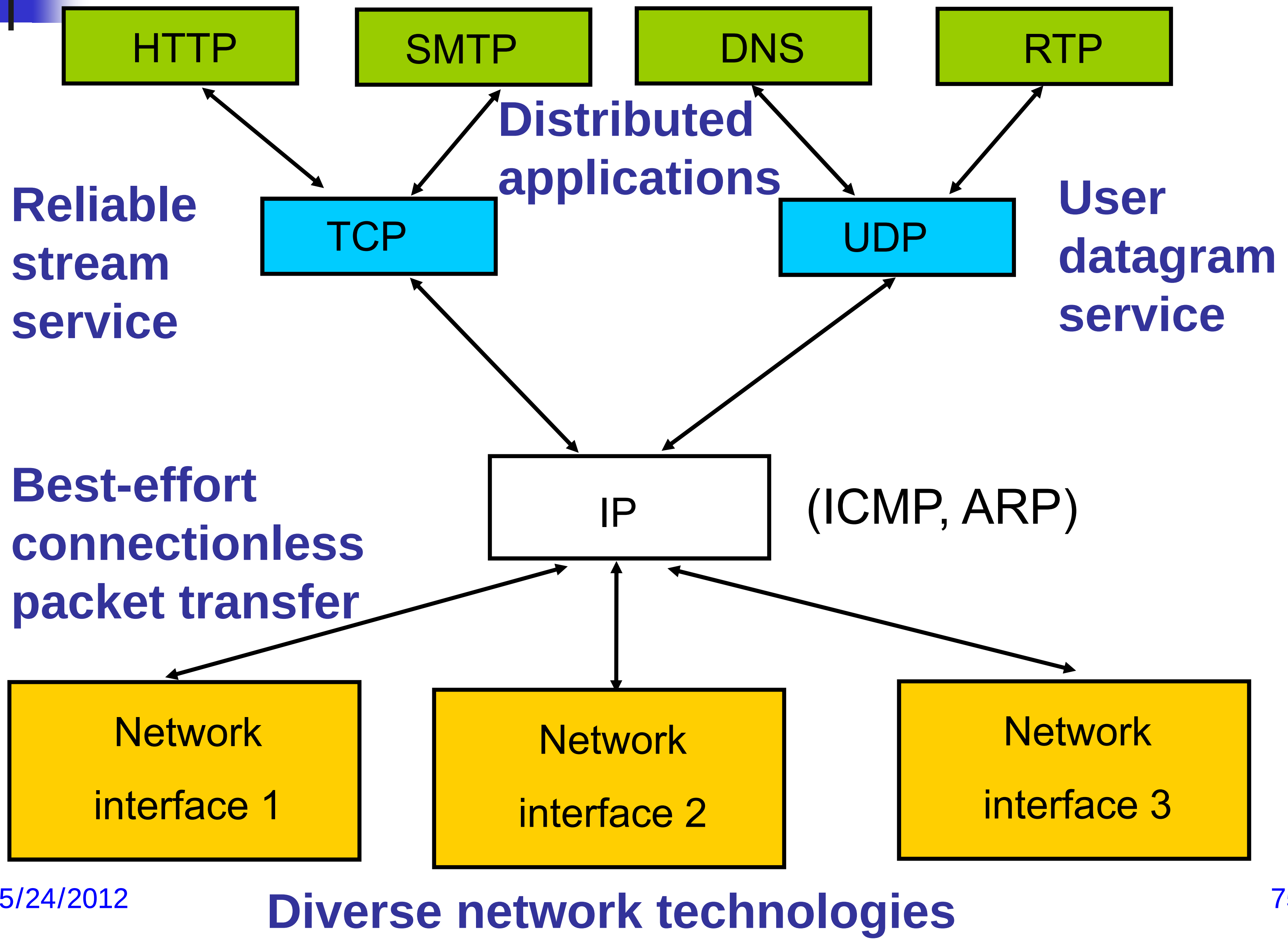


Internet Protocol Approach

- IP packets transfer information across Internet
  - *Host A IP → router→ router...→ router→ Host B IP*
- IP layer in each router determines next hop (router)
- Network interfaces transfer IP packets across networks



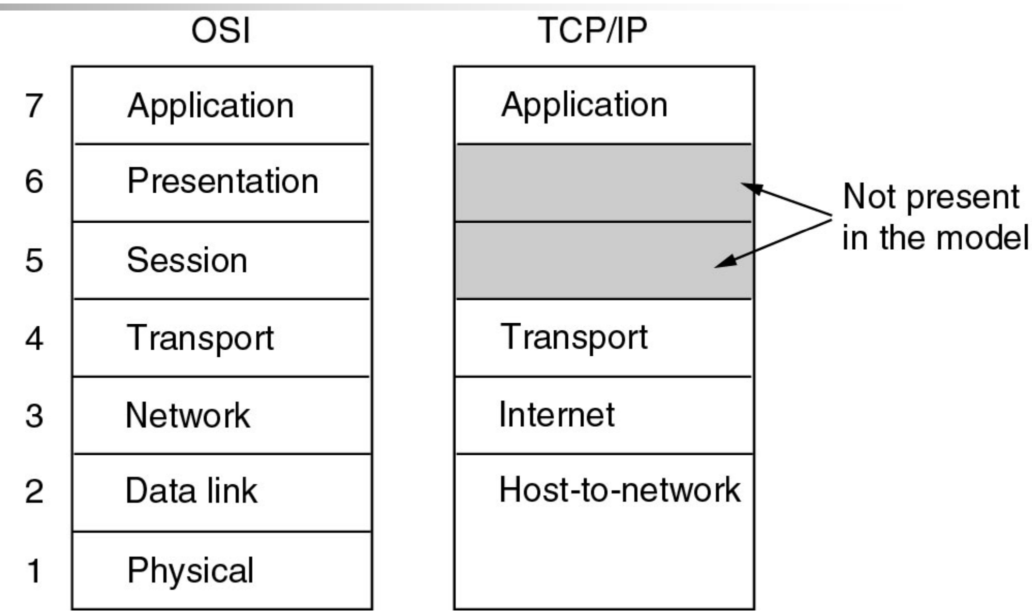
Internet Protocol Suite

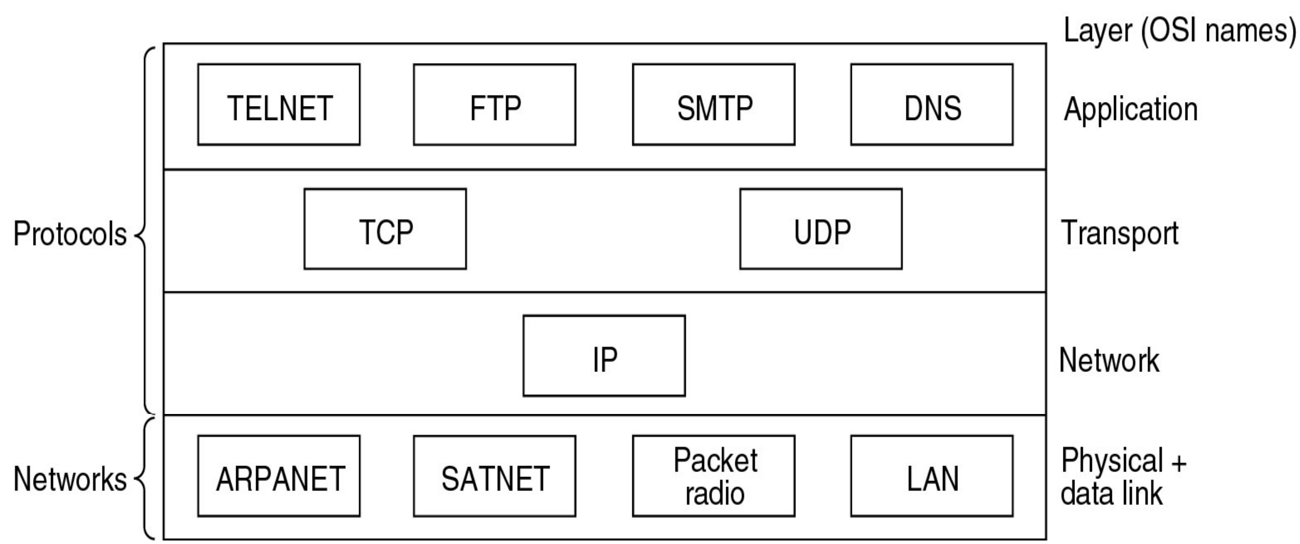


Internet Reference Model

Problems:

- **Not a general model**
- **Host-to-network "layer" not really a layer**
- **No mention of physical and data link layers**
- **Minor protocols deeply entrenched, hard to replace**



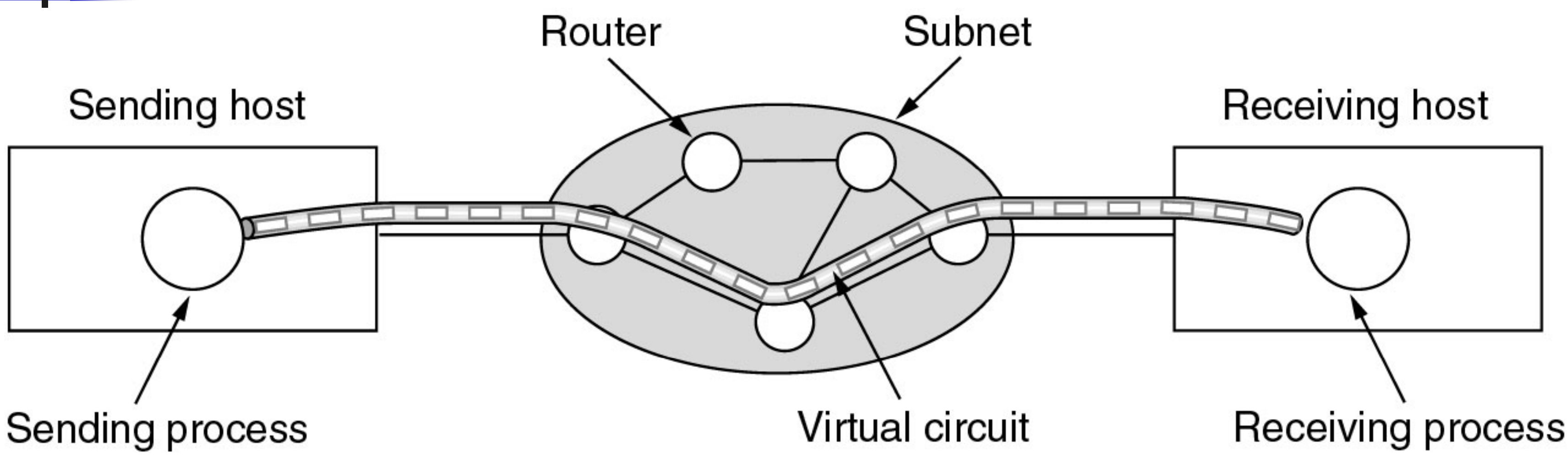


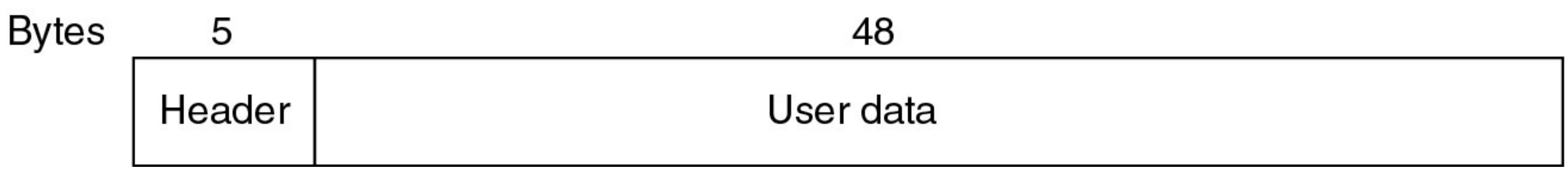
Hybrid Protocol Model

- A widely accepted model
- Reference for integrating all different networks

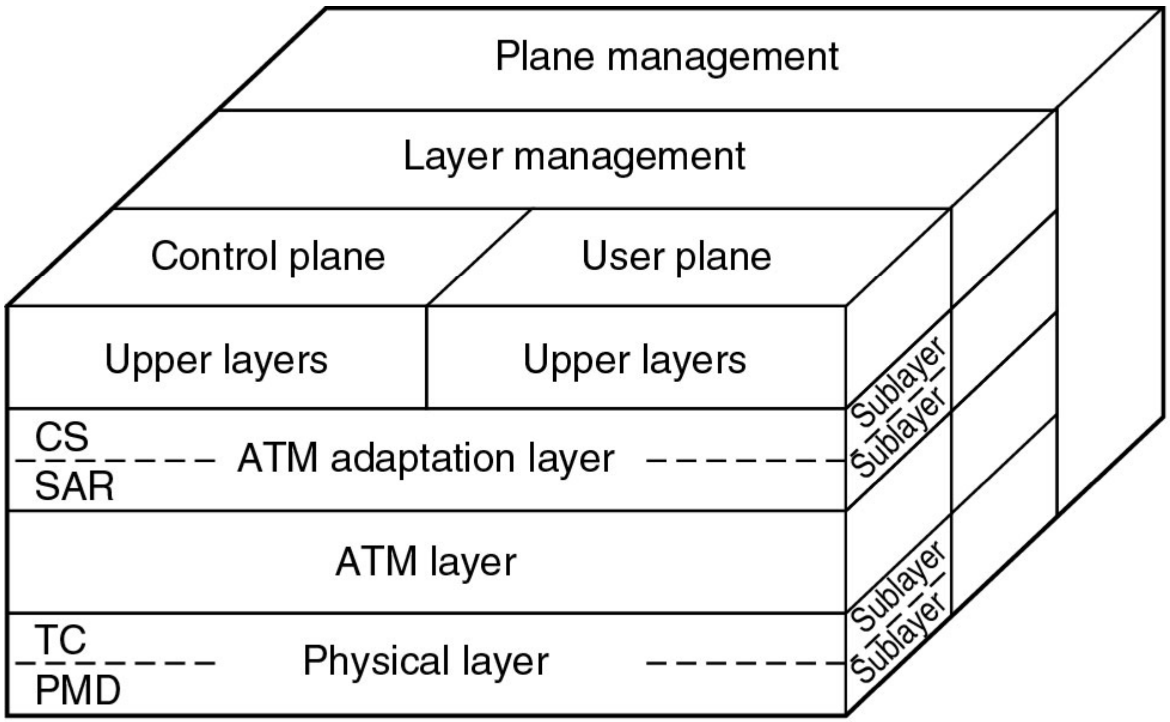
5	Application layer
4	Transport layer
3	Network layer
2	Data link layer
1	Physical layer

ATM Virtual Circuit





ATM Protocol Model



CS: Convergence sublayer
SAR: Segmentation and reassembly sublayer
TC: Transmission convergence sublayer
PMD: Physical medium dependent sublayer

ATM versus OSI

OSI layer	ATM layer	ATM sublayer	Functionality
3/4	AAL	CS	Providing the standard interface (convergence)
		SAR	Segmentation and reassembly
2/3	ATM		Flow control Cell header generation/extraction Virtual circuit/path management Cell multiplexing/demultiplexing
2	Physical	TC	Cell rate decoupling Header checksum generation and verification Cell generation Packing/unpacking cells from the enclosing envelope Frame generation
1		PMD	Bit timing Physical network access

Discussions on Layering

Standards

- Standards Committees or Groups
  - ISO
  - ITU
  - IEC
  - IEEE
  - IETF
  - ANSI
  - 3GPP, 3GPP2
  - ATM Forum
  - Many more ...

IEEE 802 Standards

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
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)
802.16 *	Broadband wireless
802.17	Resilient packet ring

Frequently Used Terms

- Network Topology
  - Point-to-point, point-to-multipoint (PMP), multipoint-to-multipoint (mesh), ad hoc
- Transmission Types
  - Unicast, multicast, broadcast
- Connectionless versus Connection Oriented
- Best Effort versus Guaranteed
- Message, Circuit, and Packet Switching
  - Virtual circuit (ATM)

Related Technologies

- Transmission Media
  - Wired, optical, wireless
- Digital Communications
  - Propagation (wired or wireless), communication theory, coding theory (channel coding and source coding, information theory
- Communication Protocols
  - Data link (MAC, ARQ, etc.)
  - Routing
  - Transport
  - Application
- Circuit Design
- Computer Systems