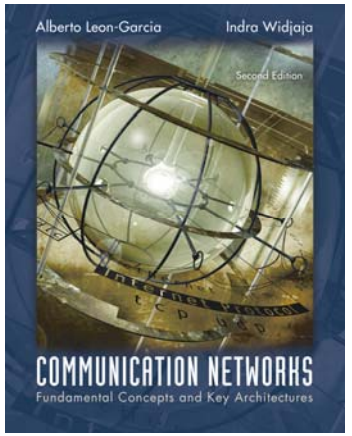
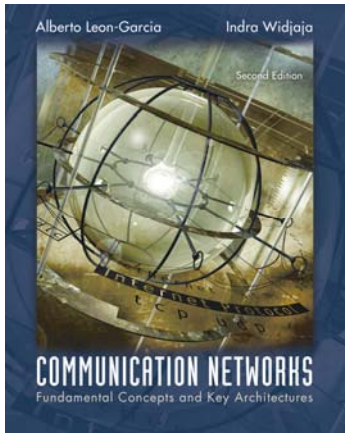
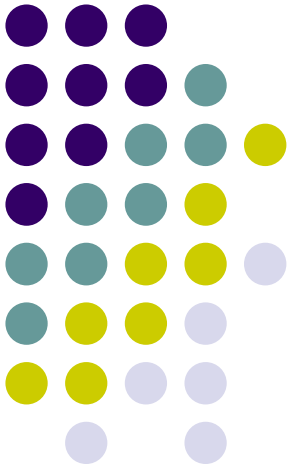
Chapter 1
Communication Networks and Services



Network Architecture and Services
Telegraph Networks & Message Switching
Telephone Networks and Circuit Switching
Computer Networks & Packet Switching
Future Network Architectures and Services
Key Factors in Network Evolution

Chapter 1
Communication Networks and Services



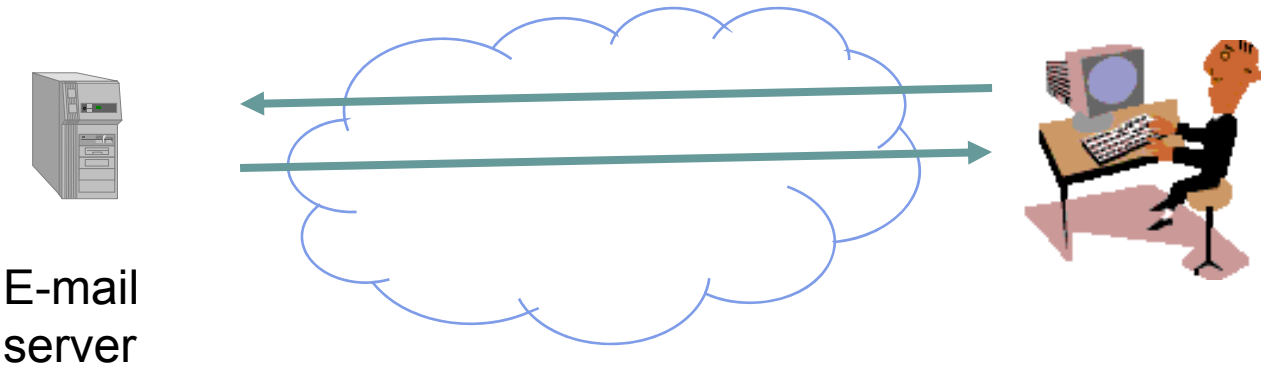


Network Architecture and Services

Communication Services & Applications

- A communication service enables the exchange of information between users at different locations.
- Communication services & applications are everywhere.

E-mail



Exchange of text messages via servers

Communication Services & Applications

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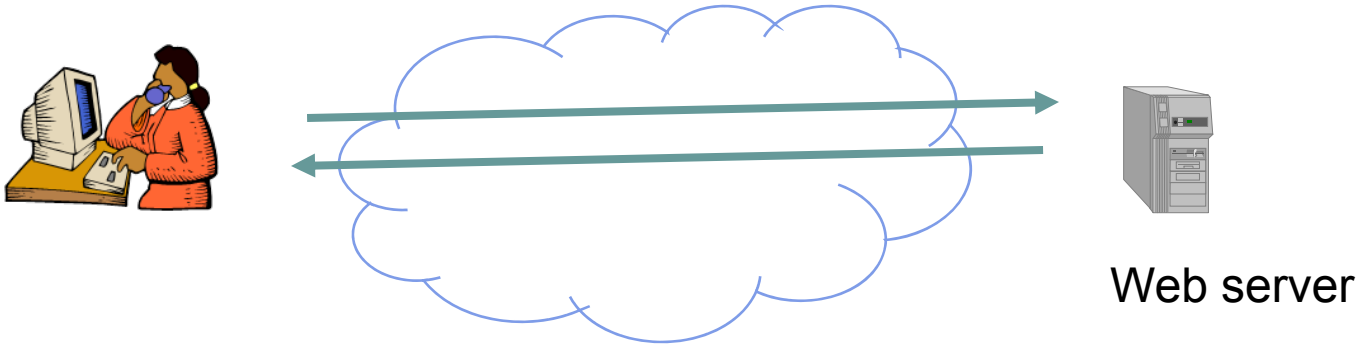
Web Browsing



Retrieval of information from web servers

Communication Services & Applications

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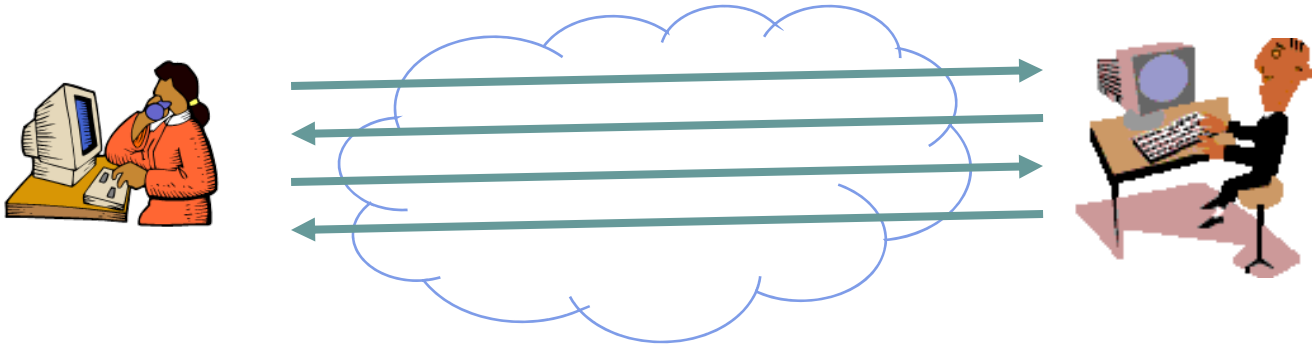
Instant Messaging



Direct exchange of text messages

Communication Services & Applications

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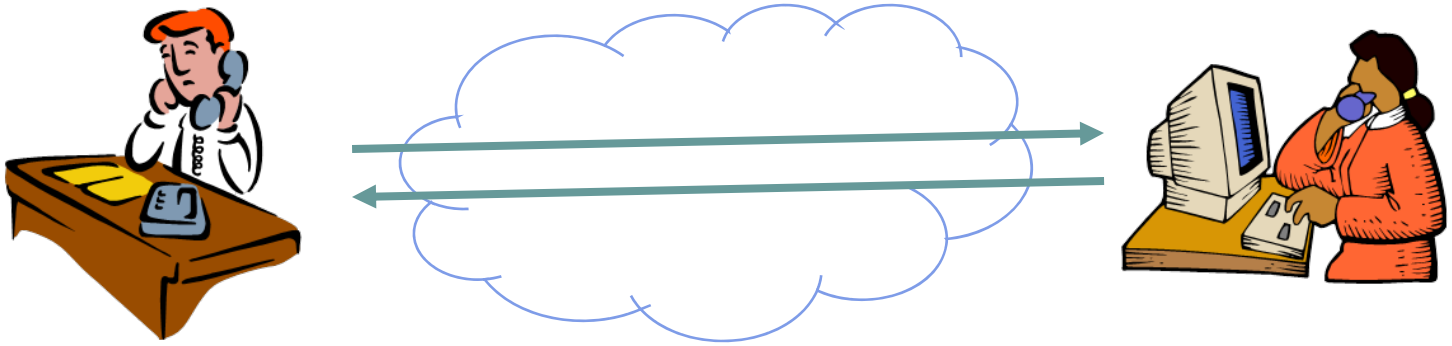
Telephone



Real-time bidirectional voice exchange

Communication Services & Applications

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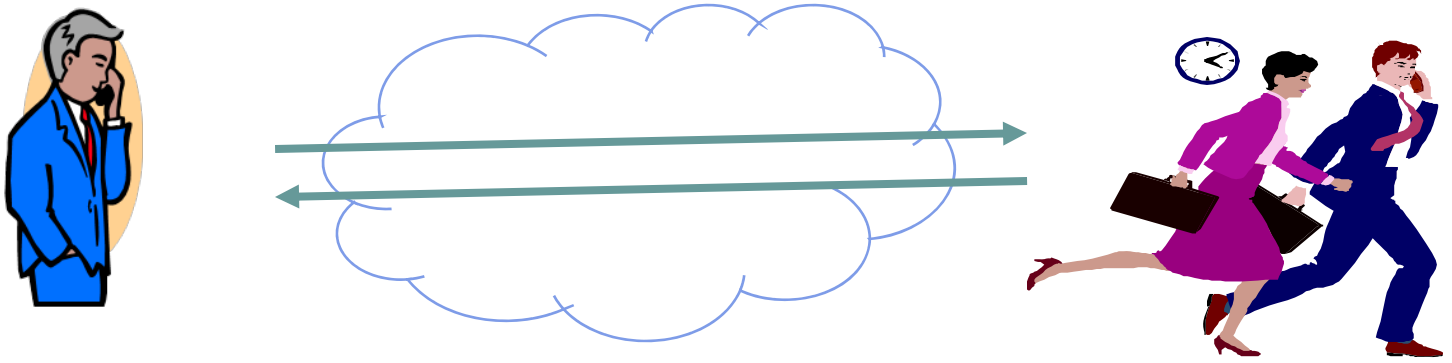
Cell phone



Real-time voice exchange with mobile users

Communication Services & Applications

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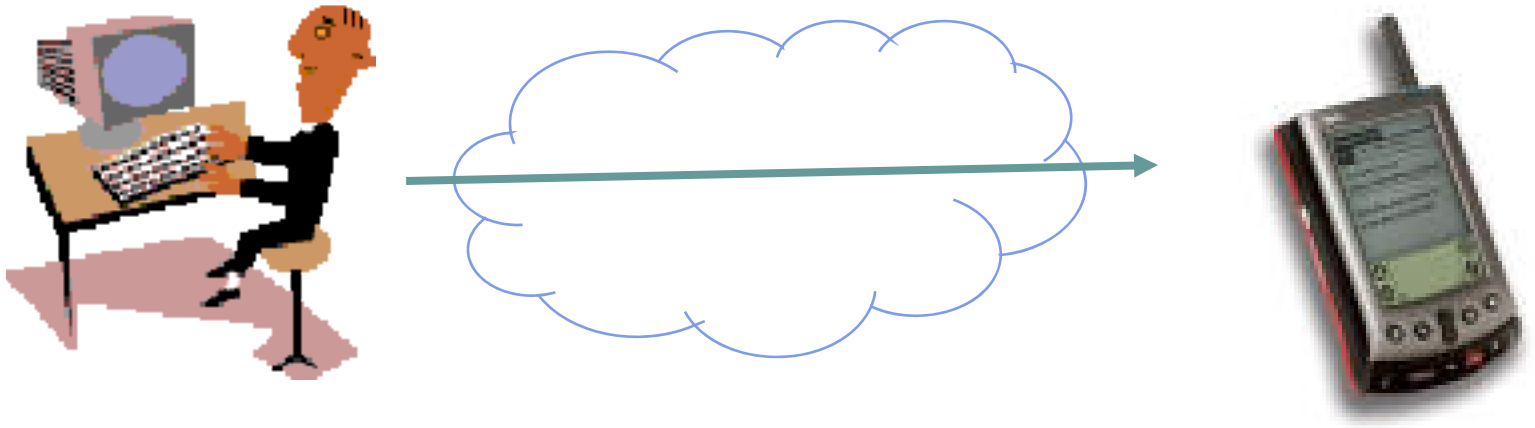
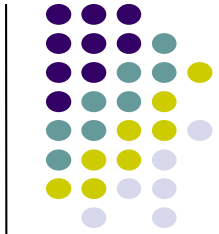
- Communication services & applications are everywhere.

Short Message Service



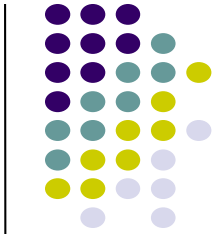
Fast delivery of short text messages

Many other examples!



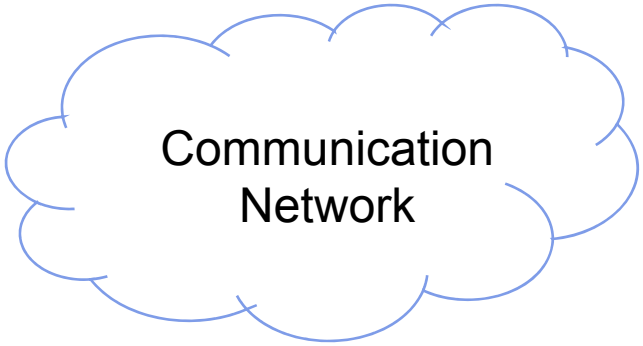
- Peer-to-peer applications
  - Napster, Gnutella, Kazaa file exchange
  - Searching for ExtraTerrestrial Intelligence (SETI)
- Audio & video streaming
- Network games
- On-line purchasing
- Text messaging in PDAs, cell phones (SMS)
- Voice-over-Internet

Services & Applications



- Service: Basic information transfer capability
  - Internet transfer of individual block of information
  - Internet reliable transfer of a stream of bytes
  - Real-time transfer of a voice signal
- Applications build on communication services
  - E-mail & web build on reliable stream service
  - Fax and modems build on basic telephone service
- New applications build on multiple networks
  - SMS builds on Internet reliable stream service and cellular telephone text messaging

What is a communication network?

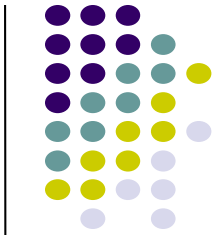


- The equipment (hardware & software) and facilities that provide the basic communication service
- Virtually invisible to the user; Usually represented by a cloud

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

How are communication networks designed and operated?

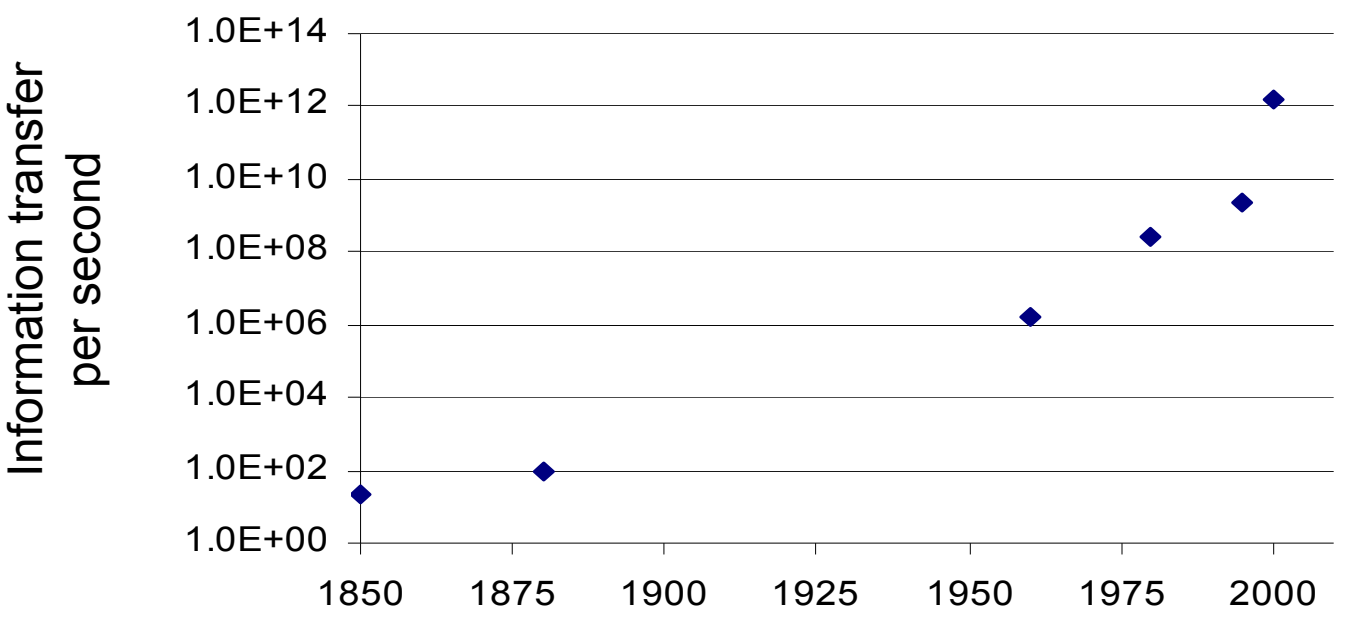
Communication Network Architecture



- *Network architecture:* the plan that specifies how the network is built and operated
- Architecture is driven by the network services
- Overall communication process is complex
- Network architecture partitions overall communication process into separate functional areas called *layers*

Next we will trace evolution of three network architectures: telegraph, telephone, and computer networks

Network Architecture Evolution



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Telegraph networks

Telephone networks

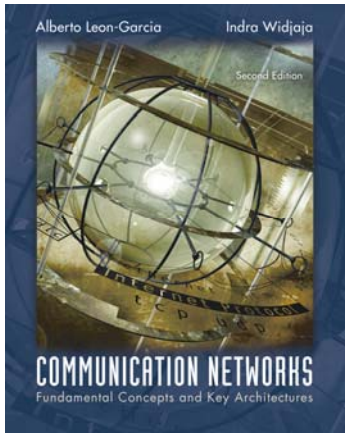
Internet, Optical & Wireless networks

Next Generation Internet

Network Architecture Evolution

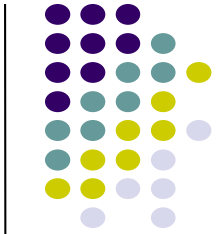
- Telegraph Networks
  - Message switching & digital transmission
- Telephone Networks
  - Circuit Switching
  - Analog transmission → digital transmission
  - Mobile communications
- Internet
  - Packet switching & computer applications
- Next-Generation Internet
  - Multiservice packet switching network

Chapter 1
Communication Networks and Services



Telegraph Networks & Message Switching

Telegraphs & Long-Distance Communications

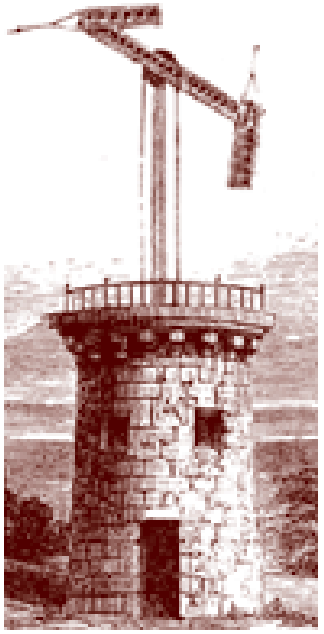


Approaches to long-distance communications

- Courier: physical transport of the message
  - Messenger pigeons, pony express, FedEx
- Telegraph: message is transmitted across a network using signals
  - Drums, beacons, mirrors, smoke, flags, semaphores…
  - Electricity, light
- Telegraph delivers message much sooner

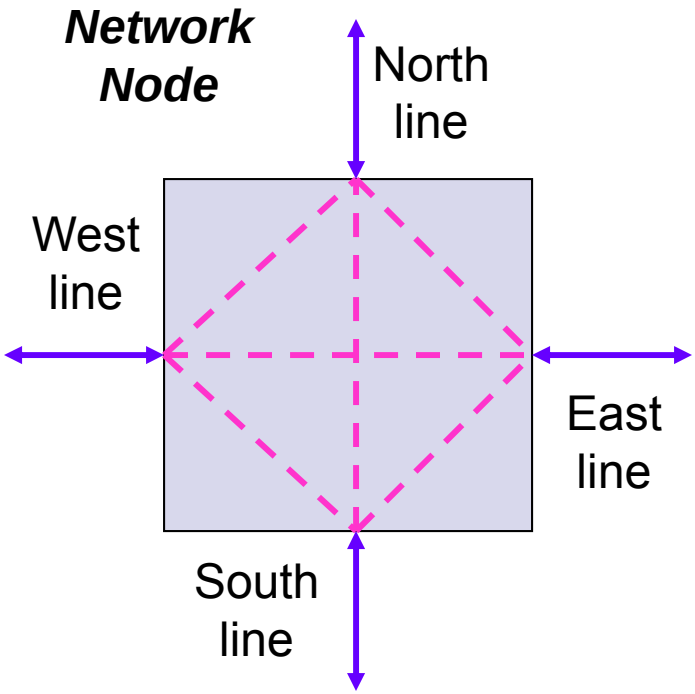
Optical (Visual) Telegraph

- 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!



Message Switching

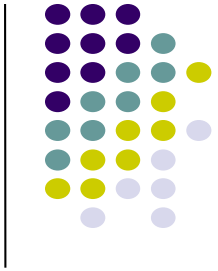
- Network nodes were created where several optical telegraph lines met (Paris and other sites)
- *Store-and-Forward* Operation:
  - Messages arriving on each line were decoded
  - Next-hop in ***route*** determined by destination ***address*** of a message
  - Each message was carried by hand to next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



Electric Telegraph

- William Sturgeon Electro-magnet (1825)
  - Electric current in a wire wrapped around a piece of iron generates a magnetic force
- Joseph Henry (1830)
  - Current over 1 mile of wire to ring a bell
- Samuel Morse (1835)
  - Pulses of current deflect electromagnet to generate dots & dashes
  - Experimental telegraph line over 40 miles (1840)
- Signal propagates at the speed of light!!!
  - Approximately 2 x 10^8 meters/second in cable

Digital Communications

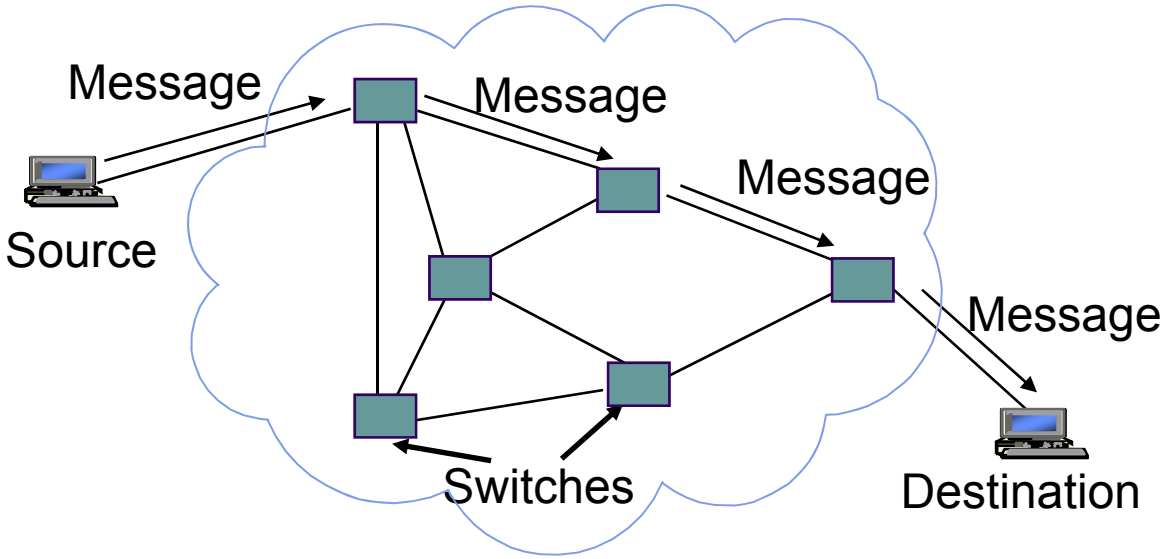


- Morse code converts text message into sequence of dots and dashes
- Use transmission system designed to convey dots and dashes

	Morse Code		Morse Code		Morse Code		Morse Code
A	· —	J	· — — —	S	· · ·	2	· · — — —
B	— · · ·	K	— · —	T	—	3	· · · — —
C	— · — ·	L	· — · ·	U	· · —	4	· · · · —
D	— · ·	M	— —	V	· · · —	5	· · · · ·
E	·	N	— ·	W	· — —	6	— · · · ·
F	· · — ·	O	— — —	X	— · · —	7	— — · · ·
G	— — ·	P	· — — ·	Y	— · — —	8	— — — · ·
H	· · · ·	Q	— — · —	Z	— — · ·	9	— — — — ·
I	· ·	R	· — ·	1	· — — — —	0	— — — — —

Electric Telegraph Networks

- Electric telegraph networks exploded
  - Message switching & Store-and-Forward operation
  - Key elements: Addressing, Routing, Forwarding
- Optical telegraph networks disappeared



Baudot Telegraph Multiplexer

- Operator 25-30 words/minute
  - but a wire can carry much more
- Baudot multiplexer: Combine 4 signals in 1 wire
  - Binary block *code* (ancestor of ASCII code)
    - A character represented by 5 bits
  - Time division *multiplexing*
    - Binary codes for characters are interleaved
  - *Framing* is required to recover characters from the binary sequence in the multiplexed signal
  - *Keyboard* converts characters to bits

Baudot Telegraph Multiplexer




Keyboard

$\ldots A_3 A_2 A_1$

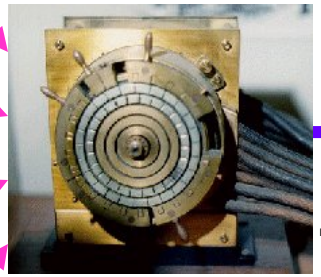
$\ldots B_2 B_1$

$\ldots C_2 C_1$

$\ldots D_3 D_2 D_1$

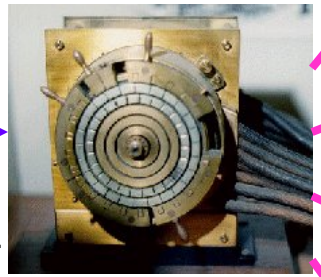
5 bits / character

Baudot Multiplexer



$\ldots A_2 D_1 C_1 B_1 A_1$

Baudot Demultiplexer



Paper Tape Printer

Paper Tape Printer

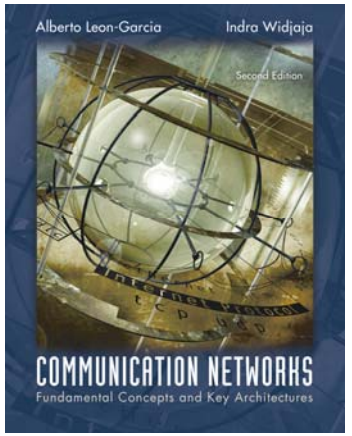
Paper Tape Printer

Paper Tape Printer

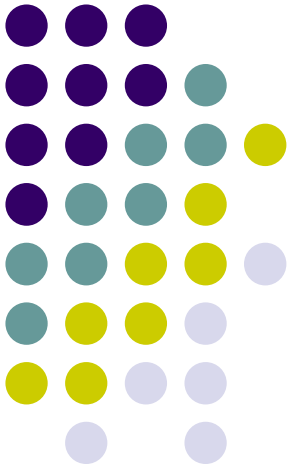
Elements of Telegraph Network Architecture

- Digital transmission
  - Text messages converted into symbols (dots/dashes, zeros/ones)
  - 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

Chapter 1
Communication Networks and Services

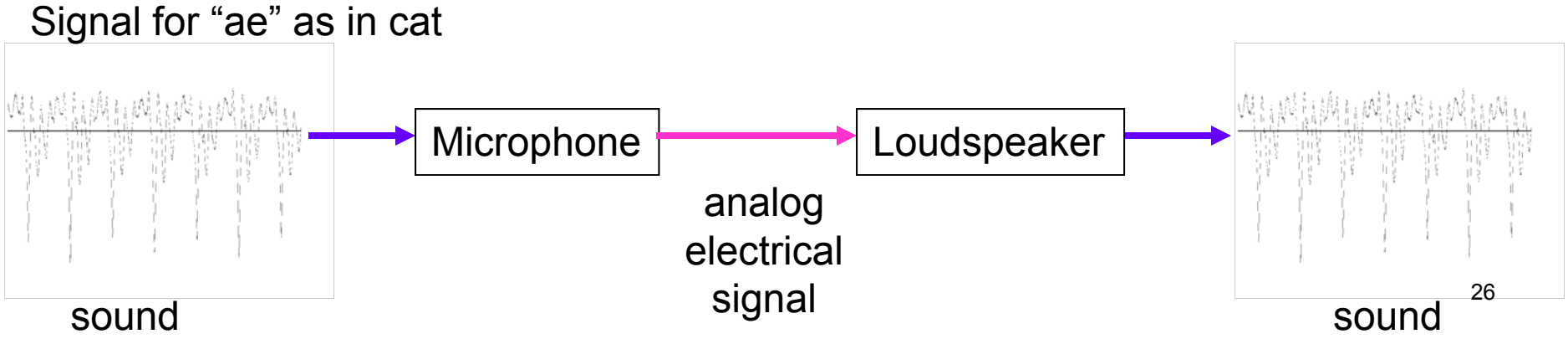


Telephone Networks and Circuit Switching

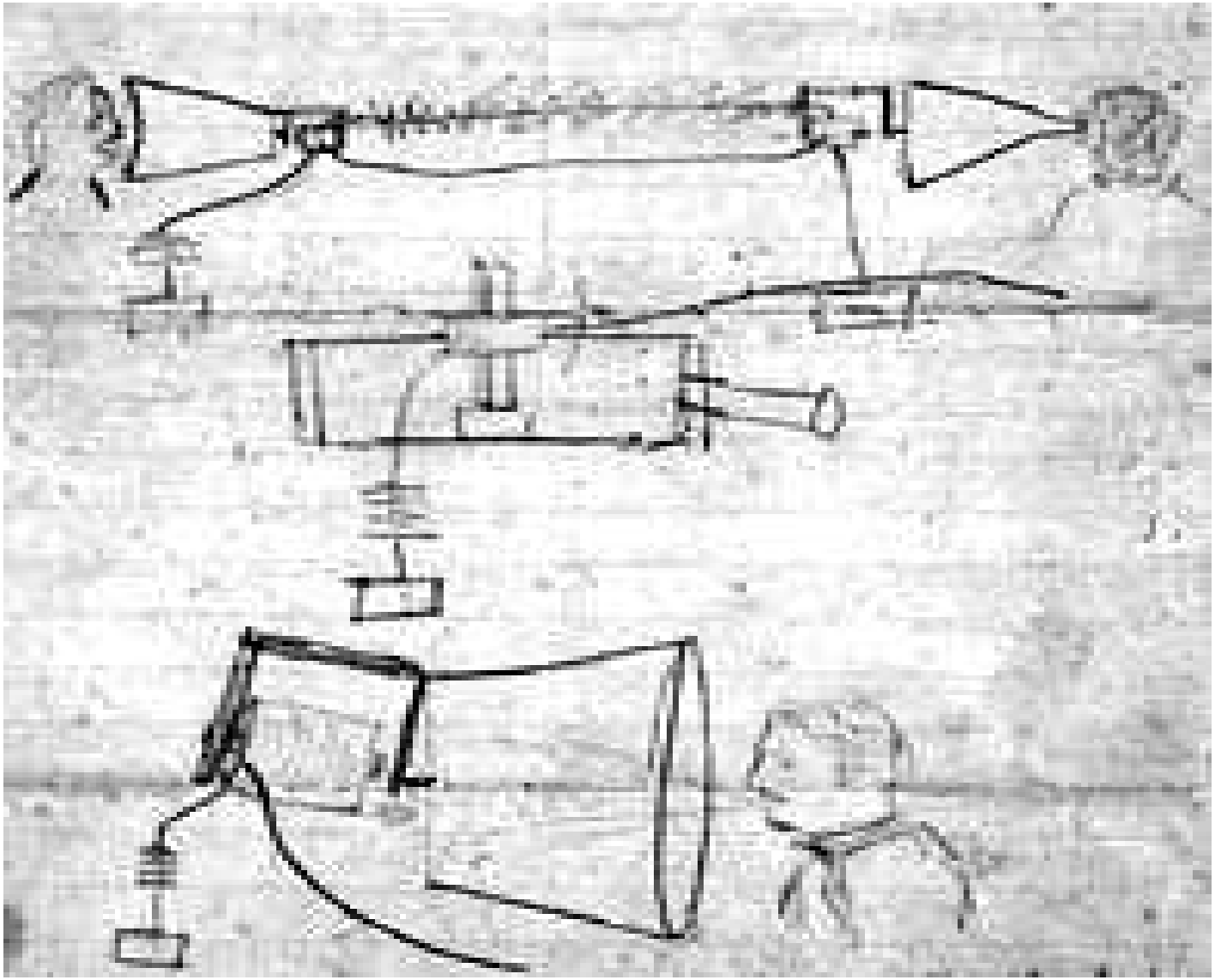


Bell's Telephone

- 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

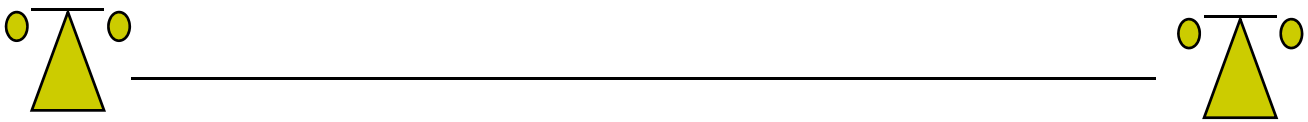


Bell's Sketch of Telephone



Signaling

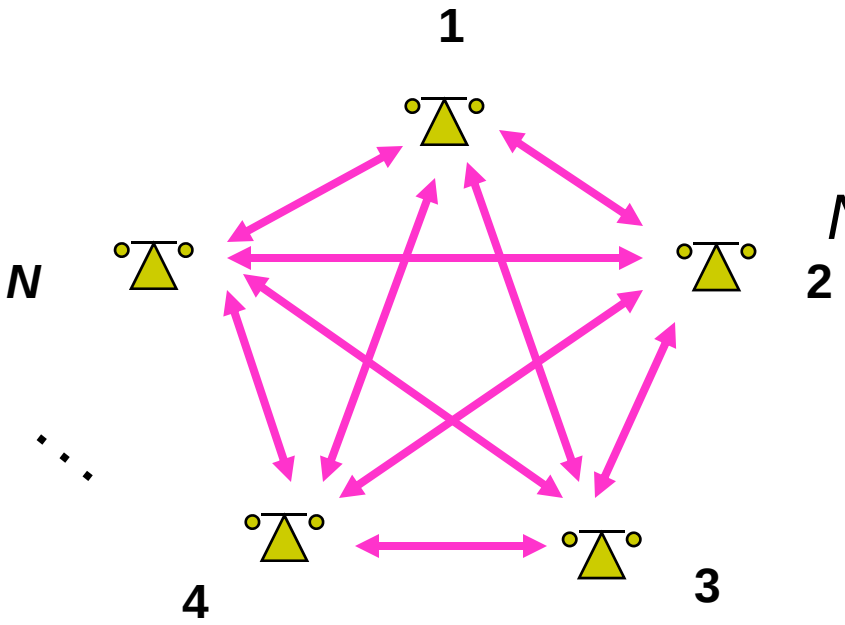
- Signaling required to establish a call
  - Flashing light and ringing devices to alert the called party of incoming call
  - Called party information to operator to establish calls



Signaling + voice signal transfer

The N^2 Problem

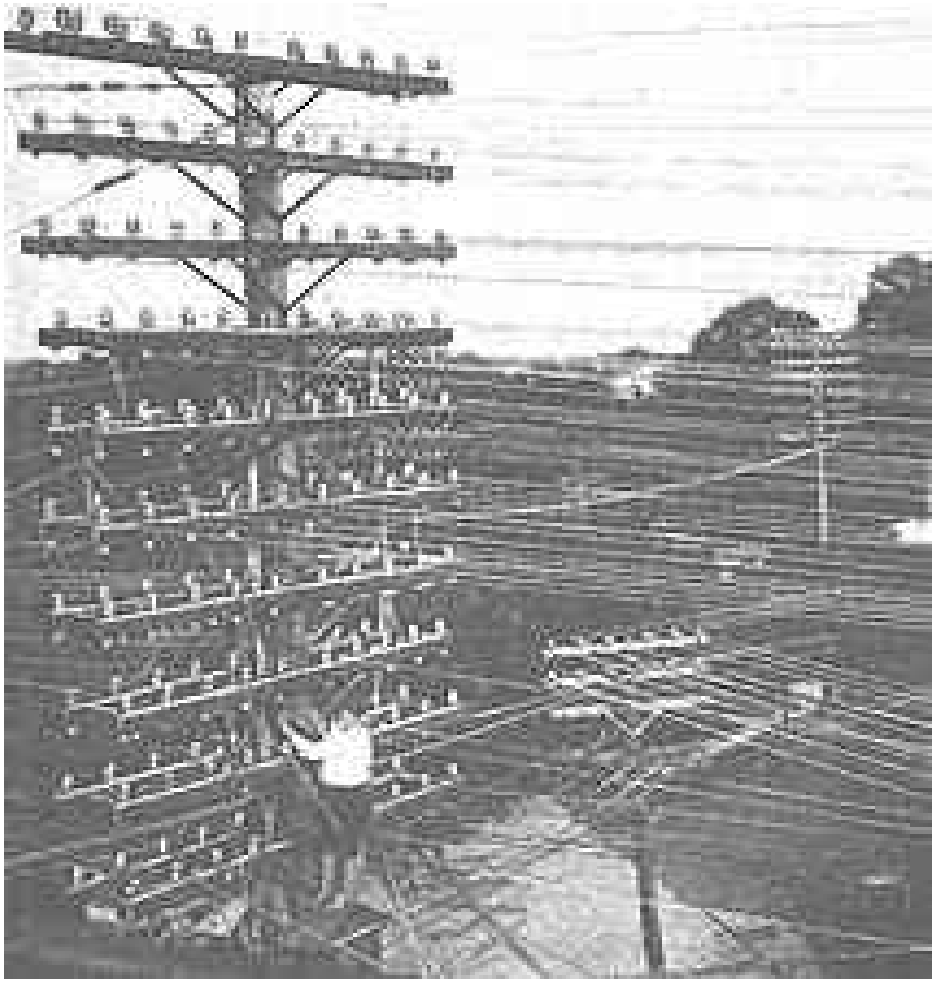
- For N users to be fully connected *directly*
- Requires $N(N-1)/2$ connections
- Requires too much space for cables
- Inefficient & costly since connections not always on



$N = 1000$

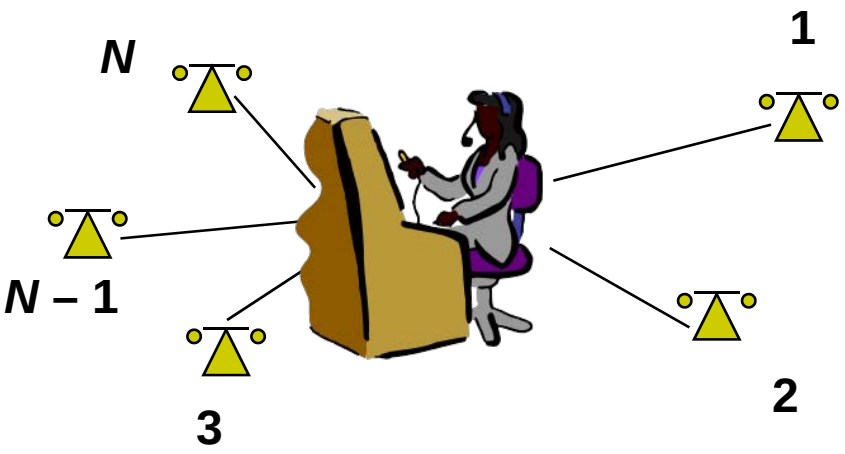
$N(N-1)/2 = 499500$

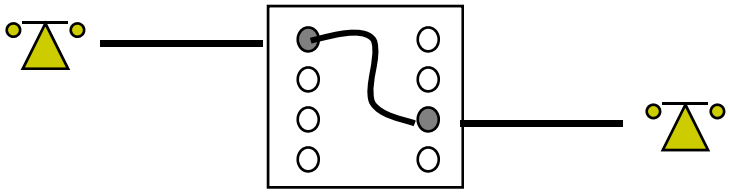
Telephone Pole Congestion



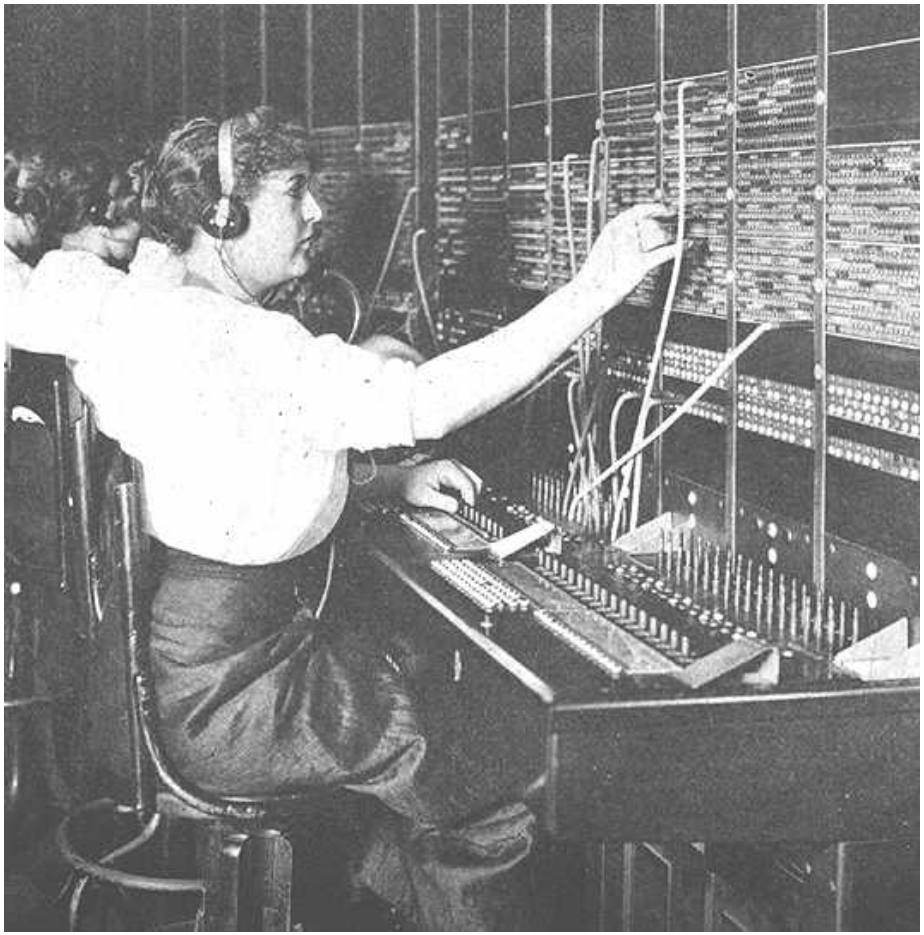
Circuit Switching

- 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



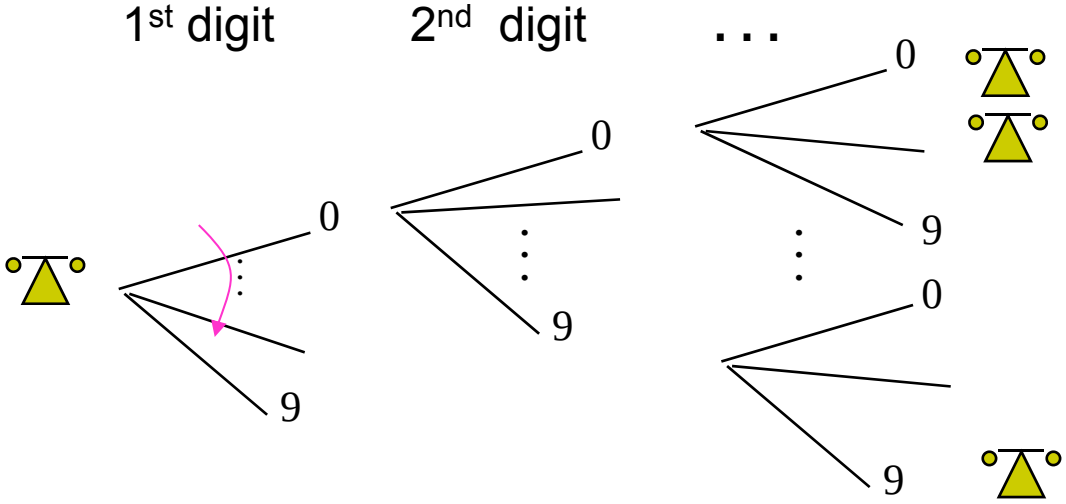


Manual Switching



Strowger Switch

- 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



Strowger Switch

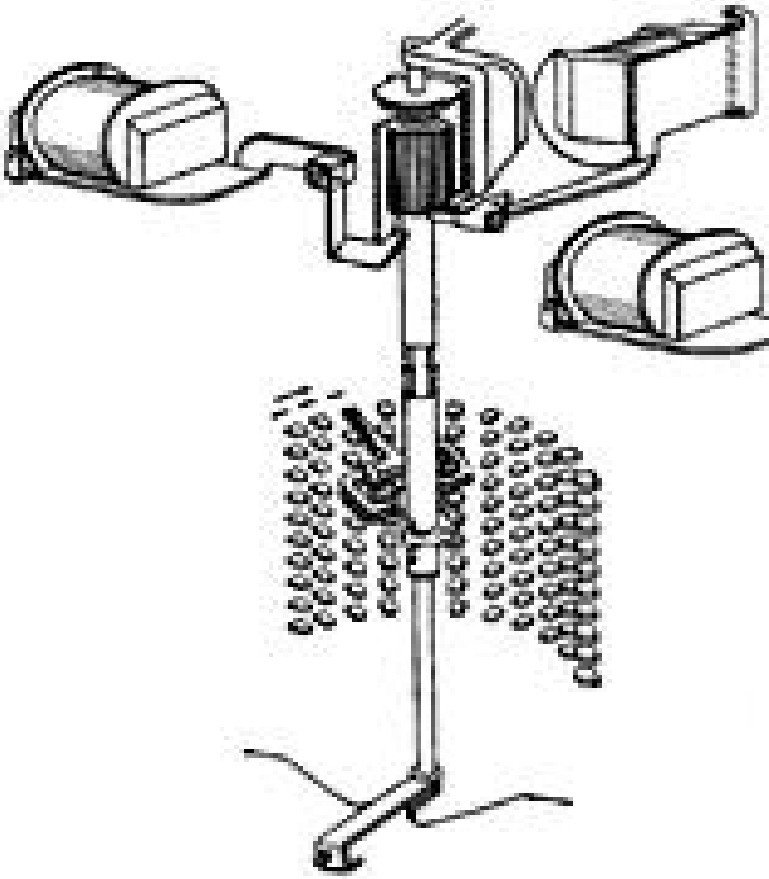


Fig. 12. The shaft carrying the wiper now begins to revolve, bringing the wiper to the third contact of the top bank.

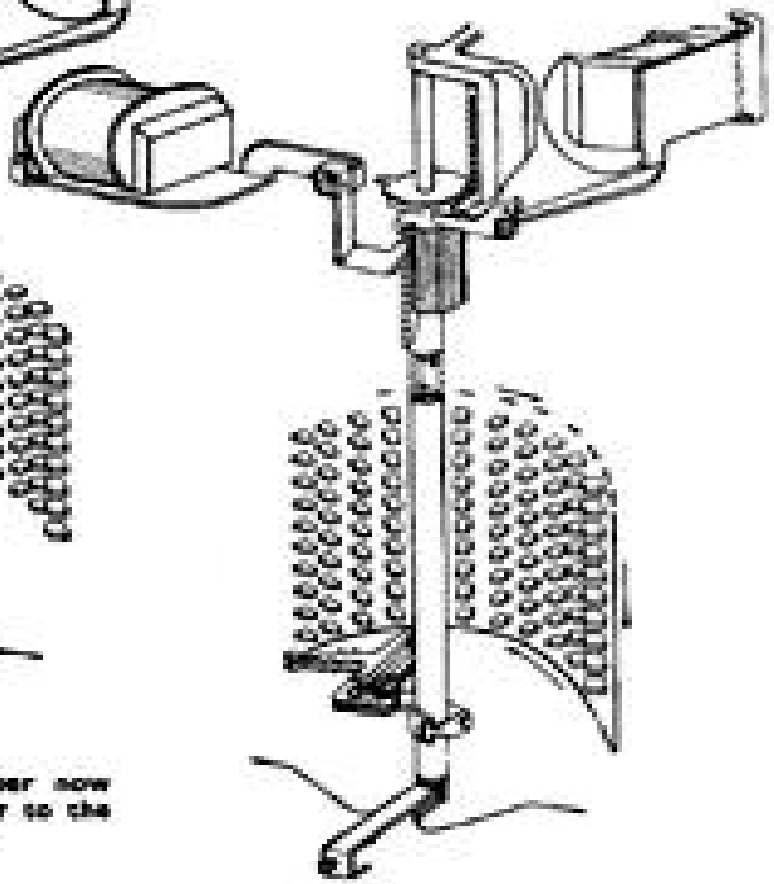
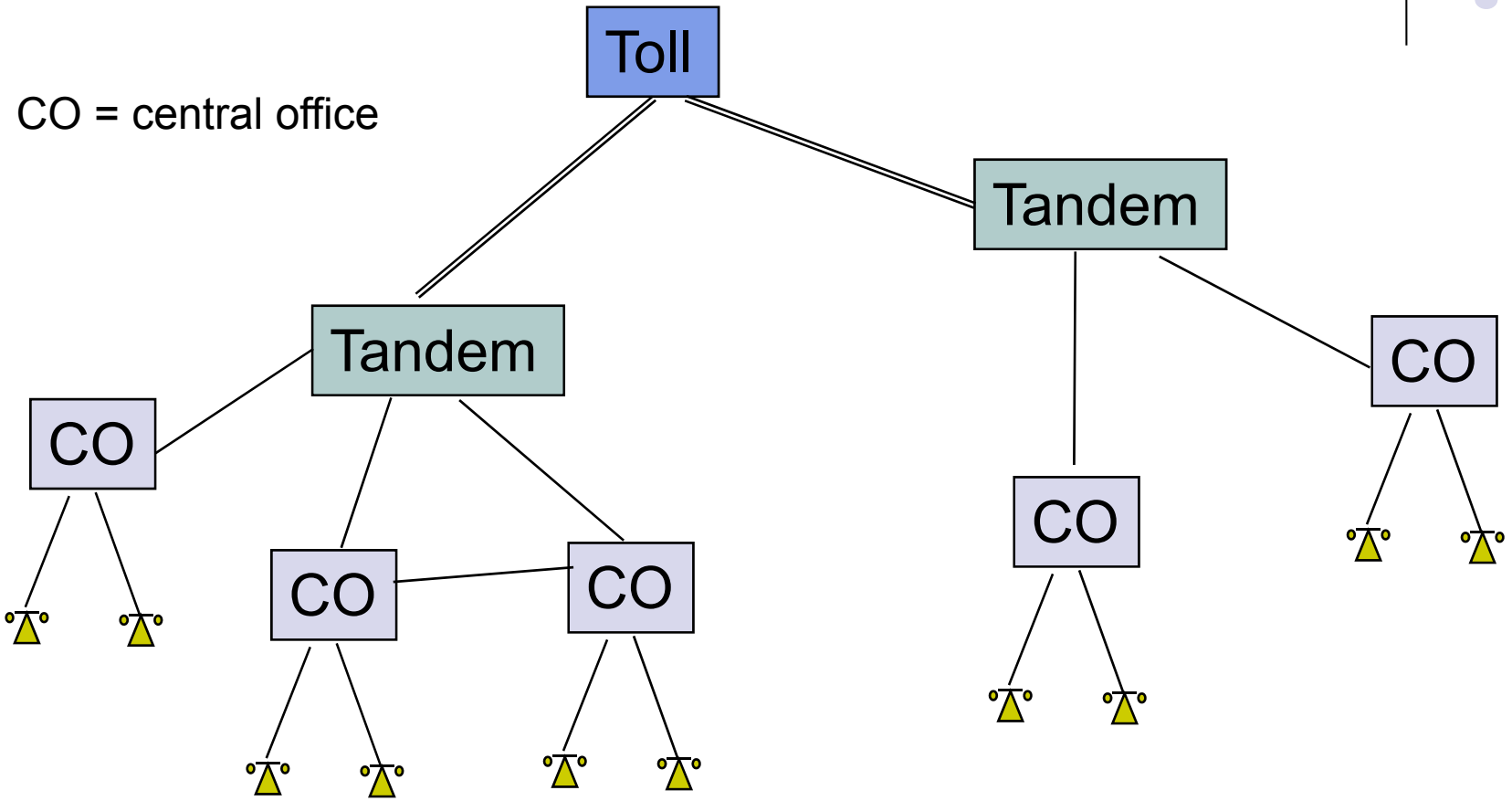


Fig. 13. The call completed, the wiper returns to its original position by the route shown by the arrows.

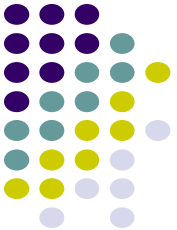
Hierarchical Network Structure



Telephone subscribers connected to local CO (central office)

Tandem & Toll switches connect CO's

Three Phases of a Connection



Connection set up

1.  Telephone network  Pick up phone

2.  Telephone network  Dial tone.

3.  Telephone network  Dial number

4.  Telephone network  Network selects route; Sets up connection; Called party alerted

Information transfer

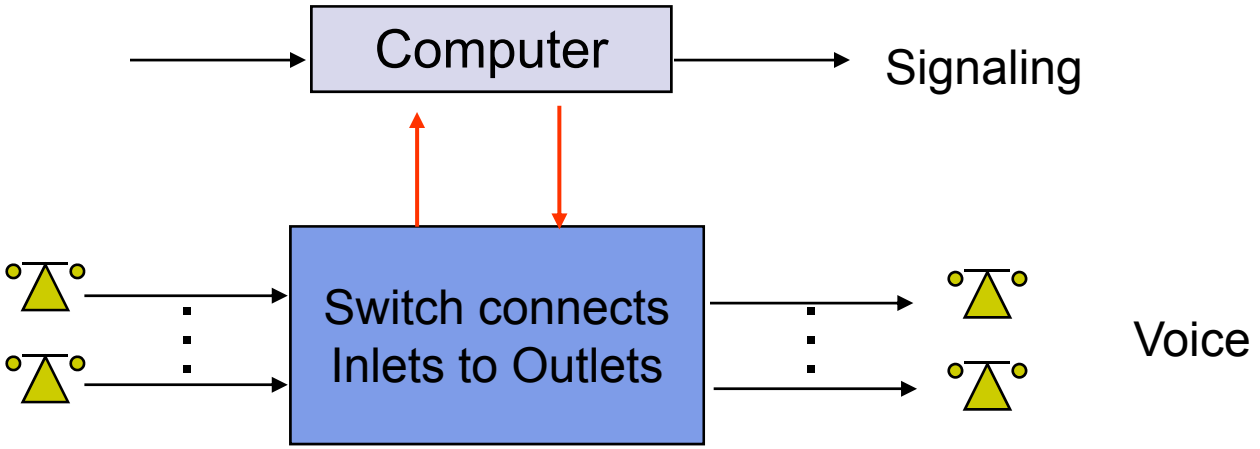
5.  Telephone network  Exchange voice signals

Connection release

6.  Telephone network  Hang up.

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

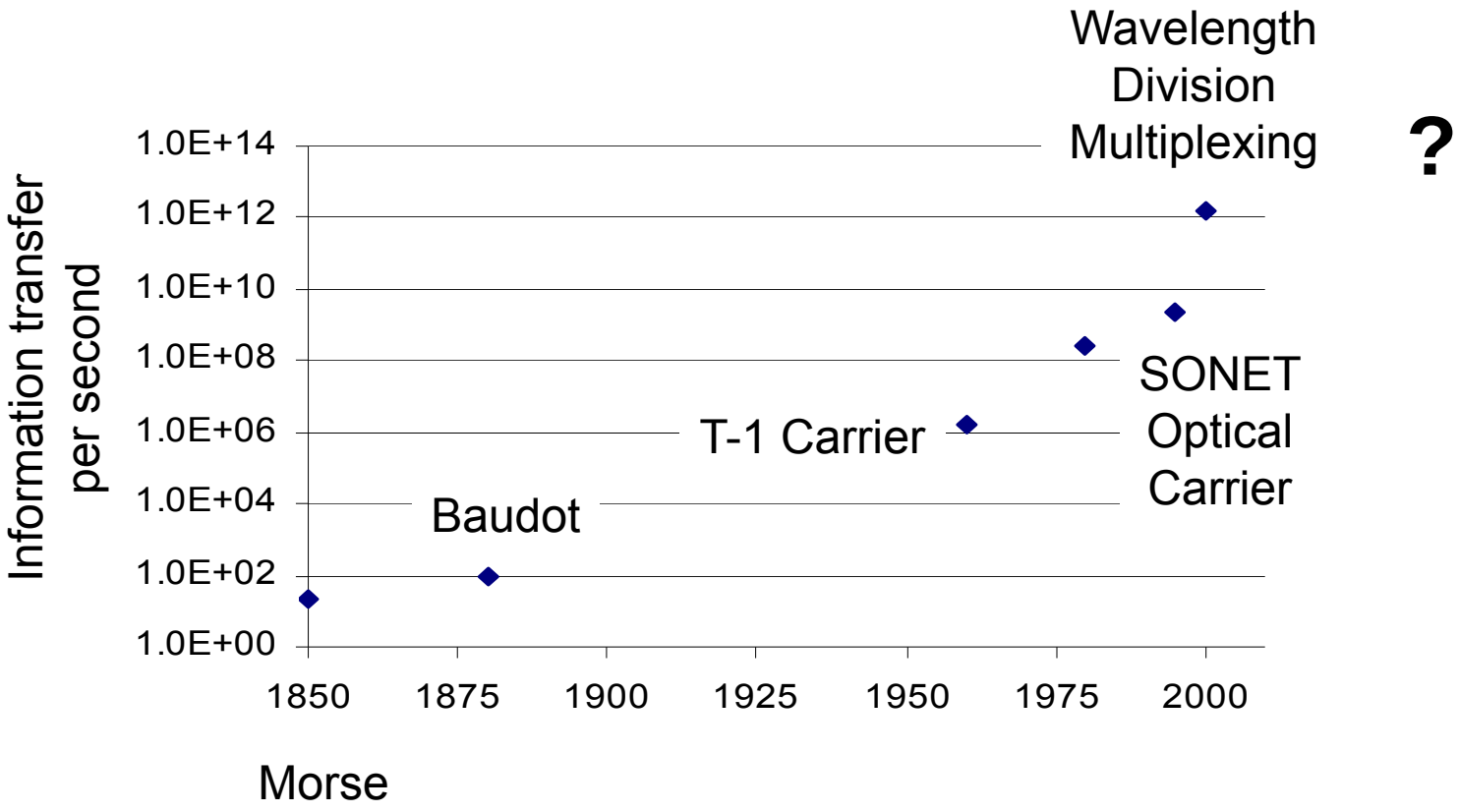


Digitization of Telephone Network

- 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

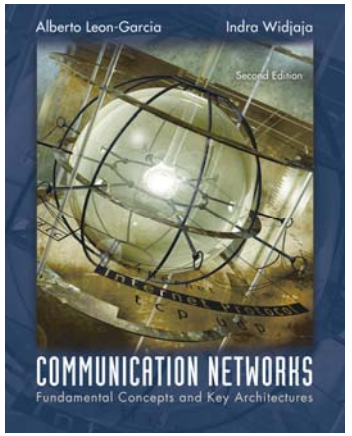
Digital Transmission Evolution

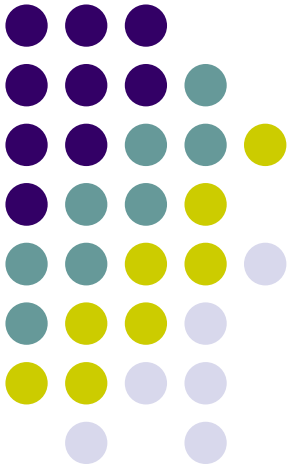


Elements of Telephone Network Architecture

- 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

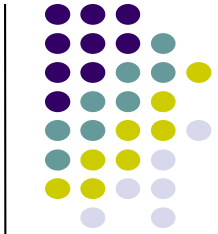
Chapter 1
Communication Networks and Services





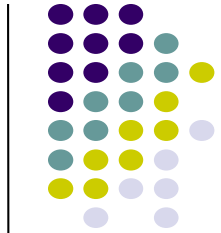
Computer Networks & Packet Switching

Computer Network Evolution Overview



- *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

What is a protocol?



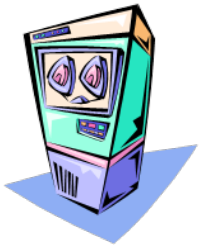
- Communications between computers requires very specific unambiguous rules
- A protocol is a set of rules that governs how two or more communicating parties are to interact
  - Internet Protocol (IP)
  - Transmission Control Protocol (TCP)
  - HyperText Transfer Protocol (HTTP)
  - Simple Mail Transfer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

A familiar protocol

Caller

Dials 411

System replies



"What city"?

Caller replies

"Springfield"

System replies

"What name?"

Caller replies

"Simpson"

System replies

"Thank you, please hold"

Caller waits

"Do you have a first name or street?"

Operator replies

Caller replies

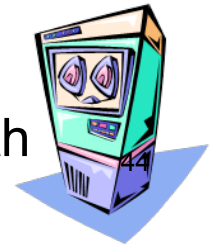
"Evergreen Terrace"

Operator replies

"Thank you, please hold"

Caller waits

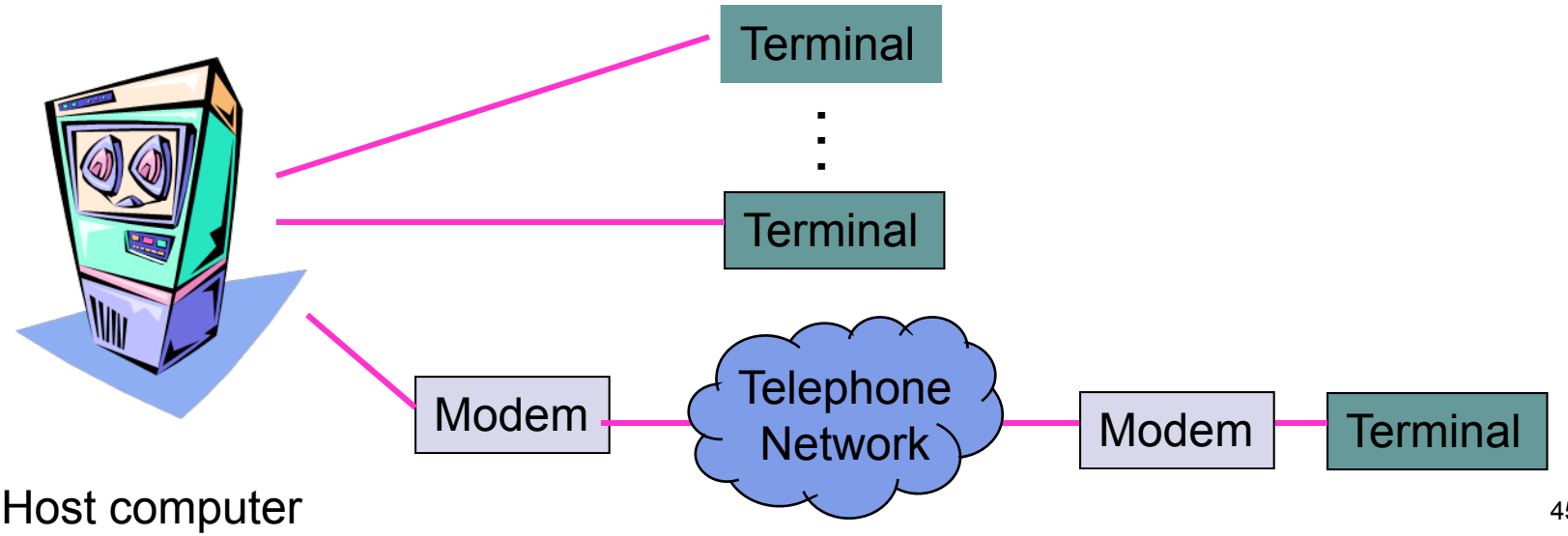
System replies with number



Caller dials

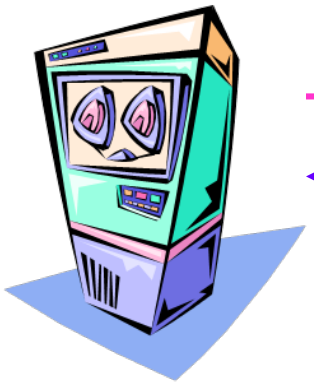
Terminal-Oriented Networks

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

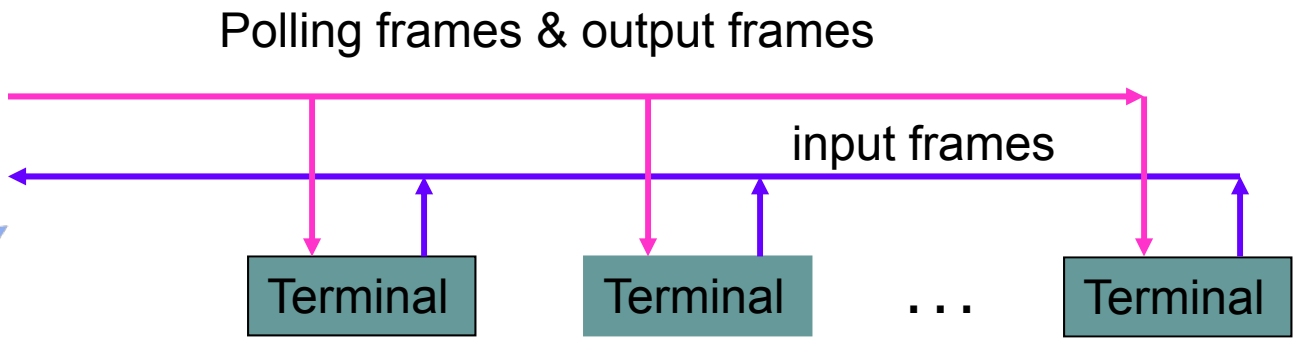


Medium Access Control

- Dedicated communication lines were expensive
- Terminals generated messages sporadically
- Frames carried messages to/from attached terminals
- Address in frame header identified terminal
- *Medium Access Controls* for sharing a line were developed
- Example: Polling protocol on a multidrop line



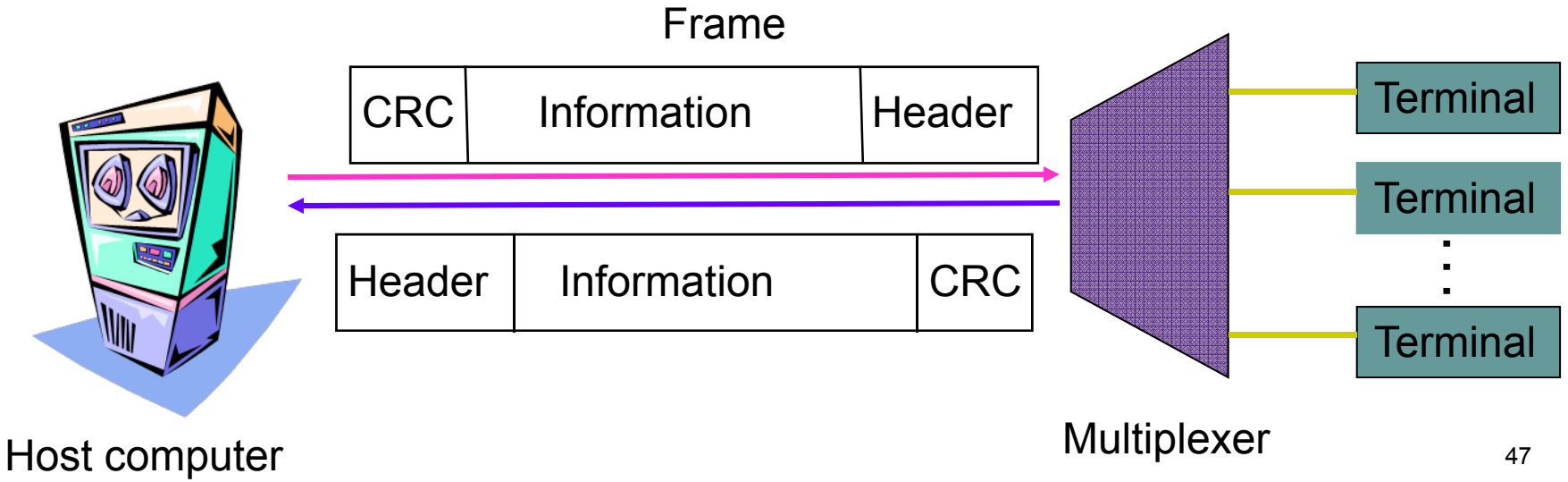
Host computer



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

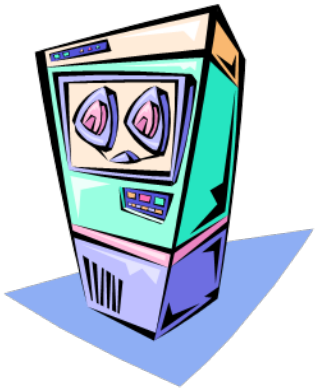
Statistical Multiplexing

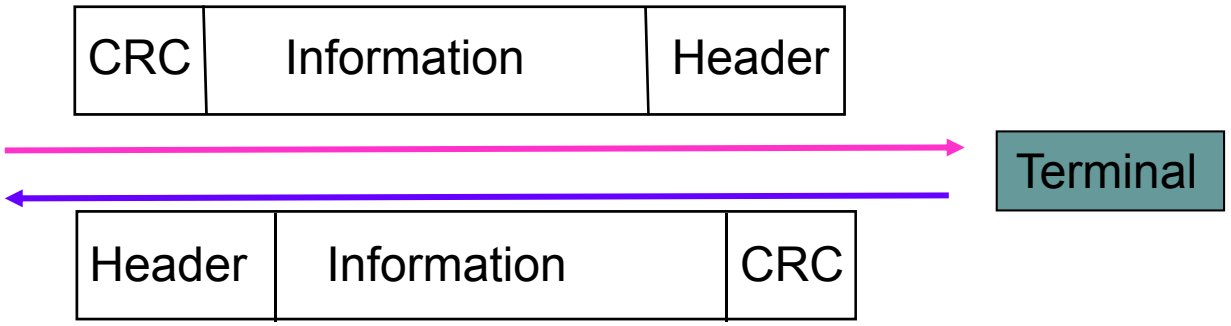
- Statistical multiplexer allows a line to carry *frames* that contain messages to/from multiple terminals
- Frames are buffered at *multiplexer* until line becomes available, i.e. store-and-forward
- *Address* in frame header identifies terminal
- Header carries other *control* information



Error Control Protocol

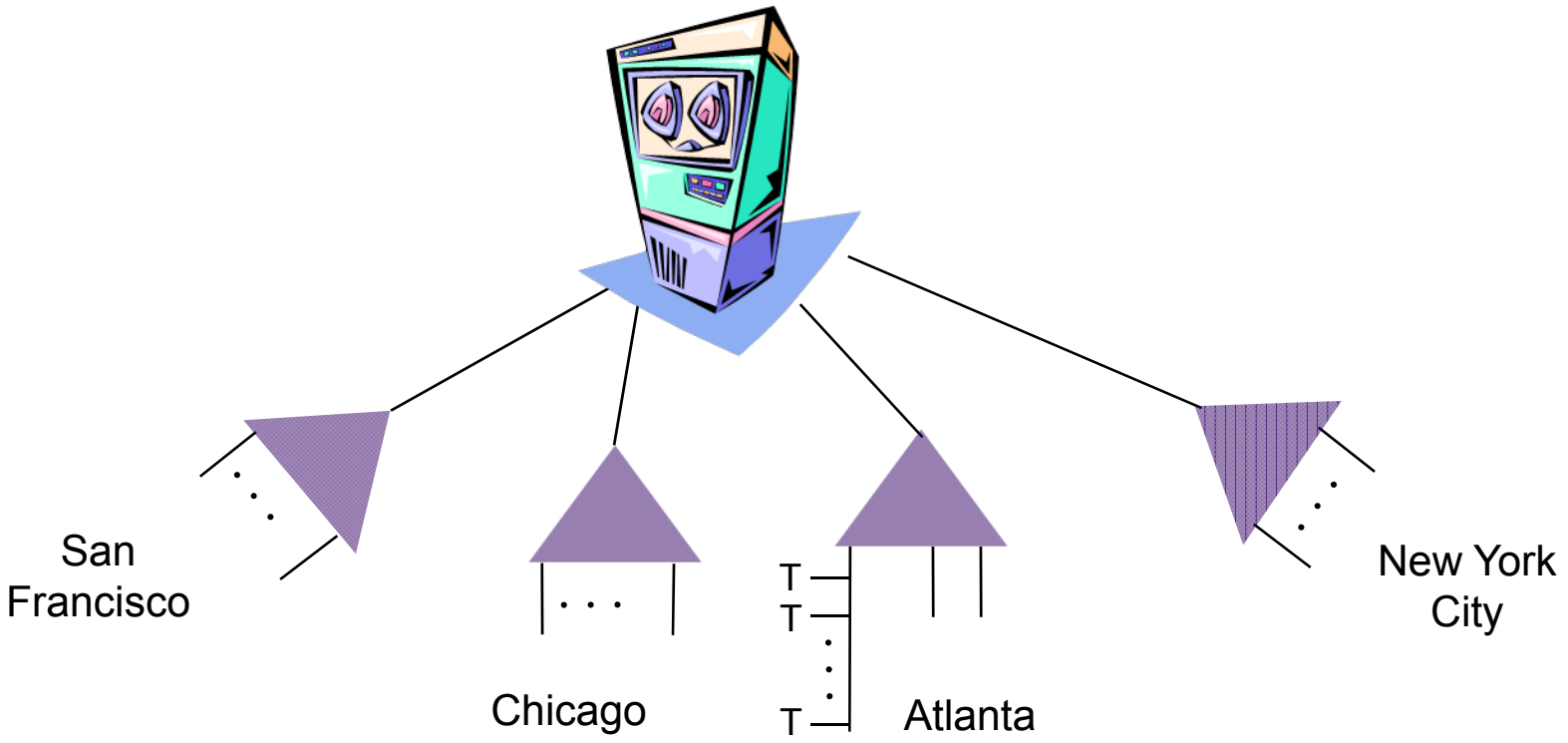
- Communication lines introduced errors
- Error checking codes used on frames
  - “Cyclic Redundancy Check” (CRC) calculated based on frame header and information payload, and appended
  - Header also carries ACK/NAK control information
- Retransmission requested when errors detected





Tree Topology Networks

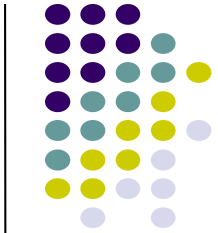
- National & international terminal-oriented networks
- Routing was very simple (to/from host)
- Each network typically handled a single application



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

Packet Switching



- Network should support multiple applications
  - Transfer arbitrary message size
  - Low delay for interactive applications
  - But in 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 testbed led to many innovations

ARPANET Packet Switching

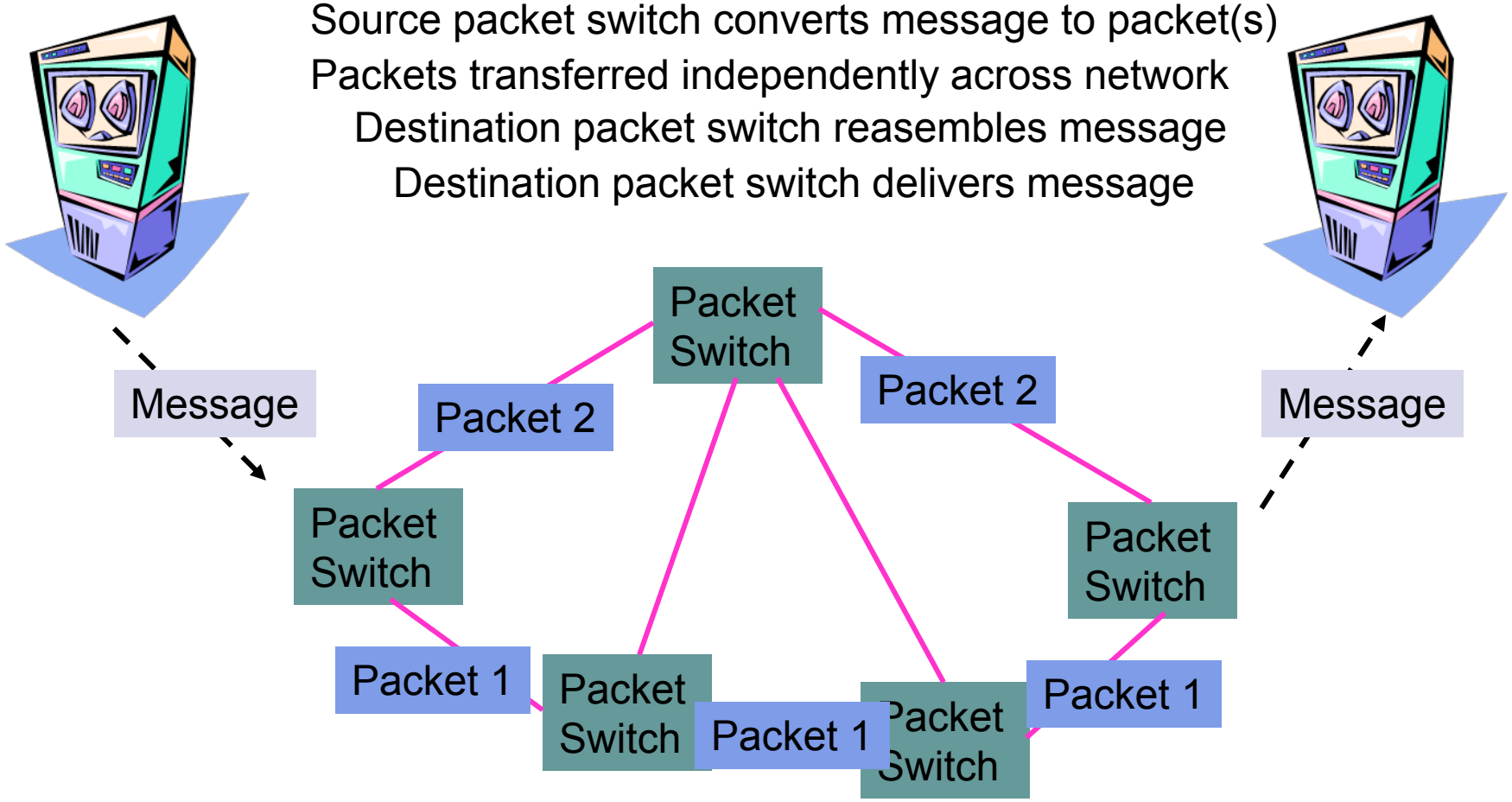
Host generates message

Source packet switch converts message to packet(s)

Packets transferred independently across network

Destination packet switch reasembles message

Destination packet switch delivers message



ARPANET Routing

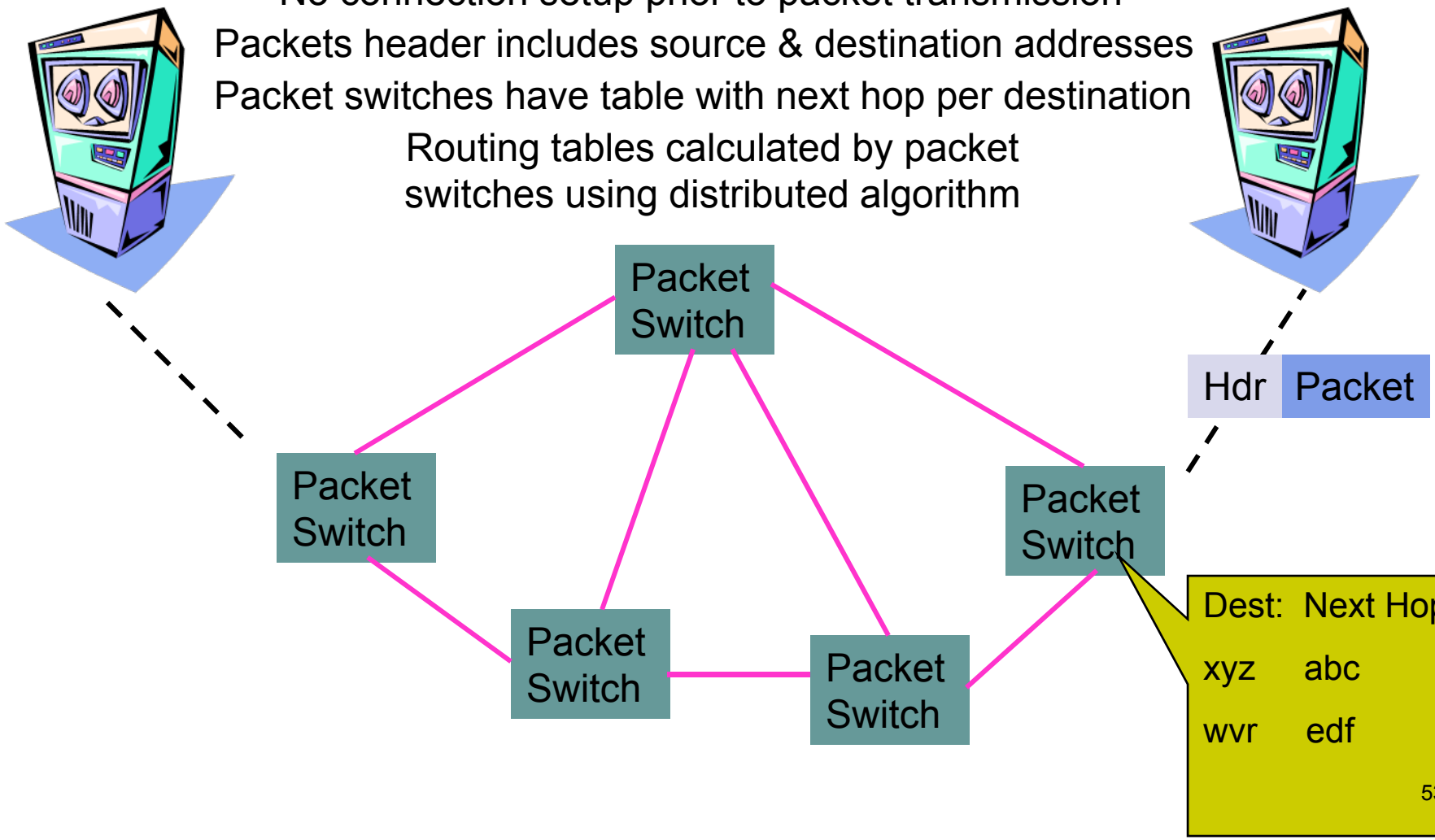
Routing is highly nontrivial in mesh networks

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

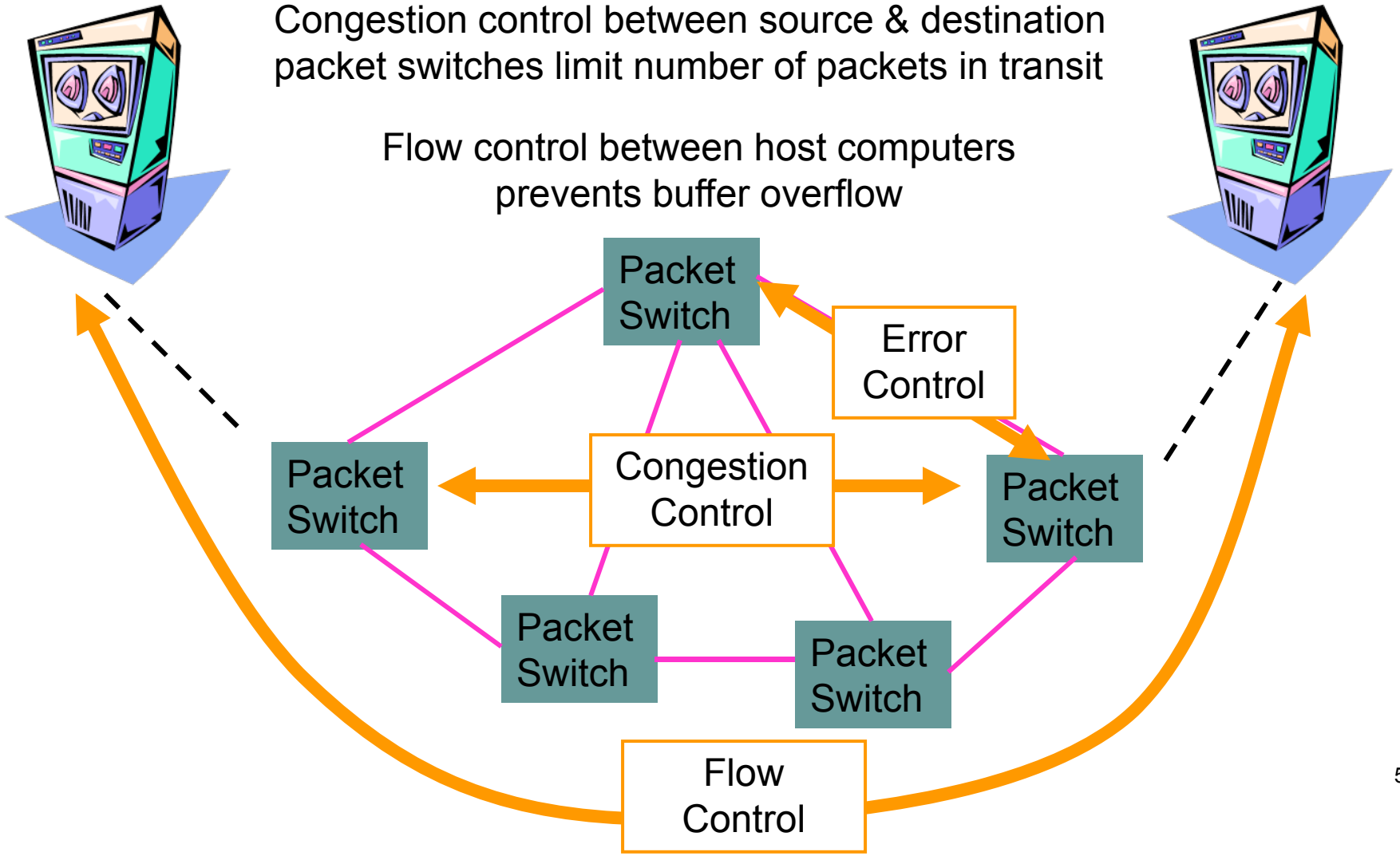


Other ARPANET Protocols

Error control between adjacent packet switches

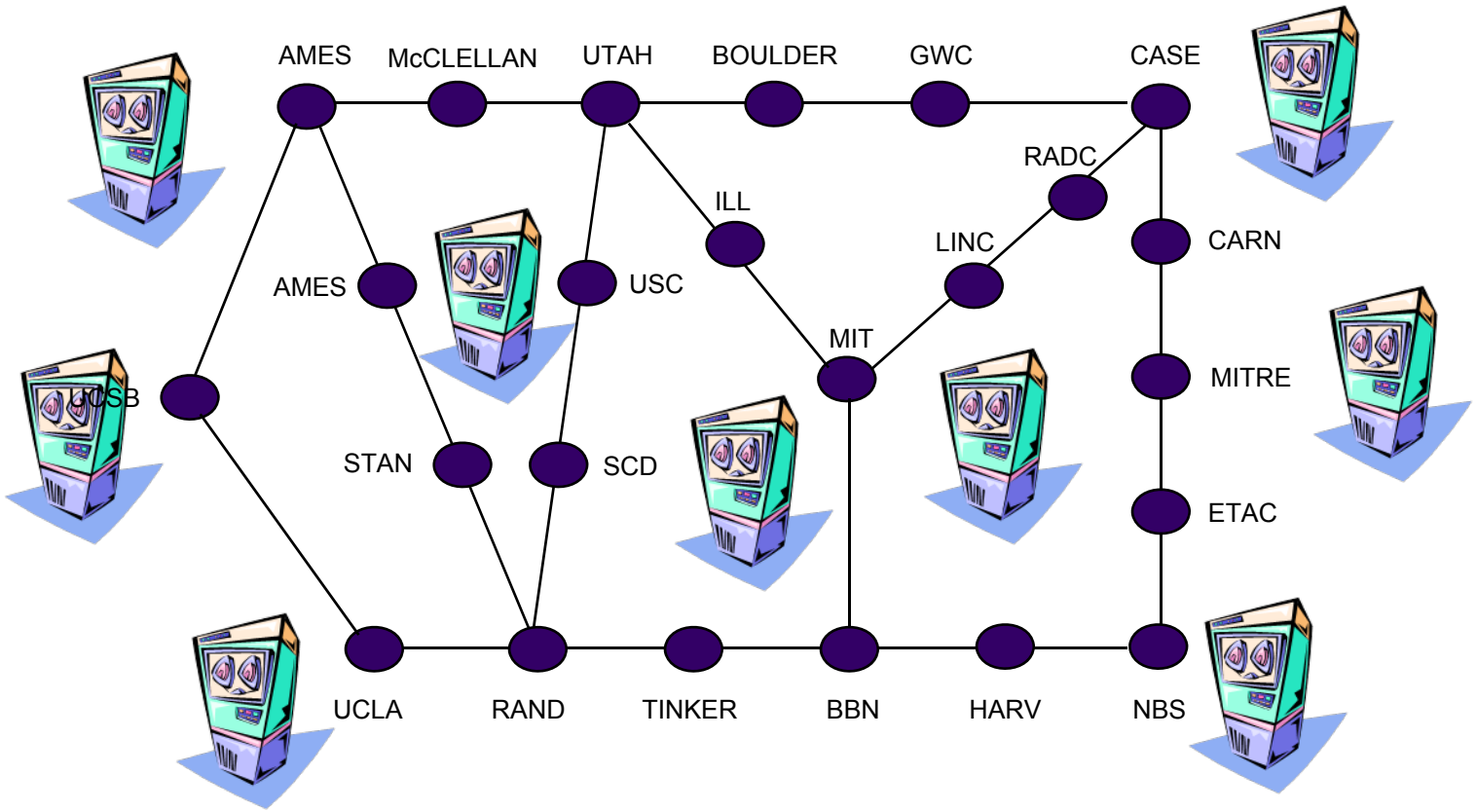
Congestion control between source & destination packet switches limit number of packets in transit

Flow control between host computers prevents buffer overflow



ARPANET Applications

- ARPANET introduced many new applications
- Email, remote login, file transfer, …
- Intelligence at the ***edge***

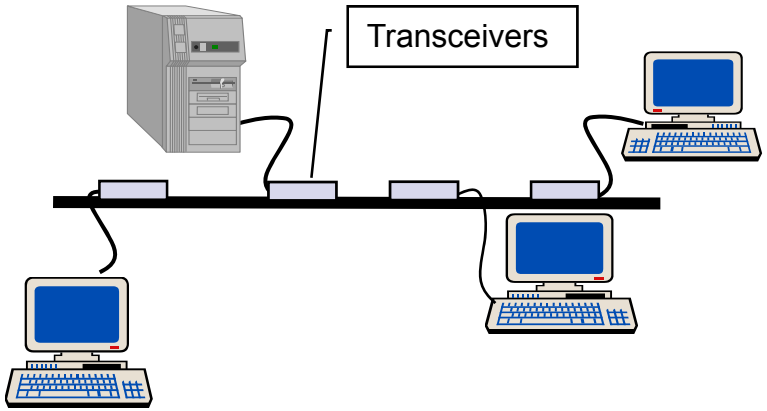


Ethernet Local Area Network

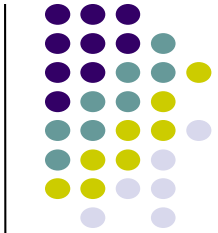
- In 1980s, affordable workstations available
- Need for low-cost, high-speed networks
  - To interconnect local workstations
  - To access local shared resources (printers, storage, servers)
- Low cost, high-speed communications with low error rate possible using coaxial cable
- Ethernet is the standard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

Ethernet Medium Access Control

- 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 and reschedule retransmissions



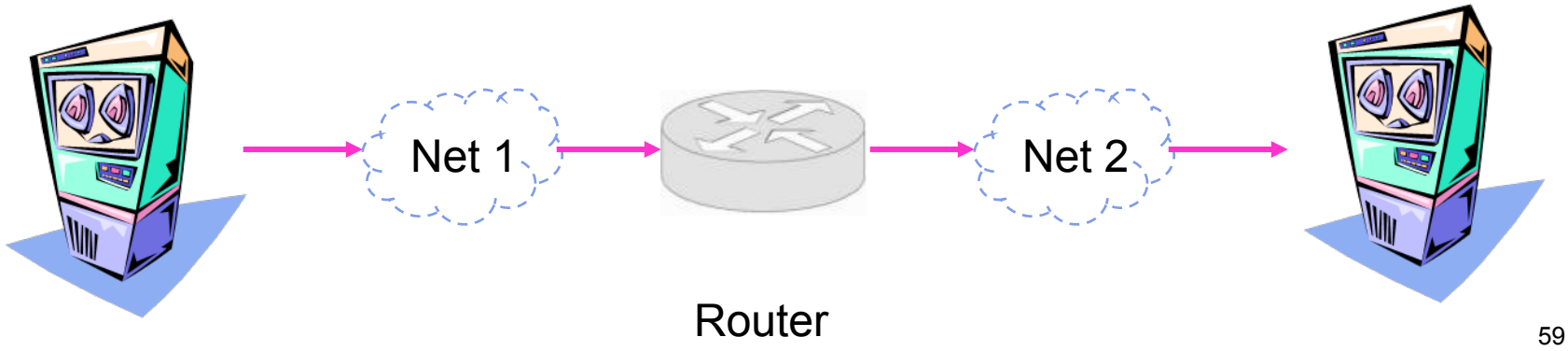
The Internet



- 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

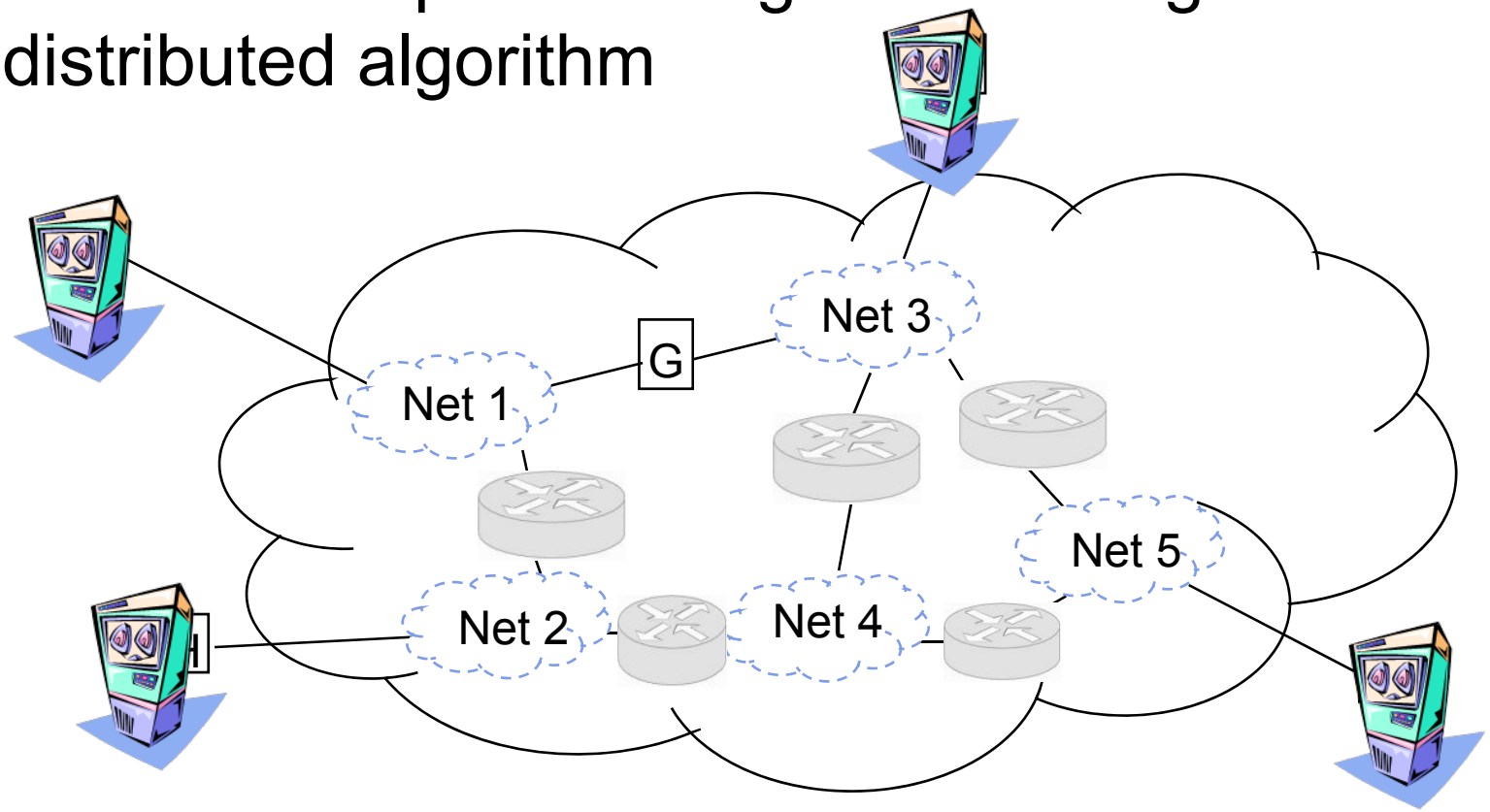
Internet Protocol (IP)

- *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



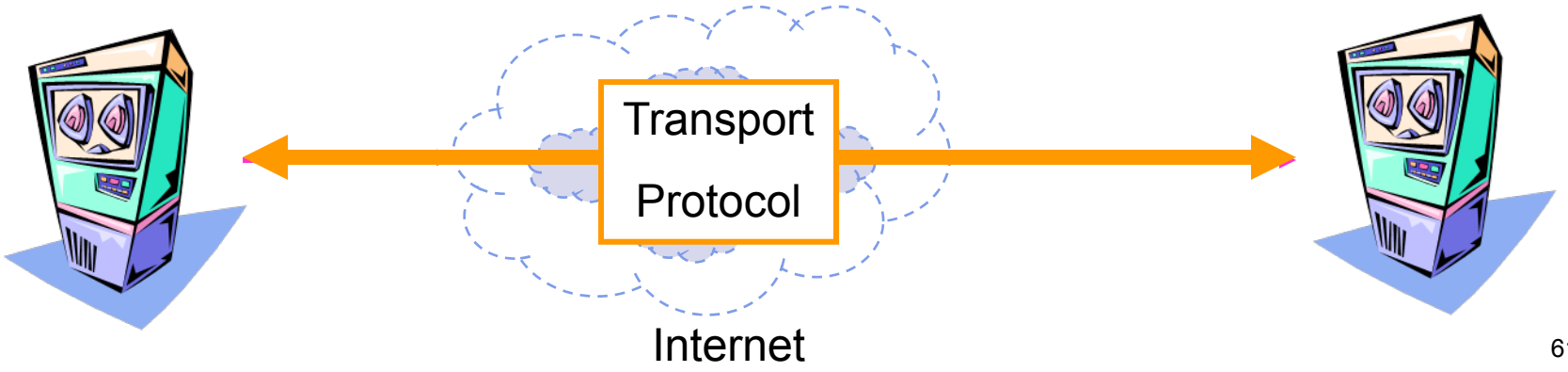
Addressing & Routing

- Hierarchical address: Net ID + Host ID
- IP packets routed according to Net ID
- Routers compute routing tables using distributed algorithm

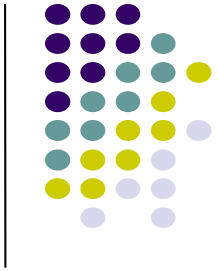


Transport Protocols

- 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

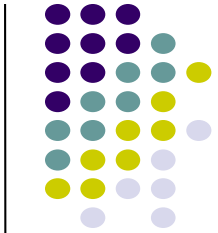


Names and IP Addresses



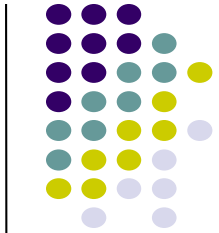
- Routing is done based on 32-bit IP addresses
- Dotted-decimal notation
  - 128.100.11.1
- Hosts are also identified by name
  - Easier to remember
  - Hierarchical name structure
  - tesla.comm.utoronto.edu
- Domain Name System (DNS) provided conversion between names and addresses

Internet Applications



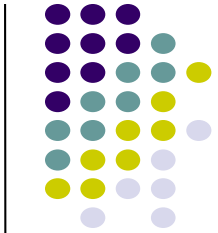
- All Internet applications run on TCP or UDP
- TCP: HTTP (web); SMTP (e-mail); FTP (file transfer; telnet (remote terminal)
- UDP: DNS, RTP (voice & multimedia)
- TCP & UDP incorporated into computer operating systems
- Any application designed to operate over TCP or UDP will run over the Internet!!!

Elements of Computer Network Architecture



- *Digital transmission*
- 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
- Distributed calculation of *routing tables*

Elements of Computer Network Architecture



- *Congestion control* inside the network
- *Internetworking* across multiple networks using routers
- *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 at the edge of the network.*