Supplementary Introduction to

Computer Networks

A Systems Approach

Peterson and Davie

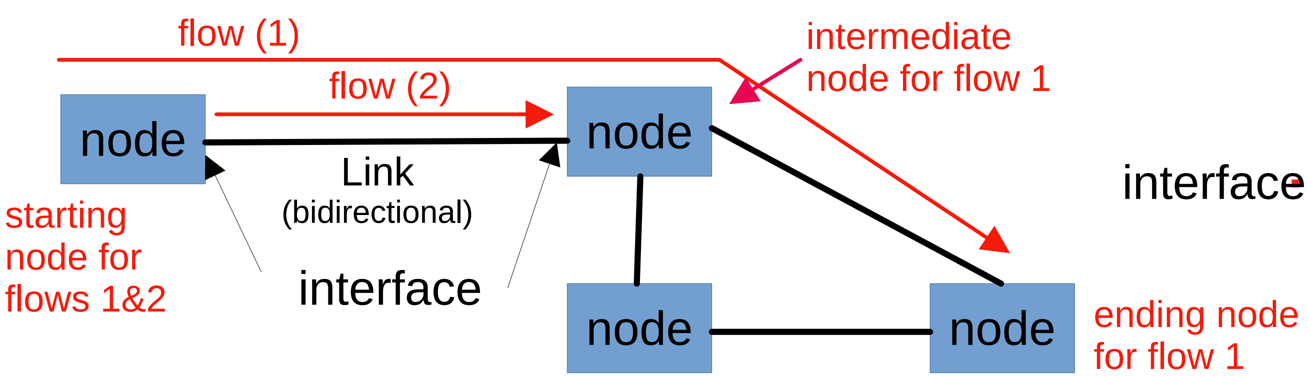
Introduction to Networks

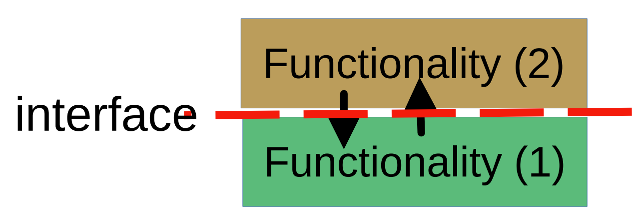
- Networks utility:
  - Organize and facilitate exchanges
  - Optimize important resource utilization

- Fields of Networks:
  - Water networks and resources planning/control
  - Sanitation networks
  - Ports networks
  - Road networks and urban planning
  - Rail networks
  - Airline/Airport networks
  - Postal networks
  - Supply chains for trade and industry
  - Industrial chains (networks of cooperating factories)
  - Electricity networks
  - Telecommunications networks
  - Computer networks
  - Information organization networks
  - Banking networks
  - Institutional networks (government, education, health, etc.)
  - Biological systems
  - ....

(abstract) Networks Concepts (1/3)

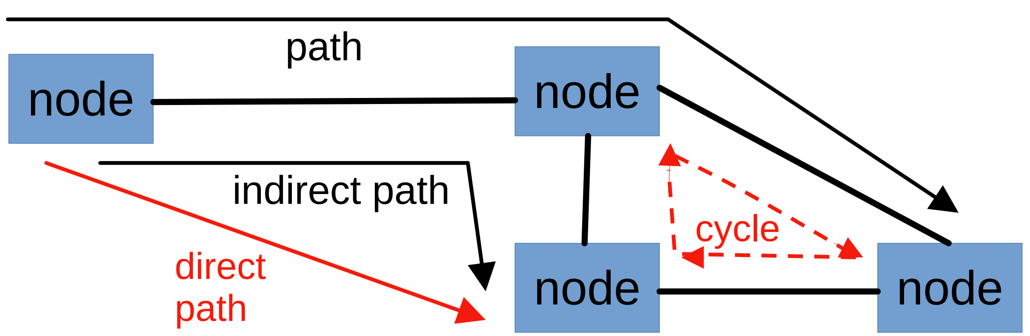
- **Network:**
  - a set of physical/logical interconnections (called "**Links**") among different entities (called "**Nodes**")
  - Links can be **bidirectional** (two ways) or **unidirectional** (one way flow) called **arcs**
- Networks utility and drivers:
  - **Facilitate interactions** (e.g., service exchanges) between nodes
  - **Service affordability** by sharing resources and avoiding unnecessary replications
  - **Standardization** of interfaces and major functionalities (reduces complexity --> mass production)
- **Interfaces:** a point where two entities meet and interact according to a set of defined protocols
- **Protocols:** sets of procedures&rules governing the interactions between different entities
- **Starting/Intermediate/Ending nodes/links:** the starting/intermediate/ending nodes/links involved in the path of a flow

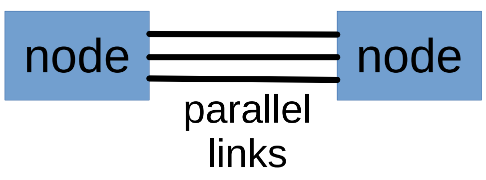




(abstract) Networks Concepts (2/3)

- **Network types:**
  - **Closed:** flows always return to the starting node
  - **Open:** flows need not return to the starting node
  - Note: most (practical) networks are a mix of open/closed networks depending on the flow type. e.g., Computer networks are open network for user messages but are closed networks for most operations control messages
- **Path/route:** the collection of links&nodes taken by (or assigned to) a flow between two end nodes
- **Direct path:** a path without intermediate nodes = a single link = single hop
- **Indirect/Multi-hop path:** a path over several links (has intermediate nodes)
- **Cycle**: a closed path
- **Tree**: a graph with no cycles
- **Parallel/Multi links:** several links between the same two end points
- **Parallel/Multi paths:** several paths between the same two end points



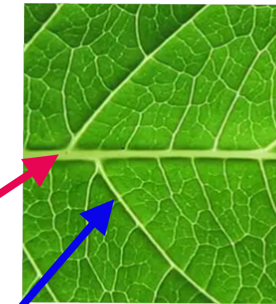


(abstract) Networks Concepts (3/3)

- **Flow:** the progress/traffic of interactions between nodes
- **(traffic) Capacity:** the maximum traffic level that be can carried/processed (e.g., max cars per minute for roads)
- **(traffic) Utilization:**
  - the ratio of dividing the actual traffic level by the capacity ->max utilization=100%
  - Note:
    - Typical Objective: is to maximize resource utilization (under certain conditions/restrictions)
    - if traffic is highly random, then low traffic delay constrains utilization to be $\leq$ 80%
- **Routing:**
  - A very important aspect of networks seriously impacting performance
  - Function: The determination of the paths to be taken by the traffic/messages between node pairs.

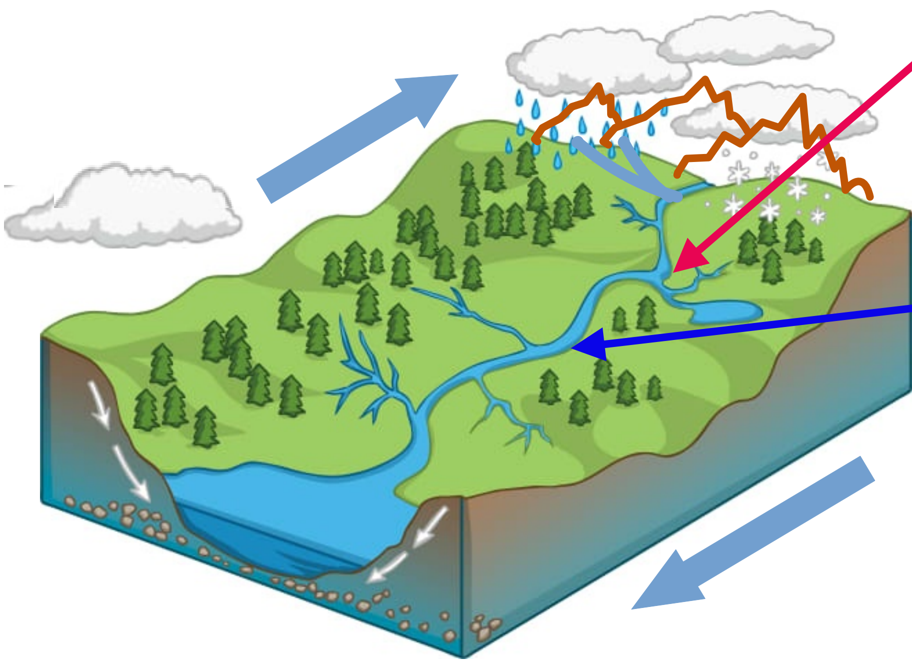
Examples of Networks in Nature (1/3)

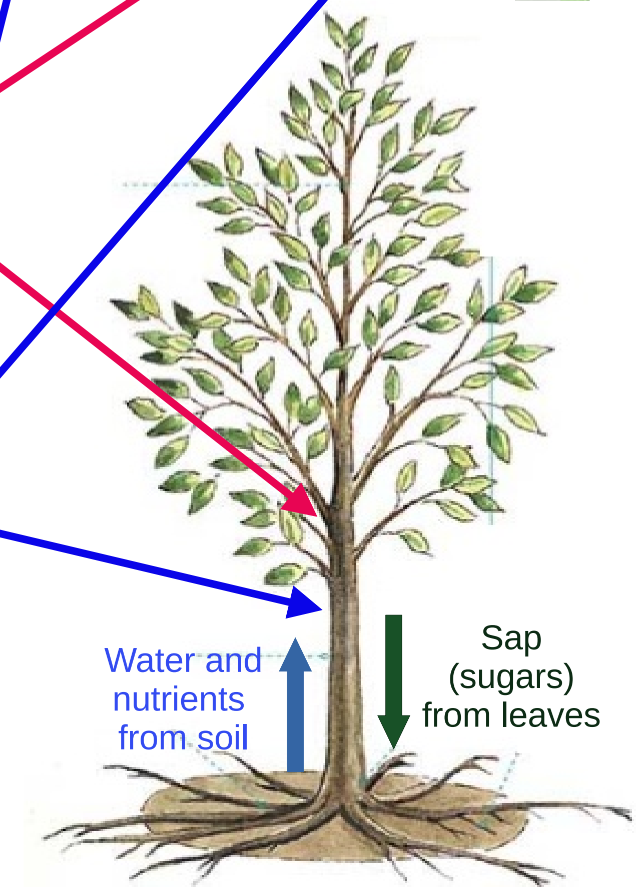
- Trees/Plants
- River systems
- Human Body: several networks
  - Blood circulatory system
  - Nervous/sensory system
  - Brain neuron networks
- Lightning



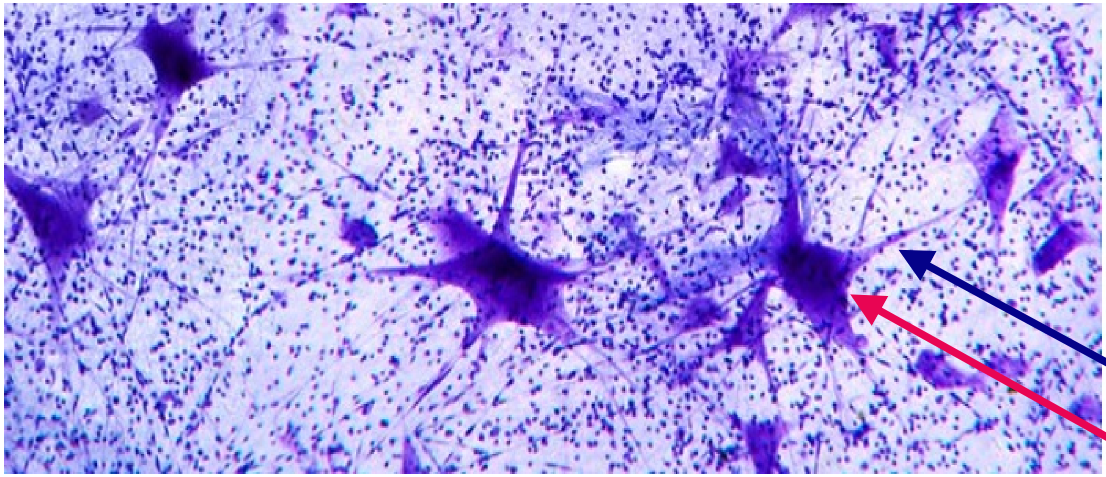
nodes

links

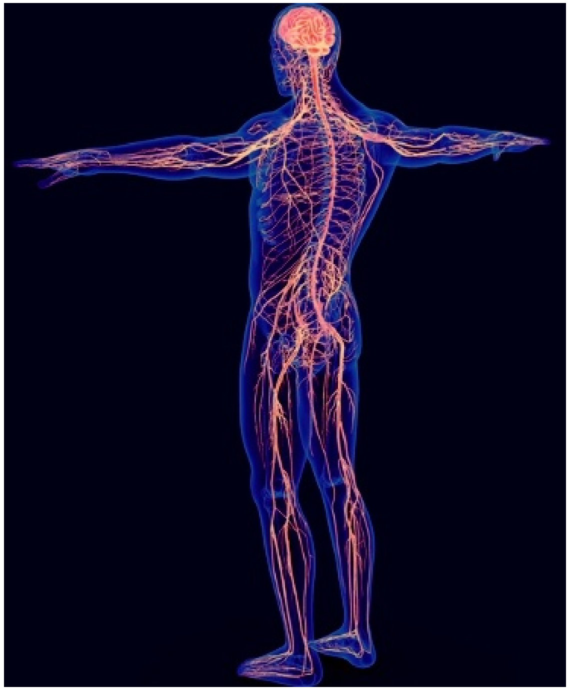




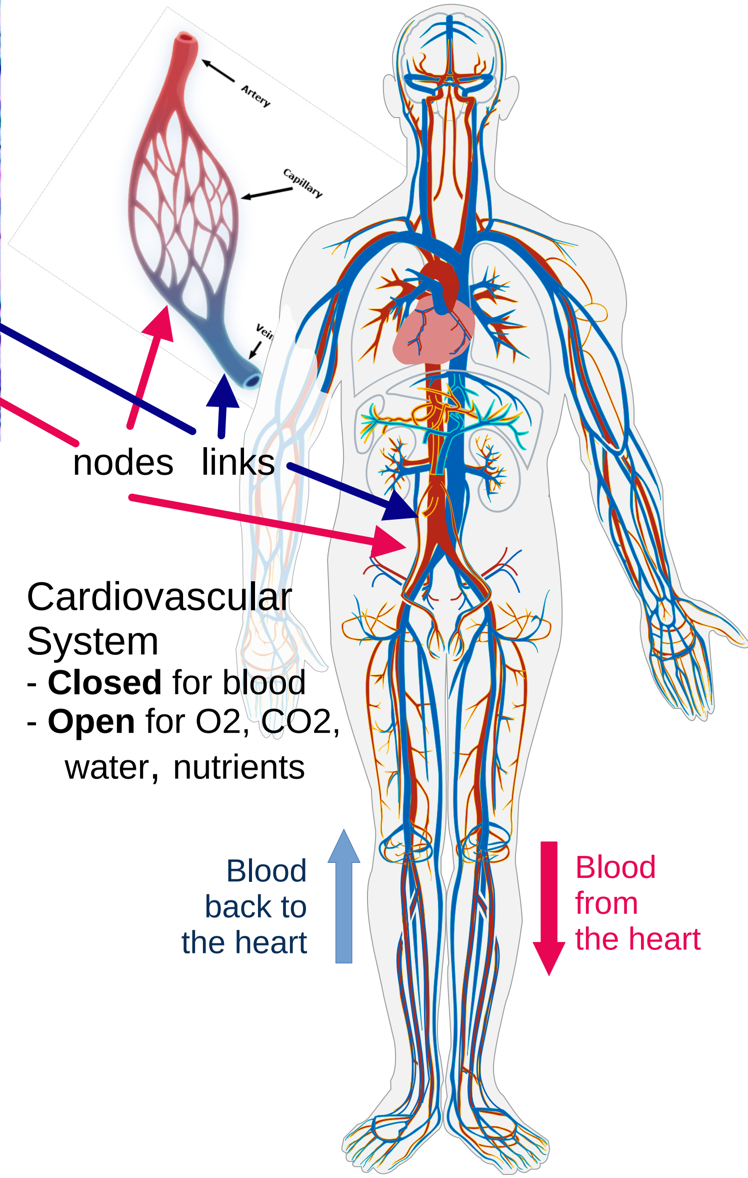
Examples of Networks in Nature (2/3)



Neural networks of the brain



Nervous System



Cardiovascular System
- **Closed** for blood
- **Open** for O_2, CO_2, water, nutrients

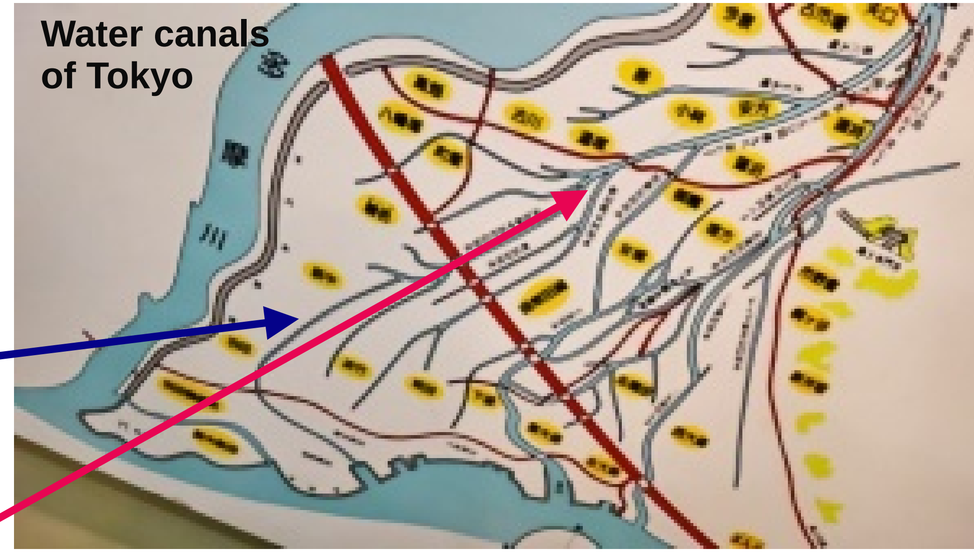
Blood back to the heart

Blood from the heart

Credit: Mariana Ruiz

Examples of Networks in Nature (3/3)

- Links ↔ river/stream segments
- Nodes ↔ river branching/joining

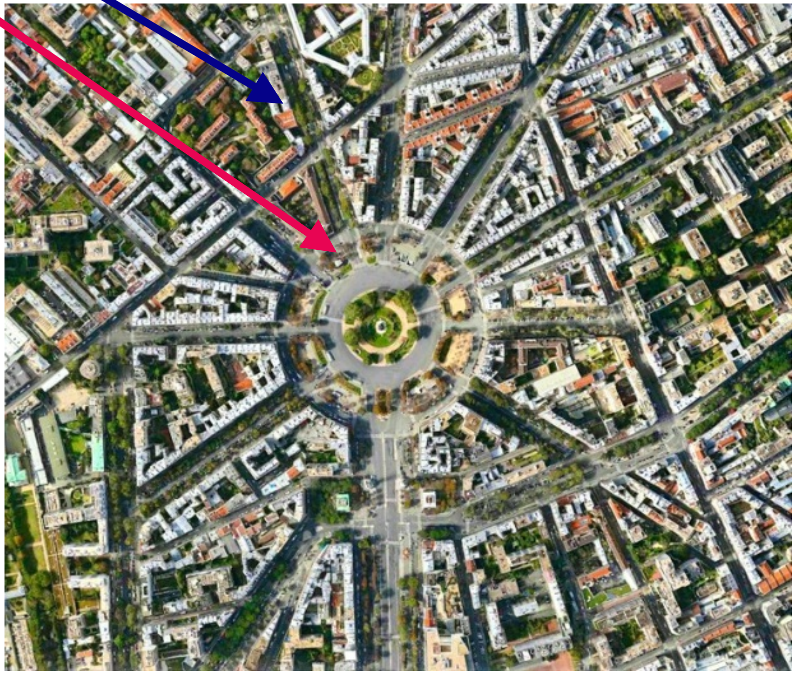


links

nodes

Built Networks - Urban Road Networks (1/4)

- Links ↔ road segments
- Nodes ↔ crossings/rotaries/branching

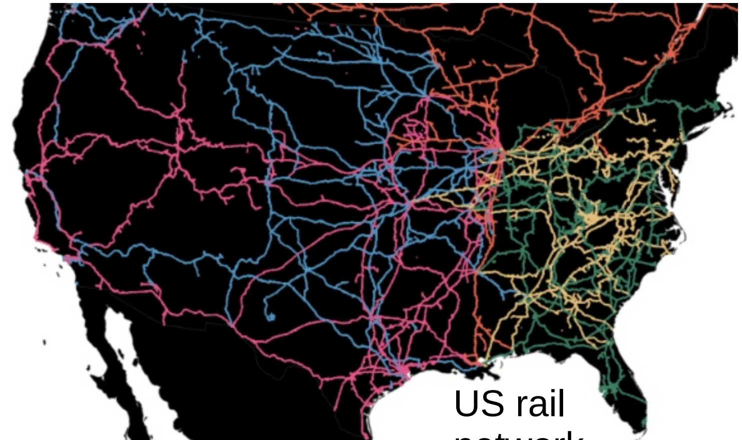


Built Networks - Transportation Networks (2/4)

Link ↔ road/track/line

Node ↔ branching/intersection

Multiplexing ↔ multiple stations on the line

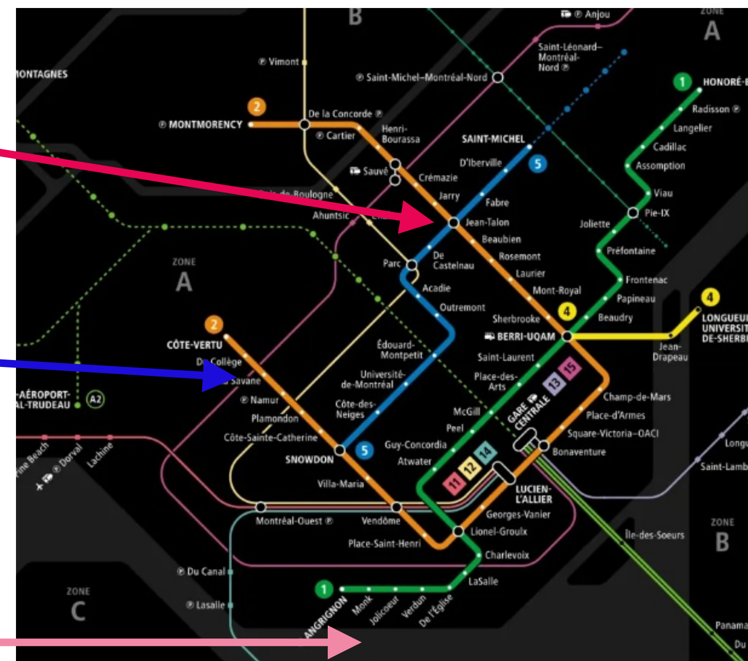


US rail network

nodes

links

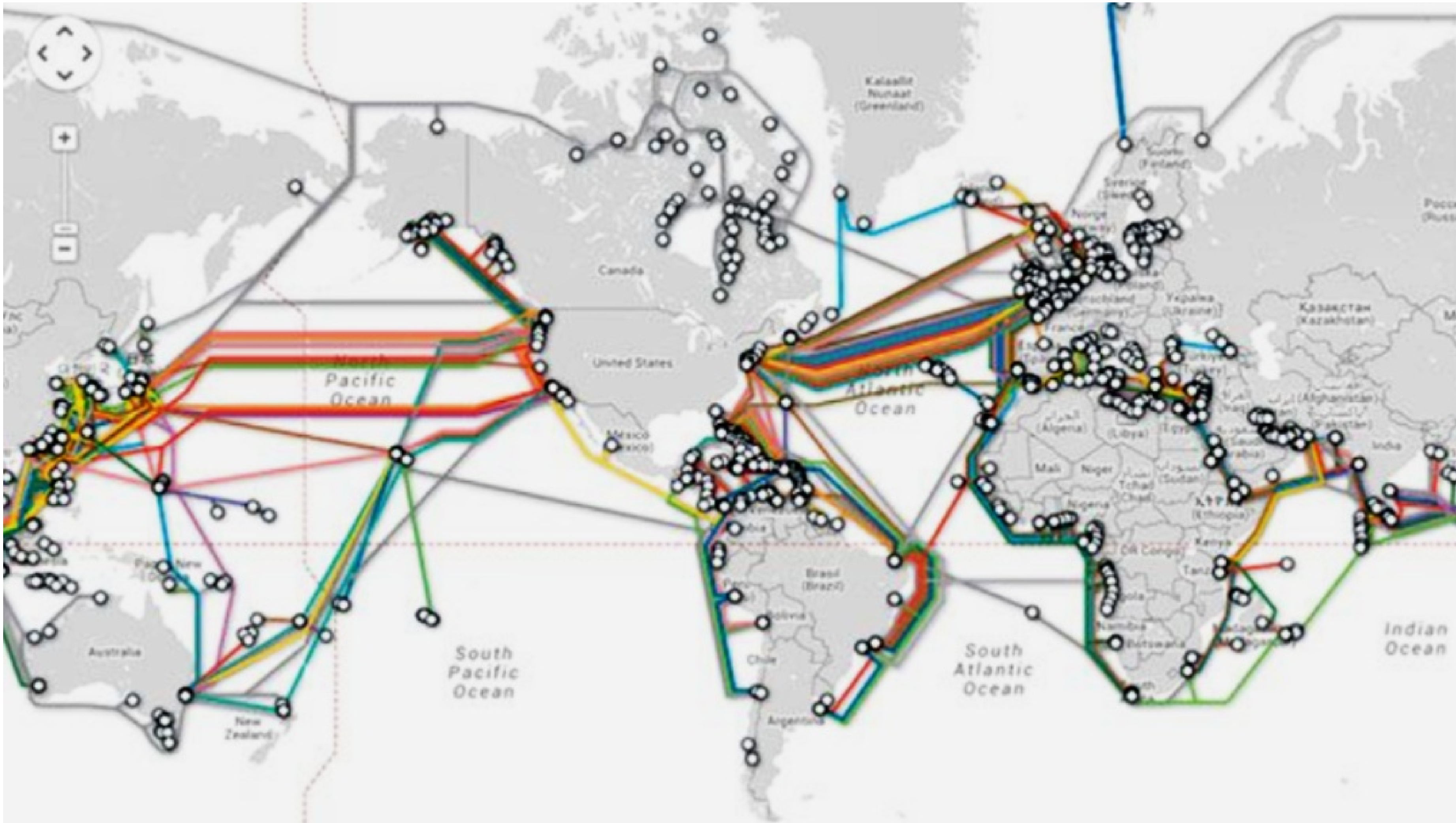
Multiplexing many stations on the line



Road network in N. California

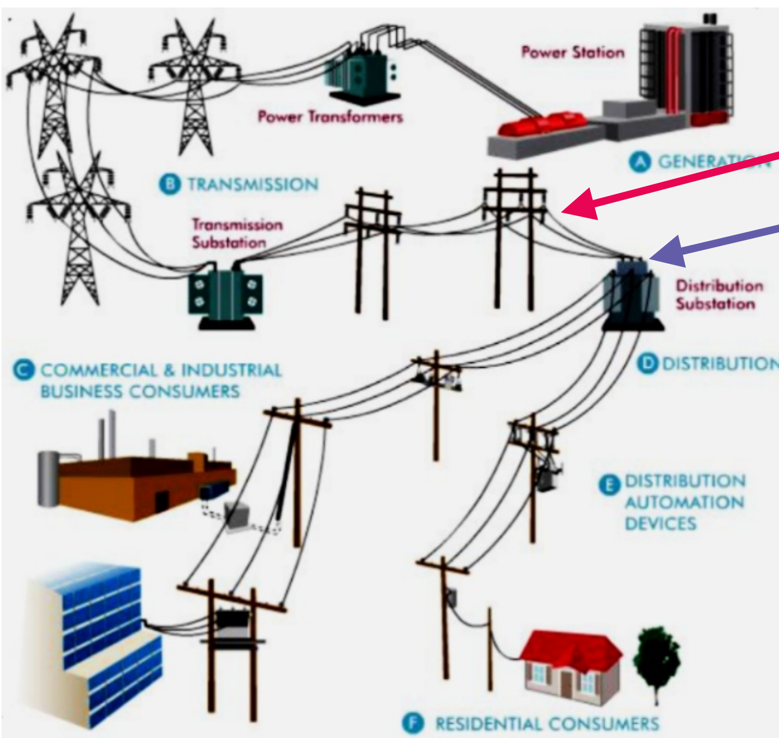
Montreal train and subway/metro network

Built Networks - Telecom&Internet Submarine Cables (3/4)



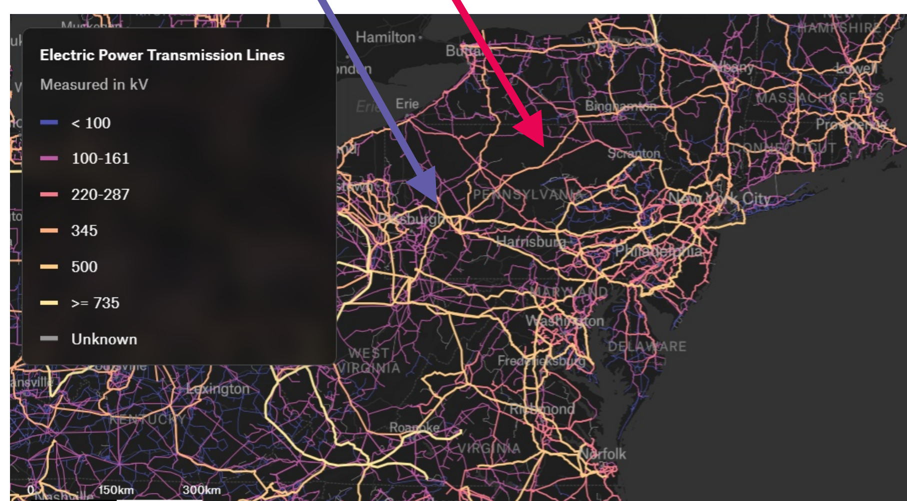
Built Networks - Electricity Grid Networks (4/4)

- Electrical Grids Structure vs Computer Networks:
  - Generators ↔ Hosts/Servers
  - Transmission lines ↔ Links
  - Substations ↔ Nodes/Routers/Switches
  - Consumers (Homes/Companies/Factories) ↔ Computers



links

nodes



New Jersey State Electric Grid

The Internet - Key Historical Milestones (1/2)

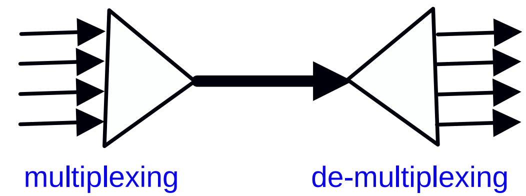
- Mainframe (Host) computers emerged in the 1950's.
- Soon inter-messaging between mainframes emerged:
  - ARPA initiated development studies for packet switched networks in mid 1960s
  - OSI (Open System Interconnection) model: a seven layer model (mid 1970s)
  - IBM SNA based network: a seven layer proprietary system (mid 1970s)
  - X.25 Networks: open packet switched networks (late 1960s) of three layers
  - Modems for long distance connectivity to mainframe computers over voice communication lines
- Optical Fibres for long distance communication (Corning Glass 1970s)
- Microprocessor development (1970s), micro-computers (late 1970s) and mini-computers/servers in 1980s
- Improved TCP/IP Unix Networking (Berkeley's BSD 4.2) in 1984:
  - IP (Internet Protocol) → a packet format that enables the interconnection of networks that uses it
  - TCP (Transfer Control Protocol) → practical packet flow (virtual) pipes over IP networks supporting flow controls and retransmissions
- Multiple access protocols in early 1980s over radio and coaxial cable networks -> Local Area networks (LANs) (Ethernet, token-rings, etc.) to interconnect computers within institutions
- IETF (Internet Engineering Task Force): established in 1986 and guided the formation of internet standards

The Internet - Key Historical Milestones (2/2)

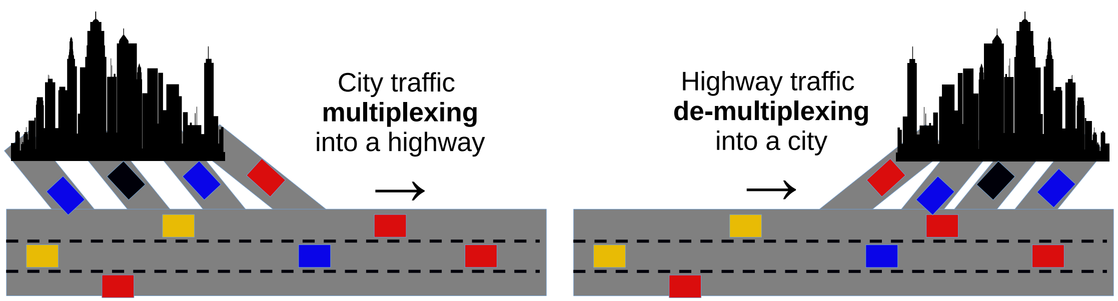
- Stanford U. (late 1980s) → formation of Cisco (early 1990s):
  - Interconnection of LANs using routers →
    Linking computers to (web) servers using TCP/IP protocols →
  - **the network of networks "the Internet"**
- HTML and HTTP:
  - Invented in 1989 by a Tim Berners-Lee at CERN Switzerland → public in early 1990s
  - HyperText Markup Language (HTML): the "Internet Killer Application"
    - A rich language to write web pages with hyperlinks, images, graphics, etc.
    - HTML based browsers (e.g., Netscape) became very popular and fuelled the internet growth
  - Hyper-Text Transfer Protocol (HTTP): defines how information are exchanged between a web browser and a web server
- Post 1995 (in an approximate chronological order):
  - Fast Ethernet (100 Mbps)/Gigabit Ethernet switches → Ethernet dominates LANs
  - Strides in transmission speeds, switching speeds, wireless access routers (WiFi) ...
  - New protocols especially VOIP (Voice Over IP) and multimedia protocols (e.g., SIP)
  - IP networks with QoS/MPLS support replace circuit switched and ATM voice core nets
  - Metro-Ethernet (extended LAN technology) extends Ethernet to metropolitan area networks
  - Cloud computing
  - Internet Broadband (high speed) access over Fiber/VDSL/Cable → video services
  - Convergence with 4G/5G cellular telecom networks → wireless IP multimedia services

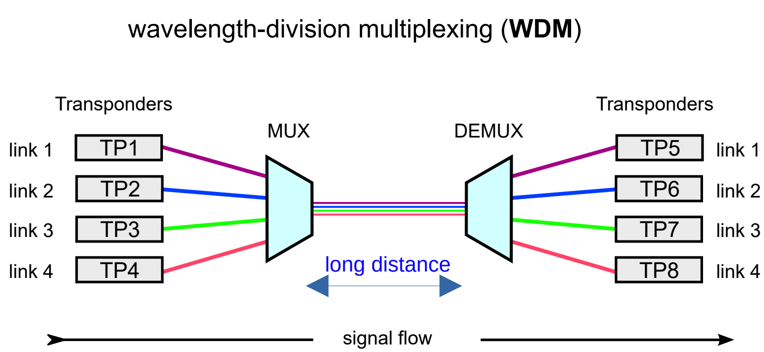
Networks - Key Concepts (1/4)

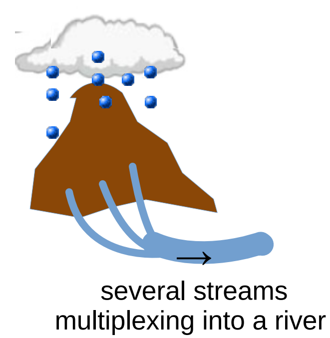
- **Mutiplexing:** the joining of several sources/links/flows into a single (bigger) source/link/flow
  - Utility: increased resource usage efficiency
  - Problems: potential congestion and instabilities

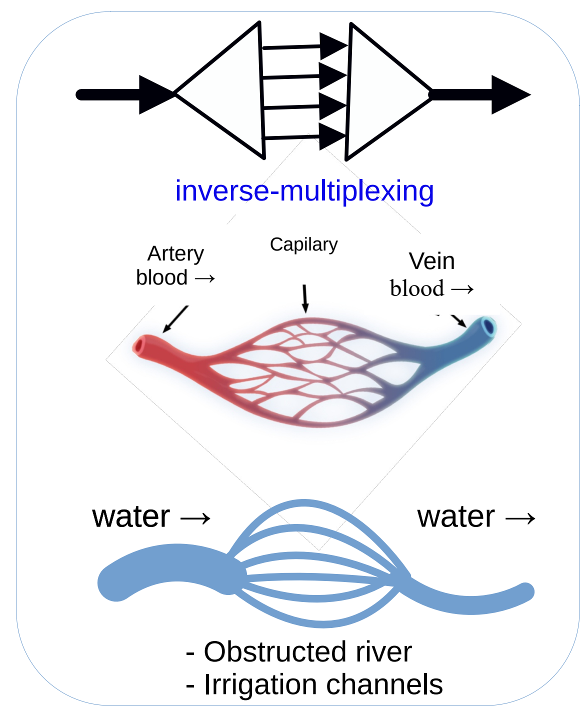


- **De-multiplexing:** the inverse of an existing multiplexing operation
- **Inverse multiplexing:** partitioning activities/flows into many activities/flows
  - Utility: if a single “small” resource cannot handle a large incoming activity/flow → use several resources



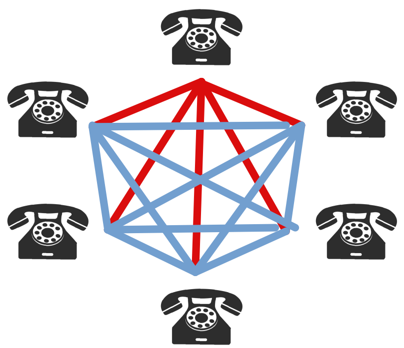




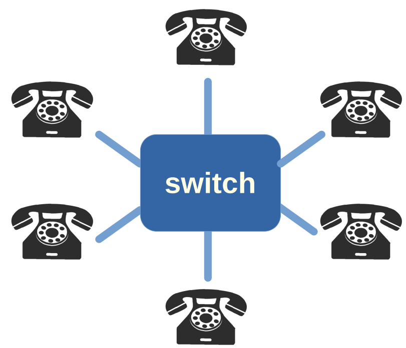


Networks - Key Concepts (2/4)

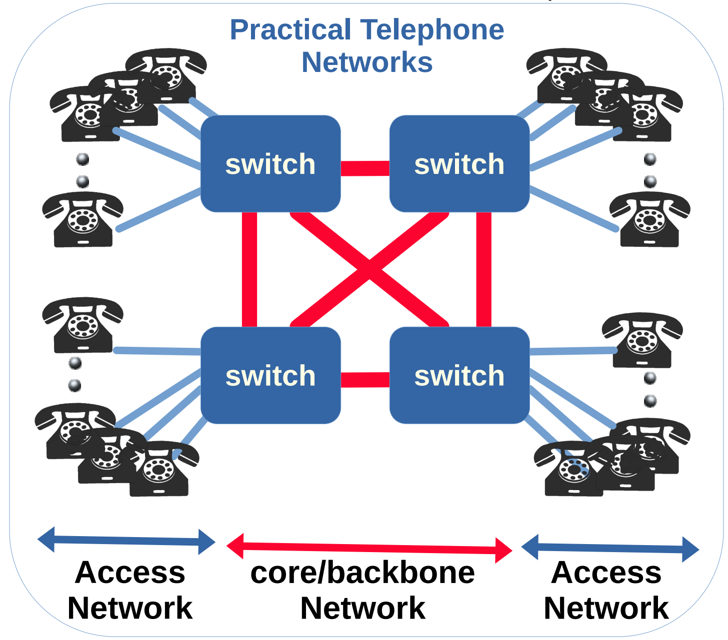
- **Switch/Router**:a node that alleviates the need for many point-to-point links
  - <u>Structure</u>: a device/place with several ports that links connect to
  - <u>Function:</u> forwards incoming traffic to one port to leave on another port (based on some control system functionality)
  - <u>Utility</u>: **drastically reduces the number of links in a network** (by confining this connectivity complexity to the inside of the switch/router → a switch/router is a network within the network)

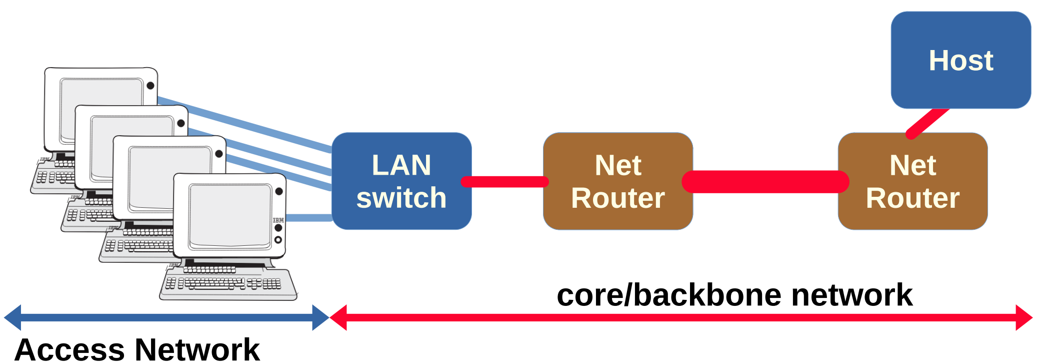


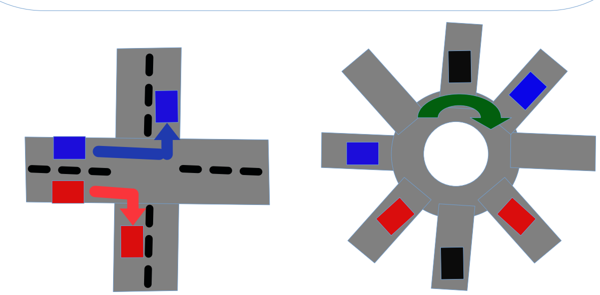
#Links = 6*5/2 = 15
For N phones → N*(N-1)/2 links
For 1000 phones → 499500 links



#Links = 6
For N phones → **N** links
For 1000 phones → 1000 links

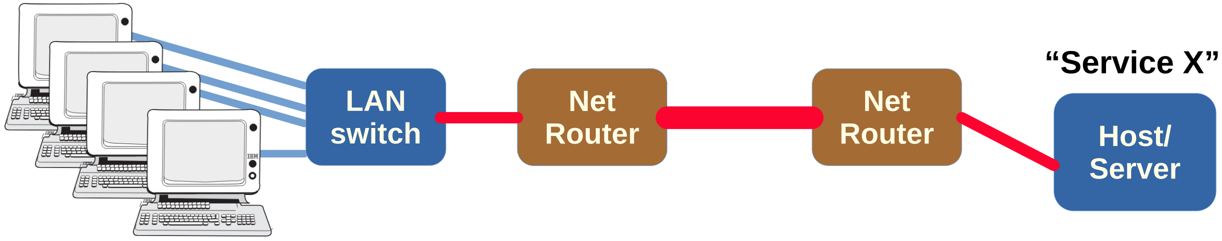






Networks - Key Concepts (3/4)

- **Network based Resource Sharing:**
  - **Benefits: improved resource utilization and service economy**
  - Examples
    - **Computer networks:** accessing specialized information/services on the web
    - **General life:** Airlines/Ship/Train travel, medical treatment, specialized services ....
  - Example: a **costly** to implement "Service X" is **required,** but is **rarely used**.
    - **Without a network:** Every device that needs "Service X" needs to implement it (i.e., as a dedicated service) → major additional cost with a poor resource utilization
    - **With a network:**
      - **Implement the service on a server/host** (i.e., as a shared networked service)
      - When the service is needed by a networked device, **it gets the service from the server/host**
      - Since the server/host services are shared by "many" devices
        - It is used frequently → **improved resources utilization**
        - Sharing → the effective **cost** of "Service X" **per device** falls dramatically



Networks - Key Concepts (4/4)

- **Routing:** A very important aspect of networks seriously impacting performance
  - Function: determination of the paths to be taken by the traffic/messages between node pairs.
  - Types of Routing:
    - **Designed routes:**
      - Optimized routes by optimization algorithms (e.g. min cost/delay, shortest path, etc.)
      - Routes are uploaded into the routing tables of the nodes
      - Update frequency: dependent on technology, traffic pattern changes, etc.
      - Advantages: good optimization, prevention of cycling by design
      - Disadvantages:
        - rigid until the next routing update
        - may not react well to instantaneous traffic changes, congestions/failures
        - requires extensive traffic collection and monitoring capabilities
    - **Adaptive automatic routing:**
      - programs sophisticated adaptive algorithms into nodes that enable optimized route discovery
      - Advantages:
        - Fast reaction to instantaneous traffic changes, congestions/failures
        - Normally, adapts well to the addition/disconnection of nodes → facilitates network expansion
      - Disadvantages:
        - May not be as optimized as designed routing
        - Requires the nodes share many information with their neighbours
        - Nodes may not learn about network conditions not in their vicinity

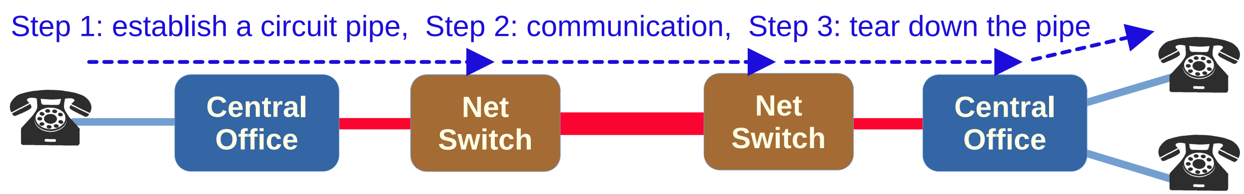
Internet/Telecom Networks – The Complexity Challenge

Large networks are naturally complex. Factors causing complexity:

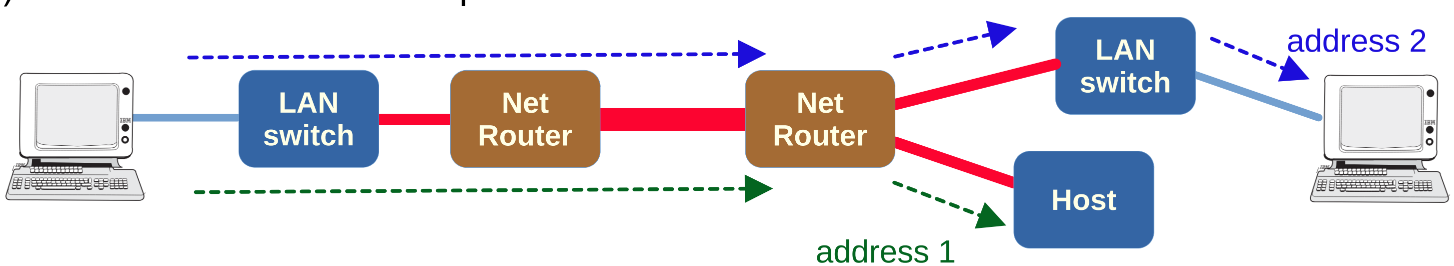
- **Connectivity patterns variations:**
  - Access vs core. Also, different networks geographic parts may have different patterns of connectivity
  - Large networks usually are **a network of networks**
- **Characteristics variation:** Different components have different properties/characteristics. Examples:
  - **Net core routers are faster and more fault tolerant than access routers.**
  - Smart phones are different than computers
  - Video servers are very different than general data servers
- **Many interactions per hour.** Examples**:**
  - Billions of voice calls and web page accesses&searches, not following a regular pattern, with bursty traffic and many control messages
  - Millions of variable multi-megabit per second rates video streams that are sustained over long periods
- **Variable performance:** Network performance **is never static**
  - Loads on the network vary with time (e.g., peaks of video traffic in the evenings and holidays)
  - Mild congestions happen often and alter traffic routing → alter traffic charactersistics throughout the network.
  - Major failures and focussed overloads drastically alter network performance
- **Network and Devices Evolution:** A new (uni-technology) network is relatively simple, but gets complex with
  - Additions of newer generation equipment while continuing to support legacy equipment
  - Interconnects with other networks especially newer generation networks
  - Expansion of its service portfolio, capacity, and geographic coverage
  - Financing since it generally prefers incremental evolution/retrofits over simplifying radical evolution

Communications Networks - Key technologies (1/5)

- (pure) **Circuit Switching:** dominated voice/telephony networks until circa 2010
  - a dedicated communication pipe for the TOTAL duration of the communication session
  - The communication pipe is (a series of interconnected circuits) established between the communicating parties (e.g., two telephones)
  - Inefficient for interactive data traffic:
    - Poor utilization: since data tend not to use the circuit most of the time
    - High initial delay to establish the pipe



- (pure) **Packet Switching:** e.g. UDP
  - Analogous to the postal system
  - No path is established.(e.g., the Internet UDP protocol)
  - Data is sent in (small) **packets** (letter like) between the source and the destination
  - **Packet structure**: **header**+[information payload]+trailer
  - Packets headers carry a **"destination Address"** that is used to control (at any intermediate node) the next link to send the packet over



Communications Networks - Key technologies (2/5)

- **Transport Control Protocol (TCP):**
  - Provides (on IP packet switched networks) a **"circuit like connection = virtual circuit (VC)"** between the communicating parties for the TOTAL duration of the communication session
  - Main benefits:
    - In sequence delivery of packets
    - Flow rate control and potentially congestion avoidance
    - Re-transmissions in cases of packet loss or packet integrity errors
  - Like circuits, VCs have **three phases**: (1) establishment, (2) Communication, (3) tear down
  - **TCP Utility:** at the cost of some lost efficiency (due to bigger header than UDP's)
    - TCP provides a much more reliable virtual circuit/pipe than UDP
    - Much better suited for sustained communications over a long time (e.g., file transfer)
- **Multi Protocol Label Switching (MPLS):**
  - Creates a much **simplified hierarchical routing** within the routers of the IP core network
  - Main idea: inside the core network, route based on an added (short) label rather than the (long) IP address
  - Analogous to movement control within airports based on the "boarding pass" instead of "Ticket+Passport"
  - Utility:
    - a clever assignment of MPLS labels → networks of virtual pipes within the core network
    - Stacking MPLS labels → increases the levels of the hierarchy → suitable for large networks
    - High traffic multiplexing on few MPLS labels in the core network → high speed operation

Communications Networks - Key technologies (3/5)

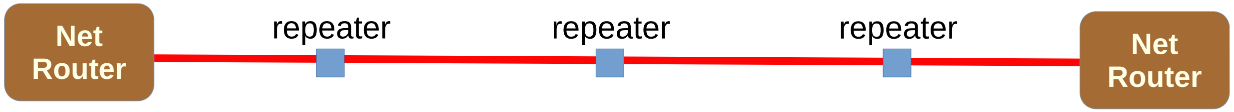
Key capabilities of Data/Computer Networks

- **Flow Control:**
  - Need: not to overwhelm the devices along the path of data packets
  - Example: a (fast) computer sending a document to a remote (slow) printer
  - Solution: protocols that regulate the source transmission process
- **Error Control:**
  - Need: some packets may be lost or arrive corrupted → retransmissions
  - Solutions:
    - Forward Error Correction (FEC), Error/loss detection and re-transmission protocols
    - Better design and technologies of the network (especially transmission links)
- **Congestion Prediction and Control**
  - Causes:
    - traffic has strong random components (random arrival process, routing around congestions/failures, retransmissions, etc.)
    - traffic demand levels change and are difficult to predict
  - Solutions:
    - congestion detection and control protocols/capabilities,
    - better network design and traffic engineering that enables automatic rerouting around congestions/failures without creating a cascade of congestions
    - better network design that reduces traffic choking points (bottlenecks)

Communications Networks - Key technologies (4/5)

Transmission Technologies

- **Analog vs Digital:** At the "physical level" there is no such thing as a digital signal
  - Sending a digital bit stream/flow, is by changing the characteristics (e.g., amplitude, phase, or both) of an analog carrier signal over "a fixed time period" for every digital symbol
  - This process is done at the transmitter, and is reversed at the receiver
- **Digital vs Analog information signal:**
  - The earliest form of modern communication was radio that broadcasted essentially the modulated (analog) electrical signal from microphones (i.e., voice or music) over the air.
  - Telephony networks used this approach initially over wires, and extended their lengths by using "repeaters" that periodically filtered noise and amplified the signal.
  - However, repeaters cannot filter out all the noise nor correction signal distortion/dispersion.
  - So, after few repeaters the signals seriously degrades, and this problem is serious for signals with high information contents
  - Going forward, there are two ways to deal with this problem:
    - Using better transmission media (e.g., fiber optic cables vs wire/coaxial cables) that have lower noise and signal attenuation, or
    - Sending digital information signal and using "digital" repeaters to detect the signal and **"regenerate"** the digital information signal. Moreover, this approach can be enhanced by using **Forward Error Correcting (FEC) codes** where extra (overhead) bits accompany the information bits, and and are used to correct some corrupted bits **without retransmissions**



Communications Networks - Key technologies (5/5)

Transmission Technologies (continued)

- **Bandwidth:**
  - For internet users: “Bandwidth” refers to the bit transmission rate per second on a link
  - However, in transmission technology, it is more detailed:
    - Links are usable only if they carry deliver to the receiver signals with the required fidelity. Naturally, signal degradation is a function of the length of the link and the type of the transmission medium
    - Bandwidth refers to the width the signal occupies in the frequency domain and faster changing signals (that carry more information) have bigger bandwidth.
    - Link bandwidth has three limiting factors: (1) the emitter&receiver, (2) transmission medium, (3) distance
    - The effect of the the last two factors → **(link length)*(media bandwidth)** metric
    - Rationale: lowering the bit rate on a very long distance link may enable it to function properly
    - Since, **this product is highest for fiber optic cables**, they are the preferred media for long distance/haul links
    - Example 1: Over a twisted copper wire pair:
      - VDSL technology can achieve 50 Mbps speeds over a short distance (e.g., curb to home)
      - while the fiber optic cables multiplex the signals from many homes to the far away (several miles) core network
    - Example 2: metroEthernet links (over medium distances) can have 100-400 Gbps bandwidth over fiber, while long haul fiber links generally have max bandwidth of 40 Gbps

The Internet - Key Developments (1/4)

The Internet is old (since 1970s), so why didn't it dominate before 2010s?

Answer: The Internet over time had to overcome several serious issues

- **Limited available speeds, processing power, and memory in early years:**
  - Packet switching is both memory and processing intensive since packet routing and switching involve many **per packet** decisions
  - Higher packet forward speeds → more frequent decisions per unit time
  - <u>Comparison: </u>for a voice call of 5 min with 10 ms packetization
    - Circuit Switching (CS):
      - circuit setup&tear down (minimal processing power and memory at switches)
      - traffic delay is basically propagation delay + (1-2) ms with no jitter (delay variation)
    - Packet Switching (PS):
      - SIP setup and termination messages (similar to CS call setup and tear down)
      - when active (40% of the time) a voice source generates 100 packets/sec → a 5 min voice call generates 100*60*5*0.4= **12 K** packets
      - all these packets need to be routed and switched → **requires huge processing power**
- **Routing Issues:**
  - The Internet did not have any hierarchical routing, and its adaptive routing required periodical procedures to discover the topology of the network →
  - Big overhead as the net expanded, and has occasionally created instabilities
  - (especially) MPLS and BGP added some routing hierarchy but these issues never disappeared especially with IPv6 static addresses and the massive network expansion
  - **Note:** the max hop count in IP packet headers is used to prevent excessive cycling of packets when the adaptive routing tables may contain cycles

The Internet - Key Developments (2/4)

- **Limited transmission speeds in early years:**
  - Over long distances, data lines either used modems over telephony lines (2.4 → 56 Kbps) In the core network, T1 (1.54 Kbps) lines were expensive, and T3 (45 Mbps) were luxuary
  - Local Area Networks (LANs) (short distances within a small building): 2-10 Mbps speeds
  - Such speeds are only capable of low bit rate data applications
  - Note: 10 Mbps LANs had the potential (but never happened) to carry few voice calls
- **Limited Switch/Router capacity in early years:**
  - Up to the mid 1990s, switches had limited port speeds and switching fabric speeds
  - Indeed, within the switch box, many switches had a LAN type of switching among the ports. e.g., an Ethernet bus, or a single/double rings).
  - So, the total switching speeds inside the bus did not exceed 10-20 Mbps. Hence the switch cannot accommodate many ports especially if they are high speed ports
- **Very Limited Network Management (NM) Systems**
  - **Network management in the Internet was really an after thought**
  - The Simple Network Management System (SNMP) standard v1 is very limited system that relies on polling nodes to request measurements
  - The Remote Monitoring (RMON) standard specified mechanisms for nodes to periodically report measurements remedied the situation somewhat
  - SNMP v2 had it shares of problems (e.g., network security)
- By comparison, until mid 90s, **specialized voice communications and video broadcast networks** were: (1) quite capable, and (2) had sophisticated network management systems

The Internet - Key Developments (3/4)

- **Starting in mid 1990s:**
  - The internet had a killer application (i.e., web browsing), and emails became common practice
  - This demand fuelled growth and accelerated development strides in transmission and switching speeds:
    - Emergence of Fast Ethernet (100 Mbps) switches, followed by the Gigabit Ethernet standards and switch dominated LANs
    - Transmission speeds over long distance/haul fiber reached 40 Gbps
    - The very low bits error rates 10^{-9} to 10^{-12} over fibers (compared to 10^{-6} over coaxial cables), meant that a data link speed approached the transmission speed (with very low Forward Error Correction (FEC) overhead)
    - Large scale packet routers/switches have emerged. This booasted the capacity of the core network and provided several Qualities of Serices (QoS) that can handle data, voice, and video traffic
    - MetroEthernet in early 2000s, extended the Ethernet from a local area LAN technology to metropolitan areas
    - MetroEthernet v2 in early 2010s: higher transmission speeds and supported QoS
    - Today, MetroEthernet supports 100 and 400 Gbps links

- The Session Initiation Protocol (SIP) dominated multimedia (data, voice, and video) call/session control replacing the voice network SS7 signaling protocol

The Internet - Key Developments (4/4)

- **Starting in mid 1990s (continued):**
  - **Broadband connectivity to homes:**
    - In late 1990s, video service providers over cable networks started to offer voice communications (Voice over IP) and data services by taking advantage of their broadband cable access → competition with voice communication operators
    - As a result, voice operators extended fiber optic links (broadband) from the core network to the access network (i.e. the last mile):
      - (pure) Fibers to the home (FTTH) for new homes using xPON technologies
      - (hybrid) Fibers to the curb (FTTC) with VDSL over copper to existing homes
    - So, the wide availability of broadband access around 2010, has transitioned the internet into being able to provide multimedia (data, voice, and video) services over IP.
    - Today, 30-100 Mbps or even 1 Gbps access speeds are available to many metropolitan areas, and therefore
      - Voice packets of 10-20 ms get transmitted in microseconds, and are delivered with a delay of 10-20 ms with 1ms jitter. Thus VOIP feels like circuit switched voice service.
      - Similarly, video services perform as well as traditional video services over cable networks
      - Long data file transfers take place in milliseconds to seconds
  - New network management protocols and **systems** for the internet have emerged and matched the capabilities of similar systems in traditional specialized networks