Computer Networks

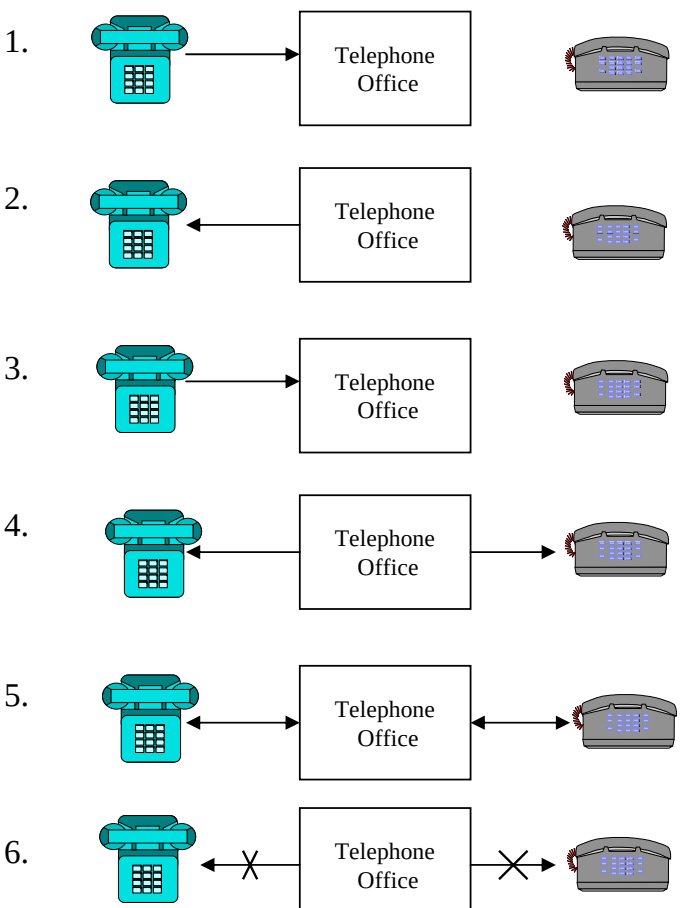
- Operation of modern communication networks highly complex
  - developed originally from telephone networks
  - interaction between many disparate systems
  - an overall coherent structure difficult to find
  - new subsystems incorporated rapidly as technology develops
- Aim here to place components in the context of the overall network
  - networks traditionally driven by the services they provide e.g. email
- Design of networks to achieve these services
  - essential functions all networks must provide
  - approaches: message switching, circuit switching and packet switching
  - development with changing technology and prevailing regulatory and business environment

- Transport Networks:
  - road and railway networks *enable* one basic service
    - » transfer of *objects*
  - which in turn enables other services
    - » postal service, passenger transport, freight transport
- Communications Networks:
  - set of equipment and facilities to transfer *information* between users at different geographical locations
    - » telephone networks, computer networks, broadcast and cable television networks, cellular telephone networks, the Internet etc.
  - an *enabling* technology which allows development of a multiplicity of new services, now and in the *future*
    - » telephone networks enable other services:
      - fax, modem, voice messaging, credit-card validation etc.
    - » the Internet provides transfer of information packets and enables services:
      - email, web browsing, e-commerce etc.

- an essential *infrastructure* of modern society
  - » pervasive in virtually all commercial activities
- can be extremely flexible and resilient in use
- communications networks work at *the speed of light* and *at very high rates*
  - » information can be gathered in very large volumes
- exchange of information enables *interaction at a distance* nearly instantaneously

- Radio and television
  - broadcasting signals simultaneously to all
  - relatively high quality audio and video expected
  - delay (seconds or more) can be tolerated even for *live* events
  - discontinuous glitches not tolerable
  - passive users
  - relatively high rate of information transfer for video

- Telephone service
  - "connection oriented"
    - » users must first interact with the network to set up a connection:



The caller picks up the phone triggering the flow of current in wires that connect to the telephone office.

The current is detected and a dial tone is transmitted by the telephone office to indicate that it is ready to receive the destination number.

The caller sends this number by pushing the keys on the telephone set. Each key generates a pair of tones that specify a number. (In the older phone sets the user dials a number which in turn generates a corresponding number of pulses.)

The equipment in the telephone office then uses the telephone network to attempt a connection. If the destination telephone busy, then a busy tone is returned to the caller. If the destination telephone is idle, then ringing signals are sent to both the originating and destination telephones.

The ringing signals are discontinued when the destination phone is picked up and communication can then proceed.

Either of the users terminate the call by putting down a receiver.

– real-time requirement for normal interaction: delays must be less than 0.25s
  » can be problematic for connections via geostationary satellites
– must be a reliable connection i.e. not dropped in middle of conversation
– a high degree of availability required i.e. whenever wanted
– voice signal quality must be adequate for intelligibility and intonation
  » but users have been brought up not to expect hi-fi
– security and privacy desirable
– enhanced services:
  » 0800 free calls
  » 0845 local charging rate calls
  » premium rate calls
  » credit-card calls
  » call-return
  » caller ID
  » voice mail
  » etc. etc.

- Cellular telephone service
  - mobility of users within an area covered by cells
    - » 98% of UK *population* coverage typical but *not* 98% of land area!
  - radio transmission may imply compromises:
    - » lower voice quality
    - » lower availability
    - » exposure to eavesdropping
  - system must handle *handing off* when users move from cell to cell
    - » automatic and transparent to user
  - providers may permit a *roaming* service
    - » use of services in another providers country or region
    - » requires agreement on *standards* e.g. GSM
  - being developed to provide higher-level services:
    - » WAP, GPRS (2½G), 3G/UMTS

- Email services
  - text messages and audio/video attachments to a specific email address
  - local mail server transmits to a destination mail server across the network
  - mail applications to retrieve mail from mail server
    - » storage of messages until retrieval by user the most important aspect
  - *not* a real-time service
    - » relatively large delays can be tolerated
  - not necessarily connection-oriented
    - » a connection does not need to be set up expressly for each message
  - reliability required
    - » in terms of likelihood of message reaching its destination without errors
    - » possible to request delivery confirmation
  - security and privacy a concern

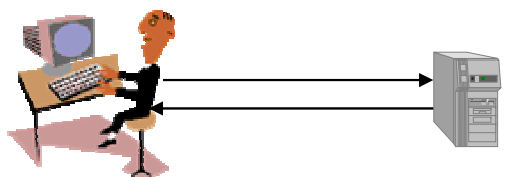
- Web browsing
  - client/server interaction and use of URLs and HTTP:

1. 

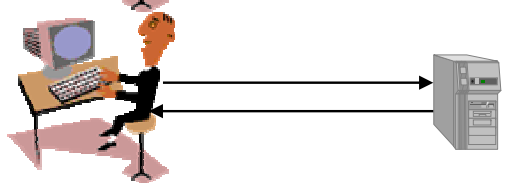
The user clicks on a link to indicate which document is to be retrieved.

2. 

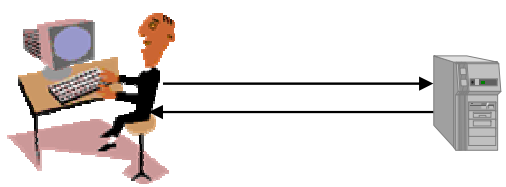
The browser must determine the address that contains the document. It does this by sending a query to its local name server.

3. 

Once the address is known the browser establishes a connection to the specified machine, usually a TCP connection. In order for the connection to be successful, the specified machine must be ready to accept TCP connections.

4. 

The browser runs a client version of HTTP, which issues a request specifying both the name of the document and the possible document formats it can handle.

5. 

The machine that contains the requested document runs a server version of HTTP. It reacts to the HTTP request by sending an HTTP response which contains the desired document in the appropriate format.

6. 

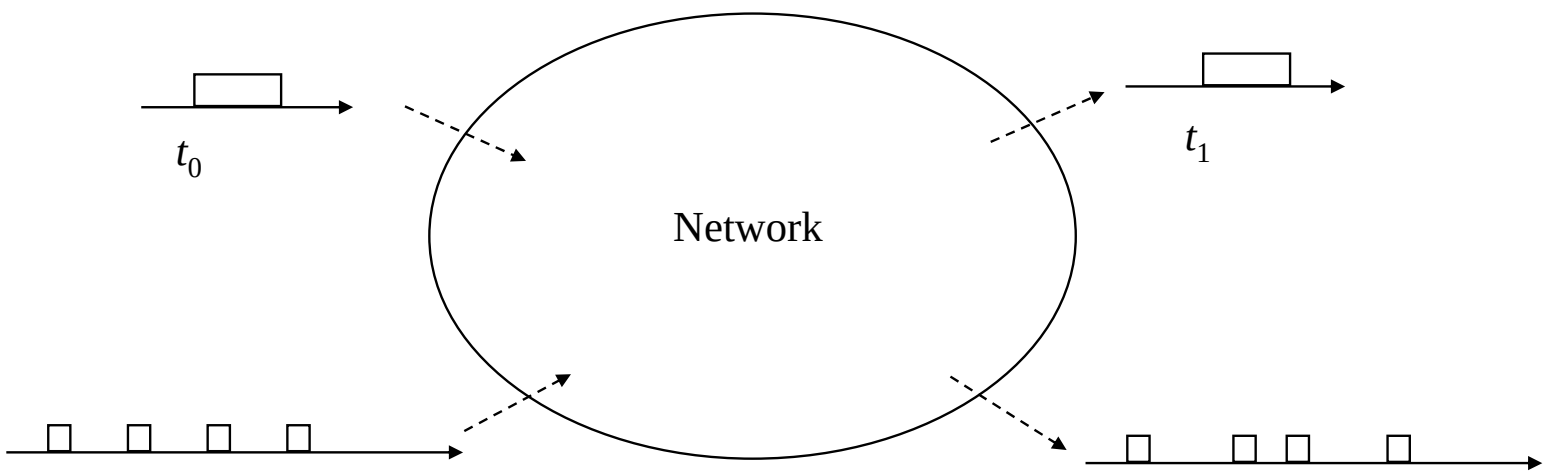
The TCP connection is then closed and the user may view the document.

- Video on Demand
  - access to a video “jukebox” at some remote site whenever the user wants
  - to provide the same controls as a VCR
    - » slow motion, fast forward, reverse, freeze frame, pause etc.
  - transactions to start the service:
    - » selection from an interactive menu
    - » payment (privacy and security a concern)
  - server transmits video information frame-by-frame as required
    - » probably too much information to transfer whole video and store it
      - but becoming possible with large discs
    - » adequate buffering required to avoid *jitter*
  - not real-time
    - » delay tolerable as long as VCR-type controls not severely affected
  - simpler “batching” of near-simultaneous user requests not adequate
    - » VCR controls not possible unless stream of video unique to each user
    - » but saves considerable retransferring of data

- Streamed audiovisual services
  - applications such as *RealPlayer* provide features of video on demand
  - the video stream starts playing as soon as the connection is initiated
  - limited interactivity
  - poorer quality than broadcast TV or DVD due to bandwidth limitations
- Audio conferencing
  - exchange of voice signals between multiple users
  - network must provide group connectivity
  - interpersonal interaction can be awkward due to lack of visual cues
- Video conferencing
  - seminars, business meetings, remote surgery
  - avoids expensive travel
  - high bandwidth required
  - much delay not tolerable
  - interpersonal interaction better but not perfect

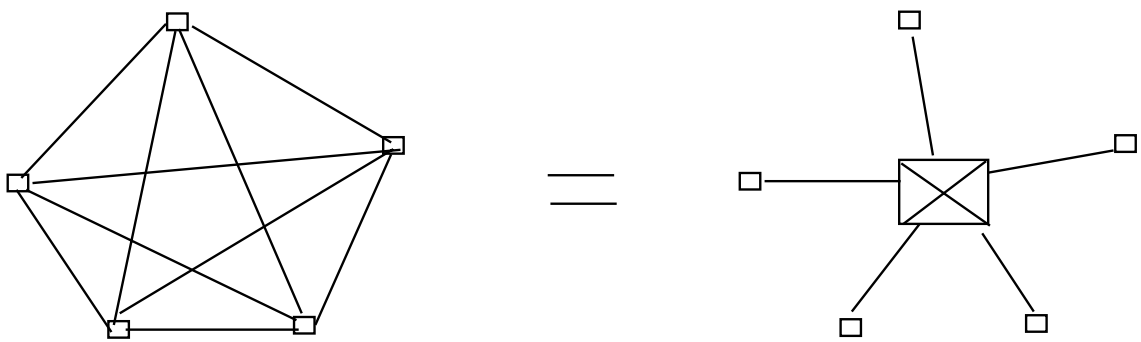
Approaches to Network Design

- Networks provide connectivity between users through a *transmission system*
  - using various types of physical media: wires, cables, radio, optical fibre etc.
  - the ability to transfer information between source and destination equipment
    - » single blocks or continuous streams



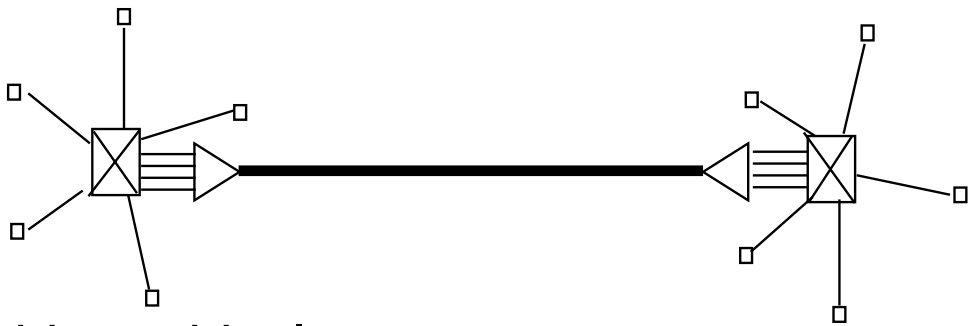
- Cost-effective design necessary to meet user requirements
  - networks usually designed to carry specific types of information
  - voice, TV, bits, characters etc.

- a network consists of point-to-point links interconnected by *switches*
  - for a multi-hop path, *routing* decides which path to take at a switch
  - *forwarding* actually moves the data in the direction decided
- pairwise interconnections would require N*(N-1) lines
  - hence a central switching *access network*, and just N access lines

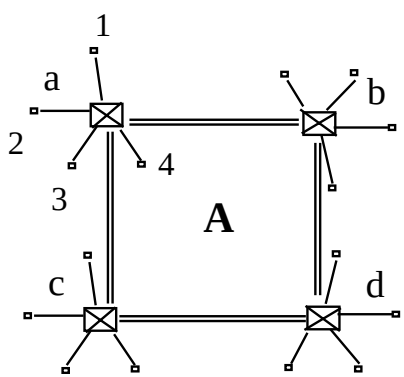


  - switches placed where it makes economic sense
    - » where there is a *community of interest* of users wishing to intercommunicate
      - users typically communicate most with other local users, within one switch
    - » but usage pattern changing as cost becoming less dependent on distance
      - distant transfers increasing with distributed communities

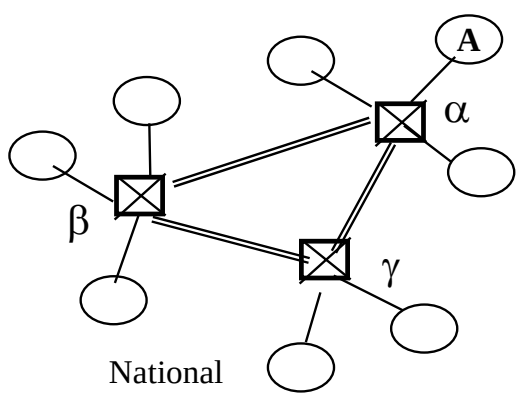
- Connections between local communities use *trunks* between local switches
  - *multiplexers* concentrate the traffic over the more expensive line
  - *demultiplexers* separate out the individual parts of the traffic for distribution



- Networks are hierarchical:
  - metropolitan networks interconnect access networks
  - regional networks connect metropolitan networks
  - national networks, international networks etc. using *backbone networks*



Metropolitan

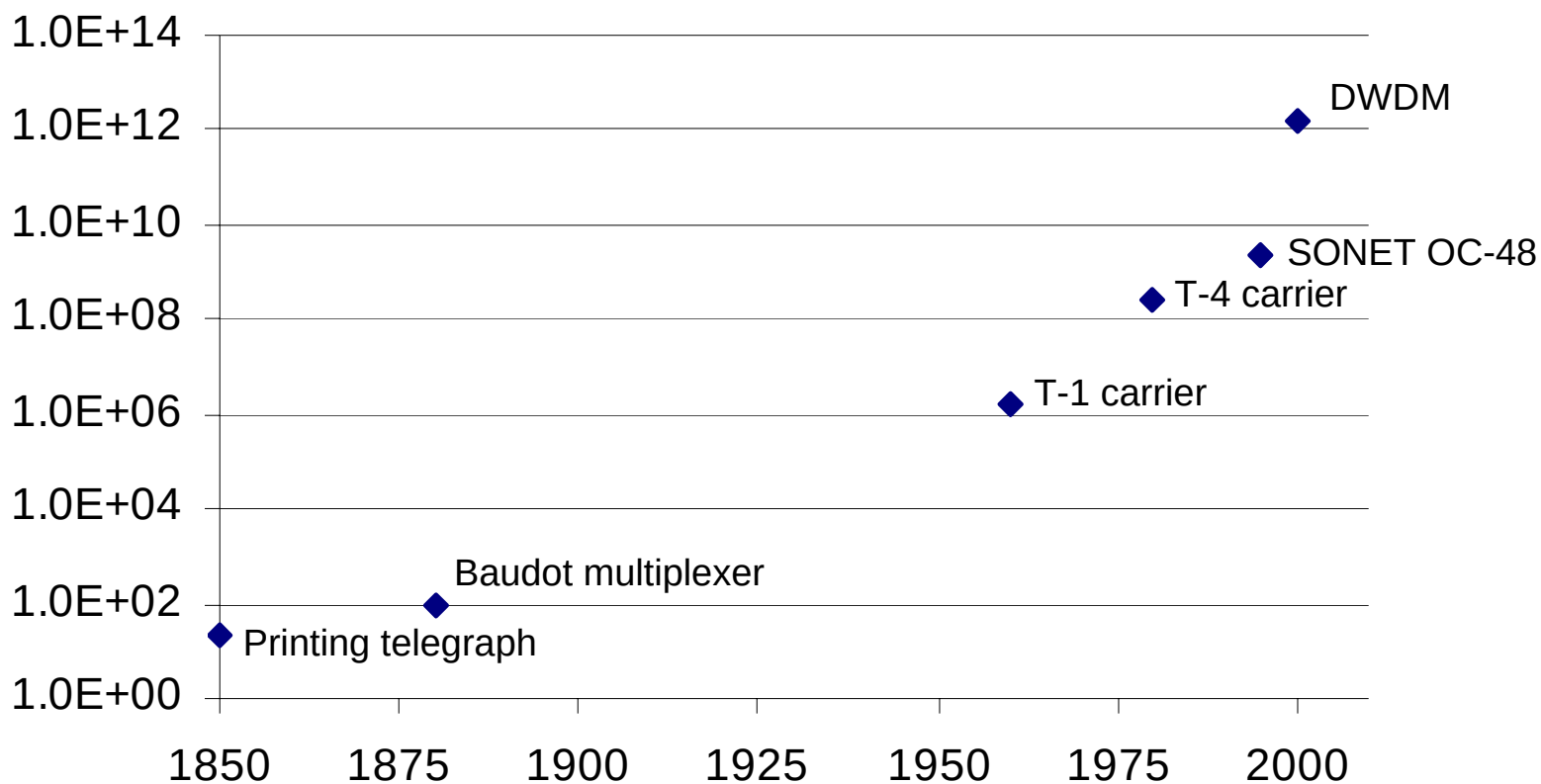


National

- Addressing required to identify source and destination end-points
  - *hierarchical* addressing uses common prefixes for end-points in the same geographical areas
    - » facilitates routing
    - » as in a postal address: country, county, town, district, street, number; the Post Office batches mail for countries and for towns, districts, streets etc.
  - hierarchical addressing in *Wide Area Networks* e.g. the Internet
    - » also facilitates routing
  - flat addressing in *Local Area Networks* e.g. ethernets
    - » adequate for the typically small number of local area end-points
- Traffic controls necessary to ensure smooth network operation
  - congestion and overload control mechanisms required
  - the Internet is resilient in that alternative routes are usually available
- Network management required
  - performance monitoring, detection and recovery from faults, configuration and reconfiguration, accounting information, security etc.

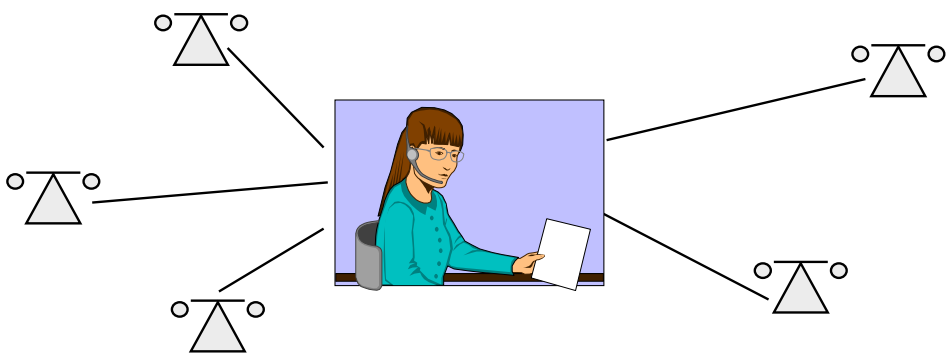
Function	Telegraph Network	Telephone Network	Internet
Basic user	Transmission of telegrams	Bidirectional, real-time transfer of voice signals	Datagram and reliable stream service
Switching approach	Message switching	Circuit switching	Connectionless packet switching
Terminal	Telegraph, teletype	Telephone, modem	Computer
Information representation	Morse, Baudot, ASCII	Analogue voice or PCM digital voice	Any binary information
Transmission system	Digital over various media	Analogue and digital over various media	Digital over various media
Addressing	Geographical addresses	Hierarchical numbering plan	Hierarchical address space
Routing	Manual routing	Route selected during call setup	Each packet routed independently
Multiplexing	Character & message multiplexing	Circuit multiplexing	Packet multiplexing, shared media access networks

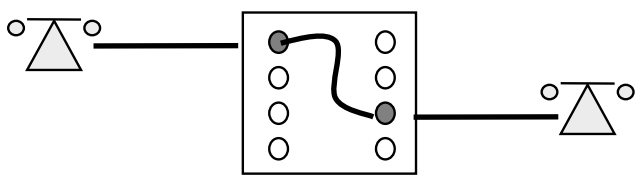
Evolution of telecommunications capacity



- Telegraph networks and Message switching
  - a telegram service using Morse-coded text
  - a digital transmission system
    - » dots and dashes efficiently coded depending on usage frequency
  - human operators at intermediate telegraph stations stored incoming messages, chose the route of the next hop and forwarded them on
  - 25-30 words per minute for a good operator
    - » equivalent to about 20 bits per second
  - Baudot multiplexing interleaved characters from several operators onto one line
    - » equivalent to about 120 bits per second
  - led to ASCII code and teletype terminals for automatic transmit and receive
  - frequency multiplexing
    - » uses sinusoidal pulses of differing frequencies over one line
    - » one frequency to represent a “0”, another to represent “1”
    - » use multiple pairs of frequencies for multiplexing several messages

- Telephone networks
  - Alexander Graham Bell (born in Charlotte Square, Edinburgh)
  - analogue signal voice transmission
  - switching by means of human operators and patch cord panels
    - » caller requests connection to destination by speaking to operator
    - » operator makes patch cord connections





  - *connection-oriented* circuit switching
    - » routing decisions made at call setup time
    - » no additional addressing information needed during call
  - dedicated end-to-end connection maintained for the duration of the call

– gradual transition to today's all digital transmission and computer technology

– pulse code modulation (PCM) converts analogue to digital

  » one voice channel : 64Kbps

– T-1 digital transmission system (USA), first deployed 1962

  » to carry voice traffic between Central Offices

  » multiplexed 24 voice calls at 1.5Mbps

– original analogue switches required intermediate D-to-A and A-to-D converters

  » development of digital switches avoided this

  » only converted back to analogue for the "final mile" to end user

– hierarchical networks:

  » Central Office access networks connected to *Tandem Switches*

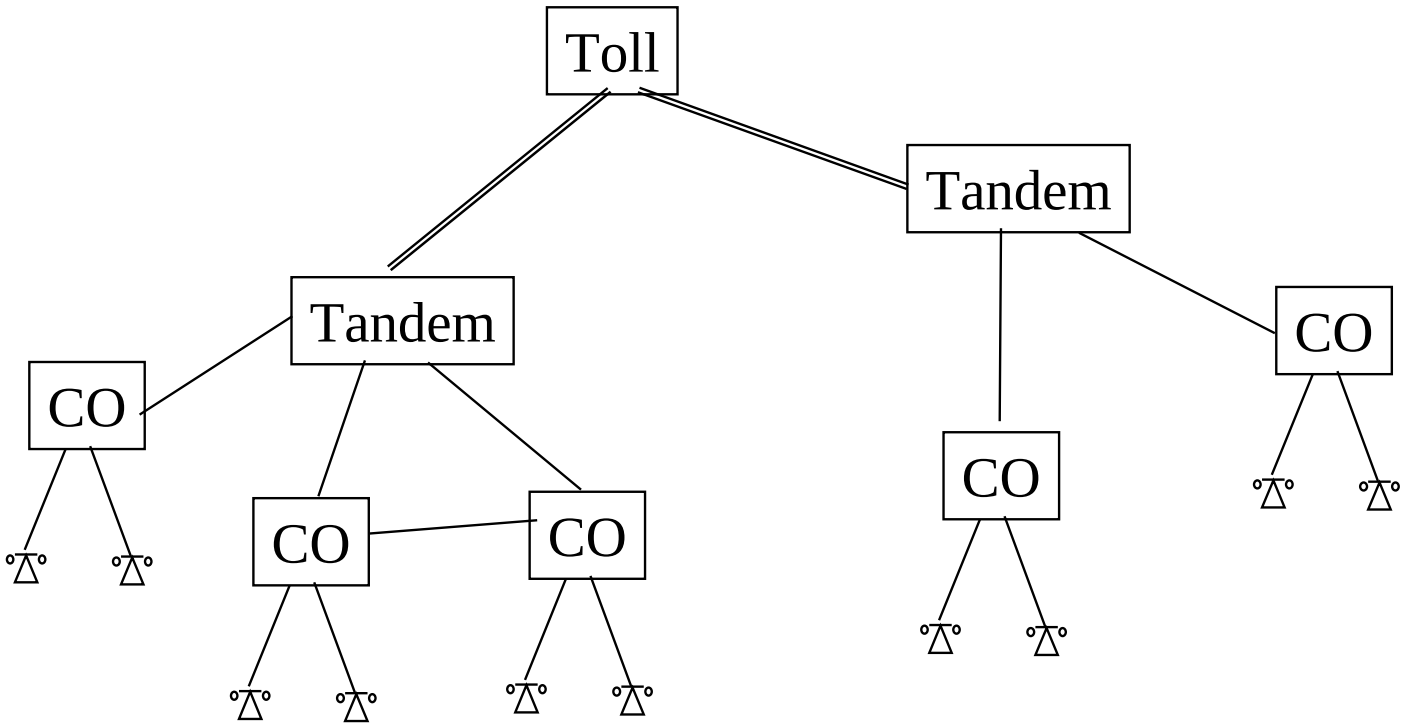
  » Tandem Switches to *Toll Switches*

– multiplexing onto higher speed lines:

  » T-2 : 96 voice channels at 6.3 Mbps

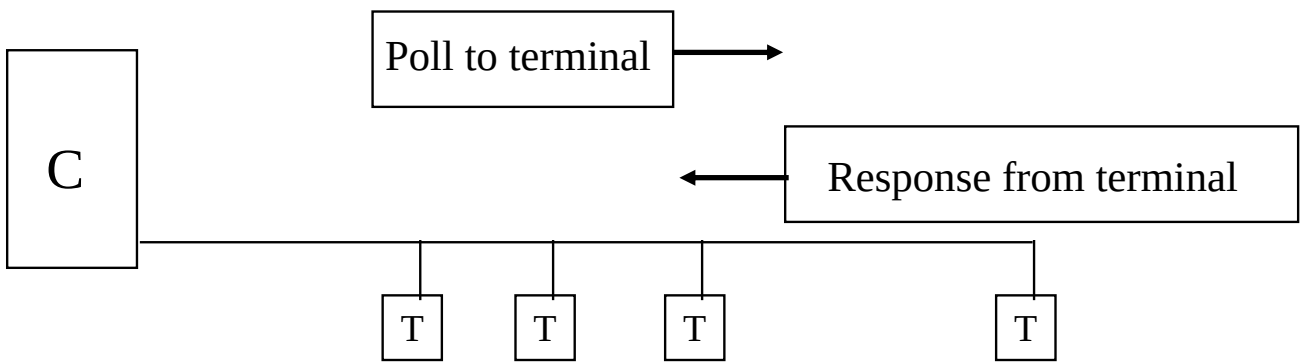
  » T-3 : 672 voice channels at 44.7 Mbps

  » T-4 : 4032 voice channels at 274Mbps

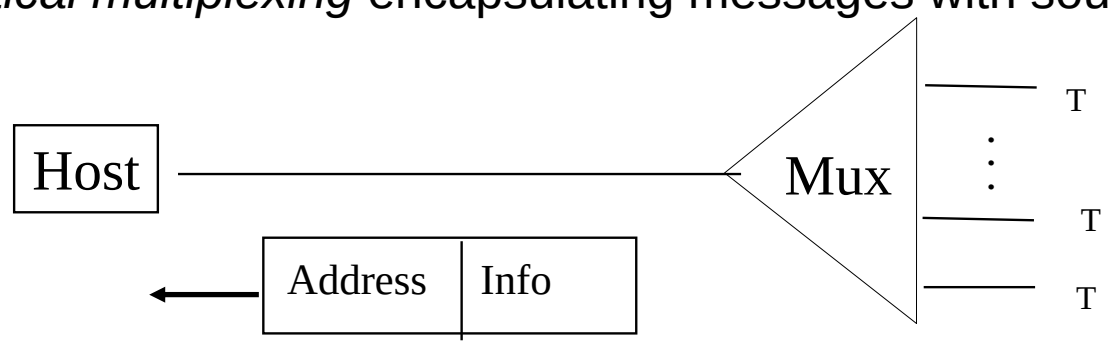


- European hierarchy similar:
  - E-1 : 30 channels : 2.048 Mbps, up to
  - E-5 : 7680 channels : 565 Mbps
- Dense Wave Division Multiplexed optical fibre systems:
  - basic 2.5Gbps and 40Gbps optical channels now multiplexed to Terabyte rates

- The Internet and Packet Switching
  - – the Internet Protocol (IP) provides for transmission of information across multiple, possibly dissimilar, networks
  - – IP (and TCP) emerged from ARPANET in 1960's and 1970's
  - – motivated by multi-access time-sharing systems
    - » characterised by short bursts of interaction from multiple users of the system
    - » line-sharing possible using *multi-drop* lines :

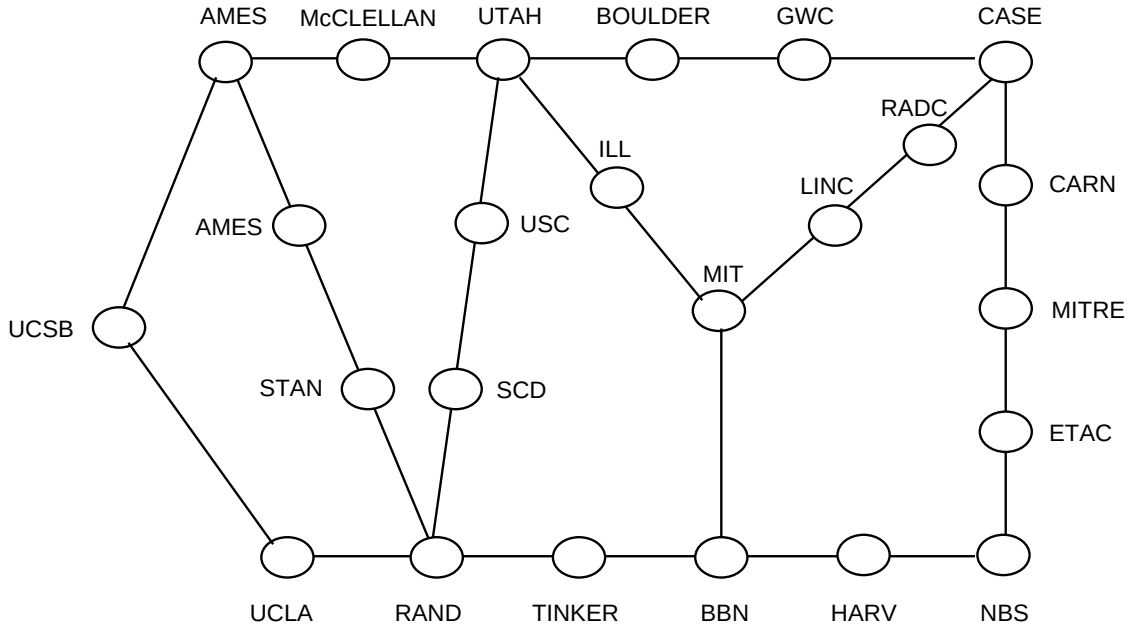


    - » or *statistical multiplexing* encapsulating messages with source address:



– interactive systems require short transit times for good interaction
  » need to impose a limit on the size of messages to the system
  » long messages might hold up interactive users
– *packet switching* addresses this problem
– *connectionless* or *datagram* packet transfer:
  » each packet routed independently of all other packets
  » as used in ARPANET and the Internet
– alternative is *virtual circuit* packet transfer
  » a route set up through switches and links in the network
  » all subsequent packets forwarded along the same path
    - used by Asynchronous Transfer Mode (ATM) networks
– an Arpanet packet consisted of:
  » a header containing a destination address
  » a data part, up to 1000 bits longs
– packet switches from BBN (Bolt, Beranek and Newman)
  » interconnected by 56Kbps lines

– Arpanet in 1972:



– each node was a packet switch which

» maintained a routing table specifying the output line for each destination

- used a *distributed route synthesis* algorithm, exchanging information with neighbouring nodes
- resilient to network failure

» contained buffers to hold packets until the line became available

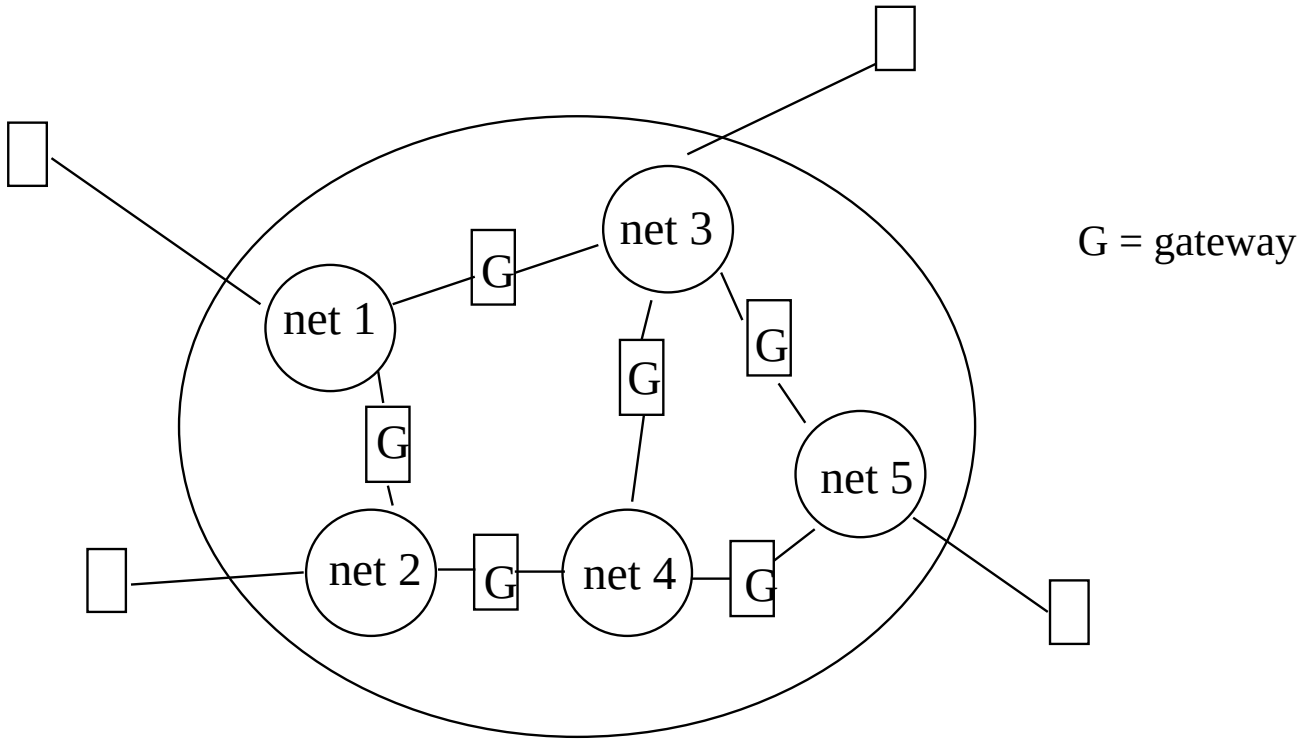
» multiplexed packets from different users onto the links

» no prior allocation of bandwidth or buffering for any user

» end-to-end *flow control* used to limit buffering requirements

» no need for switches to keep *state* information about users or packet flows

– an *internetwork* involves the interconnection of multiple networks:



– the Internet Protocol (IP) was developed to provide connectionless transfer of packets across an internet

– the component networks are interconnected by packets switches called *gateways* or *routers*, which direct the transfer of packets

– the underlying networks are responsible for transferring packets between routers

– IP provides a *best-effort* service:

» does its best but takes no additional action when packets are lost, corrupted, delivered out of order or misdirected

» an *unreliable* service to avoid complexity

» reliability can be achieved by embedding IP packets in higher level protocols

- e.g. the TCP protocol
- but more costly in time and bandwidth

– IP uses a limited *hierarchical address space* that has location information embedded in the structure

» (in IPv4) address consists of 32bits e.g. 129.215.58.7

- address 7 on the 129.215.58.0 sub-network

» allows routers to handle addresses with same prefix in the same manner

– the DNS (Domain Name System) provides more user-friendly textual equivalents

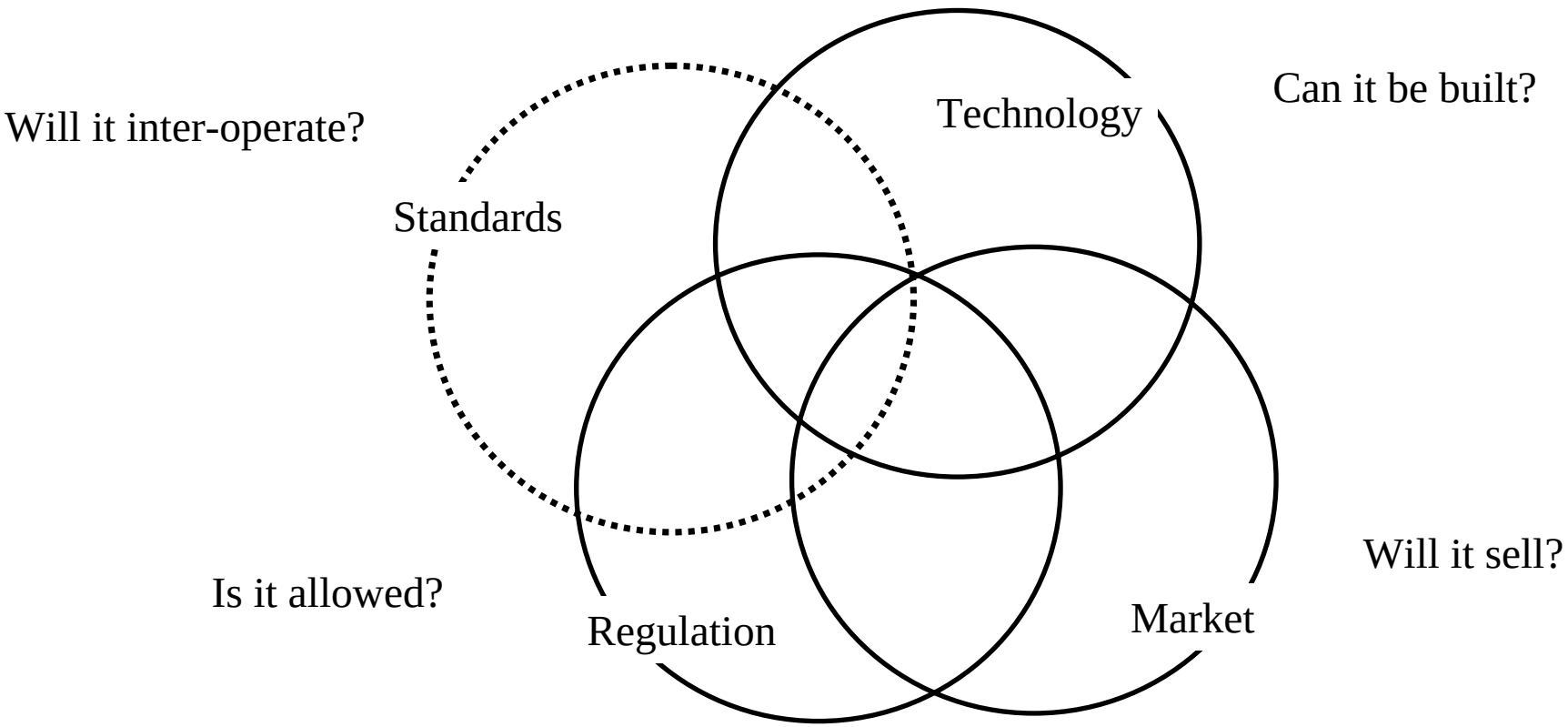
» e.g. heriot.dcs.ed.ac.uk

» translation to IP addresses provided by DNS servers

- the Transmission Control Protocol (TCP)
  - operates in a pair of end hosts across an IP internet
  - provides reliable transmission of a stream of information
    - » organises retransmission when packets in error
  - packets provided in the correct order
  - includes a mechanism for flow control when congestion occurs
  - complexity of TCP relegated to *edges of the network*
  - *Quality of Service (QoS)* issues remain
    - » e.g. guaranteed bandwidth, latency etc.
- ATM networks developed to address QoS issues
  - allows negotiation between user and network for:
    - » packet loss ratio i.e. proportion of packets lost
    - » packet transfer delay, including propagation delay, queuing delays etc
    - » packet delay variation
  - effectively a guaranteed bandwidth can be negotiated

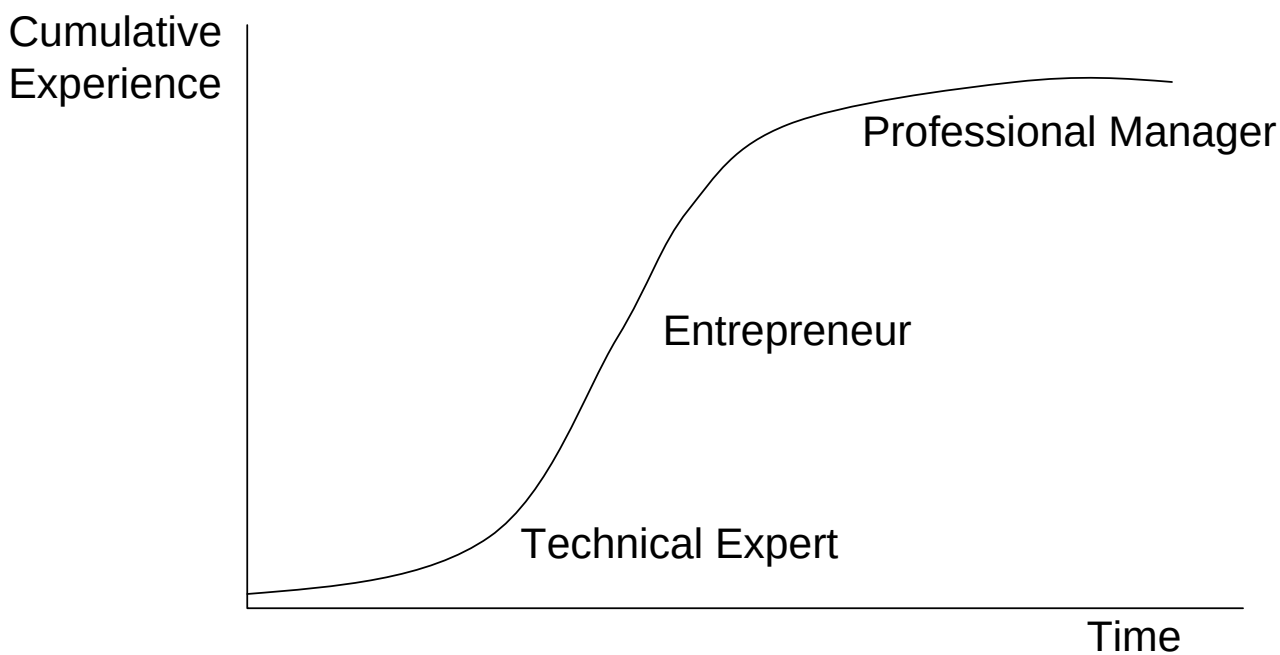
Factors in Communication Network Evolution

- Technology, Regulation, Markets, Standards

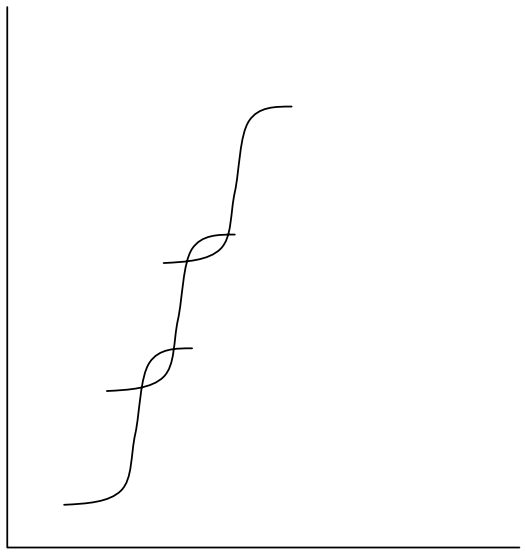


  - availability of a technology does not mean it will sell
  - never very clear beforehand whether a market exists for a product or service
  - the move away from monopoly telecomms suppliers makes standards essential

- Technology
  - – sustained improvements in technology
    - » microprocessor MIPs, RAM memory size and speed, hard disc capacities
    - » operating systems, application software
    - » digital signal processing (DSP), audio, image and video compression
    - » transmission bandwidth
    - » network protocols



– multiple technologies overlap



» e.g. copper wire, coaxial cable, optical fibre

– from 24 voice channels on T-1 to millions of channels on DWDM fibre now

– Moores Law of computer processing power (doubling every 18 months) applies even more strongly to transmission technologies

– technological advance does not happen by chance

» thousands of engineers and scientists beavering away

- Regulation
  - telecomms services have always been government regulated
    - » until very recently as state monopolies
  - deregulation and privatisation of monopolies
    - » more competition in long distance telecomms
    - » cable television and satellite broadcasting competition to terrestrial
  - radio spectrum allocation
    - » has always been closely controlled nationally and internationally
    - » cellular telephone frequencies, 900MHz and 1800 MHz allocations
    - » unregulated bands for low power use in 2.4GHz range
    - » 3G spectrum auctions
  - Office of Telecommunications (Oftel) in the UK
    - » promoting consumer interest
    - » maintaining effective competition
    - » ensuring services to meet all reasonable demands e.g. emergency services, directory information, rural services etc.

- Market
  - – new applications and services
    - » fax, email, web browsing
    - » desktop computing, word processing, multimedia, video games
    - » mobile phones, PDAs
      - 1G and 2G services mushroomed, 3G slow to arrive
    - » e-commerce
      - e.g. on-line shopping, on-line travel booking etc.
  - – entrepreneurs always searching for the “Killer App”
    - » SMS messaging on mobile phones a success
    - » WAP a failure
  - – usefulness of a service often depends on there being a critical mass of subscribers e.g. email, SMS
  - – economies of scale often vital to sustain services and develop new ones
    - » cable and satellite TV
    - » mobile phones

- Standards
  - – agreements, industrywide, with national and international scope
  - – allow interoperability of equipment made by different vendors
    - » competition reduces prices
  - – physical standards such as plugs and sockets e.g. USB
  - – usage standards such as communications protocols
    - » whether implemented by software or hardware
  - – can arise initially as *de facto* standards from a successful product
    - » e.g. ethernet
    - » internationally standardised later
  - – or developed by subcommittees of standards bodies
    - » American Standards Committee for Information Exchange (ASCII)
    - » Institute for Electrical and Electronics Engineers (IEEE)
    - » International Telecommunications Union (ITU)
    - » International Standards Organisation (ISO)