Course outline

- Networking basics
- Architecture & protocols
- Reliable Transmission
- Multiplexing
  - queuing, scheduling, congestion control, medium access
- Switching & addressing
- Routing

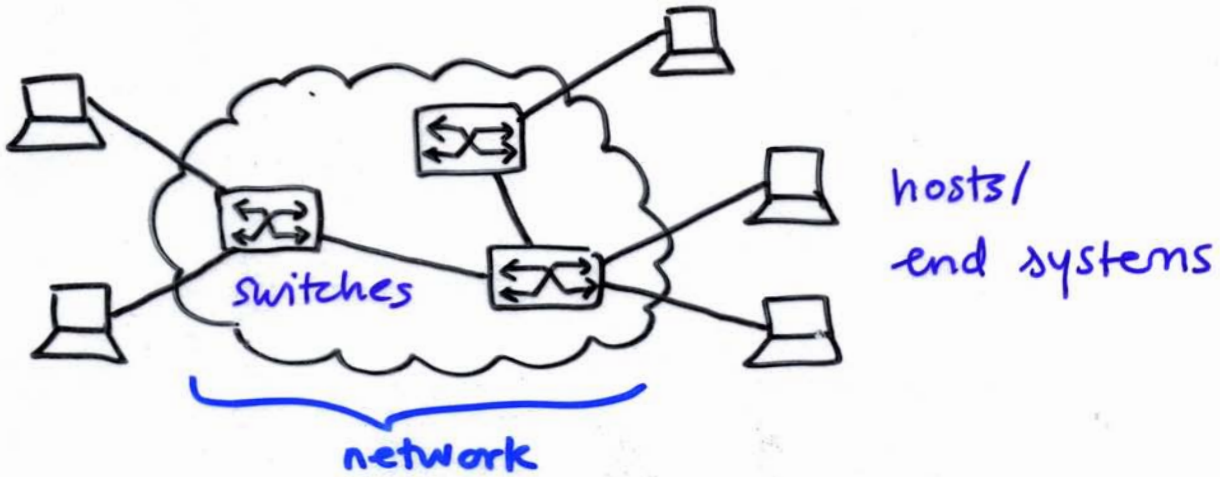
Basic requirements of a computer network

1) Connectivity

a) at the lowest level, a network can consist of two or more computers (nodes) connected directly via a physical medium (link) such as a cable or wireless

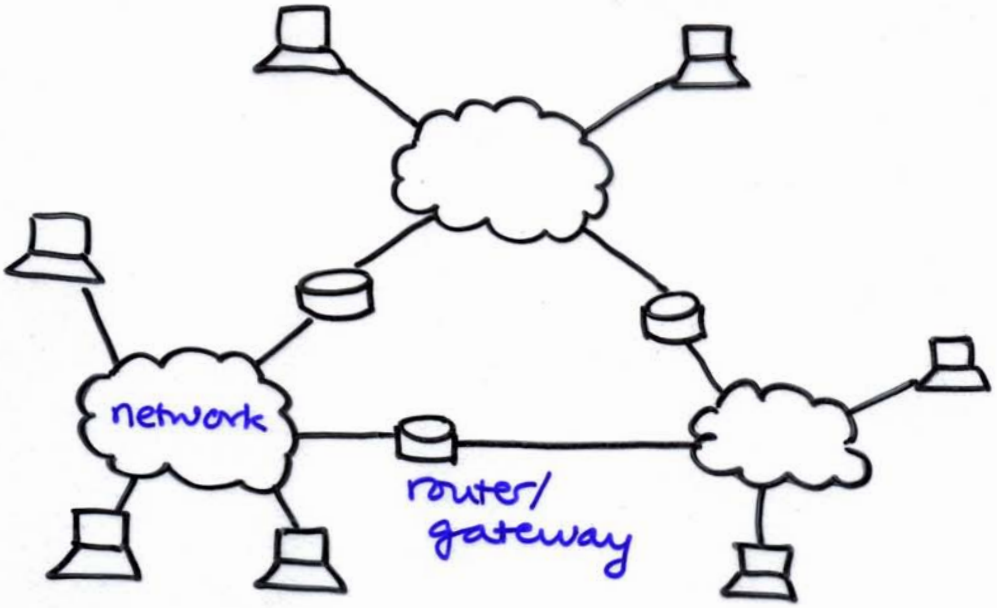
- multiple access link : single physical link shared by >2 nodes
- networks where all nodes are directly connected over a common physical medium do not scale

b) switched network



- indirect / multi-hop connections between nodes via intermediate nodes (switches)

c) internetwork / internet



- can recursively build arbitrarily large networks by interconnecting smaller networks

- host-to-host connectivity obtained by assigning an <u>address</u> to each node (byte string that identifies a node within a network)

- also need multicast & broadcast addresses

- <u>routing</u>: process by which switches & routers use address of destination(s) to determine how to forward a message

2) Resource sharing

- **multiplexing** : sharing of a system resource among multiple users
  - multiple flows can be multiplexed onto a single physical link at one switch & demultiplexed back into separate flows at another

a) **synchronous time-division multiplexing** (STDM) : multiple flows take turns in a fixed round robin fashion to use the link

b) **frequency division multiplexing** (FDM): frequency spectrum is divided among flows

- STDM & FDM are simple but limited in that
  - if a flow does not have data to send at same time, its share of the link capacity remains idle
  - the maximum number of flows needs to be fixed ahead of time

c) Statistical multiplexing

- like STDM, the link is shared over time
- unlike STDM, sharing is based on demand
  → more efficient use of resource
- need to ensure all flows eventually get their turn
  → each flow allowed to transmit only a limited amount of data at a time (packet)
    - decisions are made on a per-packet basis as to which packet is sent next
      eg FIFO, round-robin, other QoS
    - resources shared at the granularity of a packet

3) Support for common services

- Network provides logical channels with different functionality (eg. reliable/in order/private) over which application-level processes communicate
- common communication patterns
  eg file access (FTP, NFS), digital library (www), videoconferencing, peer-to-peer

- client - server model : client process on one host requests service, server process on another host provides service
  eg. web browser & web server
- different types of channels for request/reply messages & message (data) stream

• Masking failures of underlying technology
- bit errors, packet loss, link failures

Network performance: bandwidth & latency

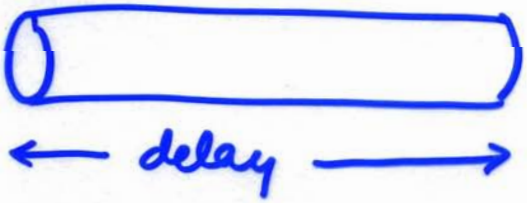
- Bandwidth (throughput): no. of bits per unit time that can be transmitted
- Latency (delay): travel time of a message
  - 3 components: propagation delay + transmit delay + queueing delay

propagation delay = distance / speed of light

transmit delay = packet size / bandwidth

- For small objects, performance is dominated by latency

  For large objects, performance is dominated by bandwith
  - effective throughput → bandwidth for large transfers



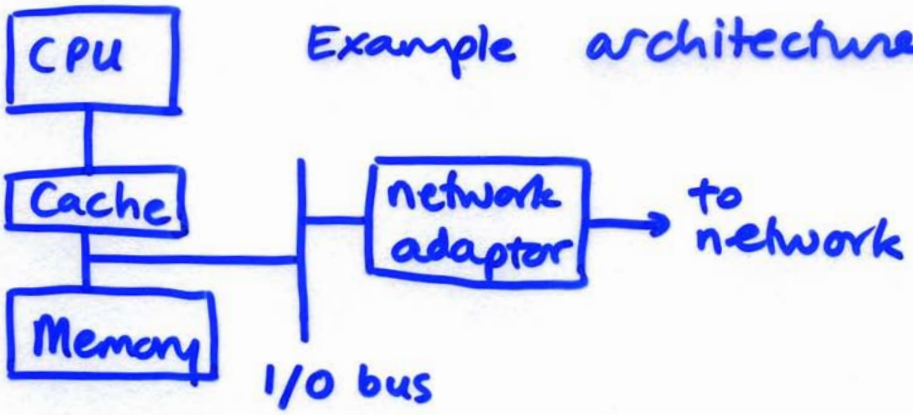
volume of pipe = delay × bandwidth

- delay × bandwidth product: no. of bits "in flight" before the first bit reaches receiver (delay here can also refer to round-trip time RTT)

- Jitter: variation in latency
  - can be caused by queueing delays in a multihop packet network

Hardware

- Nodes



Example architecture

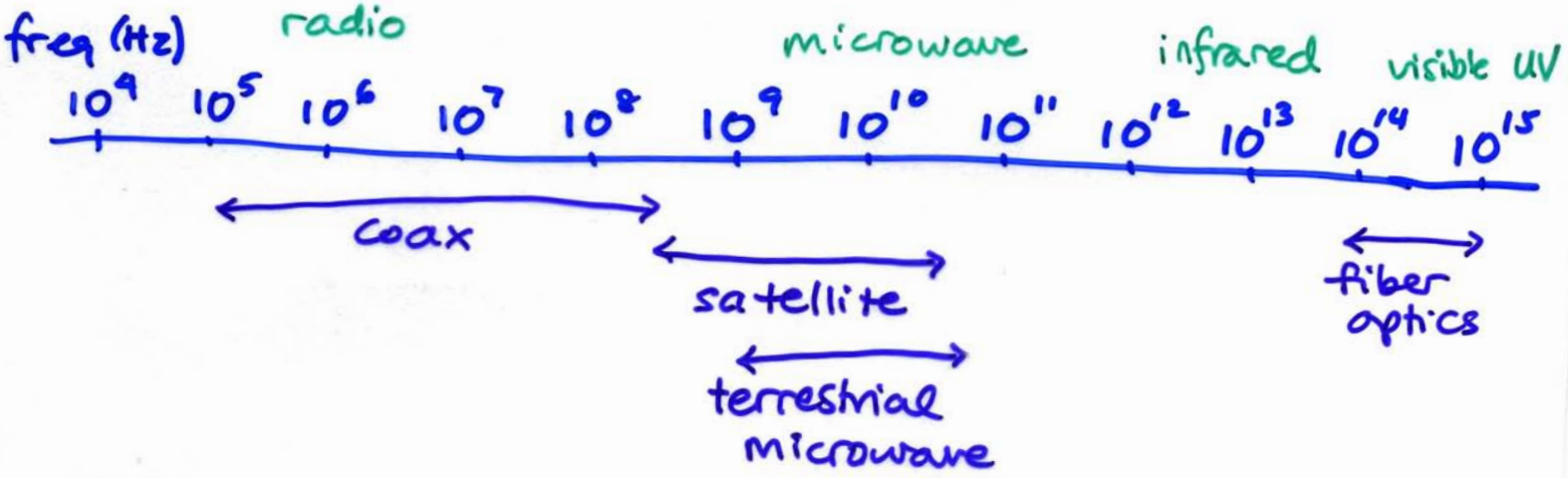
- network adapter delivers data between memory & network link, managed by device driver (software module)
- memory is one of 2 scarce resources in a network (the other is link bandwidth); needed for buffering packets at switches/routers
- memory speeds are increasing more slowly than CPU speeds → network software needs to be careful about how many memory accesses it makes

- Links

- implemented on various physical media, eg.
  - twisted pair (phone lines, DSL, LANs)
  - coaxial cable (cable TV, cable modems, LANs)
  - fiber optics (long distance phone, internet backbone)

- terrestrial radio (wireless LANs, cellular)
- satellite radio (telephone networks, internet backbone, rural areas)

- signals travel as electromagnetic waves at the speed of light (3×10^8 m/s in vacuum, 2×10^8 m/s in copper/fiber)



Access networks

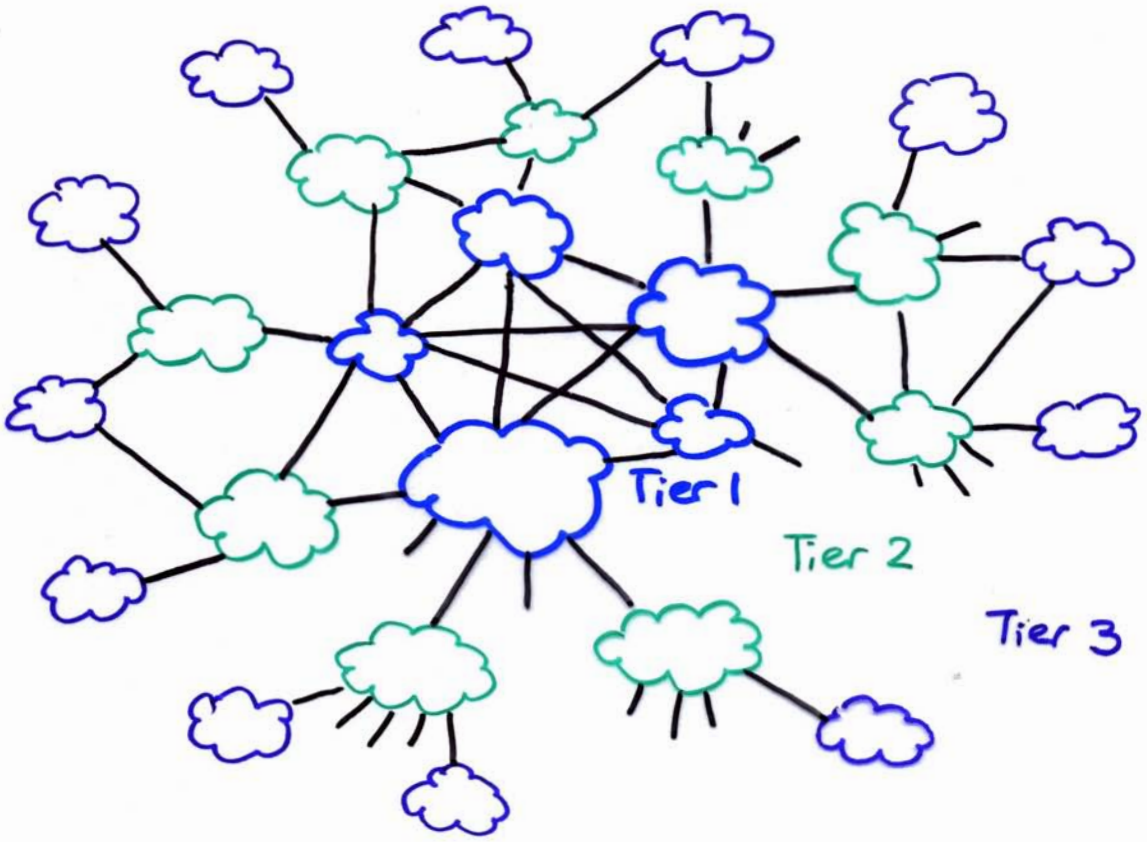
- physical links connecting an end system to its edge router (first router on a path from the end system to any other distant end system)
- residential access
  - dial-up modem: home modem converts digital PC output into analog format for transmission over analog phone line; another modem in the ISP converts analog signal back to digital for input to router (56 kbps)
  - digital subscriber line (DSL): new modem technology over existing phone lines; achieves higher rates by restricting distance between user & ISP modem (typically < 8.4 Mbps downstream, < 768 kbps upstream)
  - very high speed DSL (VDSL): < 55 Mbps
  - hybrid fiber-coaxial cable (HFC):
    - cable head end connected by optical fiber to neighborhood-level junctions, from which coaxial cable reaches homes
    - cable modem connects to PC

- Shared broadcast medium

- corporate / university
  - local area network (LAN) : various types of LAN technologies, Ethernet technology most commonly used (100 Mbps – 10 Gbps)

- wireless access
  - wireless LAN : technologies specified by IEEE 802.11 group of standards; users connect via a base station within a few tens of meters (WiFi)
  - wide area wireless : various standards
    - EVDO (Evolution-Data optimized)
    - HSDPA (High-Speed Downlink Packet Access)
    - WiMAX / 802.16 (Worldwide Interoperability for Microwave Access)

ISPs & Internet Backbones



- Tier-1 ISP / Internet Backbone network
  - eg Sprint, Verizon, AT&T, NTT
  - link speeds 622 Mbps - 10Gbps
  - directly connected to each other tier-1 ISP
  - international coverage
  - connected to many tier-2 & other networks (its customers)
- Tier-2 ISP
  - connected to only a few tier-1 ISPs (its providers)
  - may be connected directly to some other tier-2 ISPs (its peers)

- connected to lower-tier ISPs or large companies (its customers)

- economics of customer-provider & peer-peer relationships affect Internet routing

Network architecture

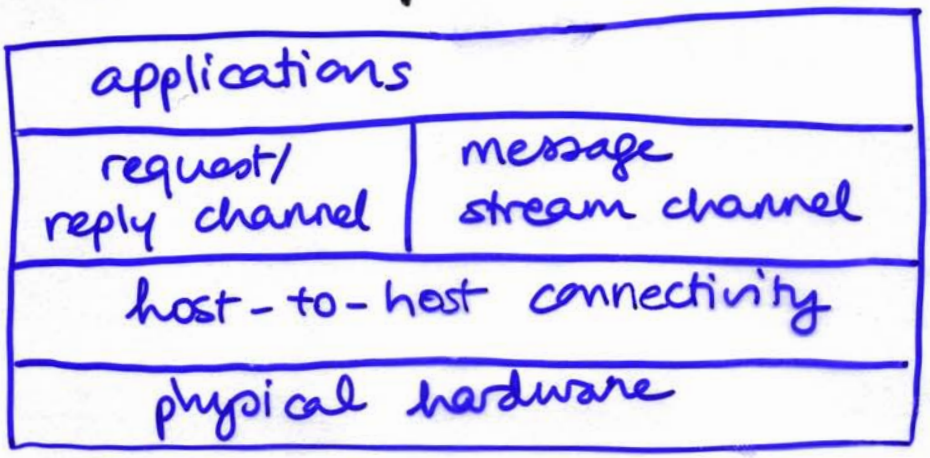
- to help manage complexity, define unifying models that guide design & implementation of networks

- identify abstractions that provide services that are generally useful & can be efficiently implemented

→ lead naturally to <u>layering</u>: each layer provides a higher (more abstract) level of service, & is implemented in terms of the services provided by lower layers

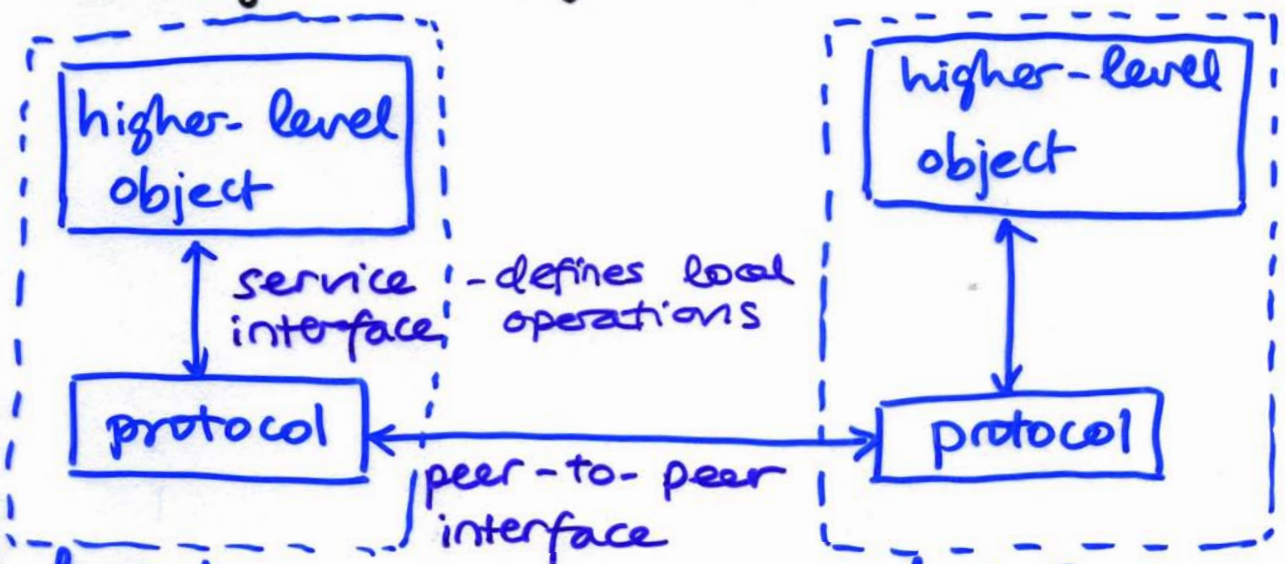
- can have multiple abstractions at a layer (eg different types of logical channels) building on the same lower-level abstractions but providing different services to higher layers

- simple example:



the abstract objects making up a layered network system are called <u>protocols</u>

a network protocol provides a communicⁿ service used by higher-level objects (protocols or application processes) to exchange messages over a network

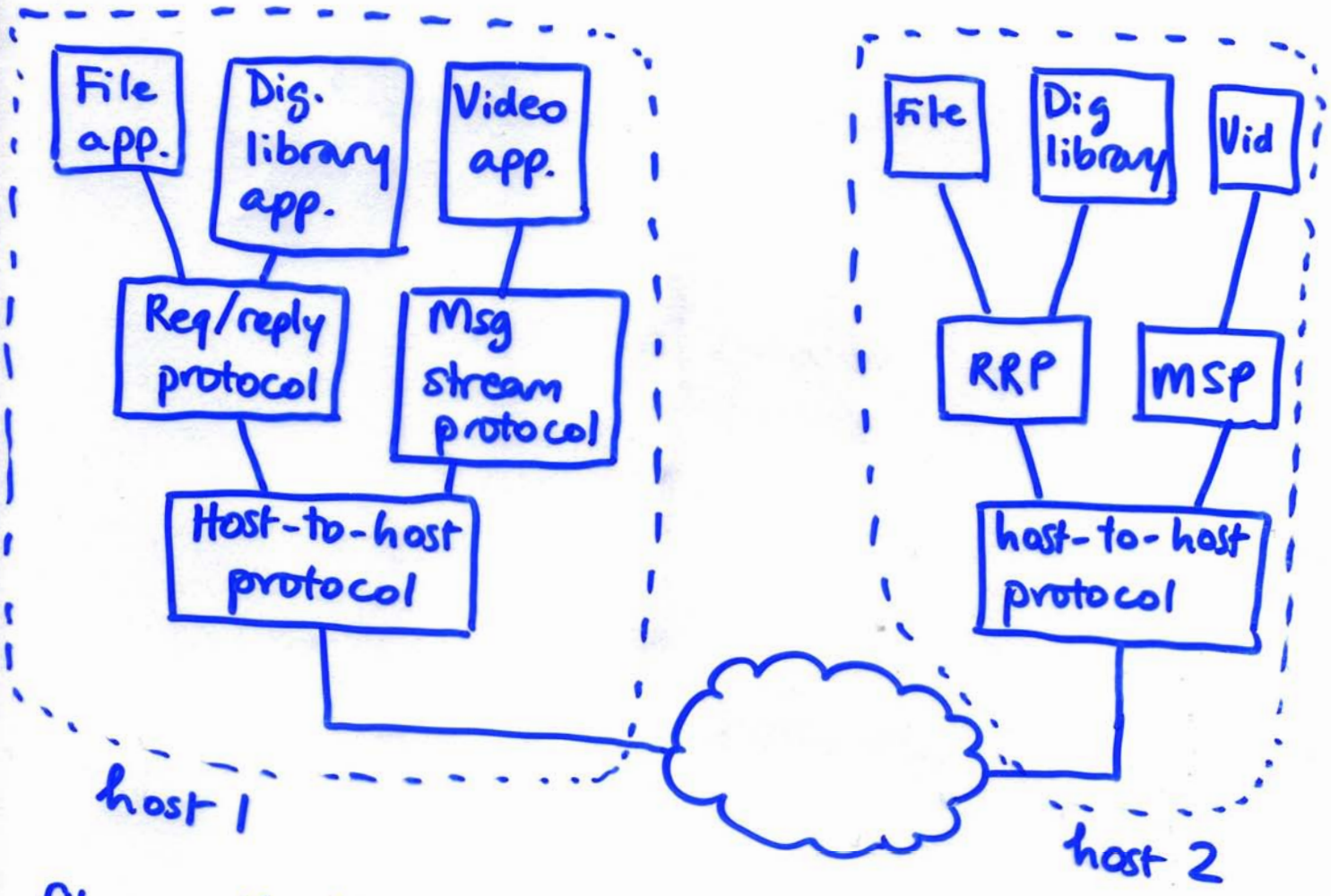


-defines format & order of messages exchanged between protocol peers to implement communicⁿ service

- except at the hardware level, peer-to-peer protocol communication is indirect: each protocol communicates with its peer by passing messages to a lower-level protocol which in turn communicates with its peer

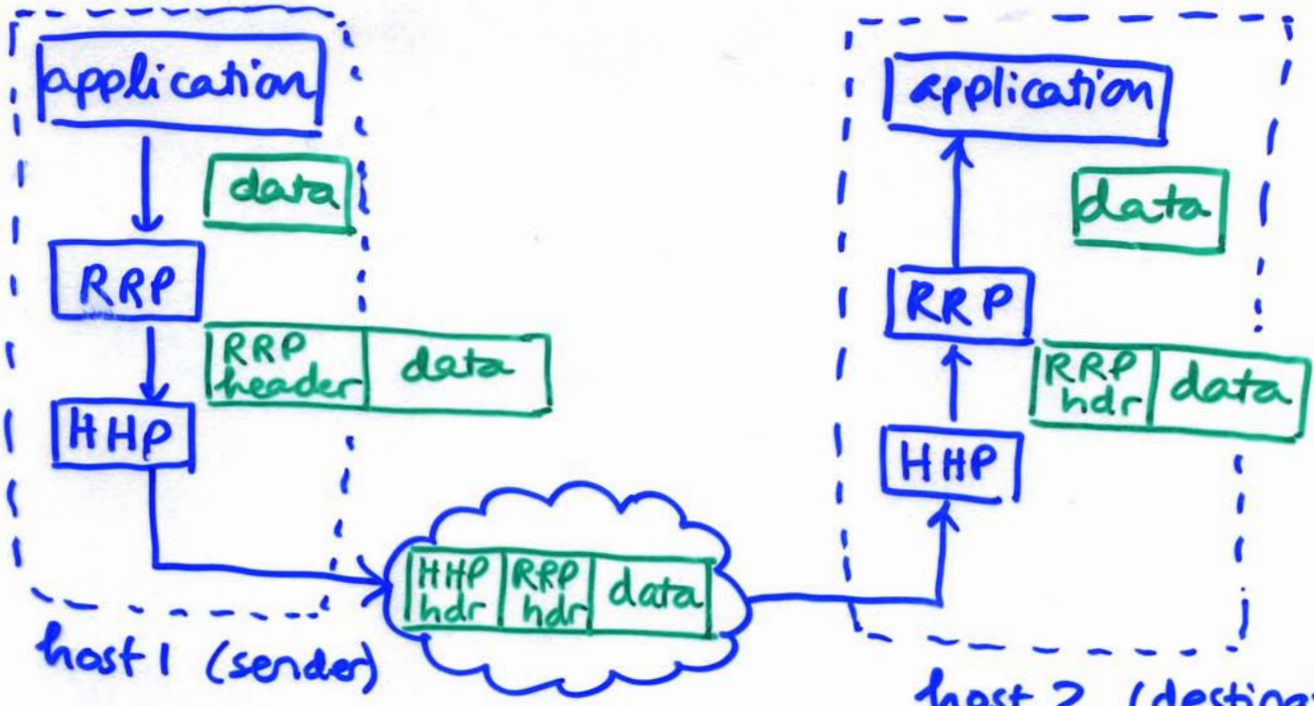
- protocol graph shows dependencies

eg.



- file application uses services of protocol stack RRP/HHP
- a protocol specification (its abstract interfaces) can be implemented in different ways
- a network architecture provides rules governing the form & content of a protocol graph

- encapsulation



- protocol at each level encapsulates message from higher level by adding a header
- header contains a demultiplexing (demux) key identifying the higher-level object to which the message belongs

- protocol at each level strips off its header
- message is passed to appropriate higher-level object based on demux key

- higher level protocols do not see lower-level headers