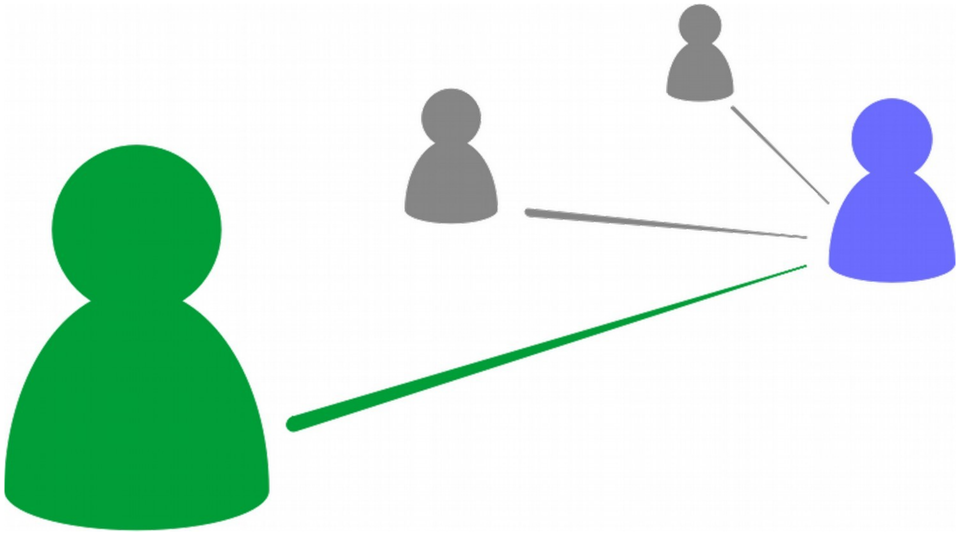
CS 470
Spring 2024

Mike Lam, Professor



Networks

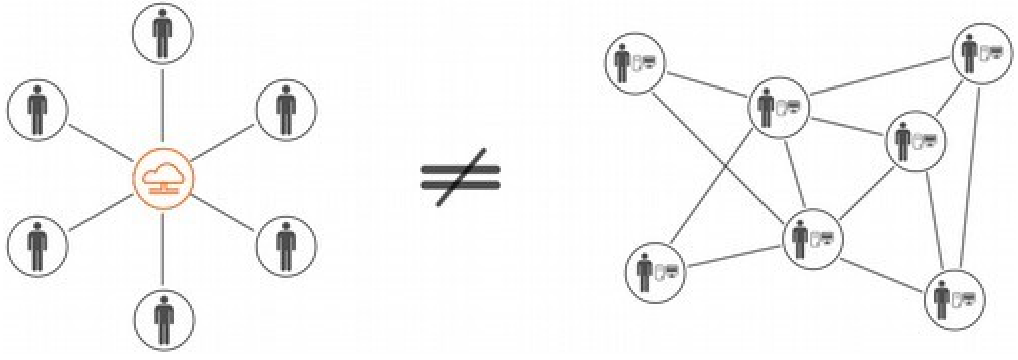
Content taken from IPP 2.3.3 and the following:

"Distributed Systems: Principles and Paradigms" by Andrew S. Tanenbaum and Maarten Van Steen (Chapter 4)

Various online sources (including wikipedia.org and openclipart.org)

Overview

- Topologies – how a network is arranged (hardware)
- Routing – how traffic navigates a network (hardware and software)
- Protocols – how machines communicate (software, low-level)
- IPC paradigms – how processes communicate (software, high-level)

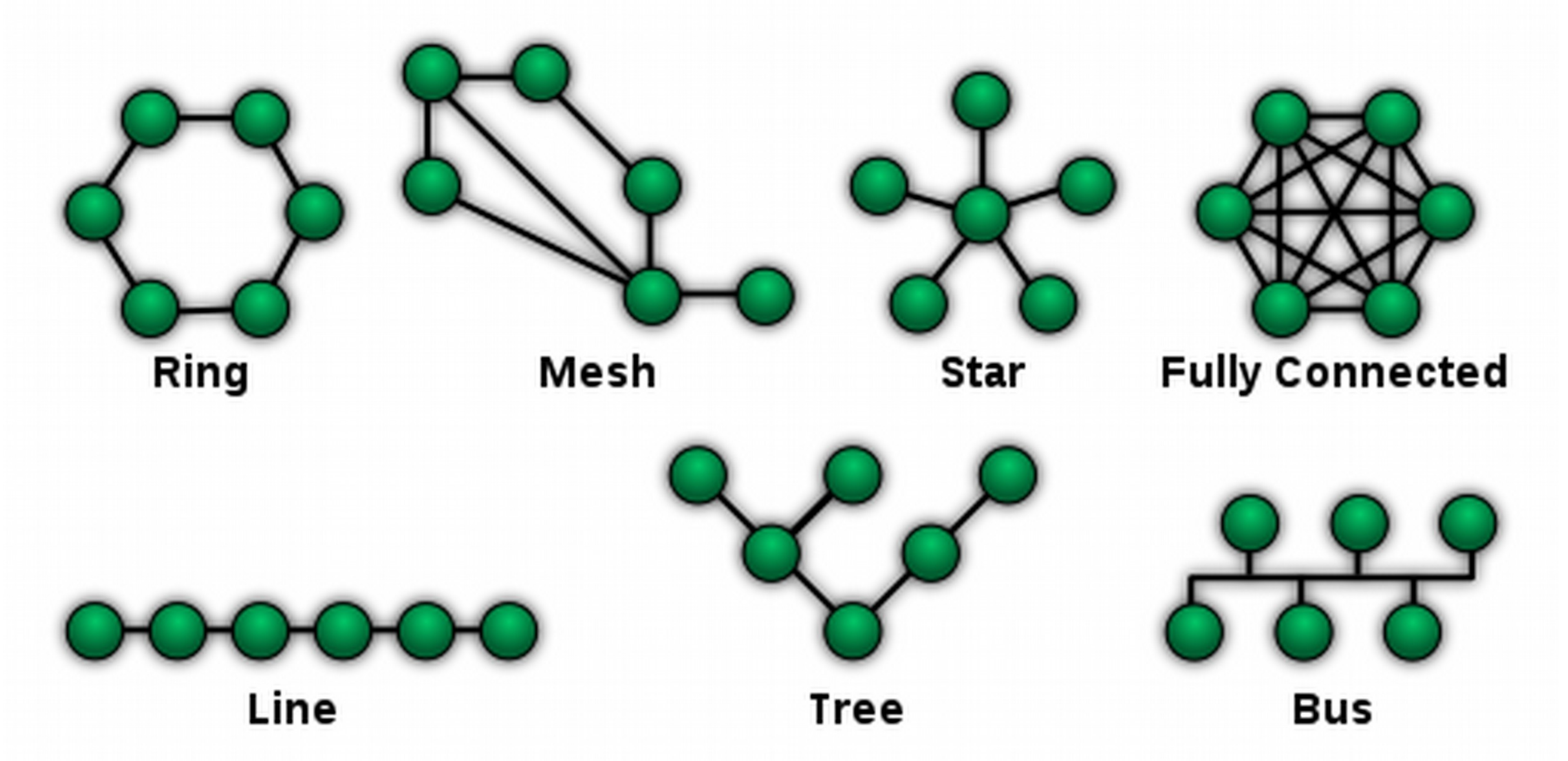


Part 1

- Topologies – how a network is arranged (hardware)

Network topologies

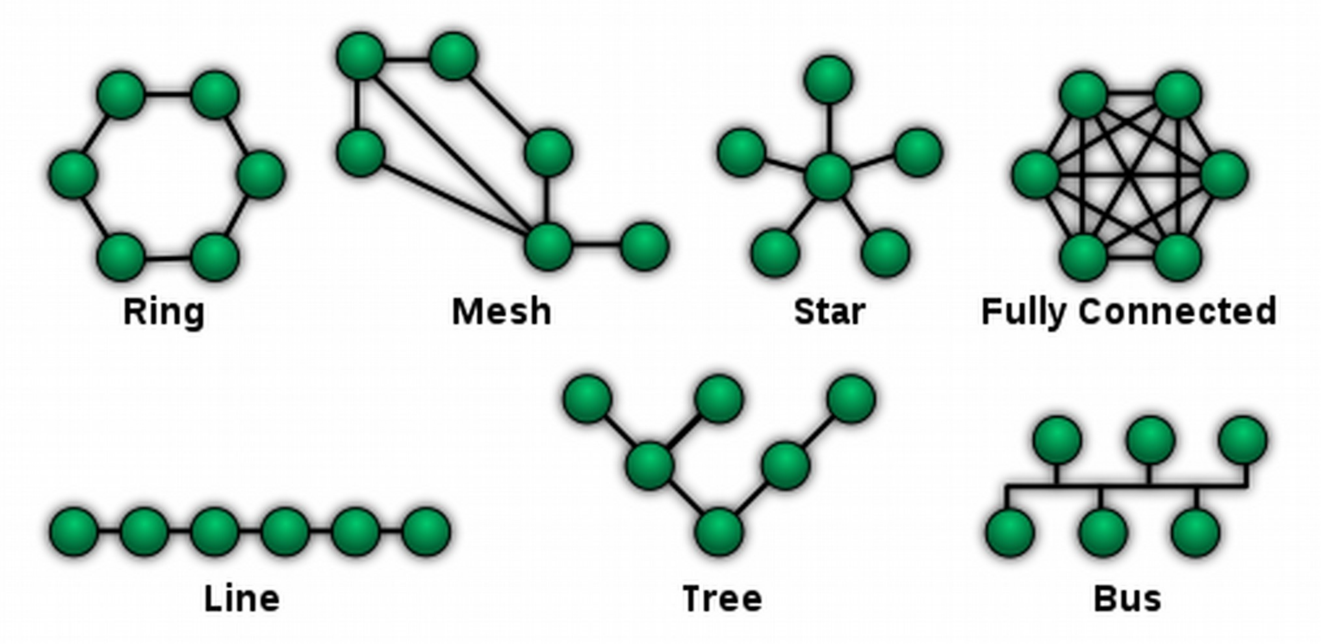
- A network topology is an arrangement of components or nodes in a system and their connections (e.g., a graph)



from `https://en.wikipedia.org/wiki/Network_topology`

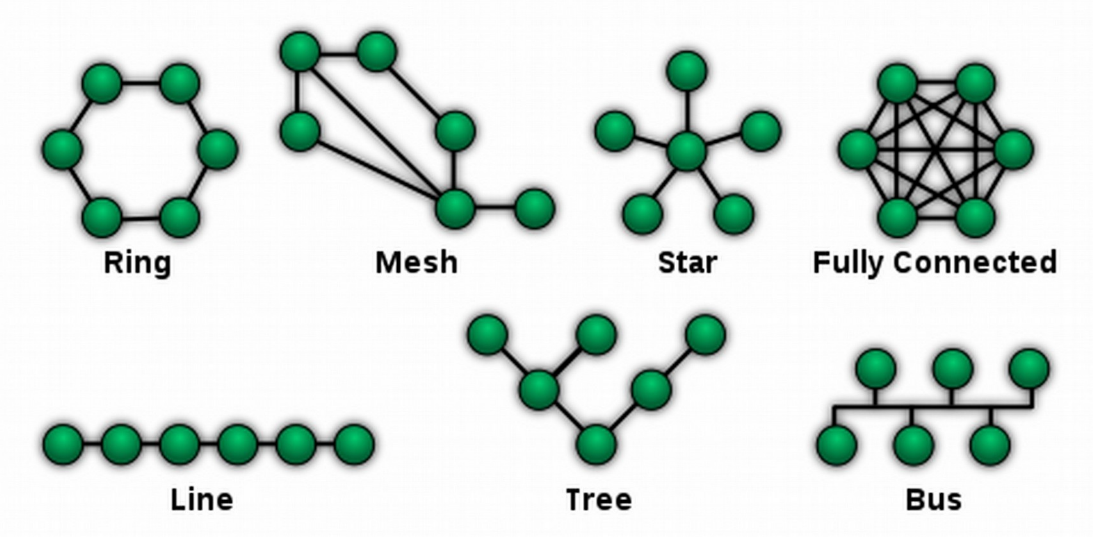
Network topologies

- In which topology is every node connected to exactly two other nodes?
  - A. Ring
  - B. Star
  - C. Fully connected
  - D. Line
  - E. Tree



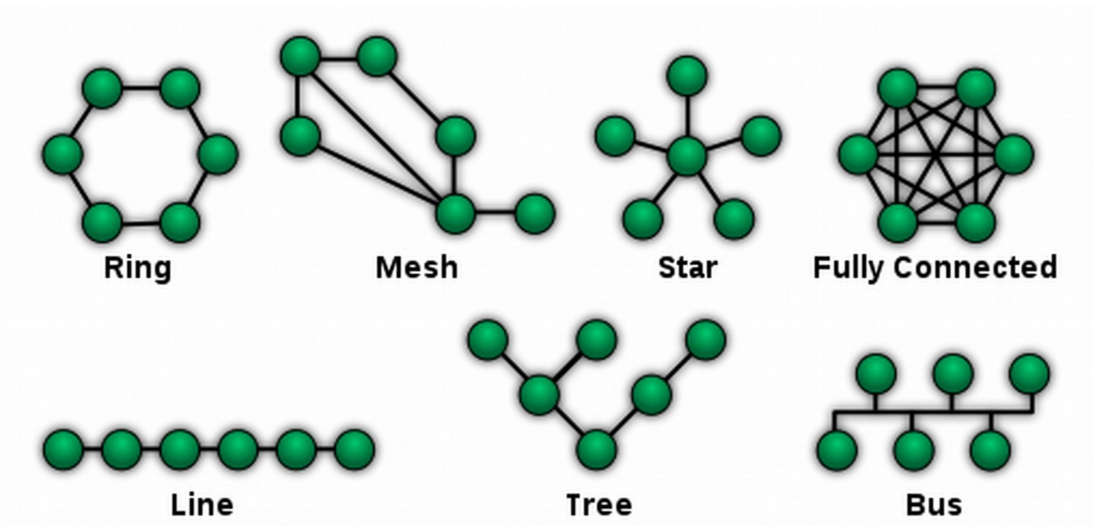
Network topologies

- A network topology is an arrangement of components or nodes in a system and their connections (e.g., a graph)
  - Ring, star, line, and tree allow simultaneous connections but disallow some pairs of point-to-point communication
  - Fully connected and bus allow direct any-to-any communication but do not scale well



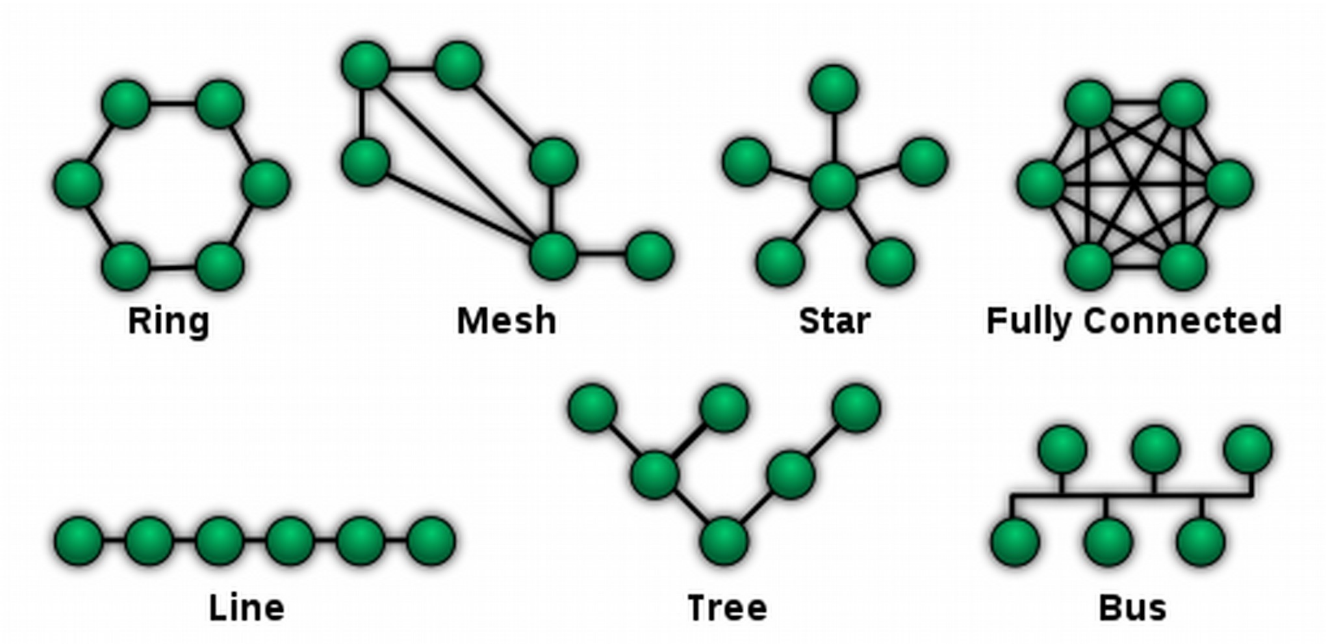
Evaluating topologies

- Bandwidth: maximum rate at which a link can transmit data
  - Throughput: measured rate of actual data transmission (usually less than theoretical maximum bandwidth)
- Latency: time between start of send and reception of first data
- Diameter: maximum number of hops between nodes on a network
- **Important**: how do these metrics scale as you add nodes?



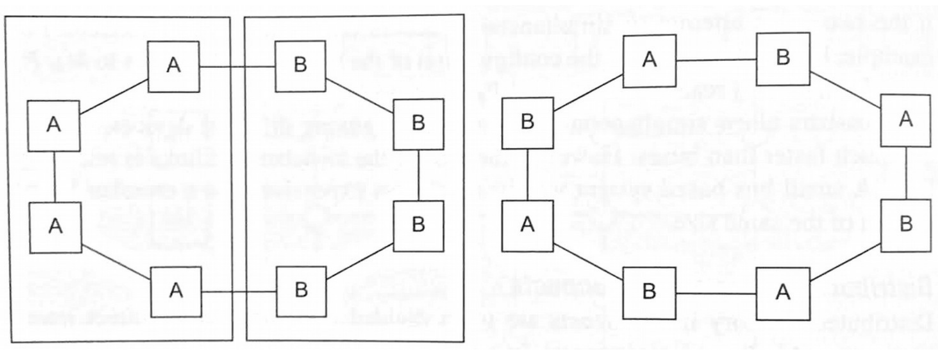
Evaluating topologies

- In which topology (or topologies) does the diameter remain unchanged as you scale up the number of nodes?
  - A. Ring
  - B. Star
  - C. Fully connected
  - D. Line
  - E. Tree



Evaluating topologies

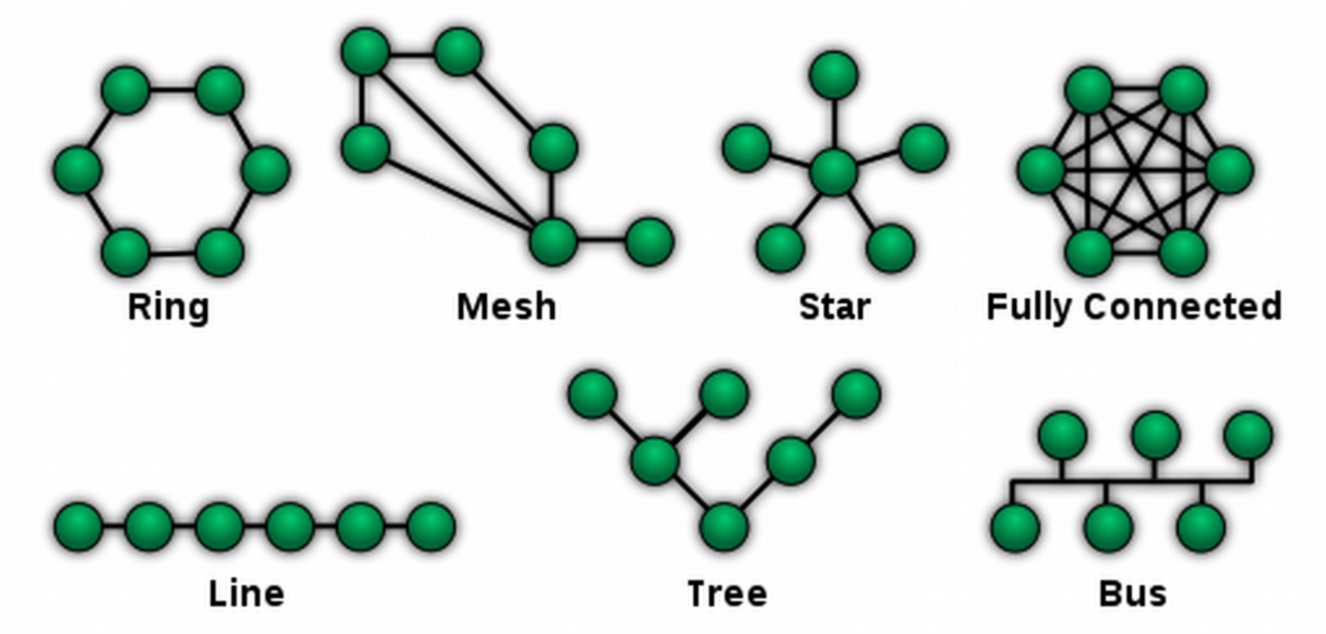
- Bisection: divide the network into two equal partitions
  - Bisection width: number of simultaneous communications between the two partitions
  - Bisection bandwidth: total data rate between the partitions
  - Typically done in such a way that minimizes bisection bandwidth
  - This represents the network performance assuming a worst-case bottleneck



Two different bisections of a network

Evaluating topologies

- In which topology is the minimum bisection bandwidth the highest as you scale up the number of nodes?
  - A. Ring
  - B. Star
  - C. Fully connected
  - D. Line
  - E. Tree

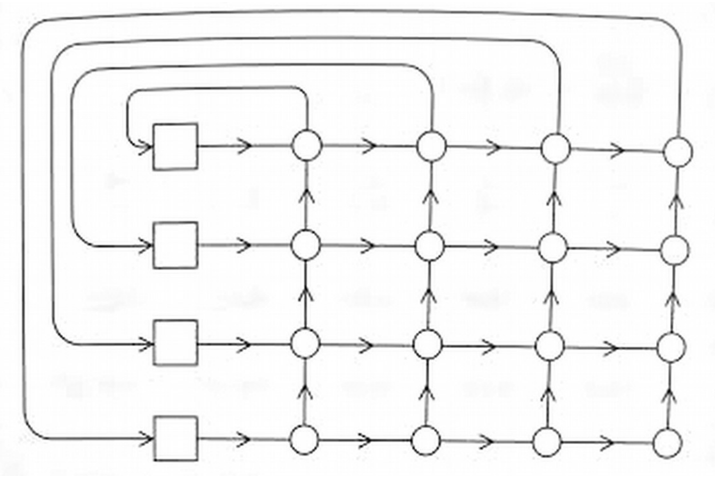


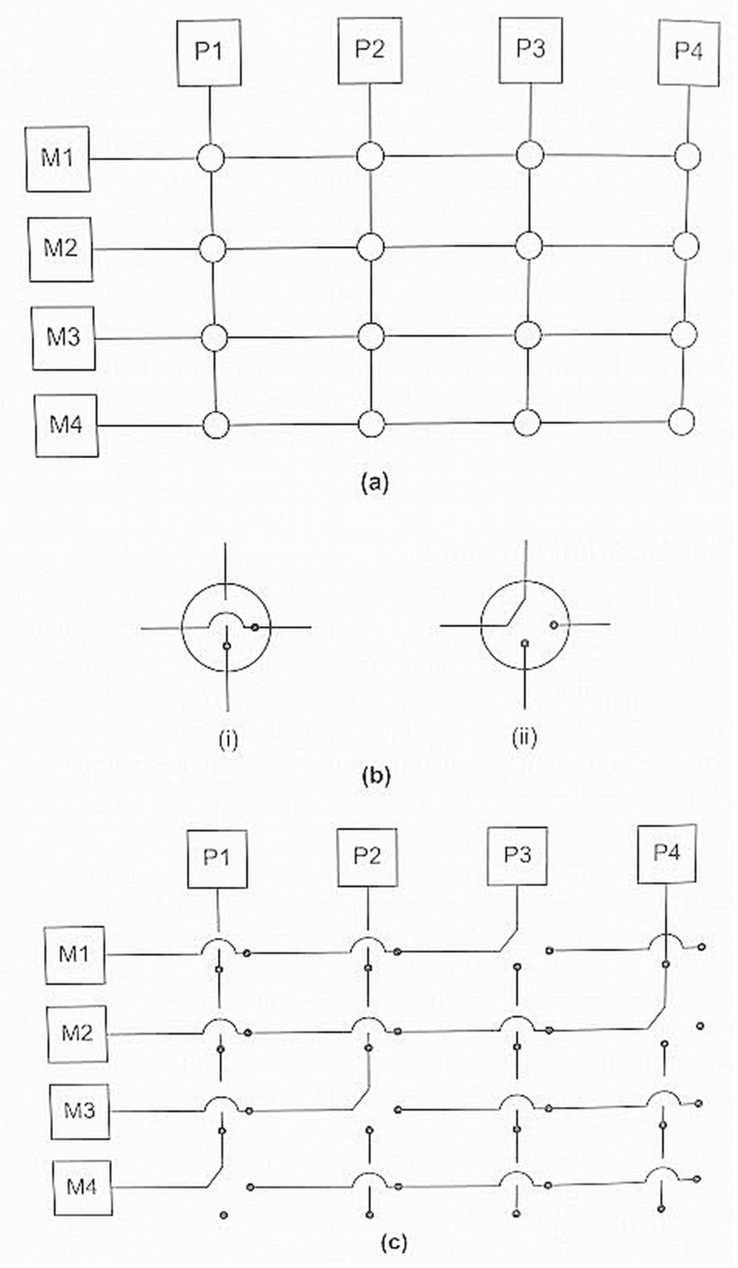
Evaluating topologies

- What is the most important network metric for a realtime distributed health monitoring system where the system must respond as soon as possible to changes in any user's heart rate, blood pressure, etc.?
  - A. Bandwidth
  - B. Latency
  - C. Diameter
  - D. Bisection width
  - E. Bisection bandwidth

Crossbar switches

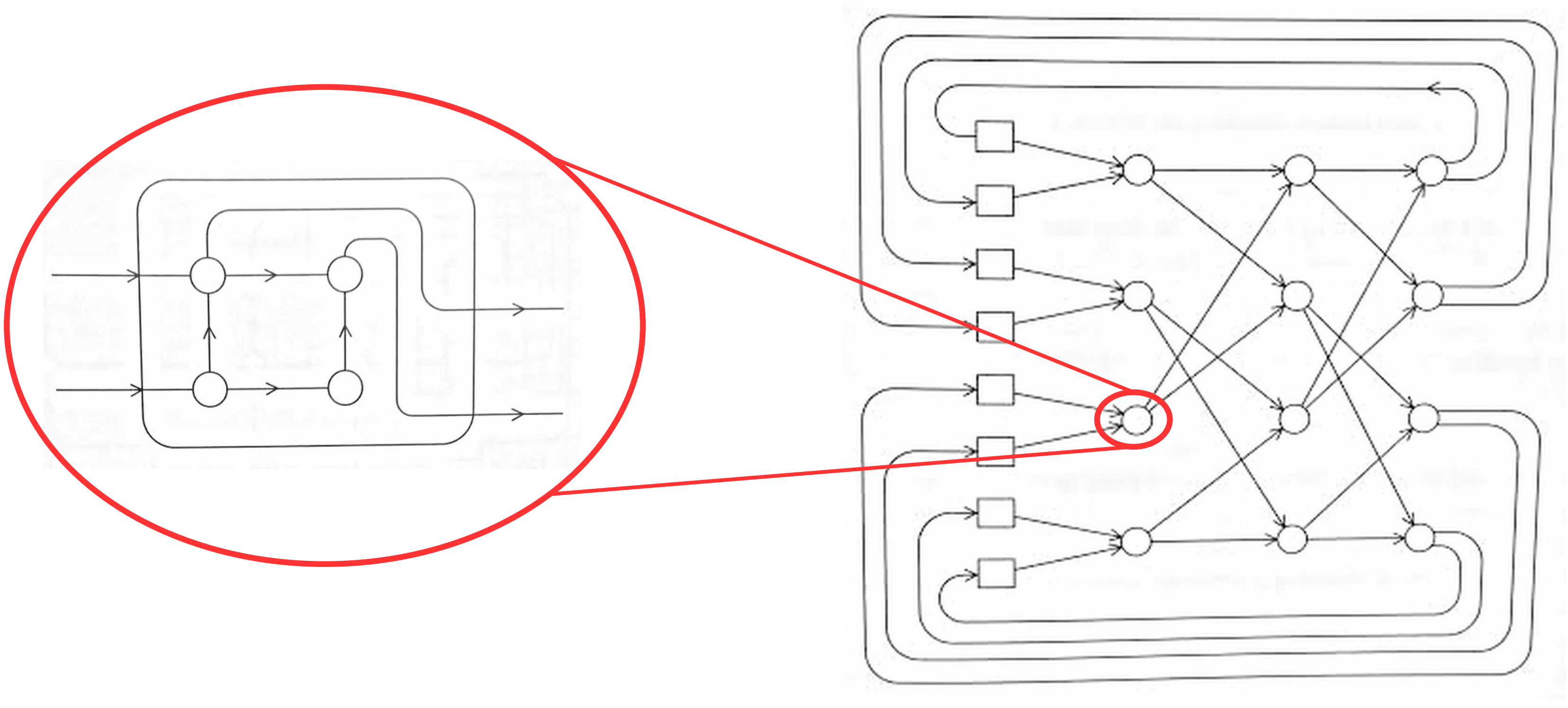
- Switched interconnects allow multiple simultaneous paths between components
  - *(Graphically, use squares for nodes and circles for switches)*
- A crossbar switch uses a matrix of potential connections to create ad-hoc paths between nodes





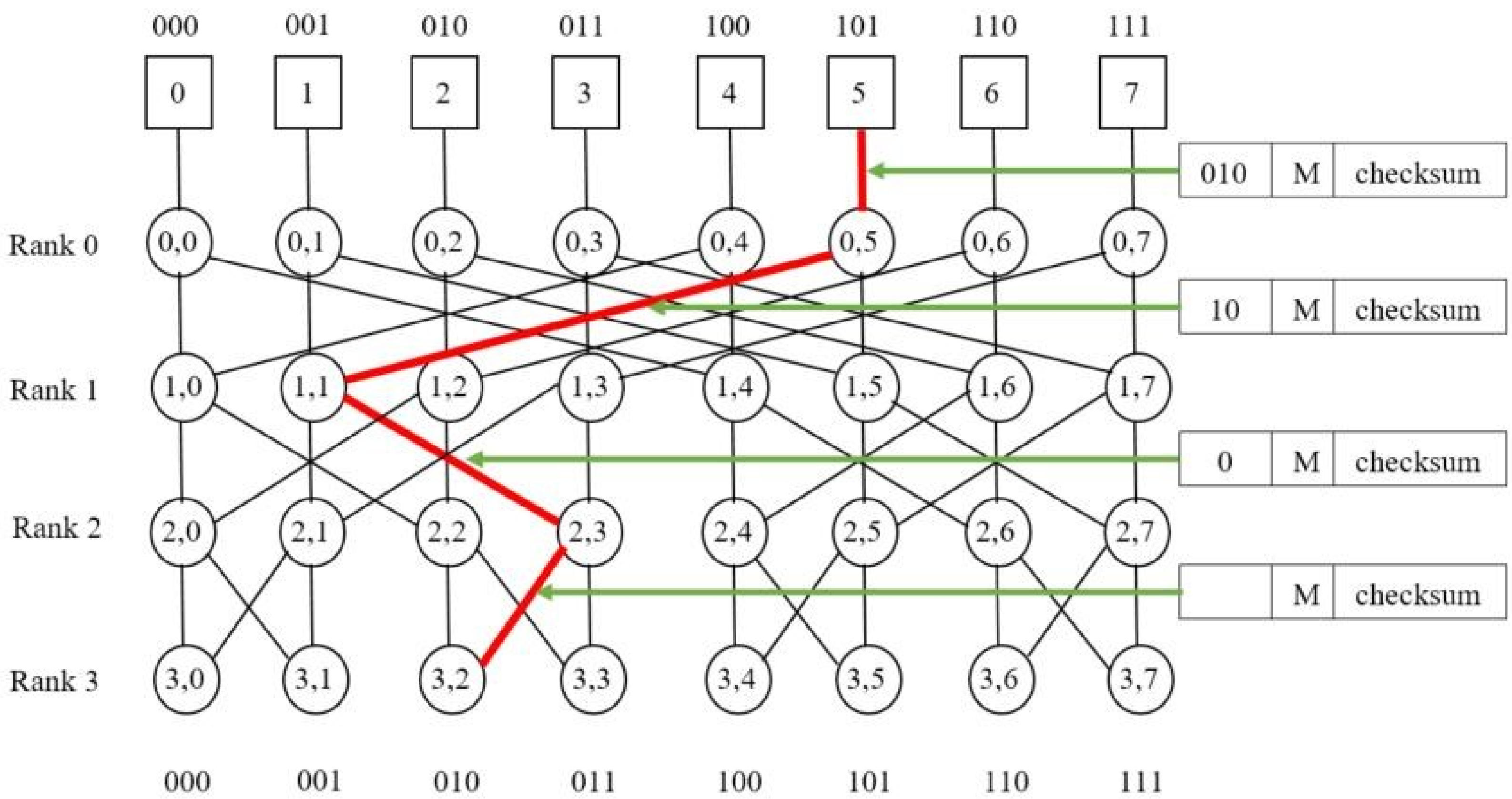
Omega networks

- Omega network: crossbar of crossbars
  - Each individual switch is a 2-by-2 crossbar



Butterfly networks

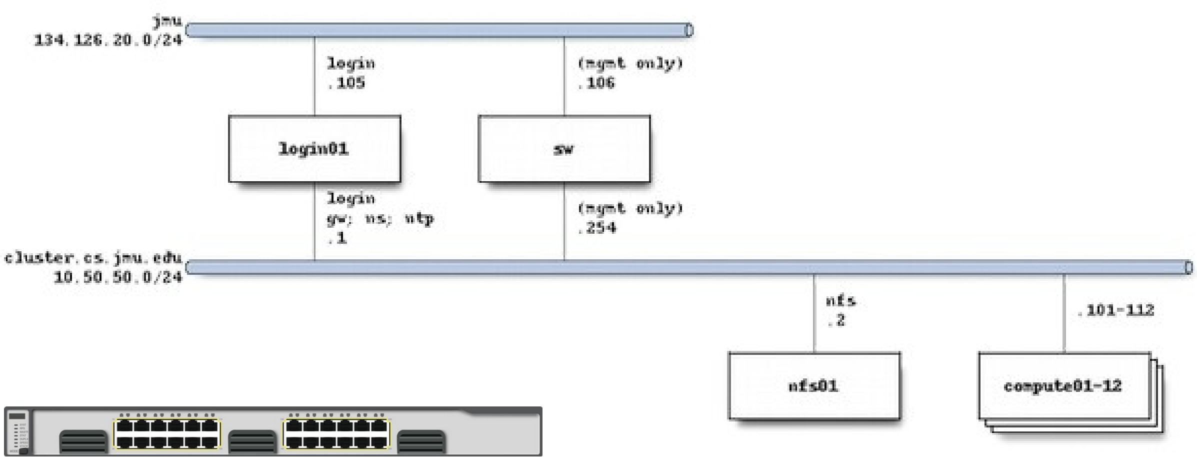
- Multi-stage network w/ dedicated switching nodes
  - Easy routing based on binary host numbers (0=left, 1=right)

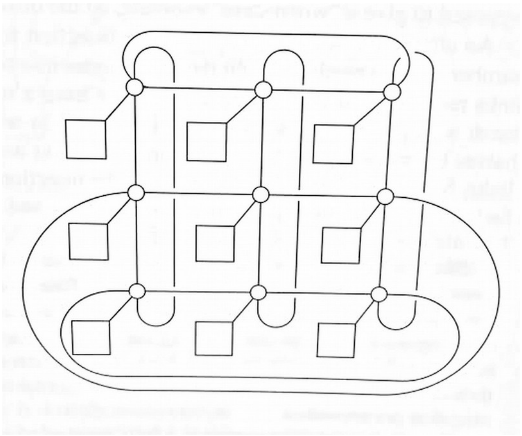


from `https://en.wikipedia.org/wiki/Butterfly_network`

HPC interconnects

- In an HPC system, the network is called an interconnect
  - Common patterns: switched bus, mesh/torus, hypercube
  - Connected via switches vs. connected directly



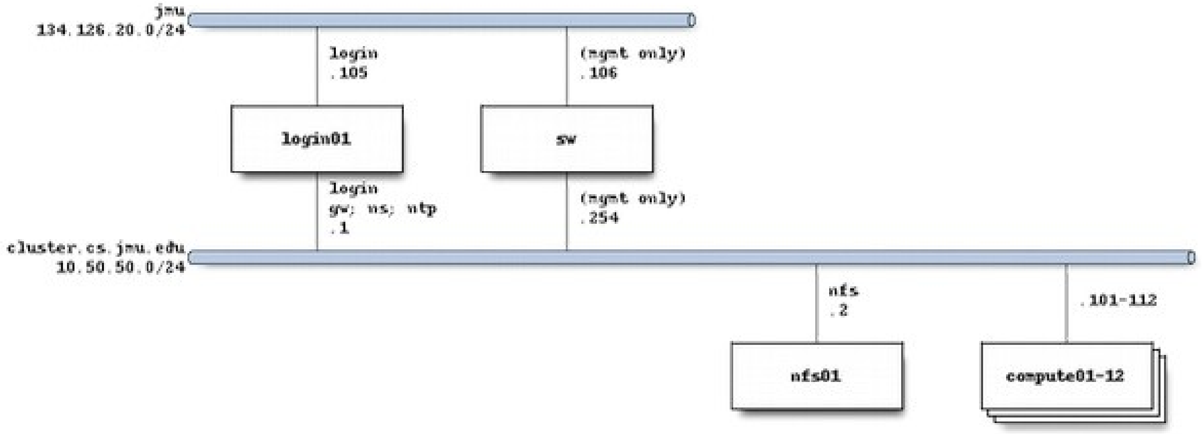


Toroidal Mesh

Our cluster (switched bus)

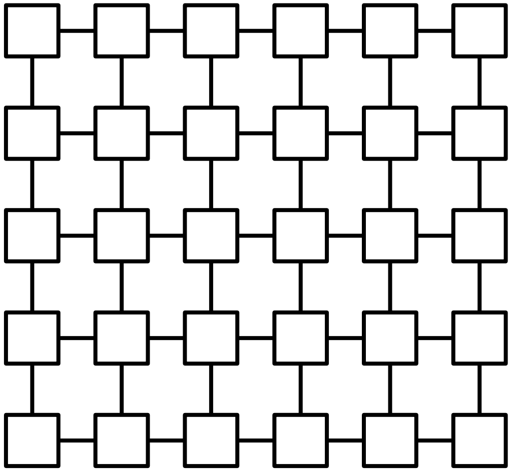
HPC interconnects

- In our cluster, which of the following is compute01 NOT connected to via a single bus hop?
  - A. compute02.cluster.cs.jmu.edu
  - B. compute08.cluster.cs.jmu.edu
  - C. nfs.cluster.cs.jmu.edu
  - D. login.cluster.cs.jmu.edu
  - E. stu.cs.jmu.edu

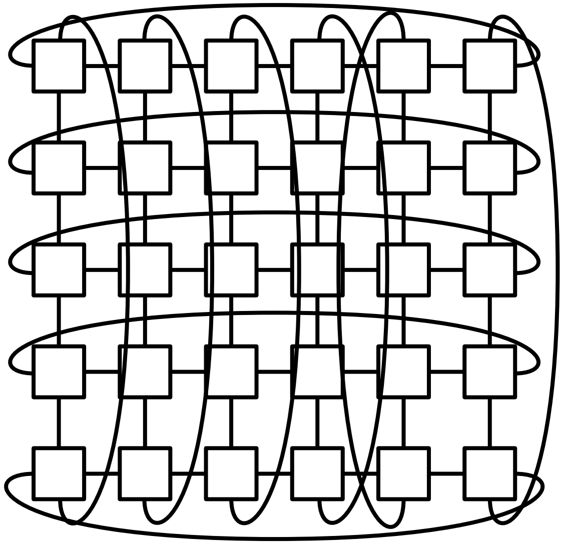


Meshes and tori

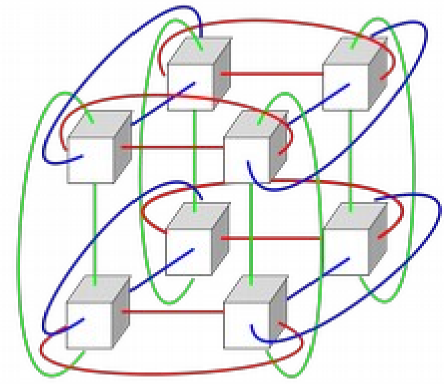
- Nodes are connected to several neighbors
  - Non-uniform memory access to non-immediate neighbors



2D Regular Mesh



2D Torus
(or “toroidal mesh”)

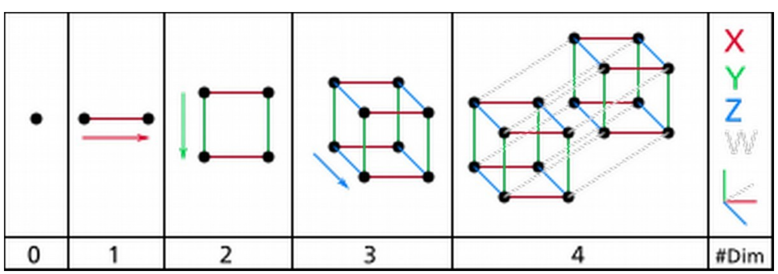


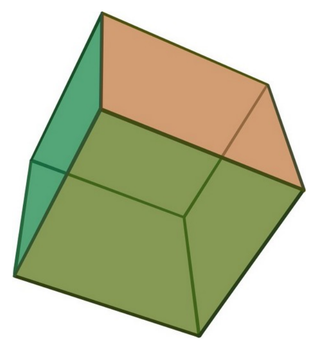
3D Torus

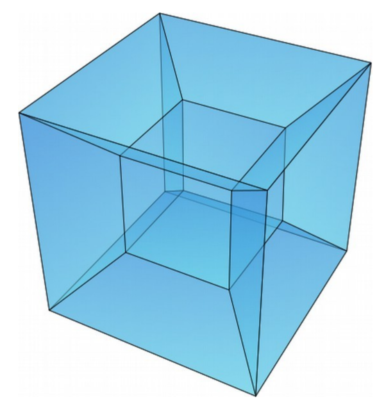
https://en.wikipedia.org/wiki/Torus_interconnect

Hypercubes

- Inductive definition:
  - 0-D hypercube: a single node
  - n-D hypercube: two (n-1)-D hypercubes with connections between corresponding nodes
    - E.g., a 3-D hypercube contains two 2-D hypercubes



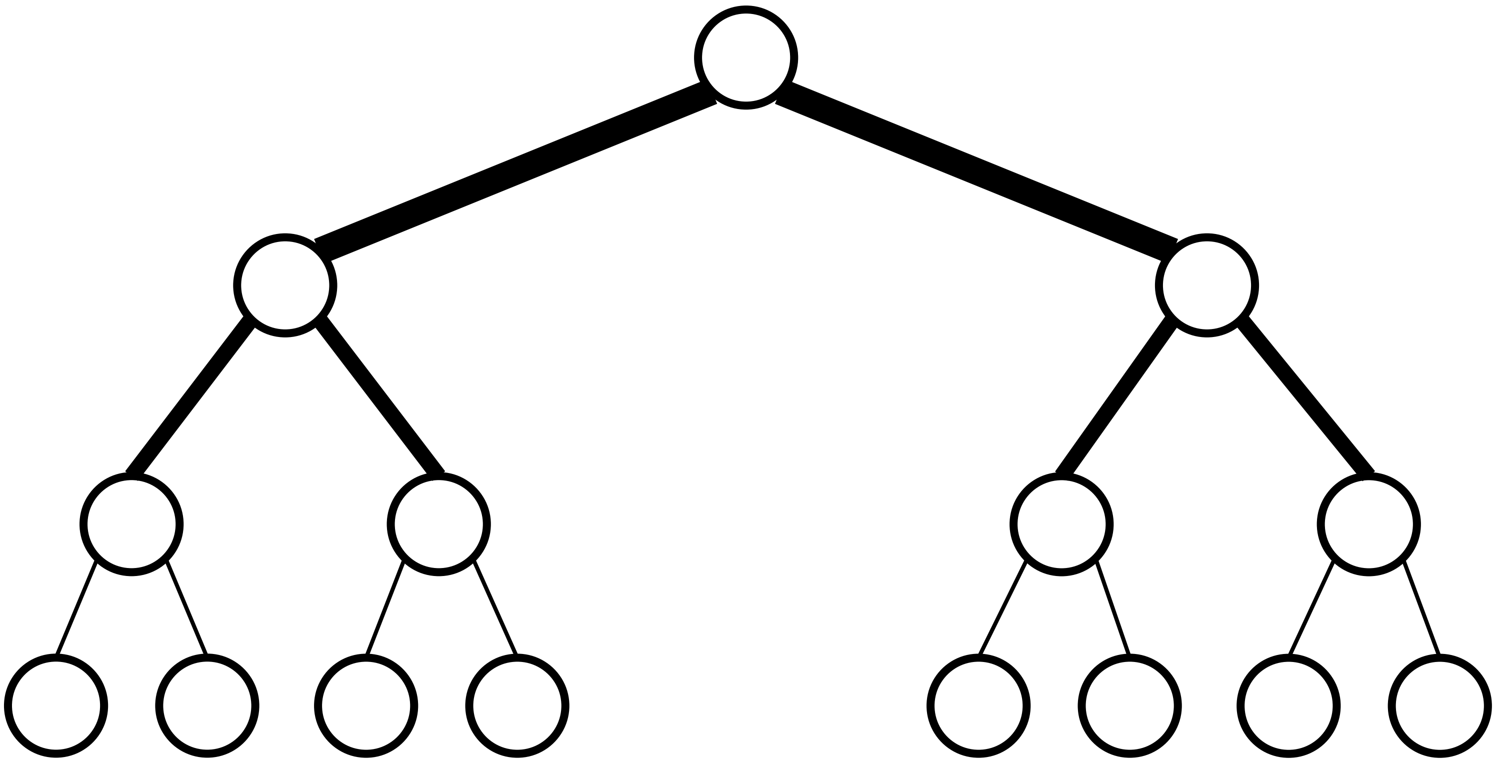




https://en.wikipedia.org/wiki/Hypercube

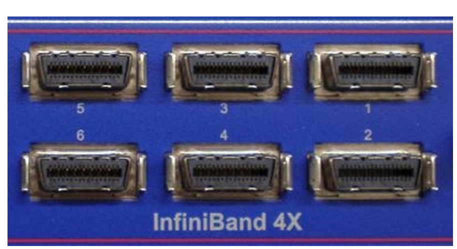
Fat trees

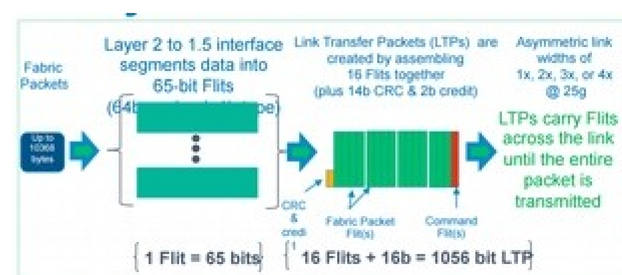
- Hierarchical tree-based topology
  - Links near the root have a higher bandwidth



HPC Interconnect Technologies

- Ethernet: 10/100 Mbps – 100 Gbps
  - Early versions used shared-medium coaxial cable
  - Newer versions use twisted pair or fiber optic with hubs or switches
- InfiniBand (IB): 24-300 Gbps w/ 0.5μs latency
  - Packet-based switched fabric (bus, fat tree, or mesh/torus)
  - Very loose API; more formal spec provided by OpenFabrics Alliance
  - Used on many current high-performance clusters
  - Vendors: Mellanox, Intel, and Oracle
- OmniPath (Intel) or Aries / Slingshot (Cray)
  - Proprietary interconnects for HPC machines





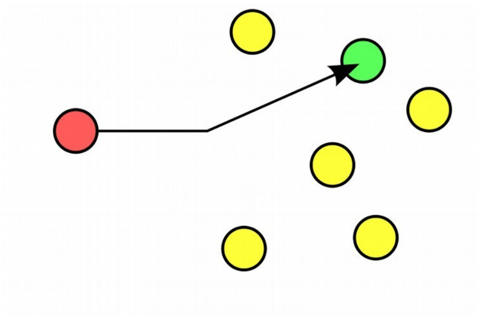
Part 2

- Routing – how traffic navigates a network (hardware and software)

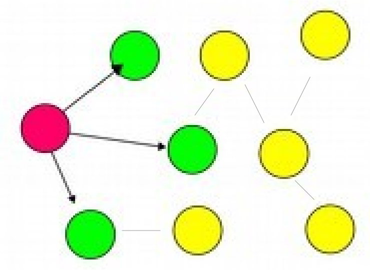
Routing

- Circuit switching
  - Paths are pre-allocated for an entire session
  - All data is routed along the same path
  - Higher setup costs and fewer simultaneous communications
  - Constant latency and throughput
- Packet switching
  - Break data into independent, addressed packets
  - Packets are routed independently
  - No setup costs and no restriction on simultaneous communications
  - Resiliency to network failures and changing conditions
  - Variable (and often unpredictable) latency and throughput

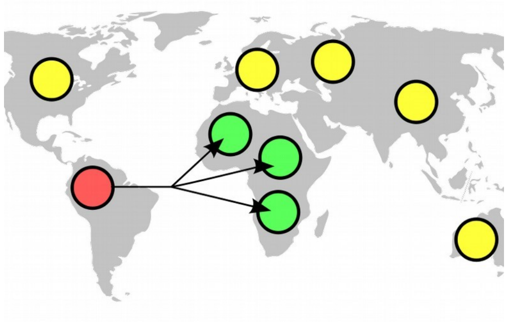
Routing



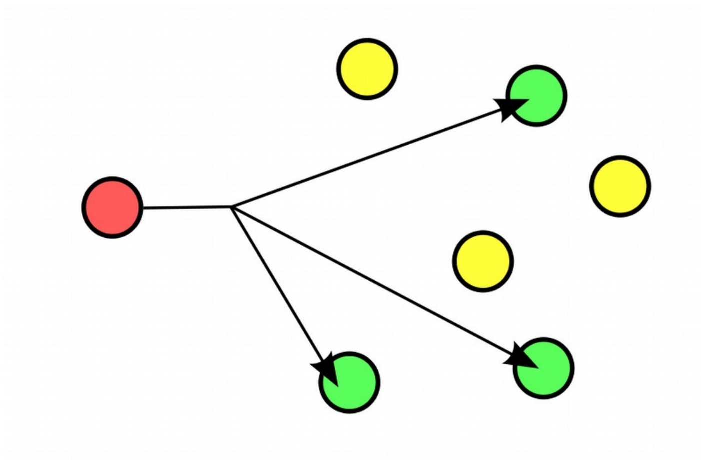
Unicast
(one-to-one)



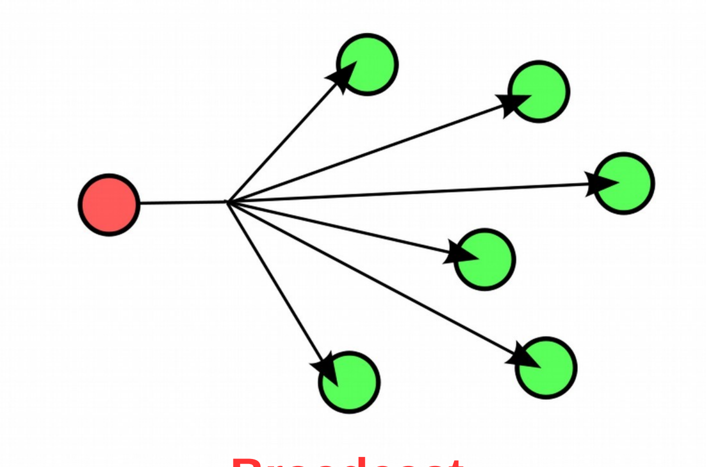
Anycast
(one-to-nearest)



Geocast
(one-to-proximate)



Multicast
(one-to-many)

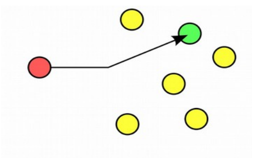


Broadcast
(one-to-all)

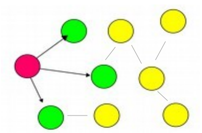
from `https://en.wikipedia.org/wiki/Routing#Delivery_schemes`

Routing

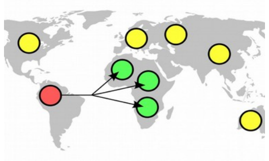
- Which routing paradigm is most appropriate for streaming the upcoming NA LCS Spring Finals?
  - A. Unicast
  - B. Anycast
  - C. Geocast
  - D. Multicast
  - E. Broadcast



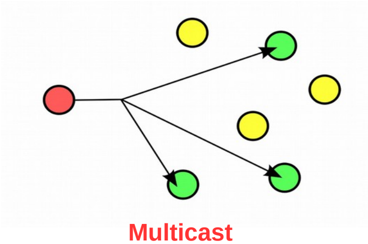
Unicast
(one-to-one)



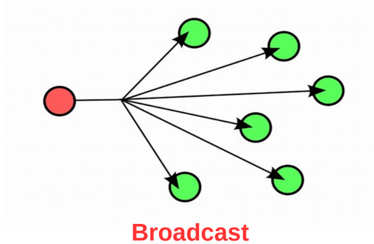
Anycast
(one-to-nearest)



Geocast
(one-to-proximate)



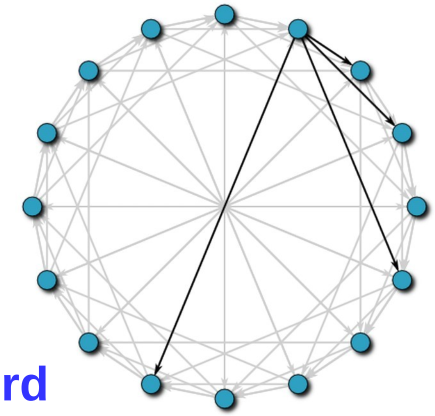
Multicast
(one-to-many)



Broadcast
(one-to-all)

Overlays

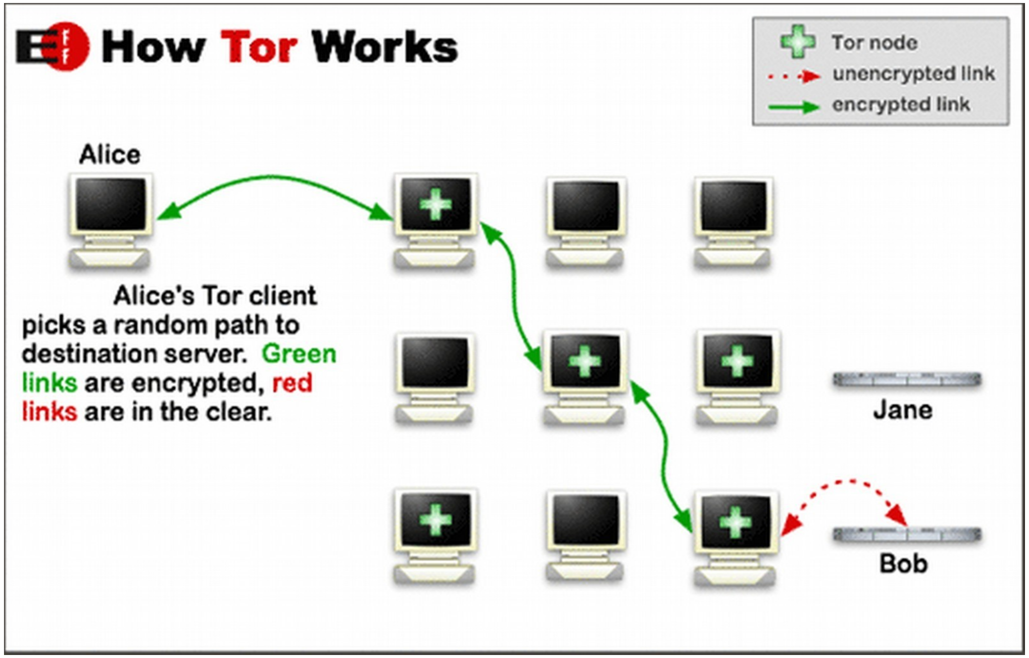
- Overlay: a network built on top of another network
  - IP multicast: technique for sending data to multiple recipients over an IP network using UDP
    - Group addressing (IGMP)
    - Tree-based distribution
  - Distributed hash tables (e.g., Chord)
  - XMPP – Jabber/Gtalk chat protocol
  - Tor network



Chord

Tor network

- Overlay network for anonymity
- Onion routing: multiple layers of obfuscation
  - At each layer, data is encrypted and sent to a random Tor relay
  - Sequence of relays form a virtual circuit that is difficult to trace
  - No single relay connects the source and destination directly



Part 3

- Protocols – how machines communicate (software, low-level)

Networking principles

- Distributed system components are often unreliable
- How do we build a **reliable** network using **unreliable** hardware and software?
  - Abstraction helps by hiding details where possible
  - Protocols define well-structured communication patterns
  - Layered / stacked protocols build on each other
  - Each layer adds metadata to help solve a specific problem
- Another guiding principle: the end-to-end principle
  - *Application-specific functions ought to reside in the end hosts of a network rather than in intermediary nodes whenever possible.*

For more info:
`http://web.mit.edu/Saltzer/www/publications/endtoend/endtoend.pdf`

Networking principles

- Which of the following is a violation of the end-to-end principle?
  - A. Public key encryption
  - B. ISP-based acceleration of Netflix traffic
  - C. Client-server chat programs
  - D. Web browser ad-blockers
  - E. Cross-platform video game multiplayer

QoS concerns

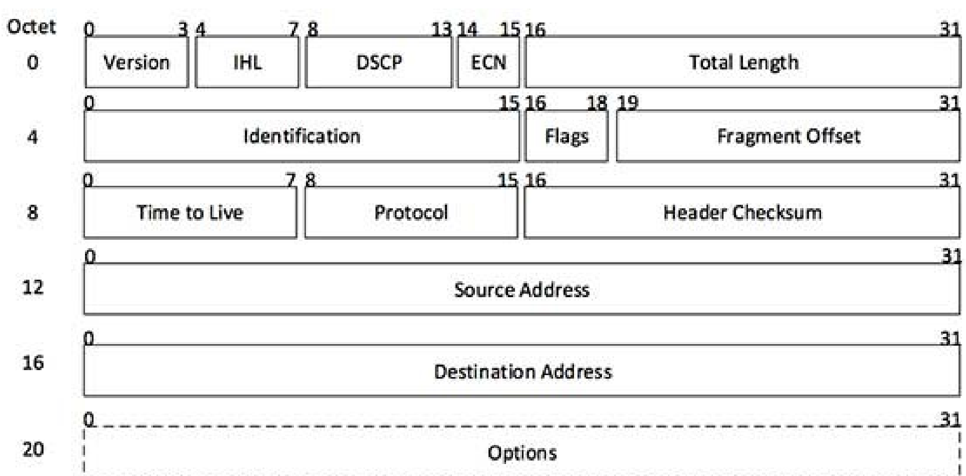
- Quality of Service (QoS) guarantees
  - Possible reasons to violate end-to-end principle
  - Minimum required bit rate (bandwidth)
  - Maximum delay to set up a session
  - Maximum end-to-end delay (latency)
  - Maximum delay variance (jitter)
  - Maximum round-trip delay
  - Possibility of expedited forwarding
  - Synchronization mechanisms
  - Examples: MPEG-2, HLS

QoS concerns

- Which QoS concern would be most important for streaming video?
  - A. Minimum bitrate
  - B. Maximum setup delay
  - C. Maximum latency
  - D. Maximum jitter
  - E. Possibility of expedited forwarding

Networking protocols

- Routing: choosing a path through a network
- Datagram: self-contained, encapsulated package of data and metadata capable of being routed
  - Also called a frame: (layer 2), a packet (layer 3), or a segment (layer 4)
- Protocol: rules for exchanging data (often using datagrams)
- Checksums: data integrity verification mechanism



[Image: IP Header]

IPv4 header

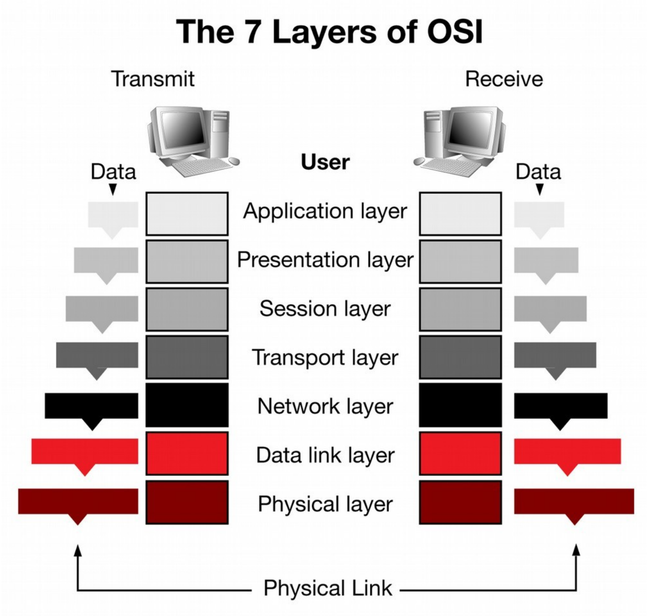
(from `https://www.tutorialspoint.com/ipv4/ipv4_packet_structure.htm`)

Protocol design issues

- Connectionless vs. connection-oriented
  - Is there a setup/teardown procedure required for communication?
  - No setup costs vs. faster speed after connection
- Synchronous vs. asynchronous
  - Does the sender block after sending?
    - E.g., `MPI_Ssend` vs. `MPI_Isend`
  - Easier to debug and verify vs. faster communication
- Persistent vs. transient communication
  - Are messages stored by the middleware?
  - Guaranteed delivery vs. simplicity of middleware

OSI model layers

1) Physical: Transmission of raw bits over a physical medium (Ethernet, 802.11)
2) Data link: Reliable transmission of frames between two nodes (FC, 802.11)
3) Network: Structured transmission on a multi-node network (IP, ICMP)
4) Transport: Reliable transmission on a multi-node network (TCP, UDP)
5) Session: Managed communication sessions (RPC, NFS)
6) Presentation: Encoding and conversion of data (HTML, XML, JSON)
7) Application: Application-level abstractions (FTP, HTTP, SSH, MPI)



Part 4

- IPC paradigms – how processes communicate (software, high-level)

IPC paradigms

- Inter-process communication (IPC)
  - Message-passing (explicit)
    - Symmetric (SPMD) vs. asymmetric (differentiated hosts)
  - Remote procedure calls (implicit)
    - Synchronous vs. asynchronous

Berkeley / POSIX Sockets

- API for inter-process communication
  - Originally designed for BSD
  - Later evolved into a POSIX standard
  - Often used for low-level TCP and UDP communication
  - Hosts identified by address (usually IP) and port number
  - Passes "messages" (packets) between hosts
  - Can use Unix pipes if both endpoints are on a single host

Socket primitives

- Server
  - Socket: Create a new endpoint
  - Bind: Attach a local address to a socket
  - Listen: Announce readiness for connections
  - Accept: Block until a request arrives
- Client
  - Connect: Attempt to establish a connection
- Server & client
  - Write: Send data over a connection
  - Read: Receive data over a connection
  - Close: Destroy a connection

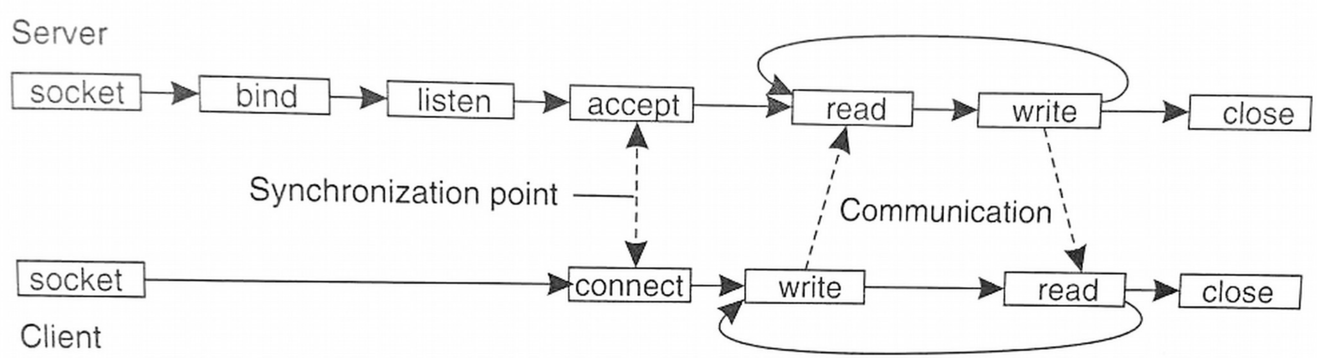


Figure 4-15. Connection-oriented communication pattern using sockets.

Socket primitives

- Which of the following is NOT a valid event sequence using sockets? (other events may occur between the events in the sequence)
  - A. accept, write, read
  - B. accept, read, write
  - C. accept, listen, read
  - D. listen, accept, read
  - E. socket, connect, write

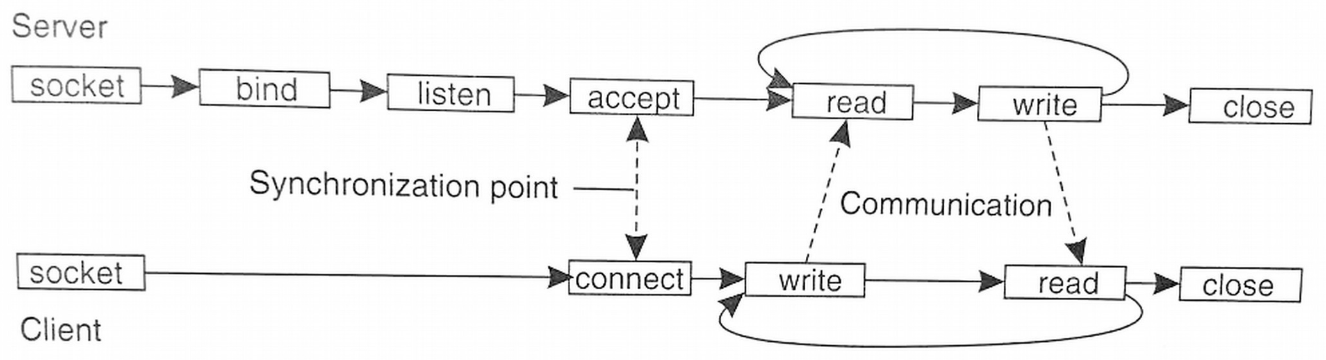
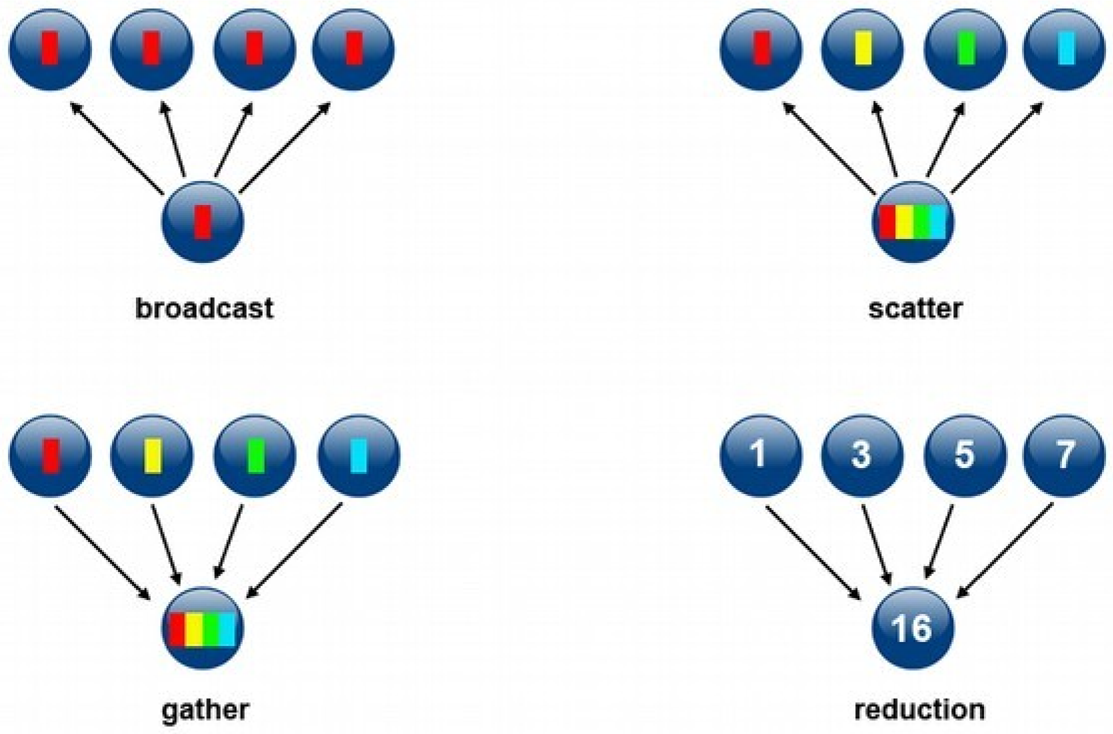


Figure 4-15. Connection-oriented communication pattern using sockets.

MPI (Message Passing Interface)

- MPI_Send
- MPI_Recv
- MPI_Bcast
- MPI_Scatter
- MPI_Gather
- MPI_Allgather
- MPI_Reduce
- MPI_Allreduce
- MPI_Alltoall



from https://computing.llnl.gov/tutorials/parallel_comp/

Remote Procedure Call (RPC)

- Key idea: transparency
  - It should look like the procedure call is happening locally
  - Similar in spirit to PGAS remote memory accesses
  - Implement server / client stubs to handle the call
- Parameter marshalling
  - Preparing parameters for transmission over a network

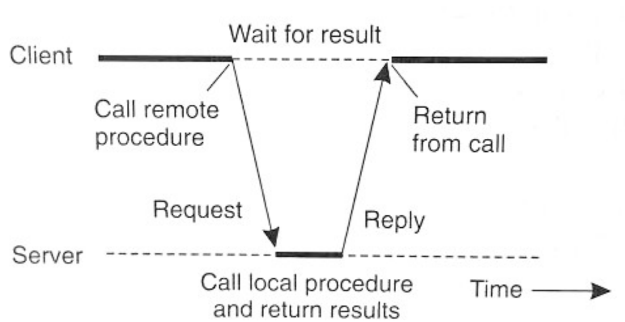


Figure 4-6. Principle of RPC between a client and server program.

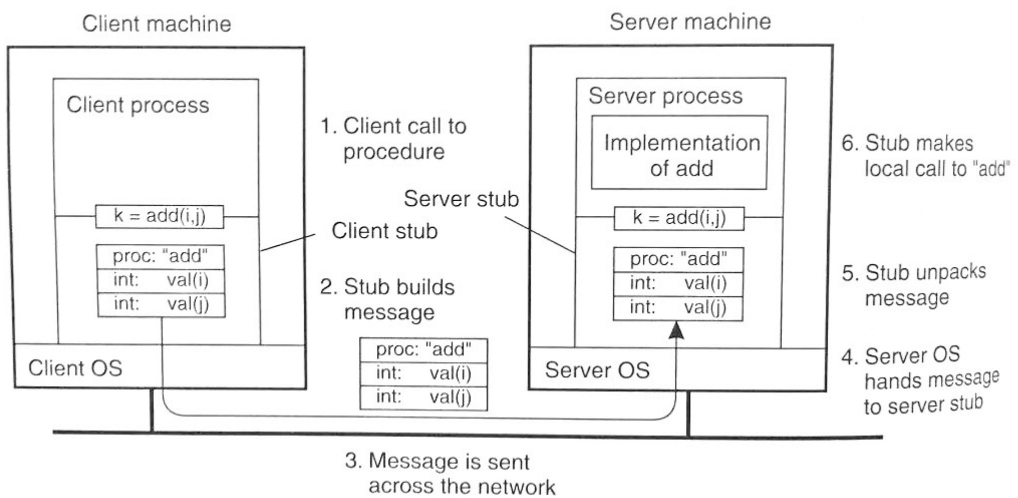


Figure 4-7. The steps involved in a doing a remote computation through RPC.

Asynchronous RPC

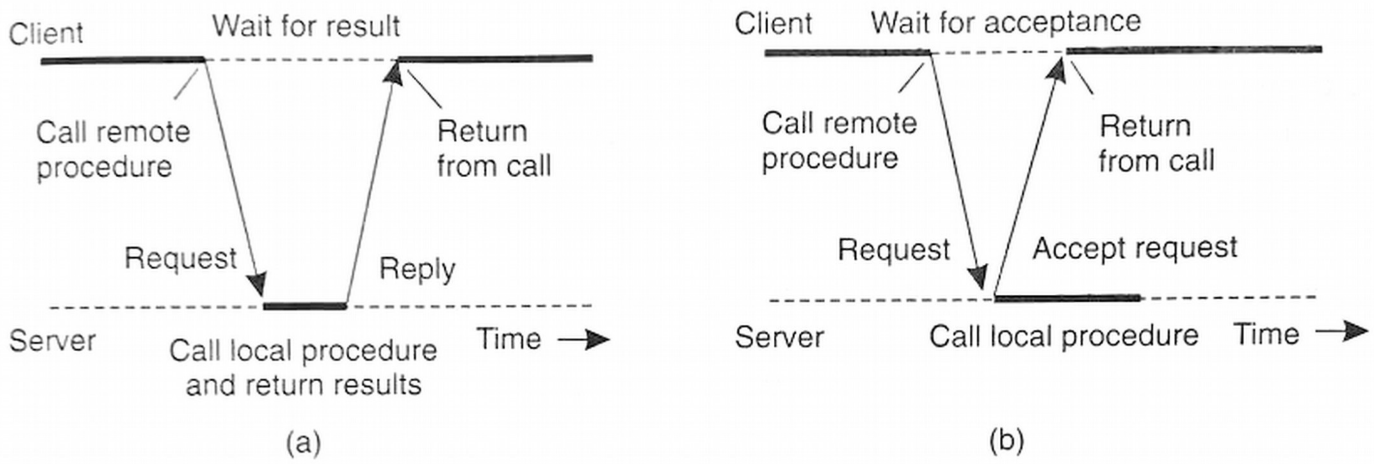


Figure 4-10. (a) The interaction between client and server in a traditional RPC. (b) The interaction using asynchronous RPC.

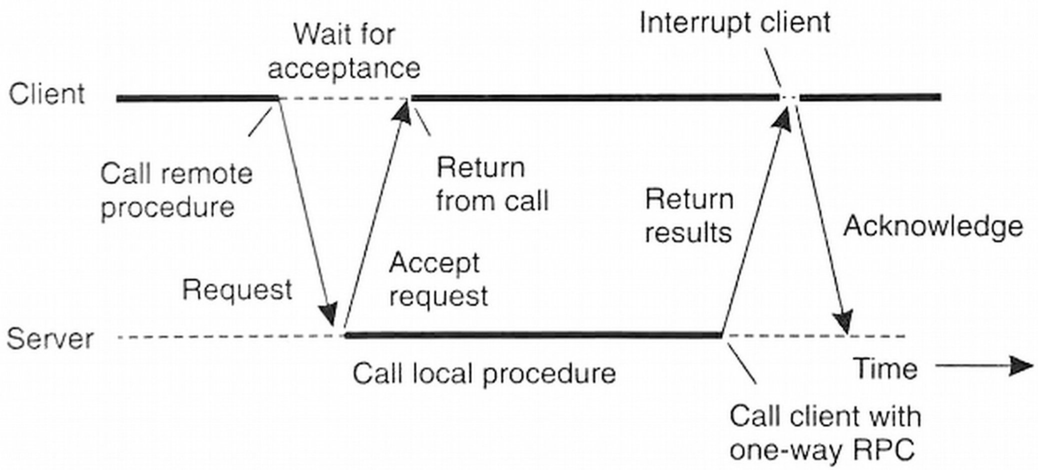


Figure 4-11. A client and server interacting through two asynchronous RPCs.

Summary

- Topologies – how a network is arranged (hardware)
- Routing – how traffic navigates a network (hardware and software)
- Protocols – how machines communicate (software, low-level)
- IPC paradigms – how processes communicate (software, high-level)

Next time: how do we **identify** hosts on a network?
(e.g., what is a host's name)