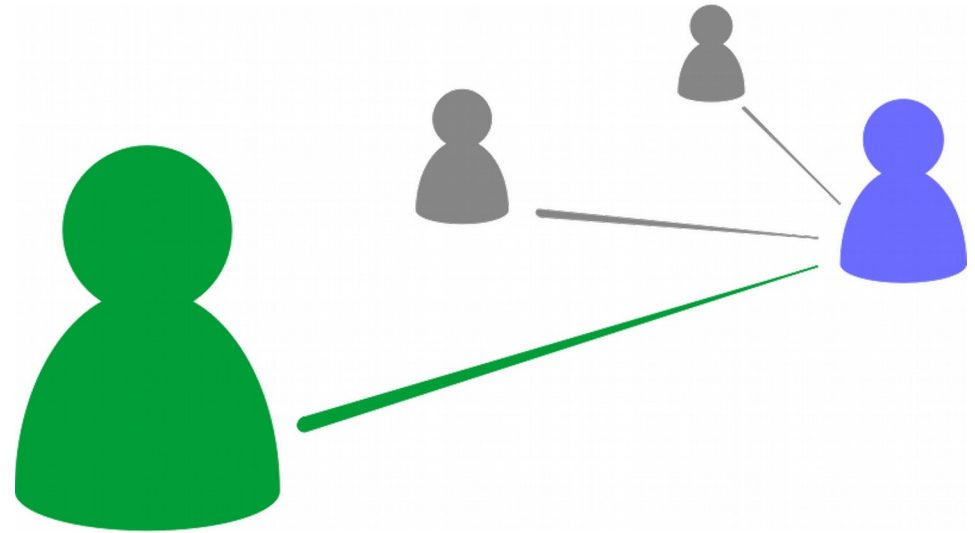


CS 470 Spring 2023

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](https://www.wikipedia.org) and [openclipart.org](https://www.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)

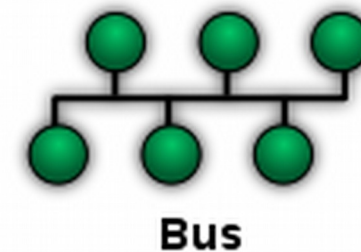
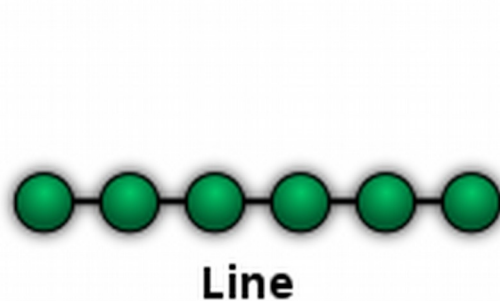
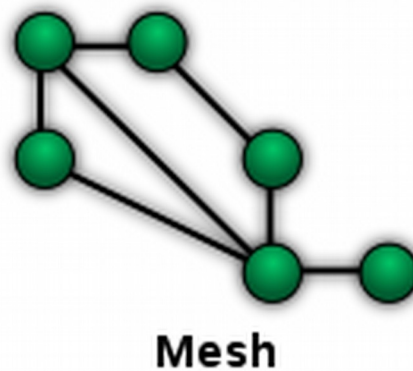
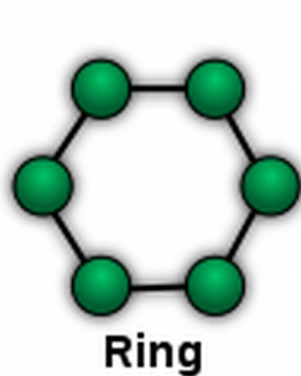


Part 1

- **Topologies** – how a network is arranged (hardware)

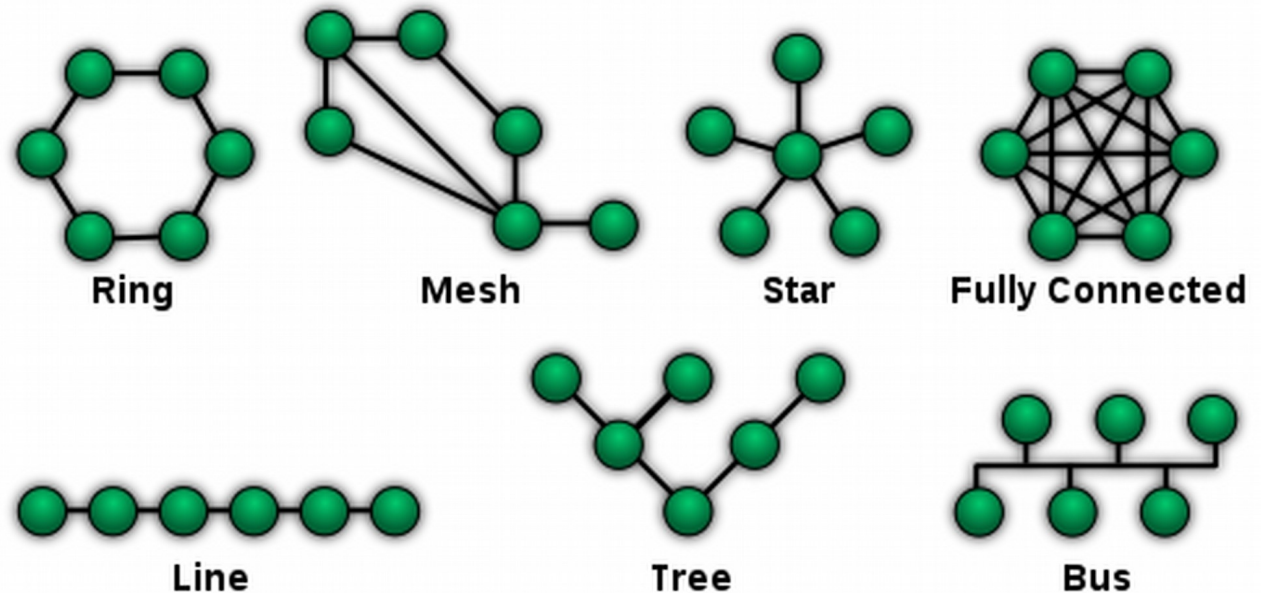
Network topologies

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



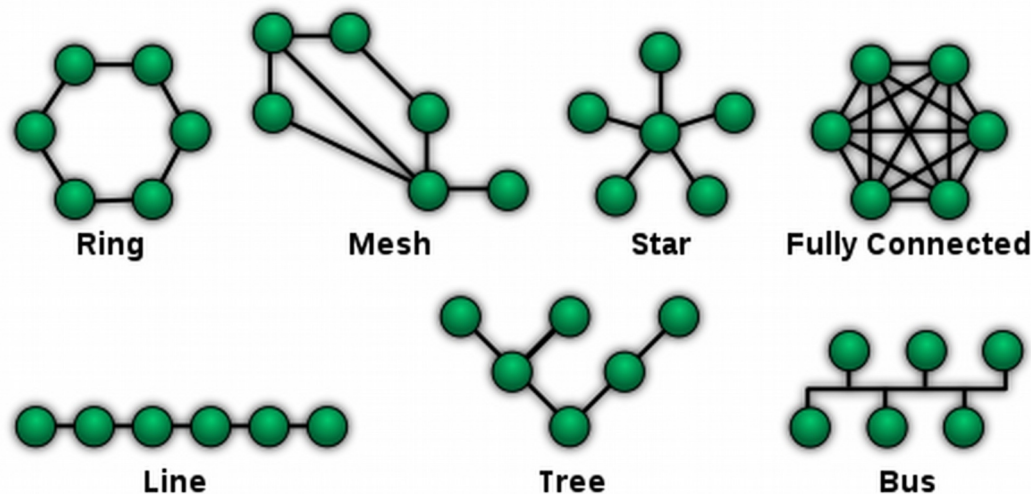
Network topologies

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



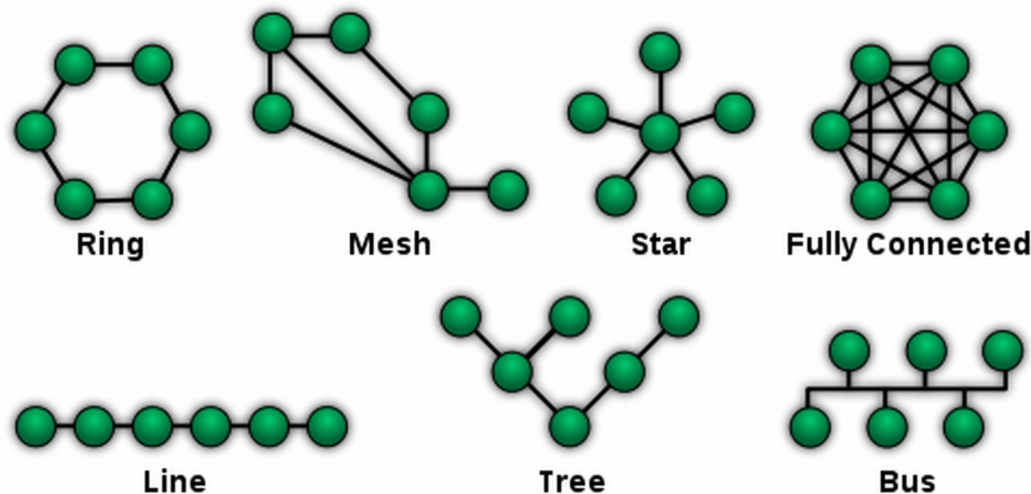
Network topologies

- 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



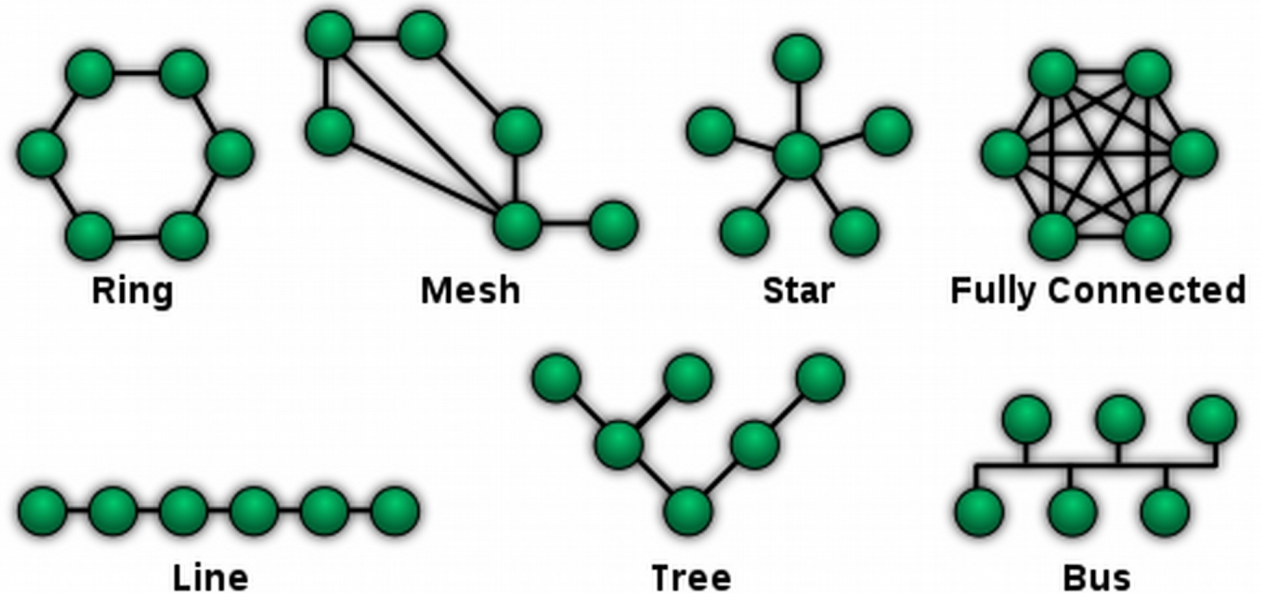
Evaluating topologies

- **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?



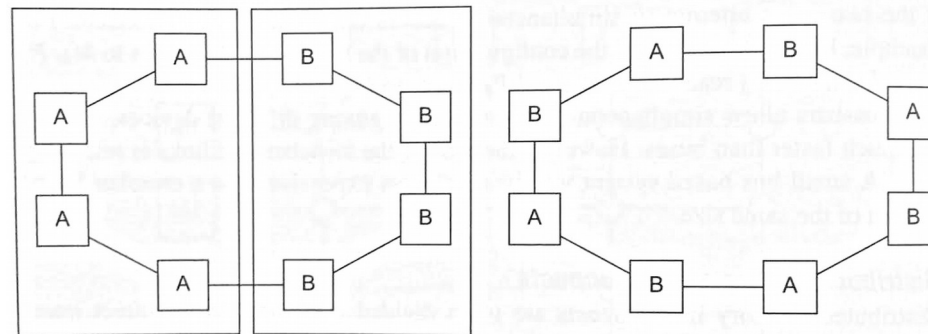
Evaluating topologies

- 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

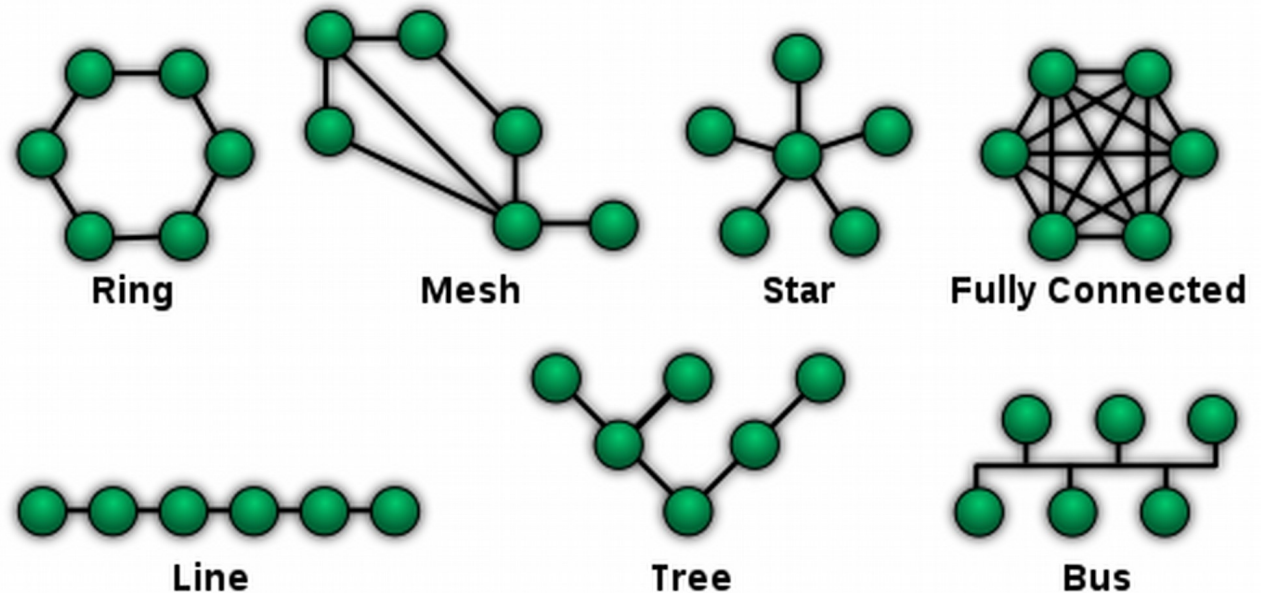
- **Bisection**: divide the network into two equal partitions
 - **Bisection width**: number of simultaneous communications between the two partitions
 - **Bisection bandwidth**: total data rate between the partitions
 - Typically done in such a way that minimizes bisection bandwidth
 - This represents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

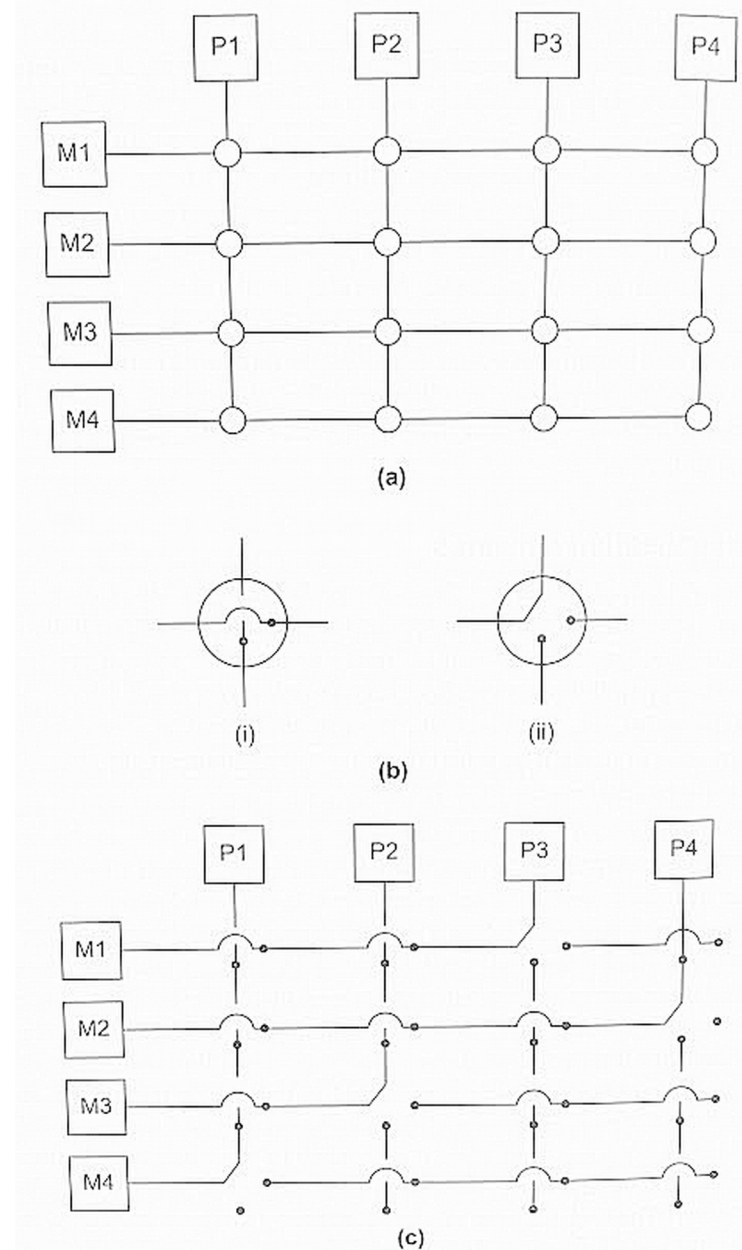
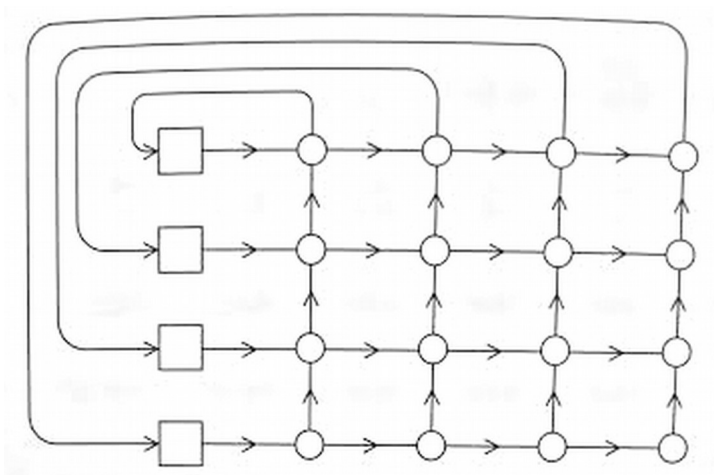


Evaluating topologies

- 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

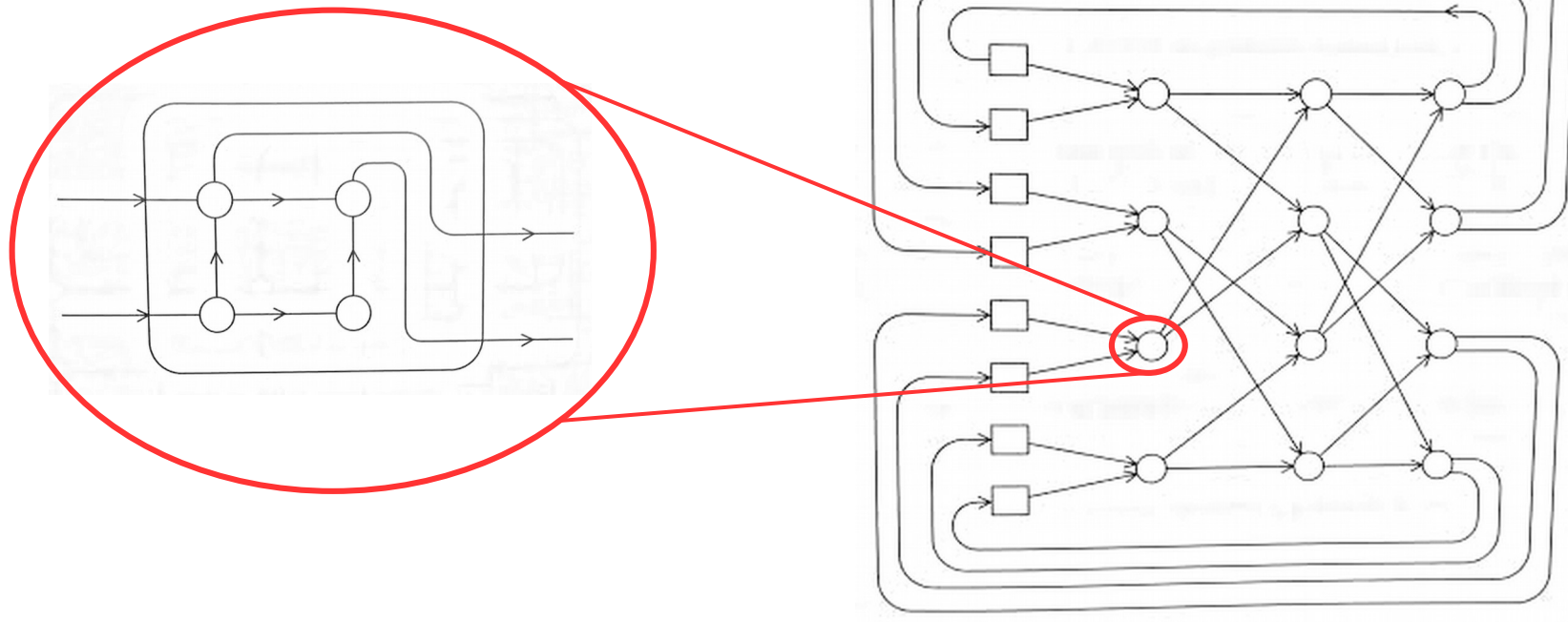
Crossbar switches

- **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



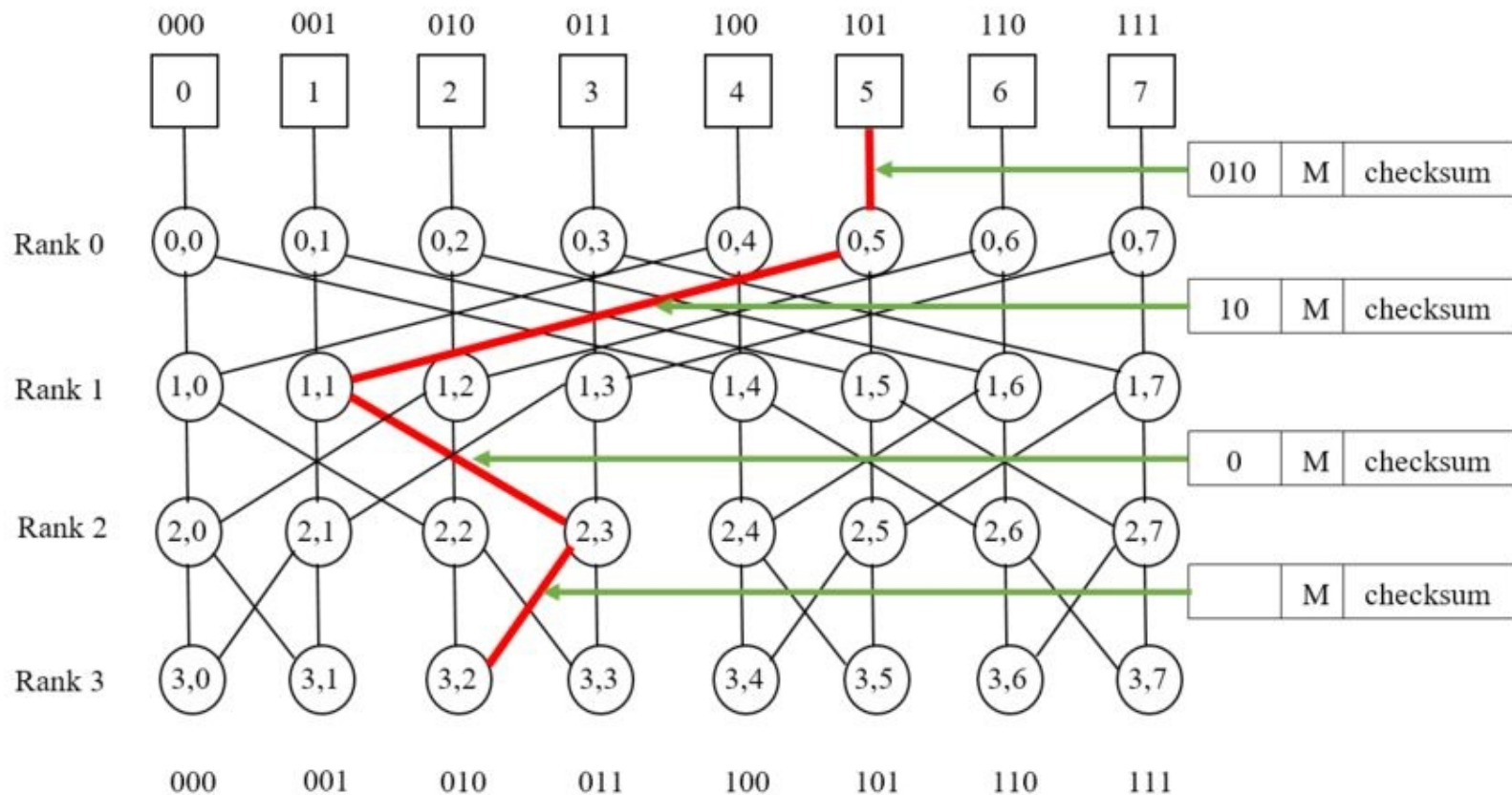
Omega networks

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



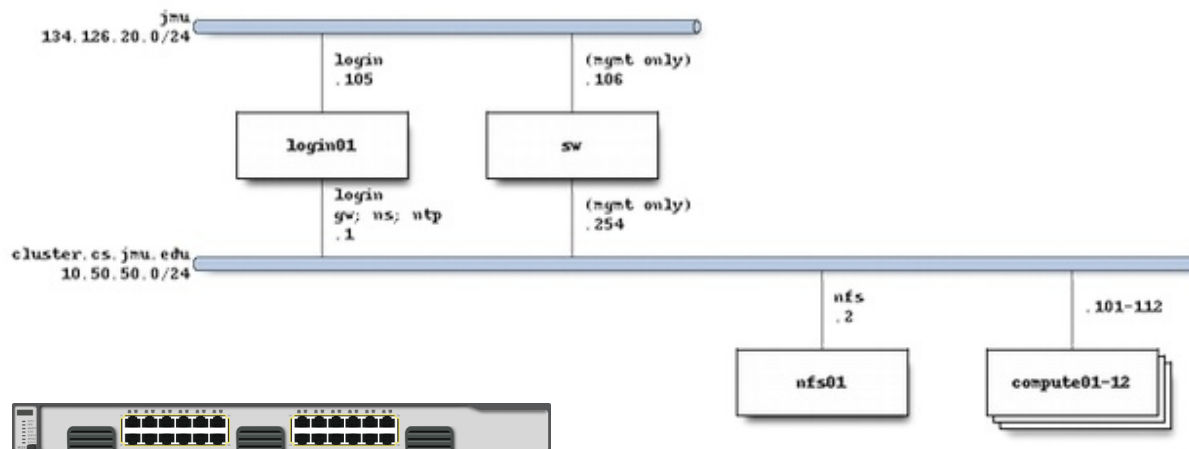
Butterfly networks

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

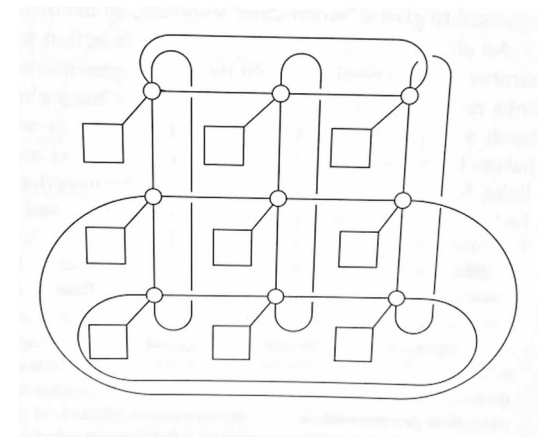


HPC interconnects

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



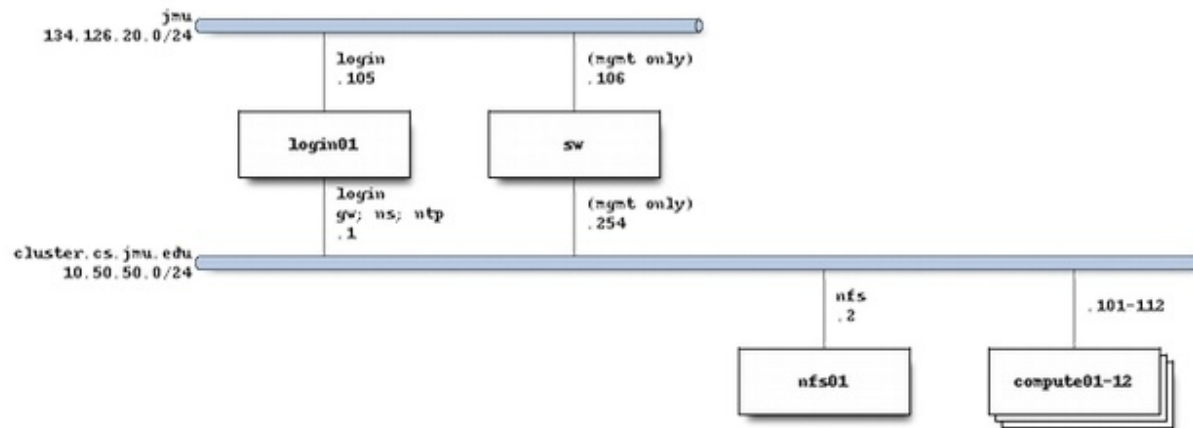
Our cluster (switched bus)



Toroidal Mesh

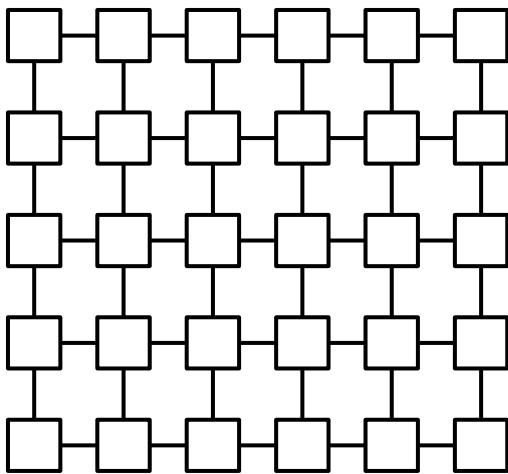
HPC interconnects

- 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

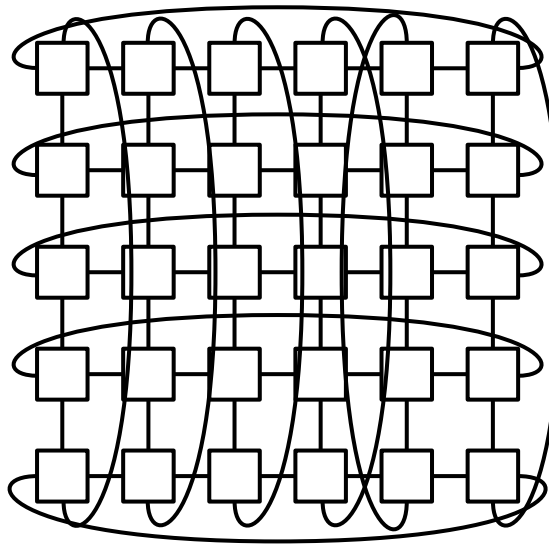


Meshes and tori

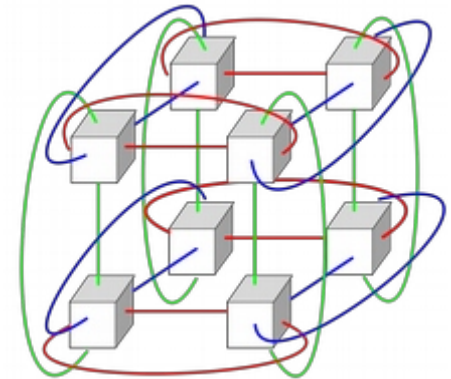
- Nodes are connected to several neighbors
 - **Non-uniform memory access** to non-immediate neighbors



2D Regular Mesh



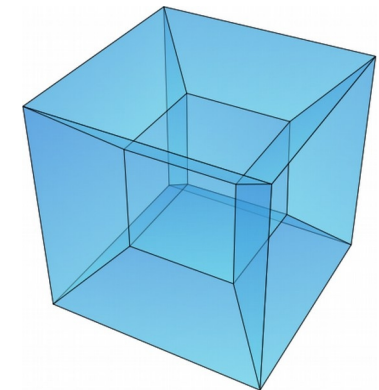
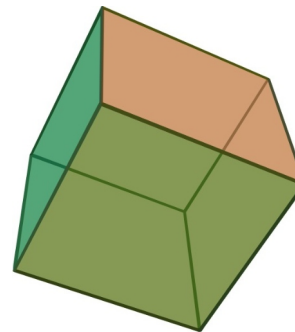
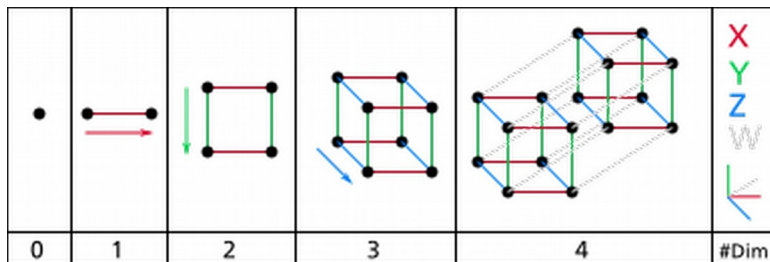
2D Torus
(or “toroidal mesh”)



3D Torus

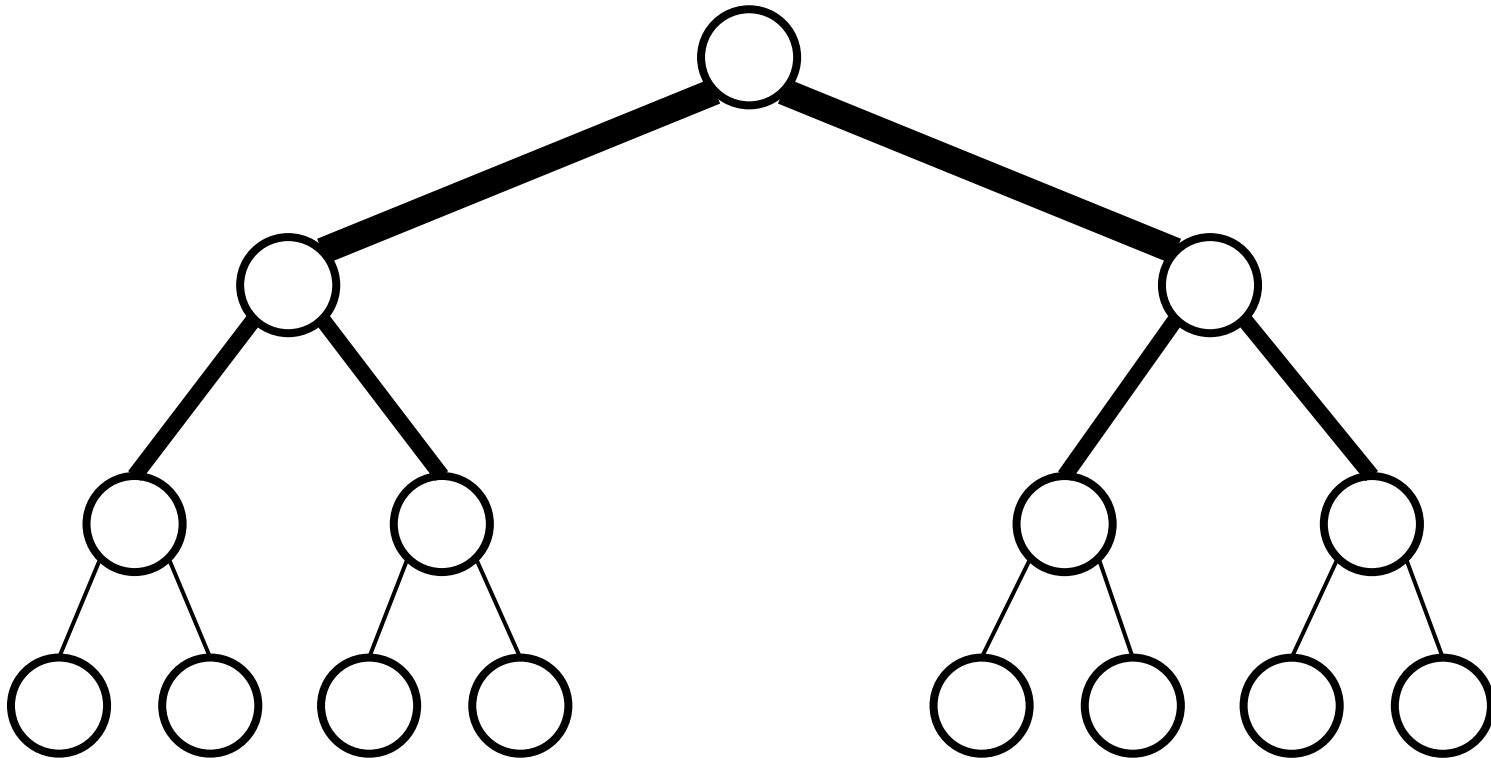
Hypercubes

- 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



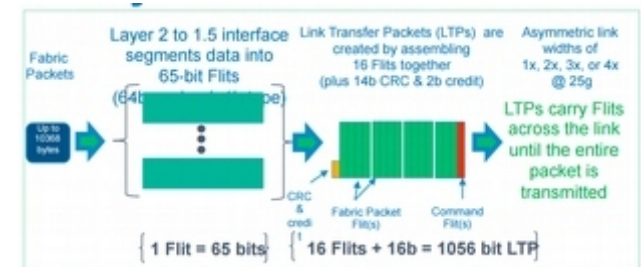
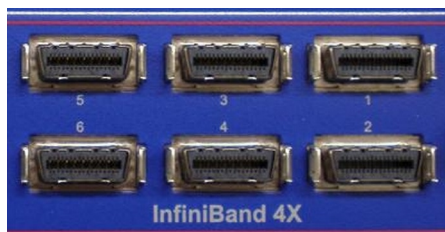
Fat trees

- 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/ 0.5 μ s 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



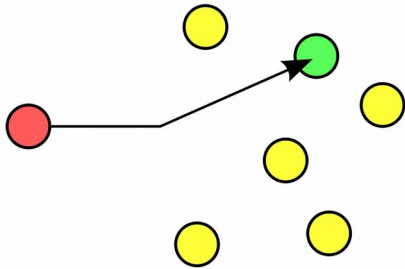
Part 2

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

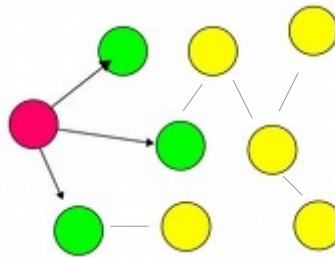
Routing

- **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

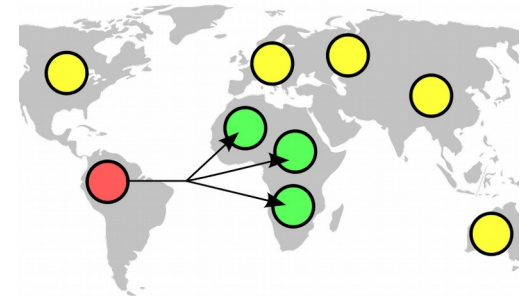
Routing



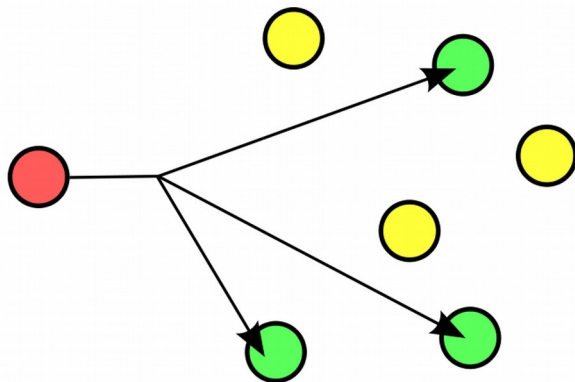
Unicast
(one-to-one)



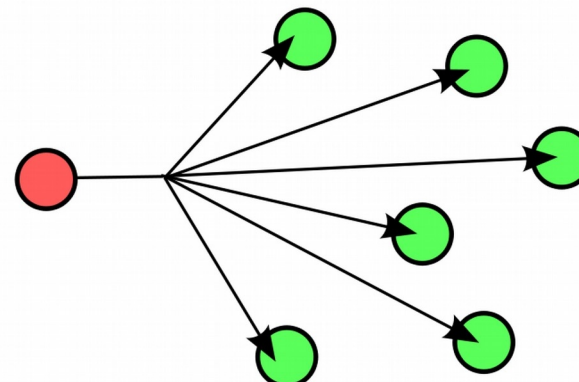
Anycast
(one-to-nearest)



Geocast
(one-to-proximate)



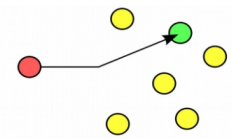
Multicast
(one-to-many)



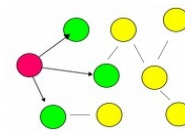
Broadcast
(one-to-all)

Routing

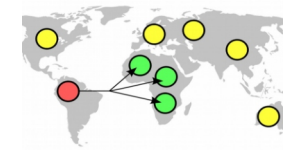
- Which routing paradigm is most appropriate for streaming the NA LCS Spring Finals next weekend?
 - A. Unicast
 - B. Anycast
 - C. Geocast
 - D. Multicast
 - E. Broadcast



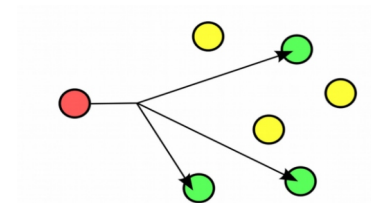
Unicast
(one-to-one)



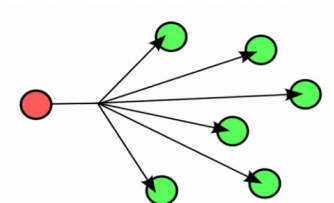
Anycast
(one-to-nearest)



Geocast
(one-to-proximate)



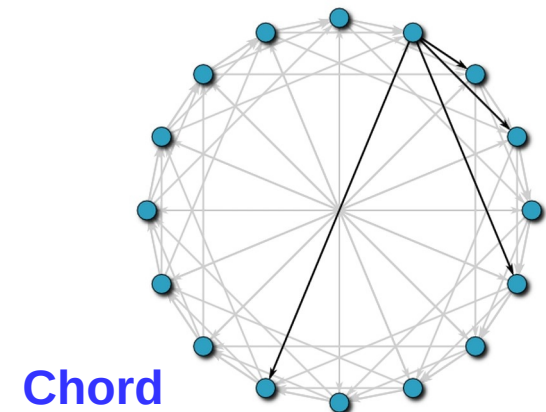
Multicast
(one-to-many)



Broadcast
(one-to-all)

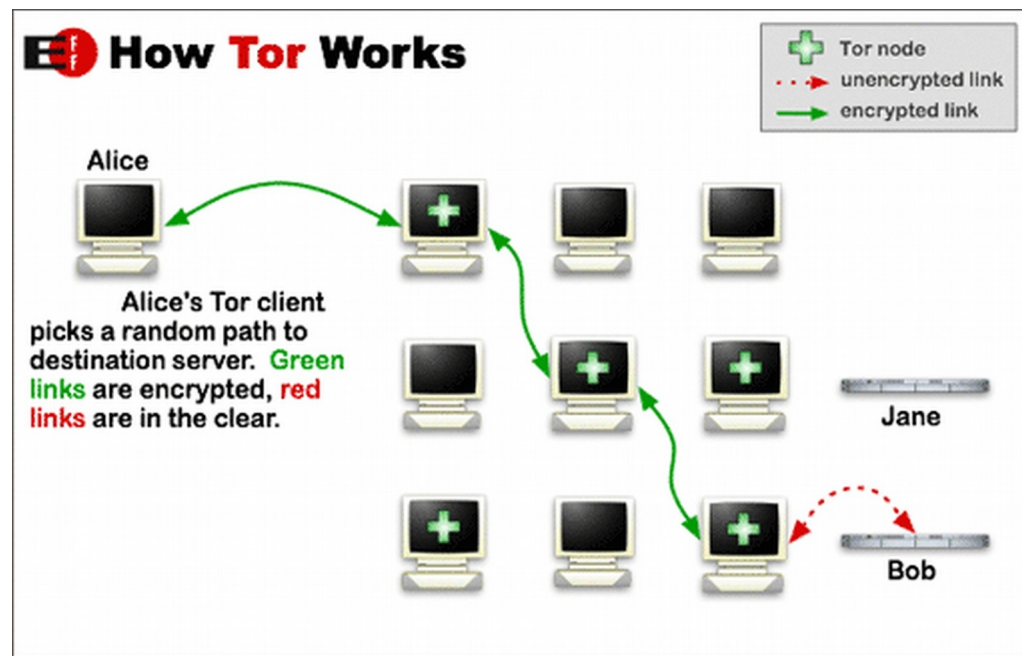
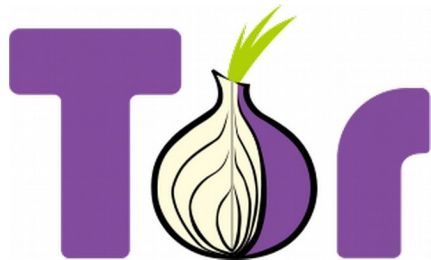
Overlays

- **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



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

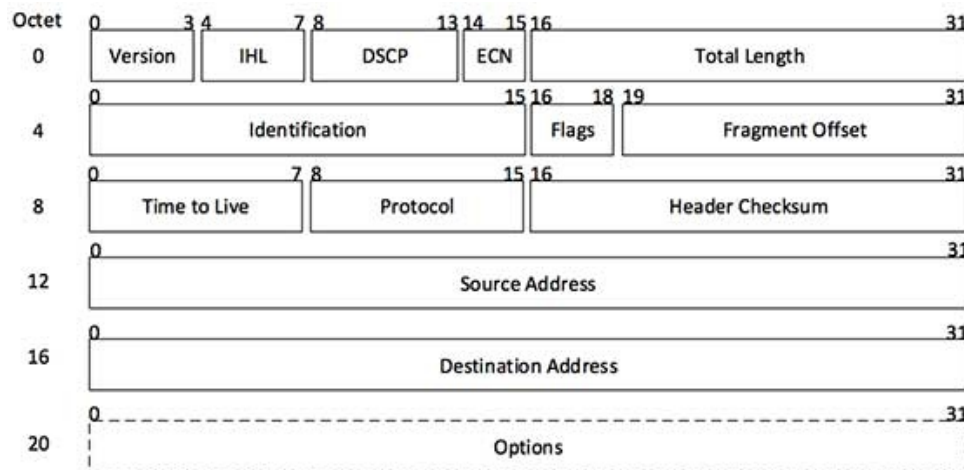
- Quality of Service (QoS) guarantees
 - Possible reasons to violate end-to-end principle
 - Minimum required bit rate (**bandwidth**)
 - Maximum delay to set up a session
 - Maximum end-to-end delay (**latency**)
 - Maximum delay variance (**jitter**)
 - Maximum round-trip delay
 - Possibility of **expedited 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

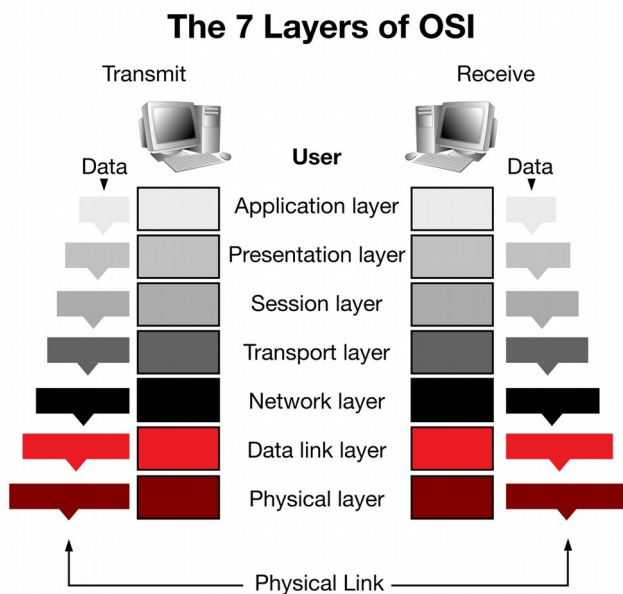
(from https://www.tutorialspoint.com/ipv4/ipv4_packet_structure.htm)

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

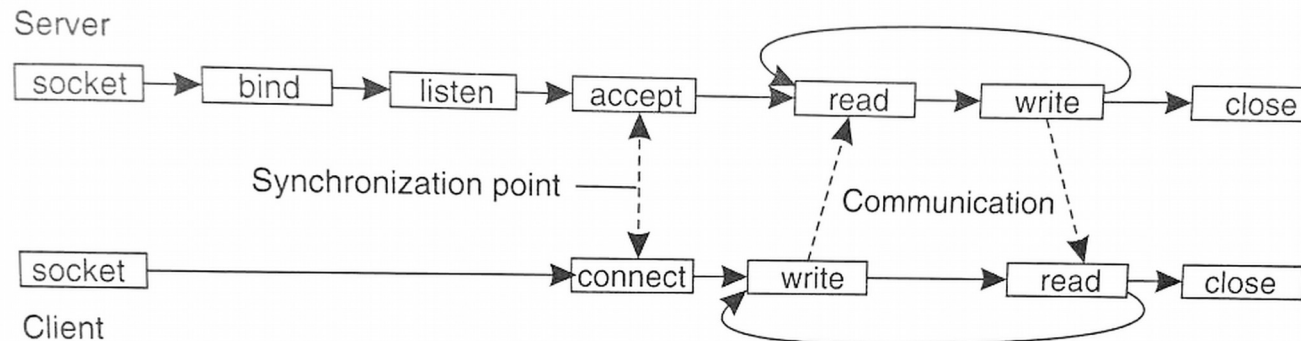


Figure 4-15. Connection-oriented communication pattern using sockets.

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

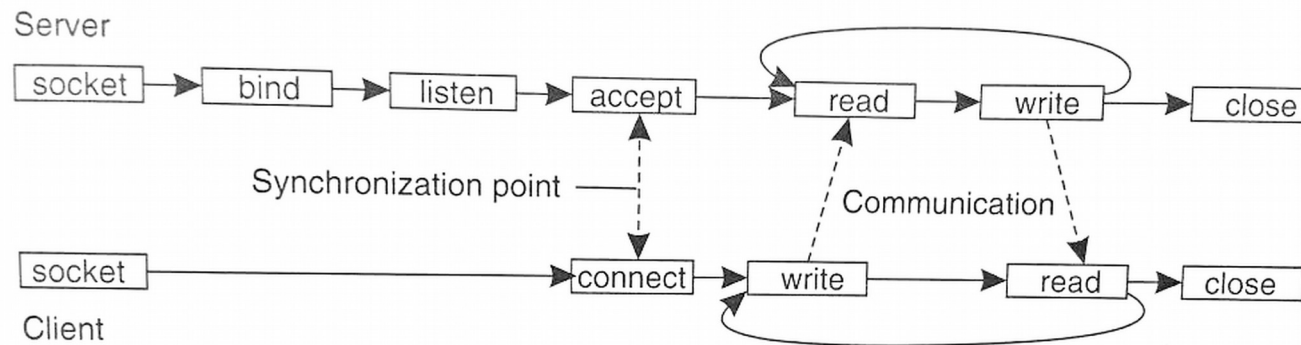
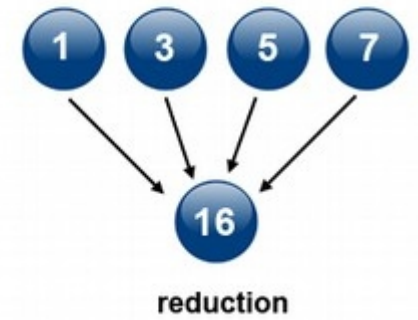
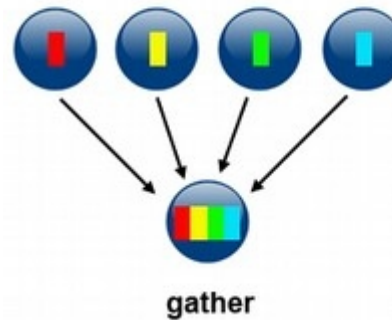
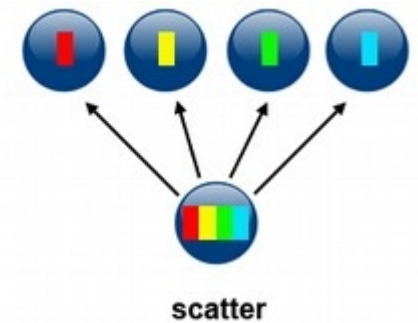
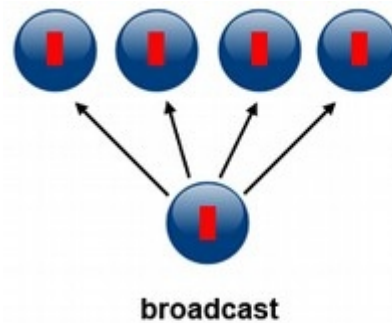


Figure 4-15. Connection-oriented communication pattern using sockets.

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

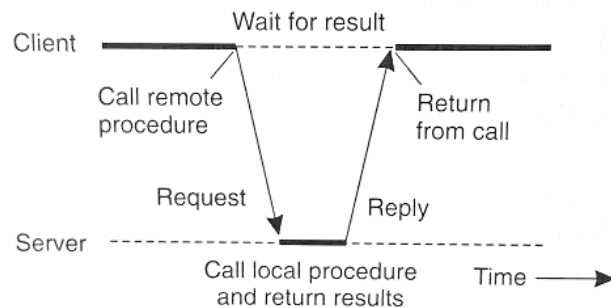


Figure 4-6. Principle of RPC between a client and server program.

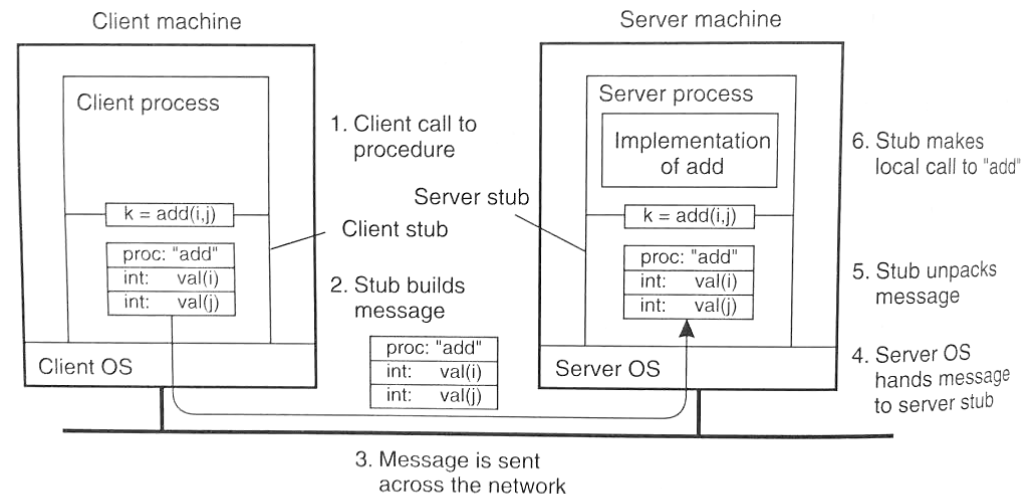


Figure 4-7. The steps involved in doing a remote computation through RPC.

Asynchronous RPC

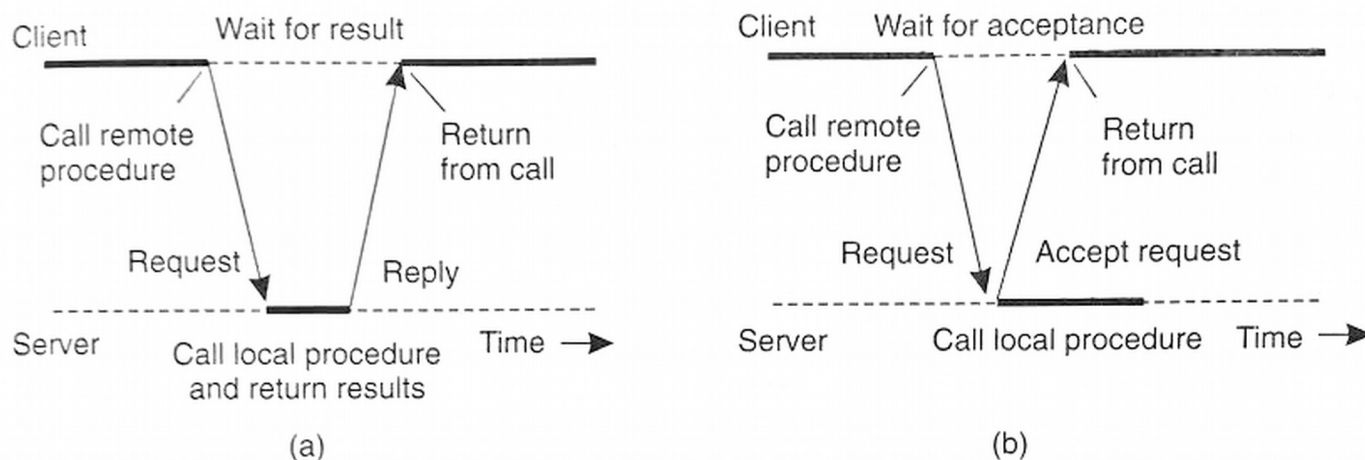


Figure 4-10. (a) The interaction between client and server in a traditional RPC.
(b) The interaction using asynchronous RPC.

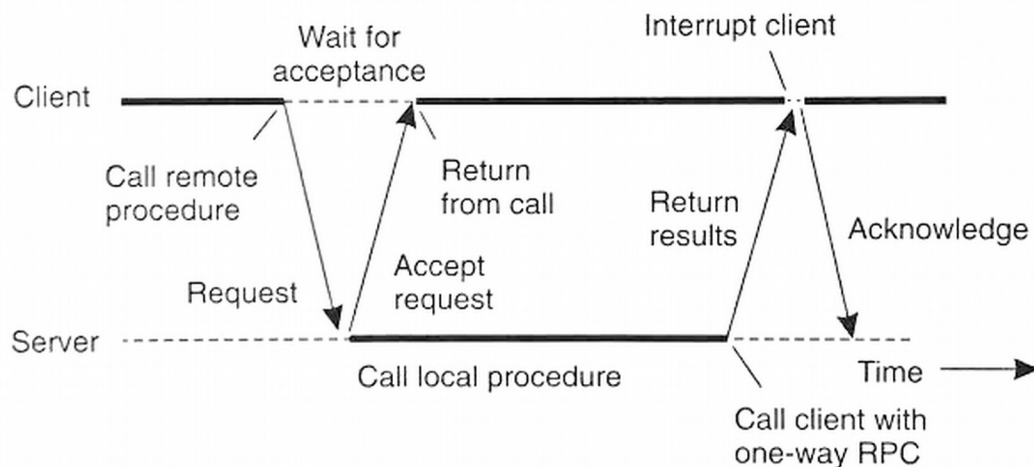
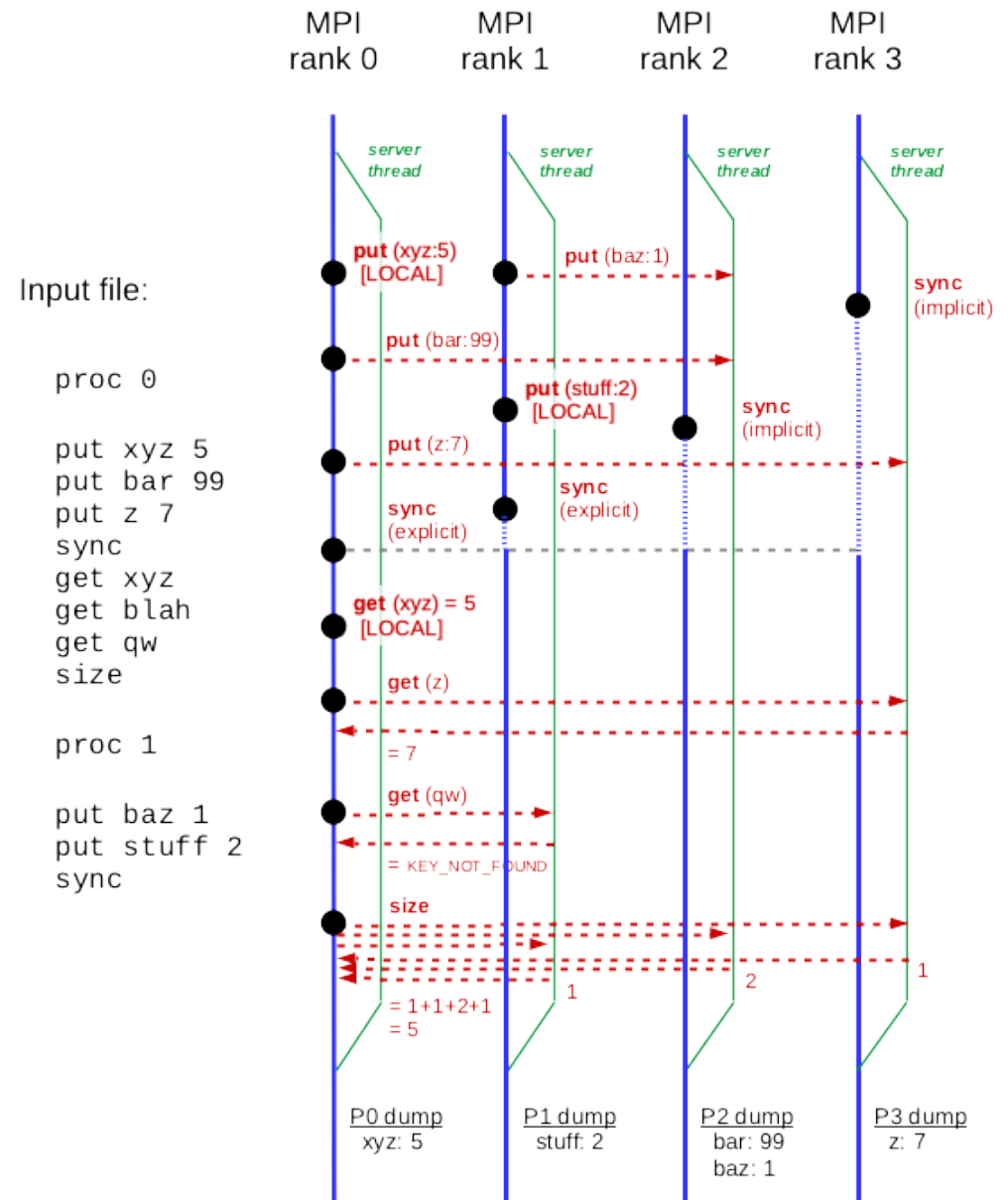


Figure 4-11. A client and server interacting through two asynchronous RPCs.

P4 - DHT

- Distributed hash table
 - MPI rank per node
 - Server
 - Client
 - RPC wrappers for local table operations
 - Rough structure suggested
 - You design the exact protocol



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)