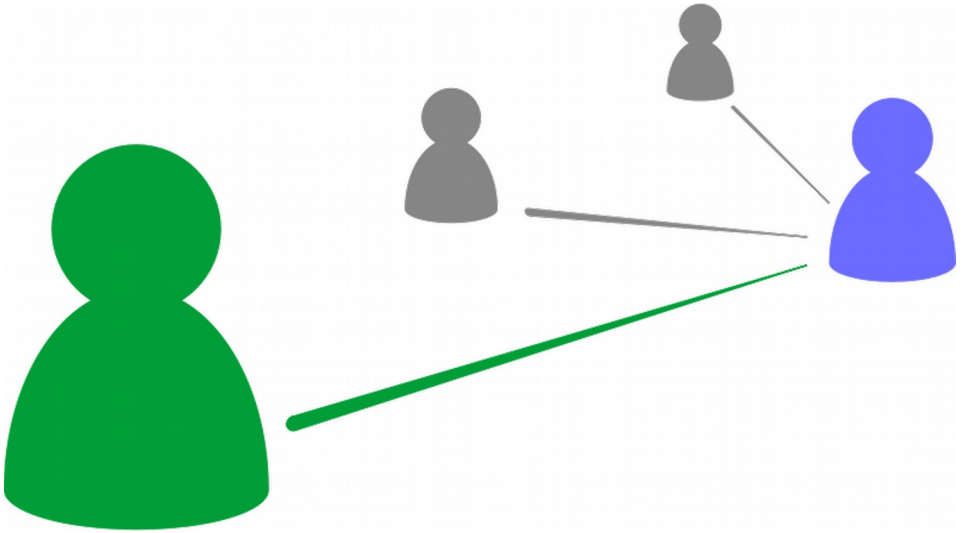
CS 470
Spring 2017

Mike Lam, Professor



Networks and Naming

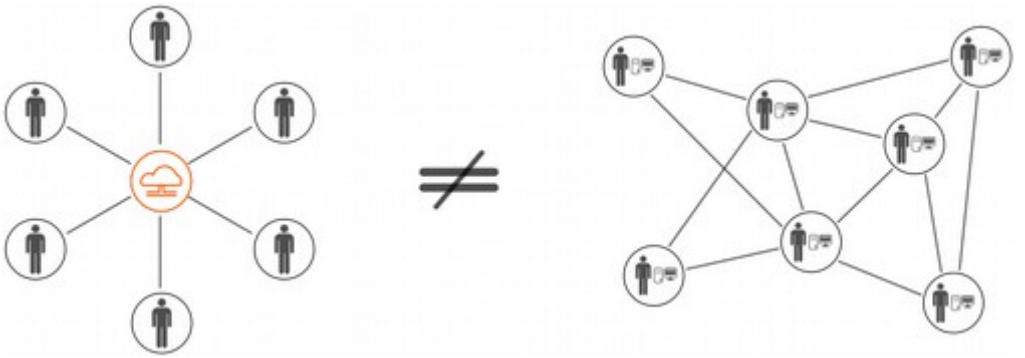
Content taken from IPP 2.3.3 and the following:

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

Various online sources (including openclipart.org)

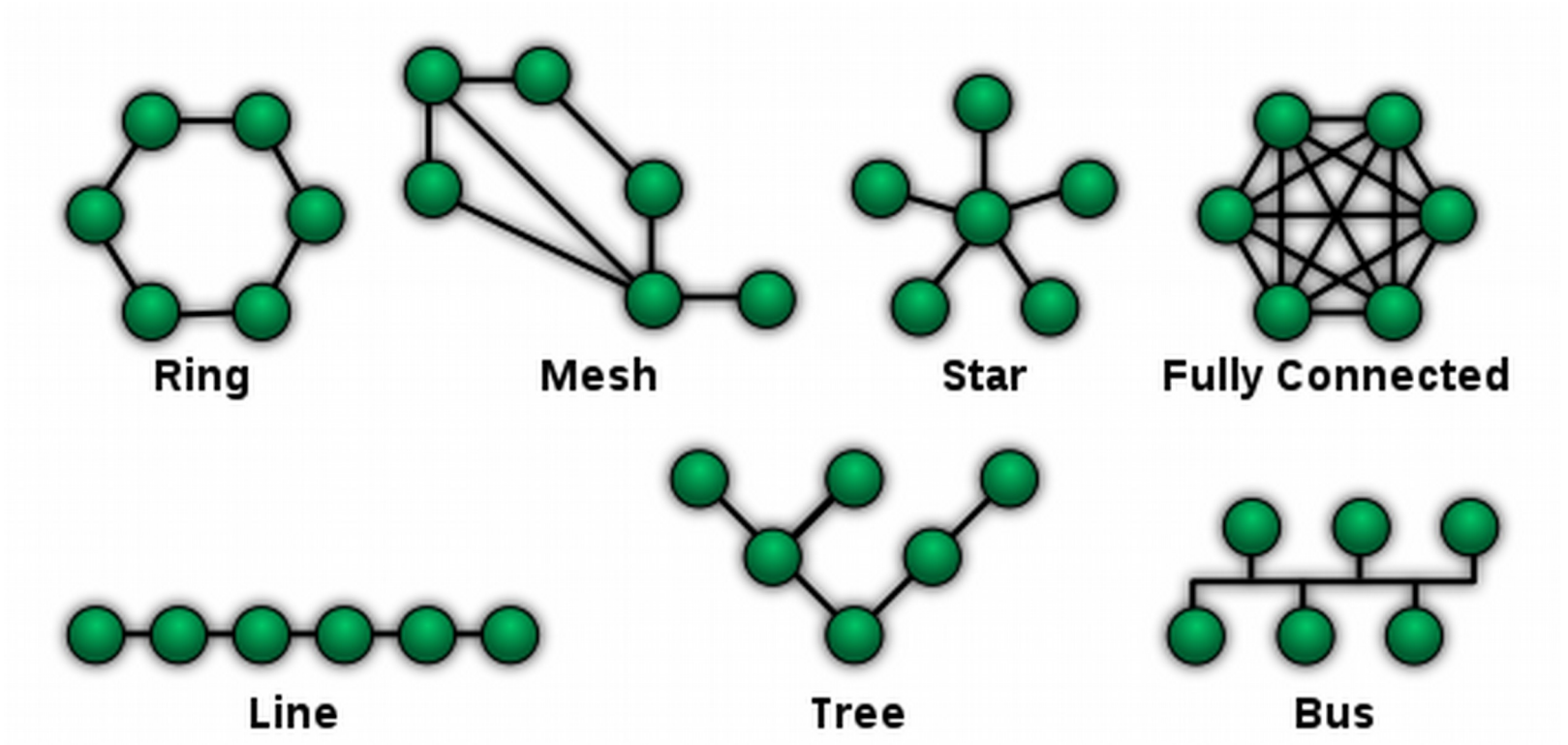
Overview

- 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)
- Naming – how hosts are identified in a system (cross-cutting)



Network topologies

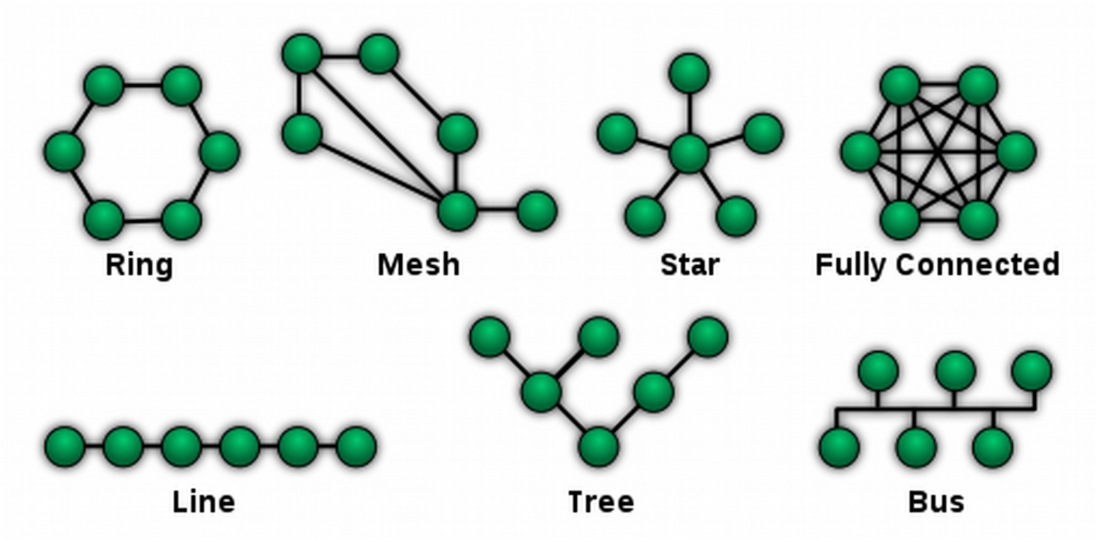
- A topology is an arrangement of components or nodes in a system



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

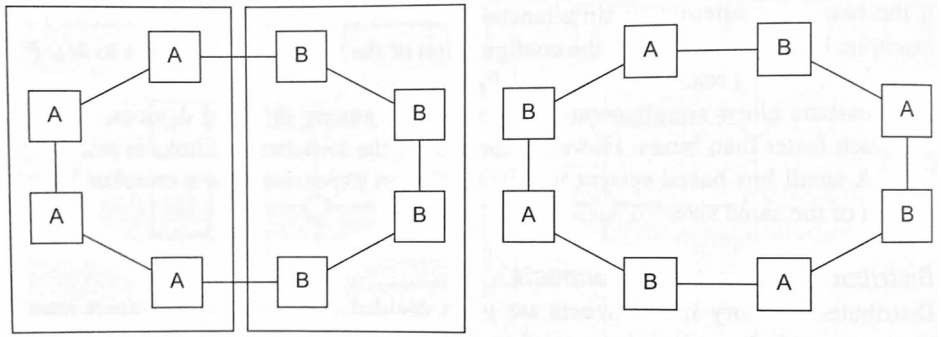
Network topologies

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

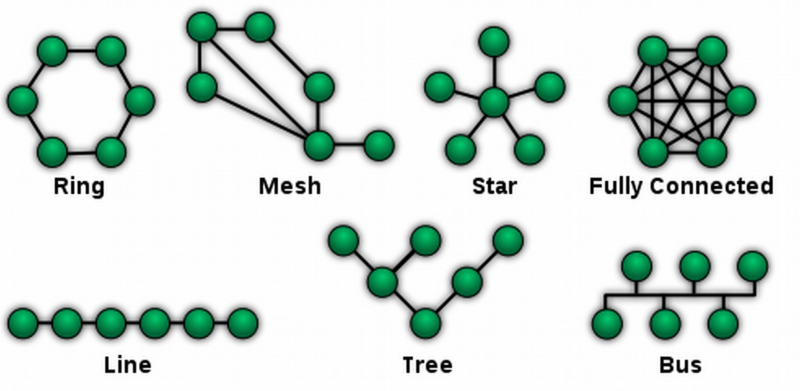


Evaluating topologies

- Bandwidth: maximum rate at which a link can transmit data
  - Throughput: measured rate of actual data transmission (usually less than bandwidth)
- Latency: time between start of send and reception of first data
- Diameter: maximum number of hops between nodes on a network
- Bisection: divide the network into two sections
  - Bisection width: how many communications could happen simultaneously between the two sections?
  - Bisection bandwidth: what is the bandwidth between the sections?
- **Important**: how do these metrics scale as you add nodes?

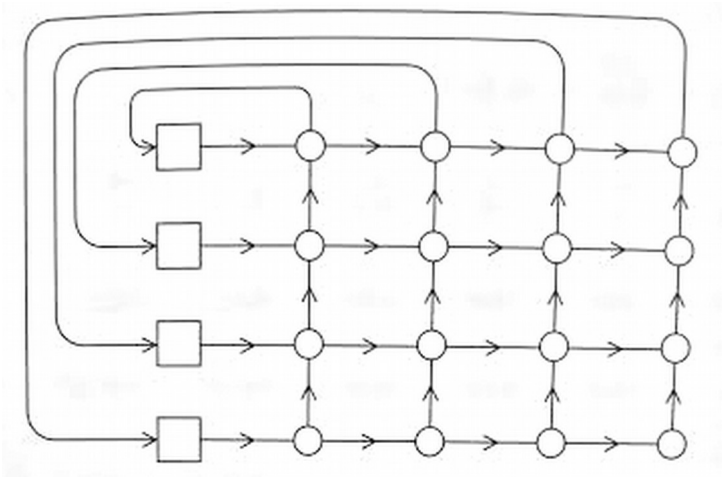


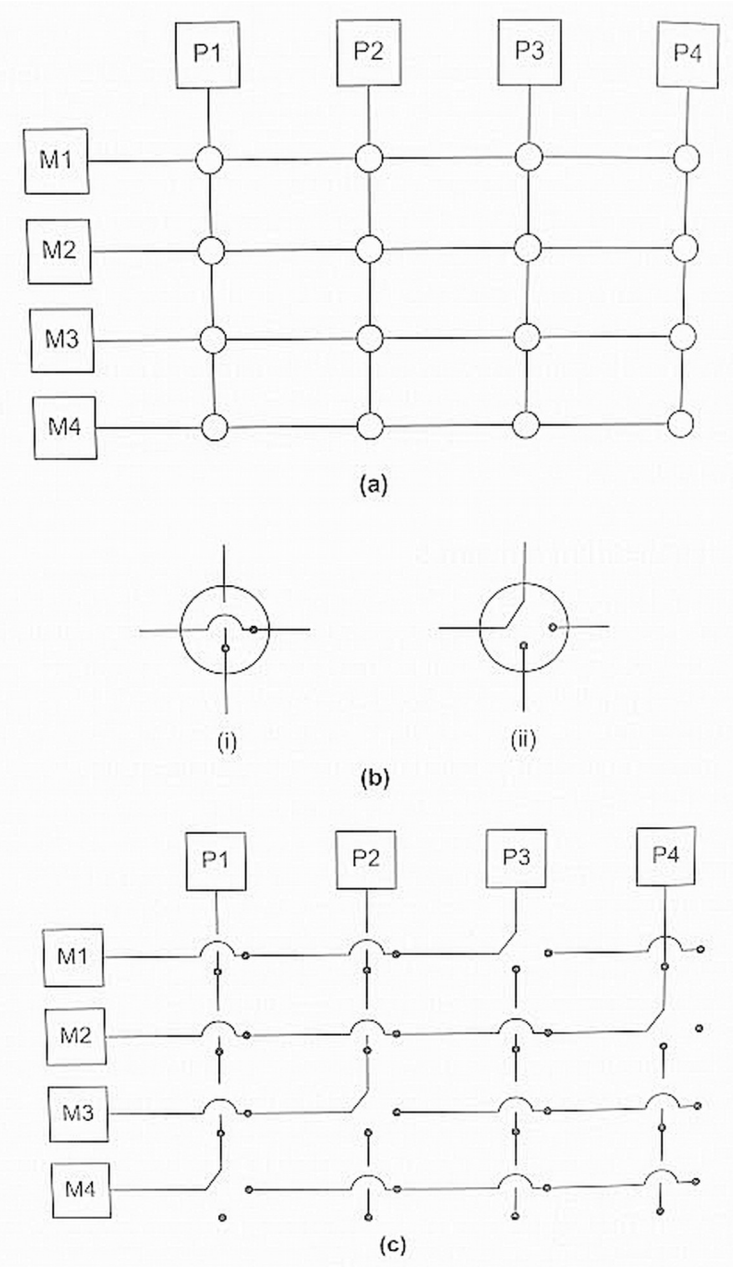
Two different bisections of a network



Crossbar switches

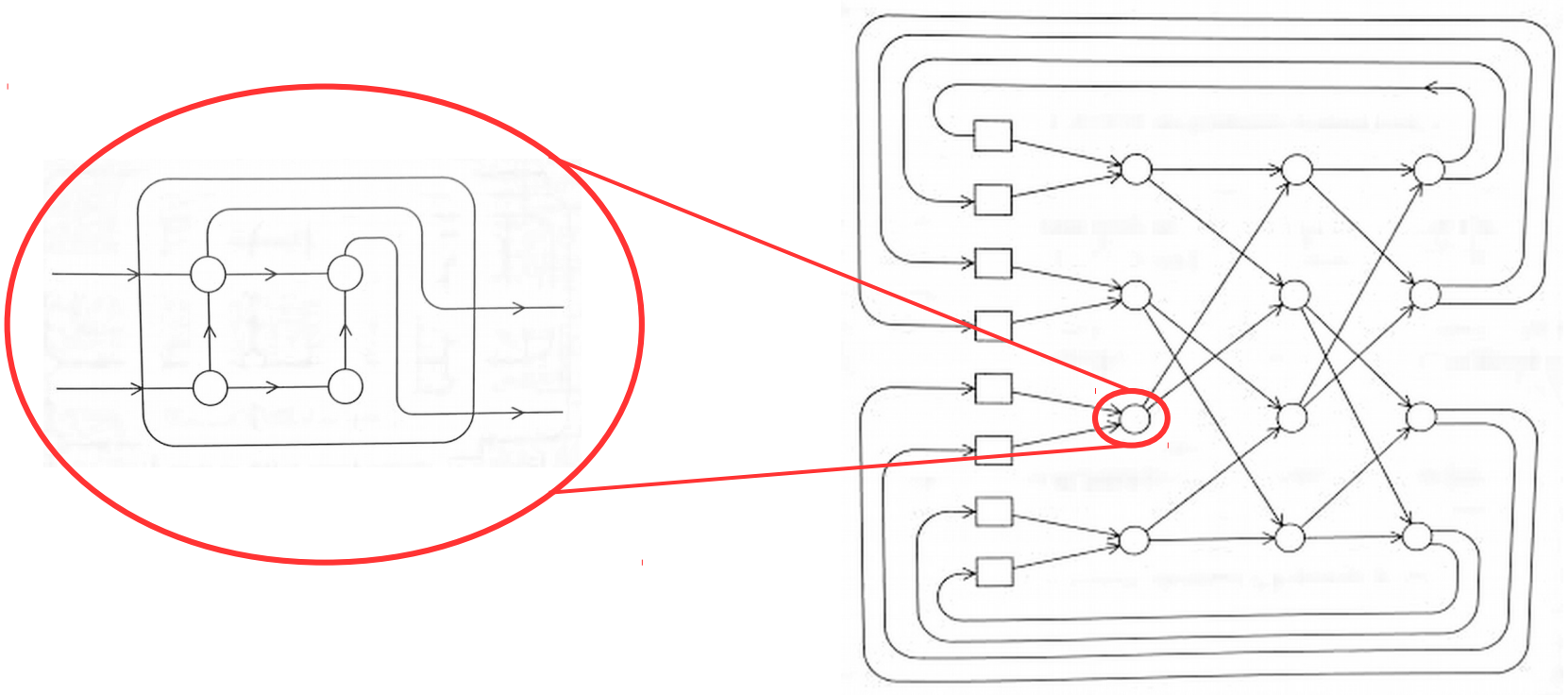
- Switched interconnects allow multiple simultaneous paths between components
  - *(Graphically, use squares for nodes and circles for switches)*
- A crossbar switch uses a matrix of potential connections to create ad-hoc paths between nodes





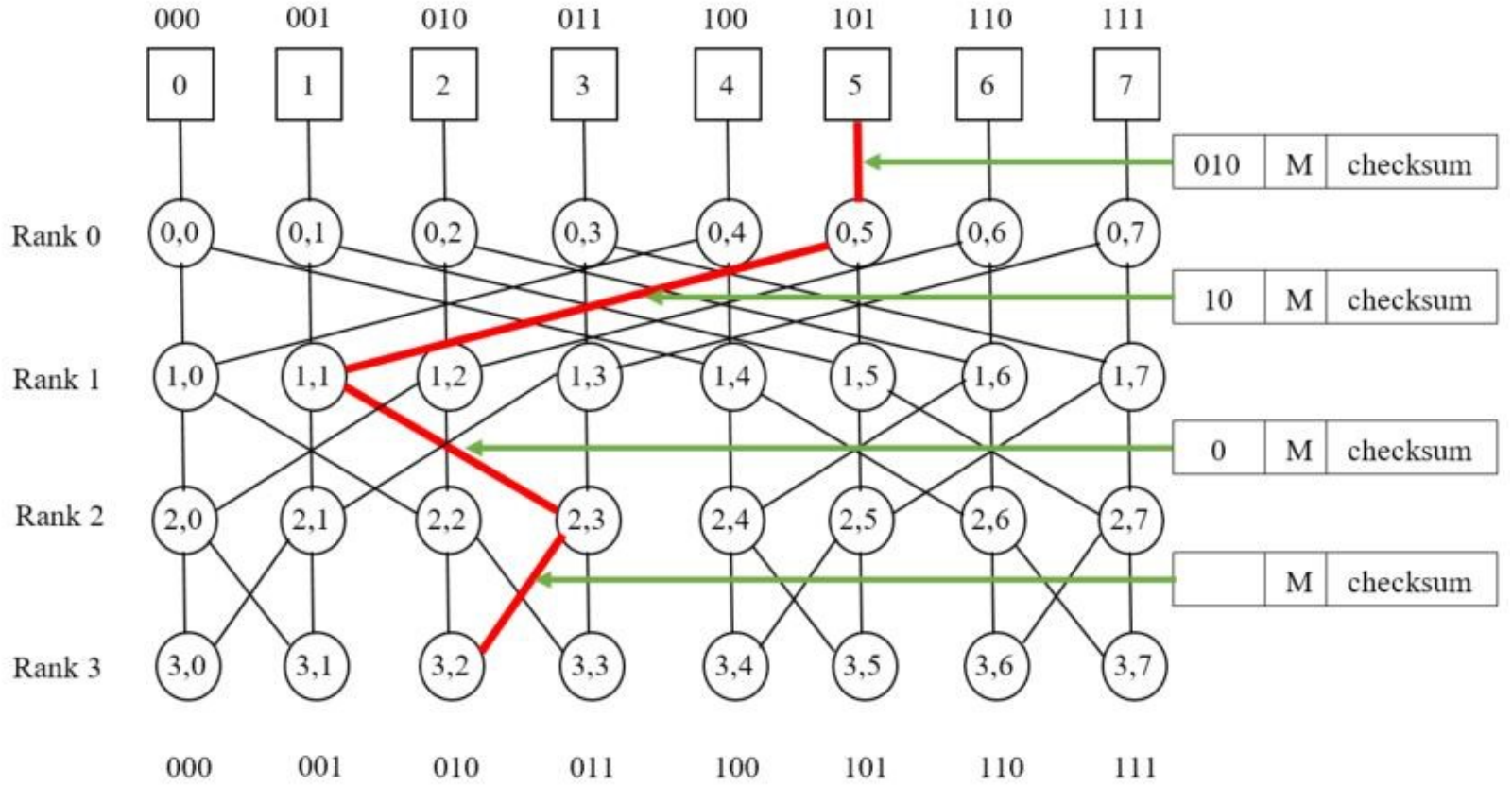
Omega networks

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



Butterfly networks

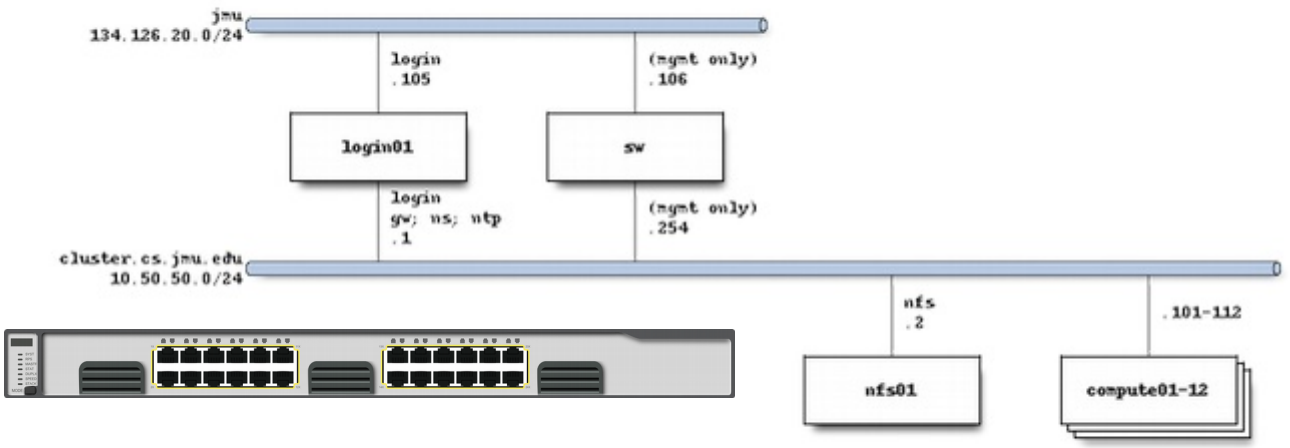
- Multi-stage network w/ dedicated switching nodes
  - Easy routing based on binary host numbers (0=left, 1=right)



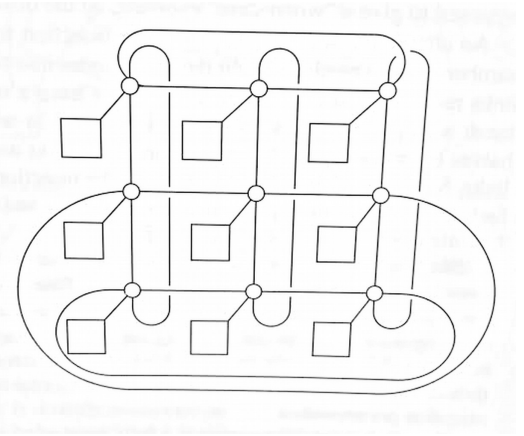
from https://en.wikipedia.org/wiki/Butterfly_network

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



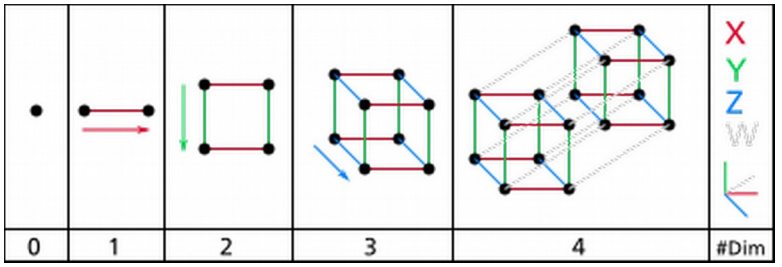
Our cluster (switched bus)

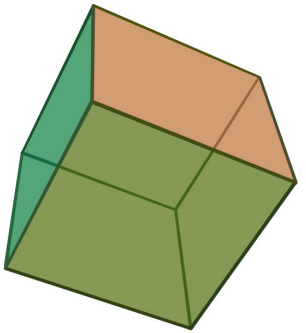


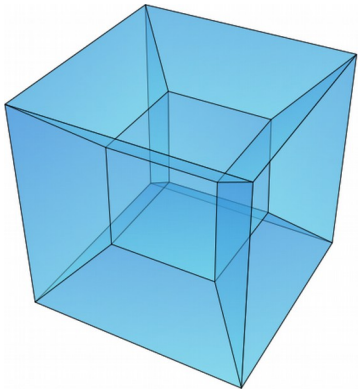
Toroidal Mesh

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

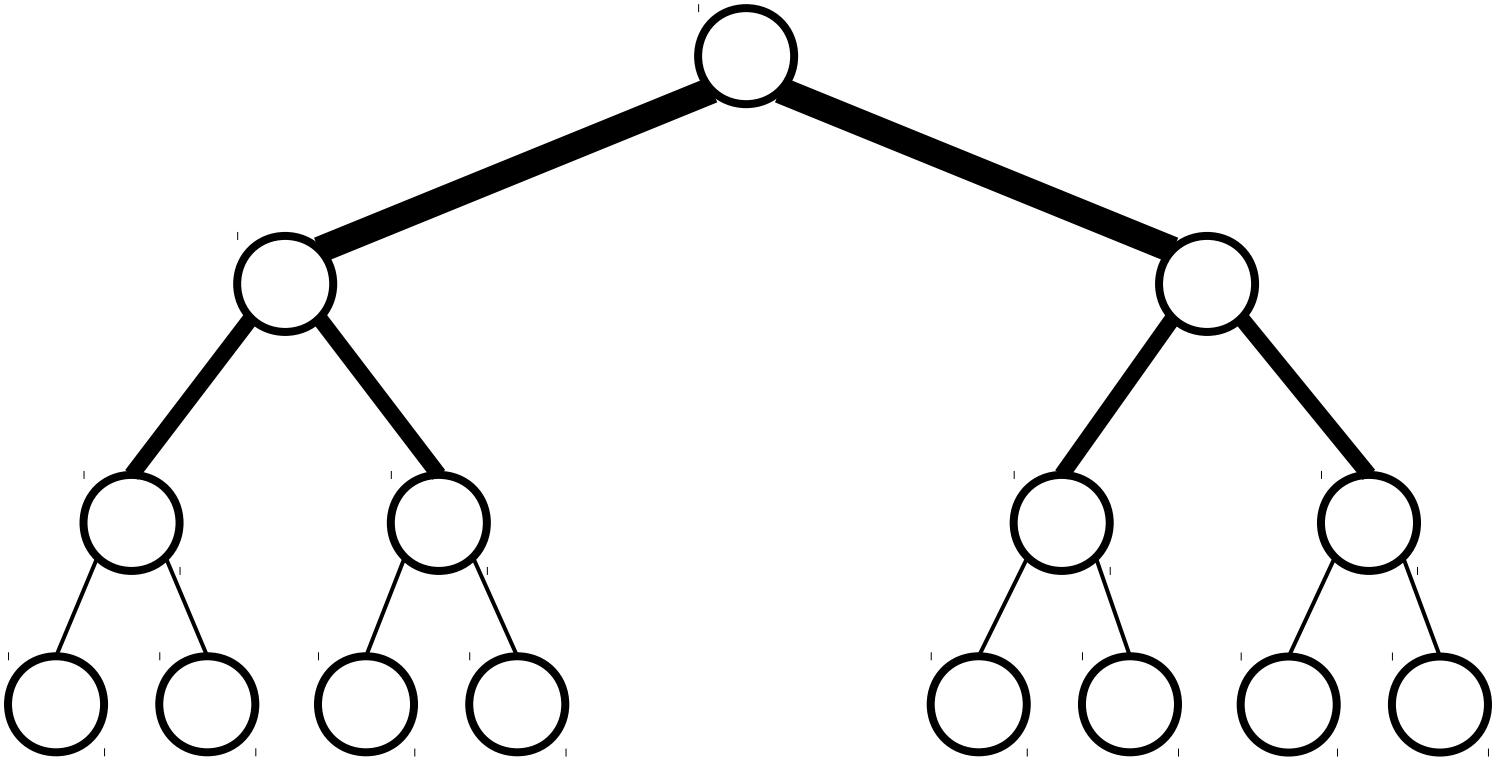






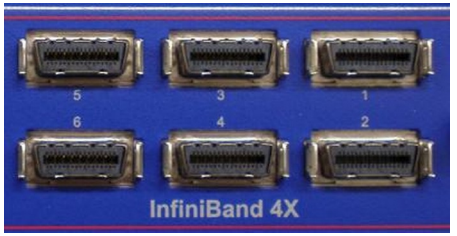
Fat trees

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

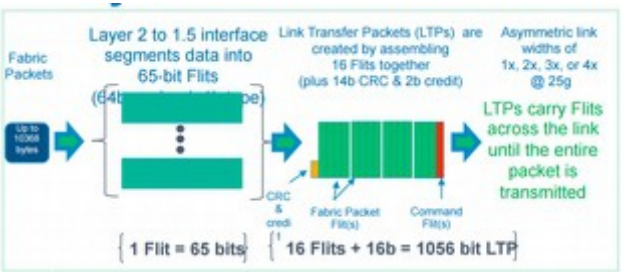


HPC Interconnect Technologies

- 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/ 0.5µs latency
  - Packet-based switched fabric
  - Very loose API; more formal spec provided by OpenFabrics Alliance
  - Used on many current high-performance clusters
  - Vendors: Mellanox, Intel, and Oracle
- OmniPath
  - New interconnect architecture by Intel; designed closely with Intel Phi
  - "Layer 1.5" Link Transfer Protocol for reliable layer 2 transmission



OPENFABRICS ALLIANCE



Routing

- Circuit switching
  - Paths are pre-allocated for an entire session
  - All data is routed along the same path

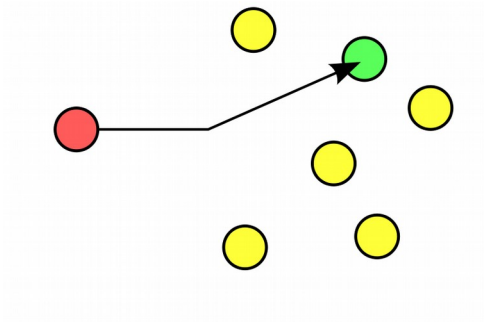
- Packet switching
  - Break data into independent, addressed packets
  - Packets are routed independently

Routing

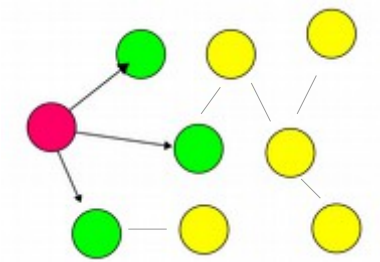
- Circuit switching
  - Paths are pre-allocated for an entire session
  - All data is routed along the same path
  - Higher setup costs and fewer simultaneous communications
  - Constant latency and throughput

- 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

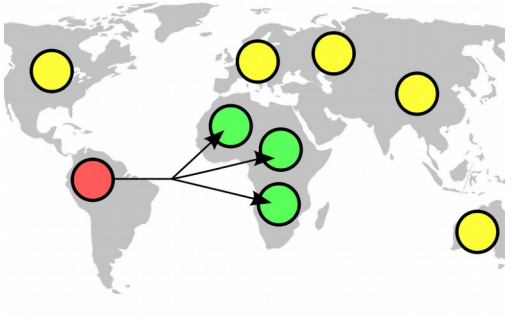
Routing



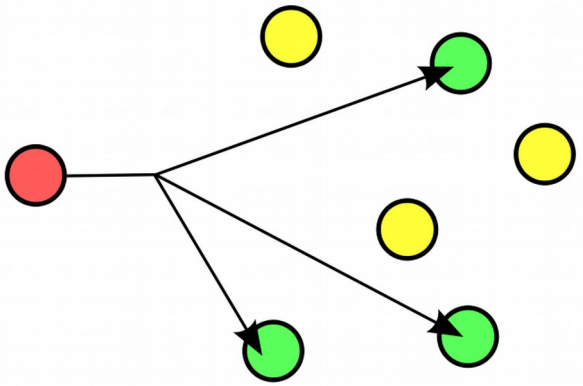
Unicast
(one-to-one)



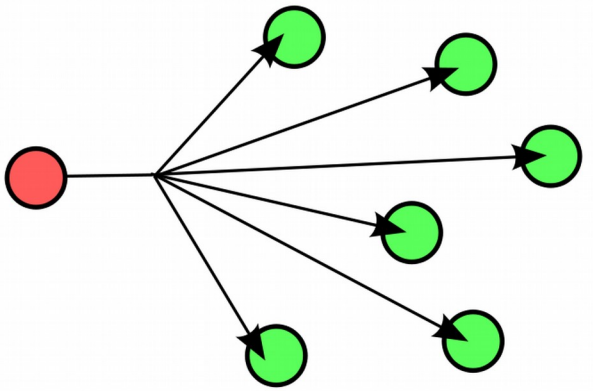
Anycast
(one-to-nearest)



Geocast
(one-to-proximate)



Multicast
(one-to-many)

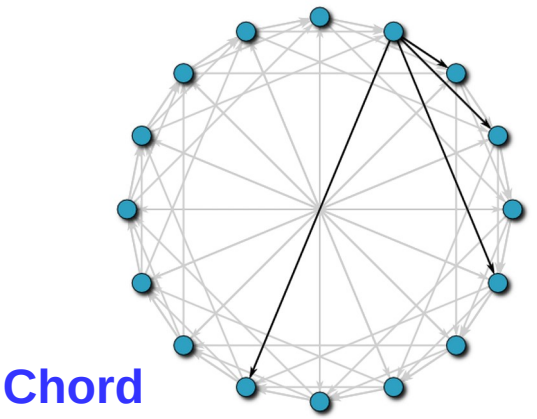


Broadcast
(one-to-all)

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

IP multicast and Overlays

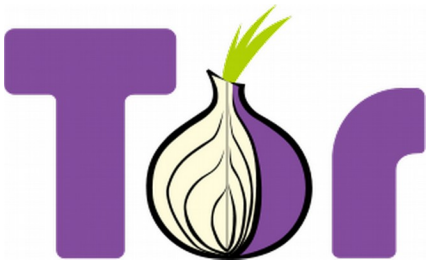
- IP multicast: technique for sending data to multiple recipients over an IP network using UDP
  - Group addressing (IGMP)
  - Tree-based distribution
- Overlay: a network built on top of another network
  - Distributed hash tables (e.g., Chord)
  - XMPP – Jabber/Gtalk chat protocol
  - Tor network

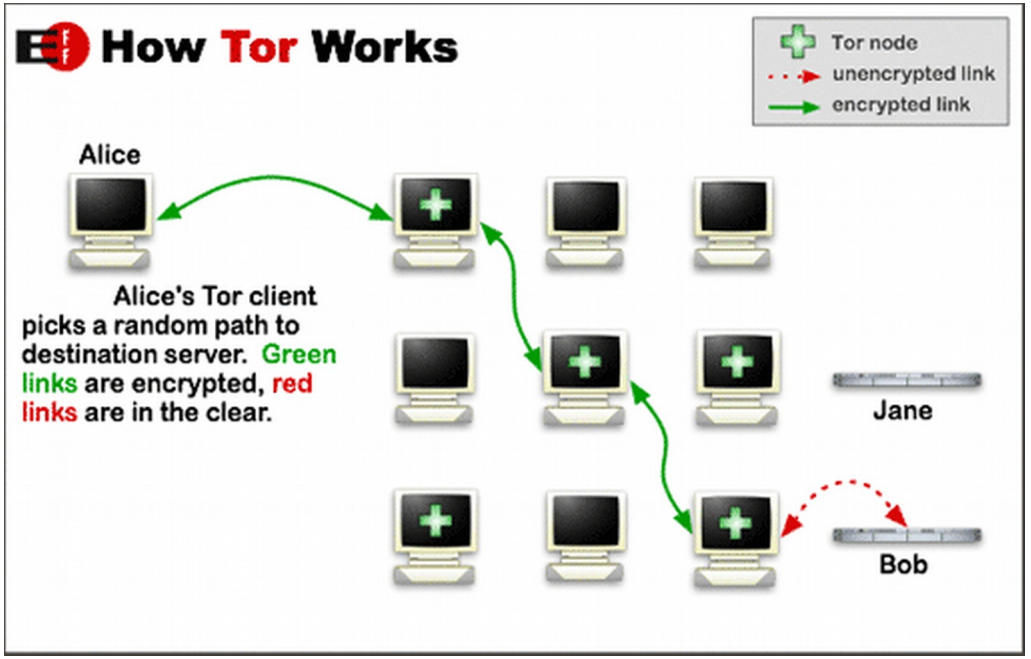


Chord

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





Networking principles

- Distributed system components are often unreliable
- How do we build a **reliable** network using **unreliable** hardware and software?

Networking principles

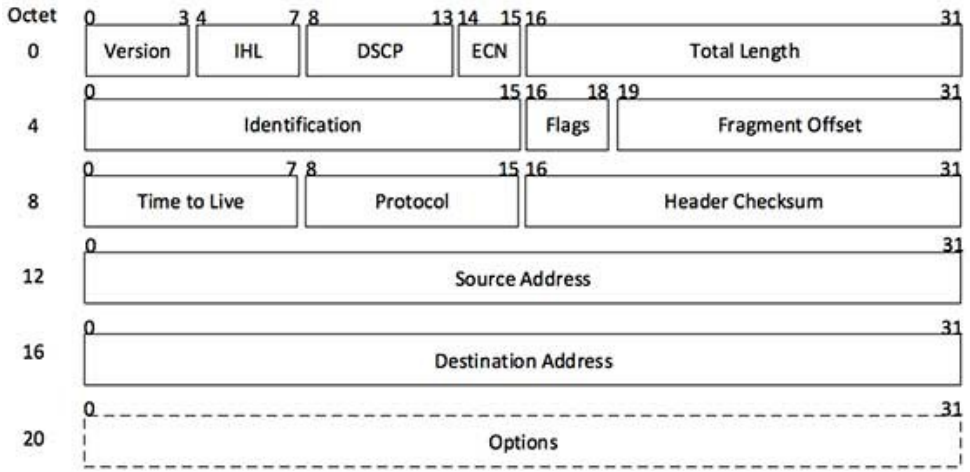
- Distributed system components are often unreliable
- How do we build a **reliable** network using **unreliable** hardware and software?
  - Abstraction helps by hiding details where possible
  - Protocols define well-structured communication patterns
  - Layered / stacked protocols build on each other
  - 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 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

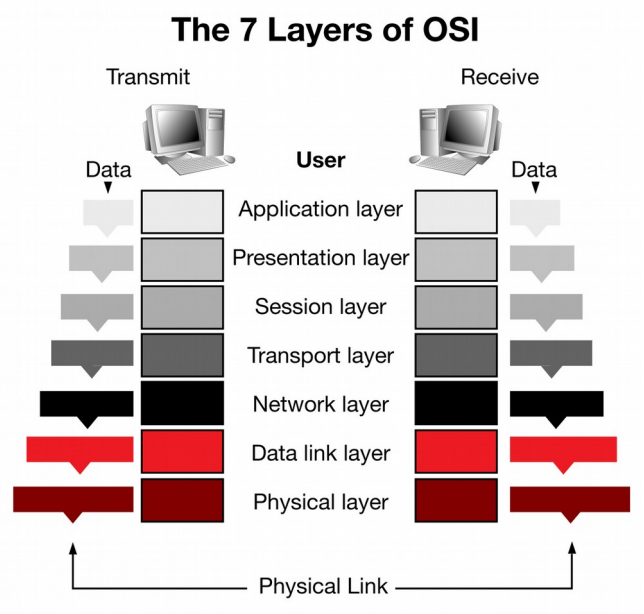
- Connectionless vs. connection-oriented
  - Is there a setup/teardown procedure required for communication?
- Synchronous vs. asynchronous
  - Does the sender block after sending?
    - E.g., `MPI_Ssend` vs. `MPI_Isend`
- Persistent vs. transient communication
  - Are messages stored by the middleware?

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)



IPC paradigms

- Inter-process communication (IPC)
  - Message-passing
    - Symmetric (SPMD) vs. asymmetric (differentiated hosts)
  - Remote procedure calls
  - Streaming-oriented

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
  - Send: Send data over a connection
  - Receive: Receive data over a connection
  - Close: Destroy a connection

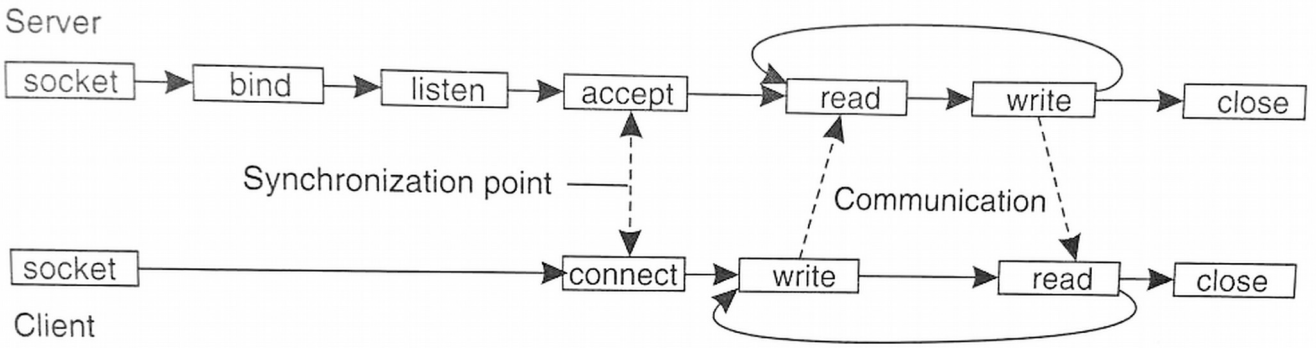
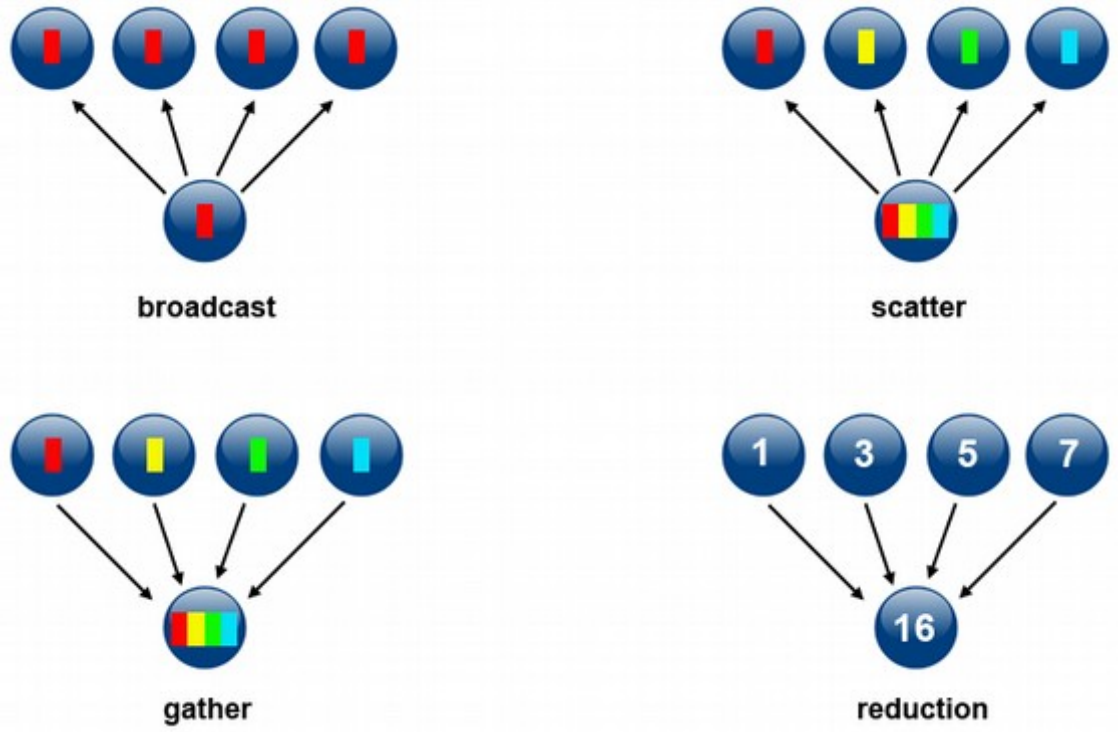


Figure 4-15. Connection-oriented communication pattern using sockets.

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

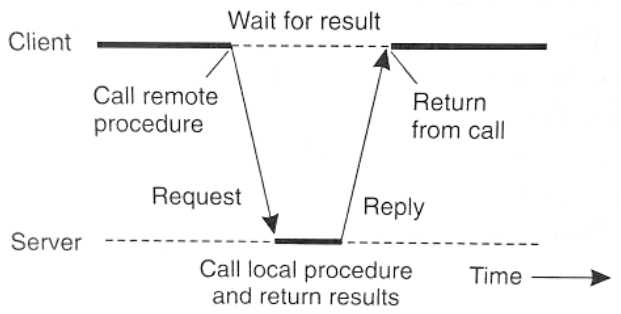


Figure 4-6. Principle of RPC between a client and server program.

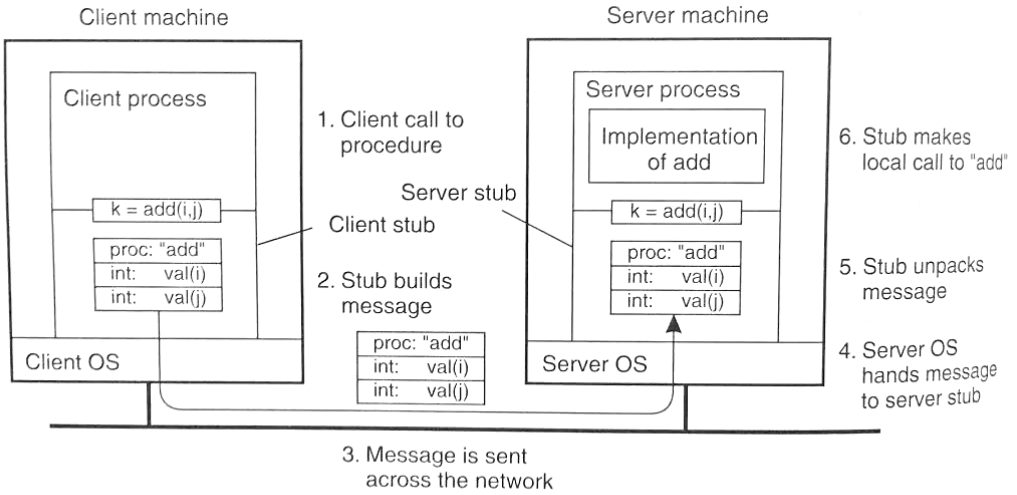


Figure 4-7. The steps involved in a doing a remote computation through RPC.

Asynchronous RPC

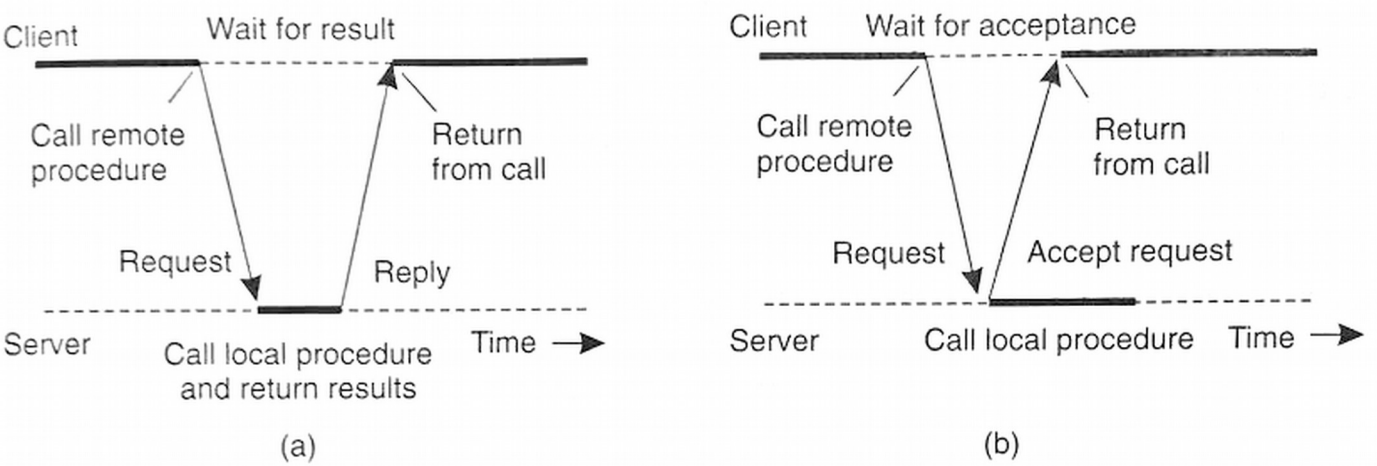


Figure 4-10. (a) The interaction between client and server in a traditional RPC. (b) The interaction using asynchronous RPC.

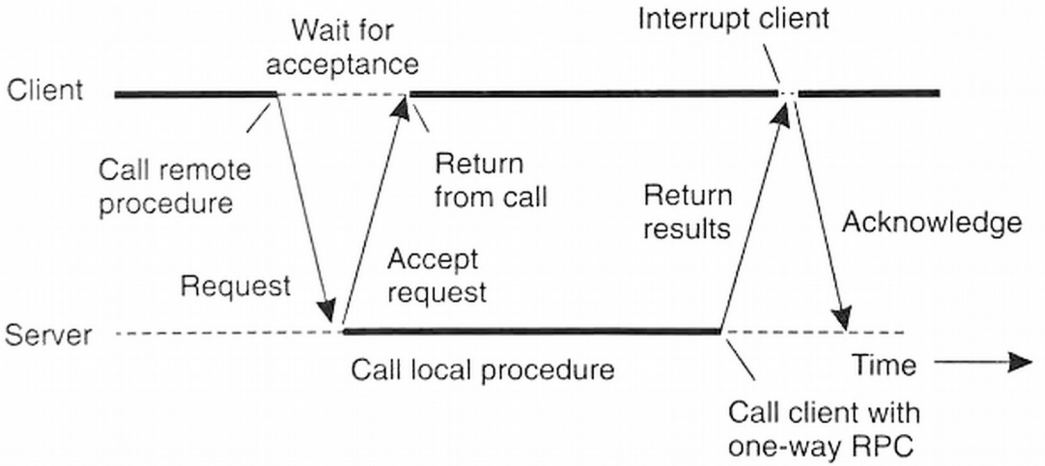


Figure 4-11. A client and server interacting through two asynchronous RPCs.

Data streams

- Stream-based communication
  - Popular in "big data" applications like MapReduce
- Simple vs. complex (multiple substreams)
- Timing variations
  - Asynchronous: no timing constraints
  - Synchronous: maximum end-to-end delay
  - Isochronous: maximum and minimum delay

QoS concerns

- Quality of Service (QoS)
  - 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

Naming

- "What's in a name?"
  - *"That which we call a .com by any other TLD would load just as quickly."*

Addressing

- Concept of an entity vs. its address
- True identifiers
  - Each identifier refers to at most one entity
  - Each entity is referred to by at most one identifier
  - Identifiers are never re-used at another time
- Name-to-address binding
  - Name space: domain of all possible names
  - Static vs. dynamic
  - Central vs. decentralized
    - Name server: central host responsible for maintaining bindings

Naming schemes

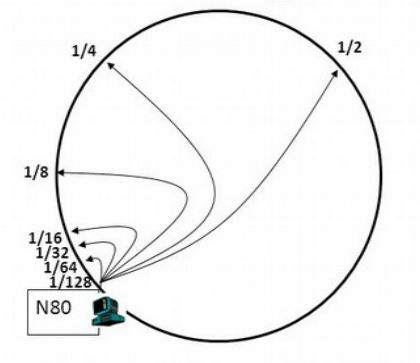
- Flat
- Structured
- Attribute-based

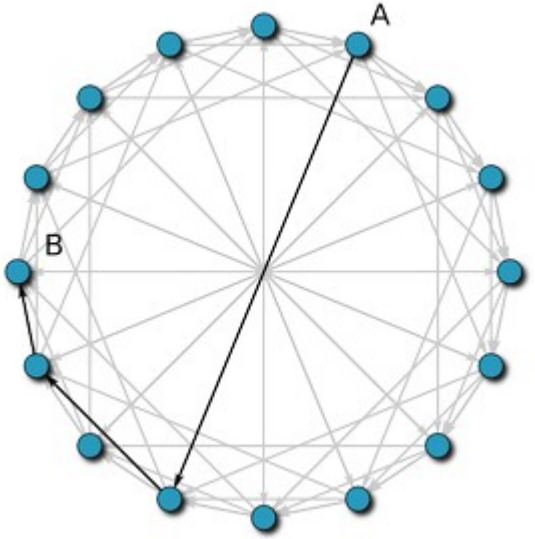
Flat naming

- Identifiers contain no location information
- Various lookup approaches
  - Broadcast / multicast
  - Forwarding pointers
  - Proximity routing
- Examples: ARP, Chord

Distributed hash tables

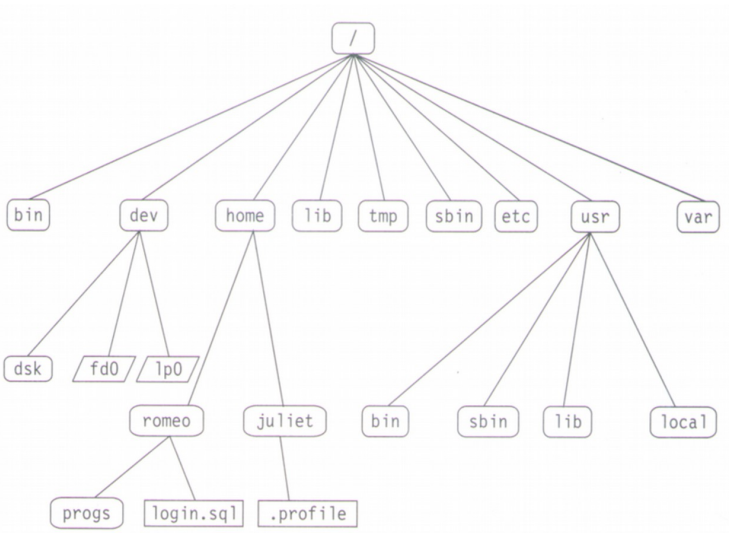
- Chord uses an m-bit identifier space and modulo arithmetic
- Key k is stored at succ(k), the node with the smallest id ≥ k
- Each node maintains a finger table of forward shortcuts
- To look up k, repeatedly follow lookups in finger table
  - Goal: halve distance to destination every hop



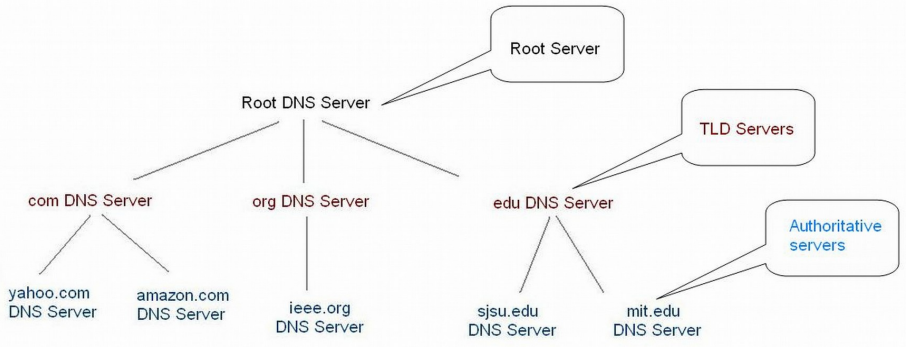


Structured naming

- Root vs. leaf nodes
- Absolute vs. relative names
  - Global vs. local names
- Iterative vs. recursive resolution
- Linking and aliasing
  - Hard vs. soft (symbolic) links
- Mounting and mount points
- Examples: file systems, DNS, NFS

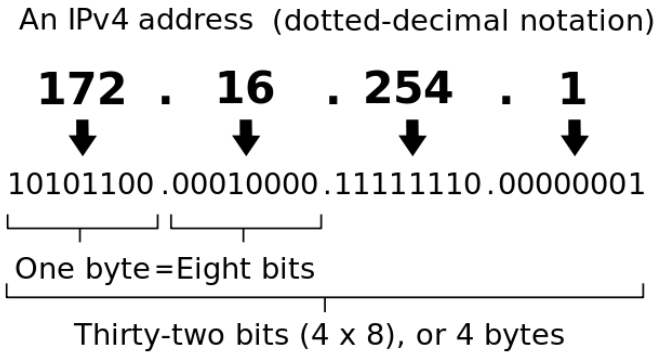



```
Filesystem                          Size  Used Avail Use% Mounted on
/dev/mapper/rhel_login01-root        50G   23G   28G  46% /
/dev/sda6                           497M  206M  292M  42% /boot
nfs.cluster.cs.jmu.edu:/nfs/home    100G  4.6G   96G   5% /nfs/home
nfs.cluster.cs.jmu.edu:/nfs/scratch 2.0T  862G  1.2T  43% /scratch
```



IPv4

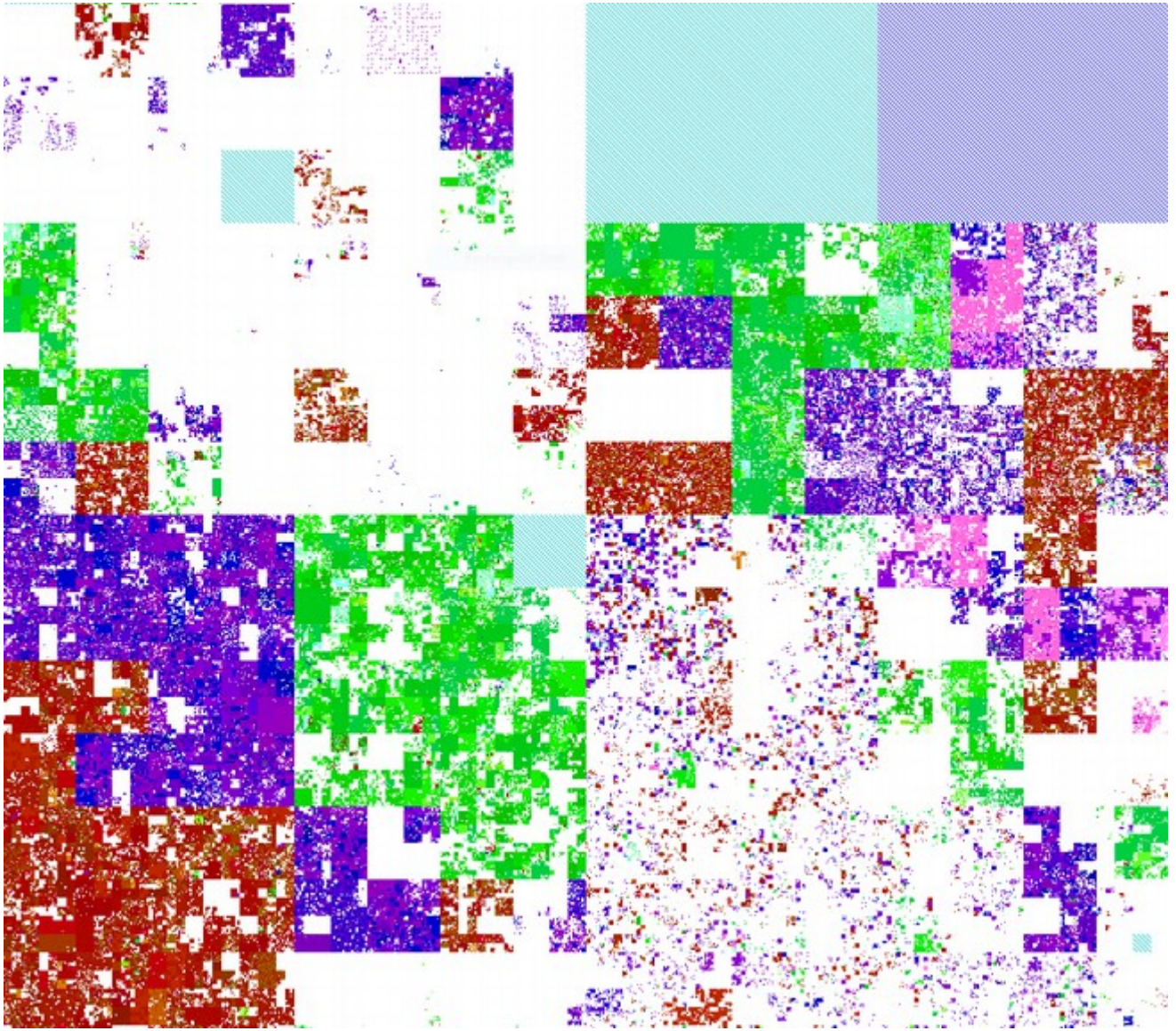
- IPv4: four octets w/ CIDR notation (/8, /16, etc.)
  - Classful addressing: Class A, Class B, Class C
  - IETF and IANA allocate addresses (32 bits - 4 billion total addresses)
  - Published in 1981; now nearly exhausted
- Notable networks
  - Private (10.0.0.0/8)
  - Loopback (127.0.0.0/8)
  - JMU (134.126.0.0/16)
  - Private (192.168.0.0/16)



from https://en.wikipedia.org/wiki/IPv4

https://xkcd.com/195/

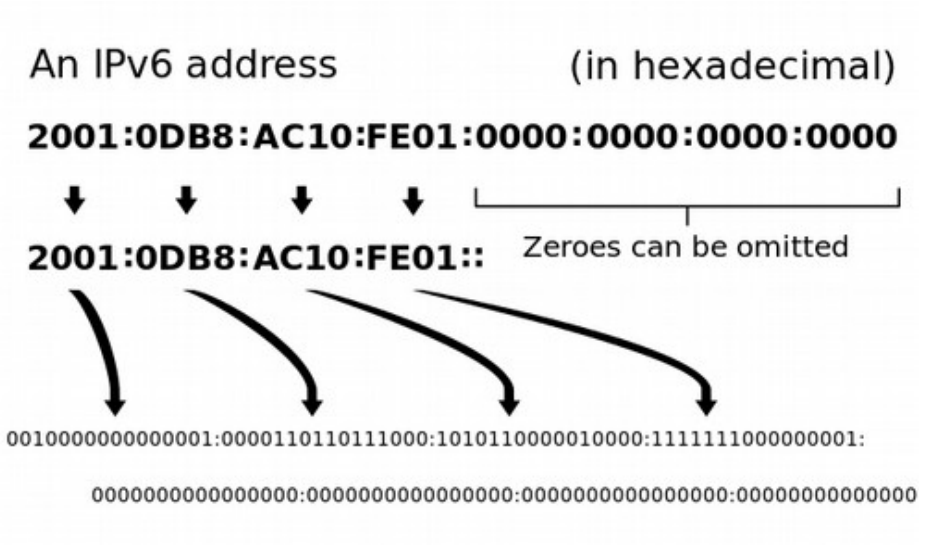
IPv4 map



from https://ant.isi.edu/address/browse/index.html

IPv6

- IPv6 published in 1998
  - 128 bits - 3.4×10^{38} total addresses
  - Eight groups of 16 bits (4 hex chars)
  - 64-bit routing prefix, 64-bit host/interface identifier
  - Slow uptake due to migration complications



from `https://en.wikipedia.org/wiki/IPv6`

IPv4 vs. IPv6

- The IPv6 name space is larger than you might think!
  - In fact, there is NO WAY to draw the two address spaces to scale. If IPv4 were a 1.6-inch square, IPv6 would be a square the size of the solar system!
  - $2^{128} \approx 10^{38} \gg$ the number of drops of water in all the world's oceans (10^{25}) or the number of stars in the observable universe (10^{23})
  - "If we had been assigning IPv6 addresses at a rate of 1 billion per second since the earth was formed, we would have by now used up less than one trillionth of the address space."
  - "We could assign an IPv6 address to every atom on the surface of the earth – and have enough addresses left over for another hundred earths."

Sources:

- http://waitbutwhy.com/2014/11/1000000-grahams-number.html
- http://www.tcpipguide.com/free/t_IPv6AddressSizeandAddressSpace-2.htm
- http://www.brucebnews.com/2010/10/ipv6-and-really-large-numbers/

Attribute-based naming

- Human-friendly resource identifiers
- Storage of (key, value) pairs
- Often implemented with distributed hash tables
  - Centralized vs. decentralized lookups
  - You will implement this in P4!
- Semantic overlay networks
  - Nodes maintain links to "semantically proximate" nodes
  - Most useful in distributed peer-to-peer networks
  - Exploit small-world effect