COMPUTER NETWORKS
CS 45201
CS 55201

CHAPTER 4
Internetworking

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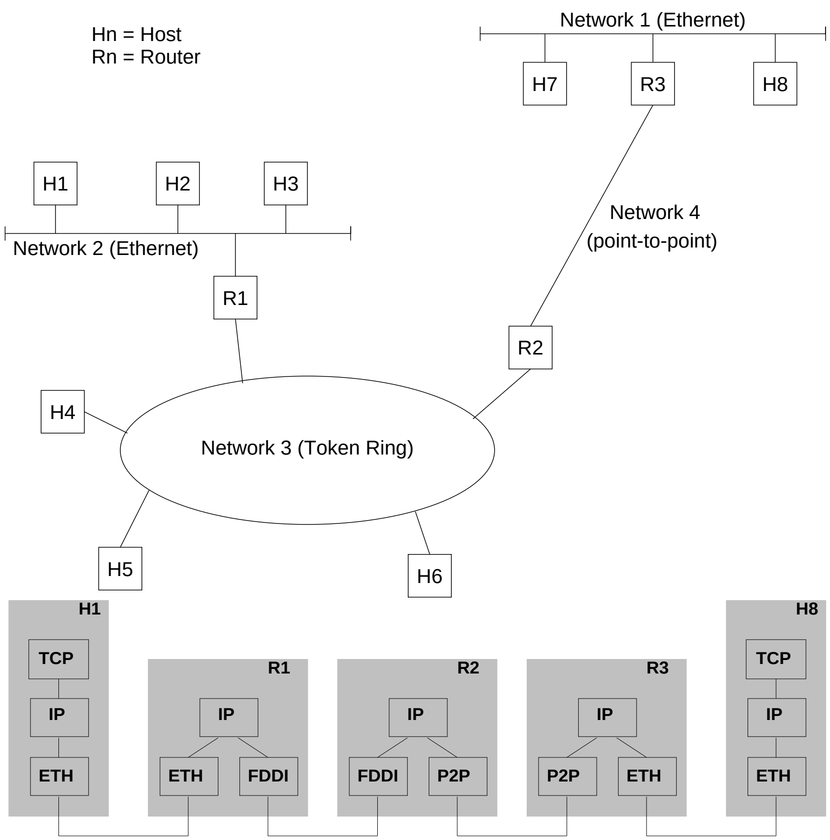
Contents

Internetworking

Definition: Logical network built from multiple physical networks.

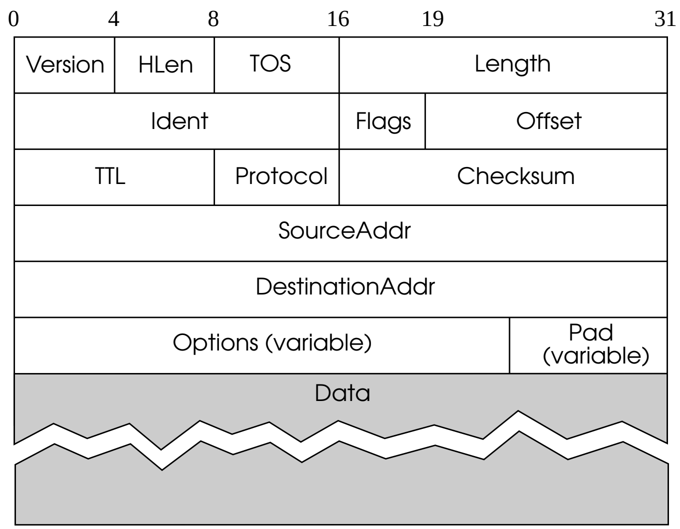


IP Service Model

- Packet Delivery Model
- Global Addressing Scheme

IP Datagram Packet Delivery Model

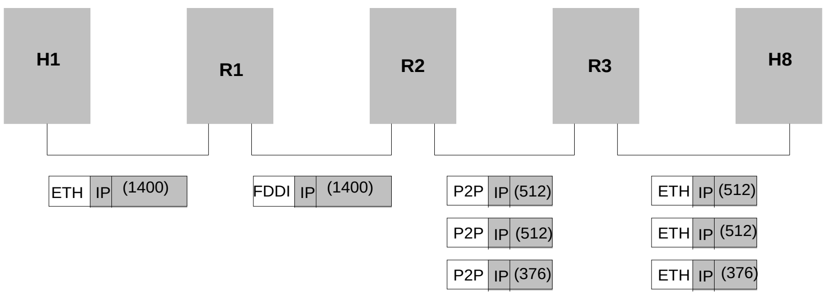
- Connection-less (datagram-based)
- Best-effort delivery (unreliable service)
  - packets are lost
  - packets are delivered out of order
  - duplicate copies of a packet are delivered
  - packets can be delayed for a long time
- TCP/IP standards given by RFCs (Request-for-Comments)

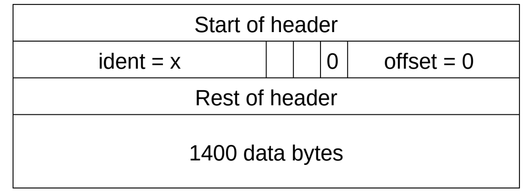


- Datagram format
  - Version (4): currently 4
  - Hlen (4): number of 32-bit words in header
  - TOS (8): type of service (not widely used)
  - Length (16): number of bytes in this datagram
  - Ident (16): used by fragmentation
  - Flags/Offset (16): used by fragmentation
  - TTL (8): number of hops this datagram has traveled
  - Protocol (8): demux key (TCP=6, UDP=17)
  - Checksum (16): of the header only
  - DestAddr & SrcAddr (32)

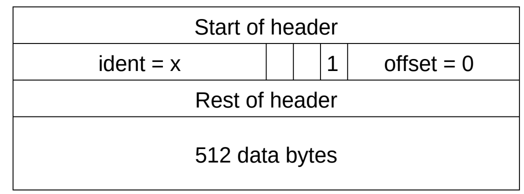
Fragmentation and Reassembly

- Each network has some MTU (Max Transmission Unit)
- Strategy
  - fragment when necessary (MTU $<$ Datagram)
  - IP packet needs to fit in payload part of frame
  - use CS-PDU (not cells) for ATM $\Longrightarrow$ CS: convergence sublayer
  - try to avoid fragmentation at source host
  - refragmentation is possible at routers etc.
  - fragments are self-contained datagrams
  - all fragments contain same value in ident field
  - each fragment is re-encapsulated in frame
  - delay reassembly until destination host
  - do not recover from lost fragments
- Example

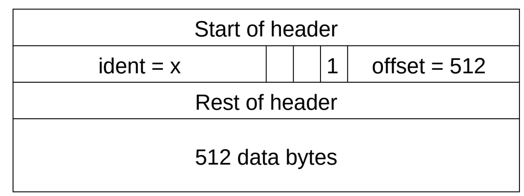




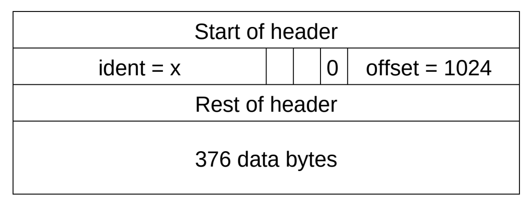
Unfragmented Packet



First Fragment



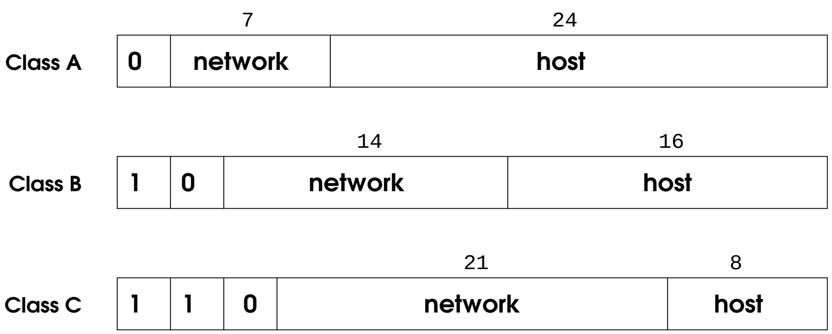
Second Fragment



Last Fragment

Global Addresses

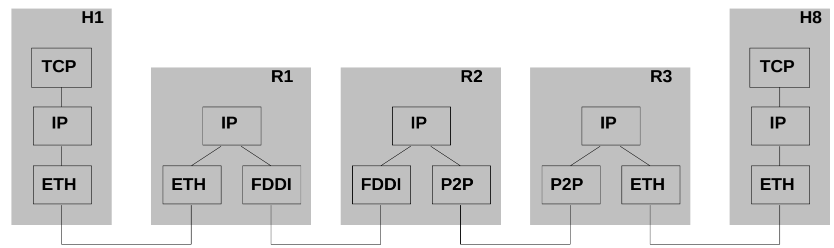
- Properties
  - globally unique
  - hierarchical: network + host
- Format



- Dot notation
  - 10.3.2.4
  - 128.96.33.81
  - 192.12.69.77

Datagram Forwarding

- Strategy
  - every datagram contains destination's address
  - if directly connected to destination network, then forward to host
  - if not directly connected to destination network, then forward to some router
  - forwarding table maps network number into next hop
  - each host has a default router
  - each router maintains a forwarding table



- Example (router R2)

Network Number	Next Hop
1	R3
2	R1
3	interface 1
4	interface 0

Address Translation

- Map IP addresses into physical addresses
  - destination host
  - next hop router
- Techniques
  - encode physical address in host part of IP address
  - table-based
- ARP (Address Resolution Protocol)
  - table (cache) of IP to physical address bindings
  - broadcast request if IP address not in table
  - target machine responds with its physical address
  - table entries are discarded if not refreshed
- Notes
  - table entries timeout in about 10 minutes
  - update table with source when you are the target
  - refresh table if already have an entry
  - do not refresh table entries upon reference
  - do not add to table if not there and not target

- Request format

HardwareType=1		ProtocolType=0x0800
HLEN=48	PLEN=32	Operation
SourceHardwareAddr		
SourceHardwareAddr		SourceProtocolAddr
SourceProtocolAddr		TargetHardwareAddr
TargetHardwareAddr		
TargetProtocolAddr		

  - HardwareType: type of physical network (e.g., Ethernet)
  - ProtocolType: type of higher layer protocol (e.g., IP)
  - HLEN & PLEN: length of physical and protocol addresses
  - Operation: request or response
  - Source/Target Physical/Protocol addresses

The Address Resolution Protocol, ARP

- Every machine on the Internet has one (or more) IP addresses.
- These addresses cannot be used for sending packets because data link layer does not understand IP addresses.
- LAN addresses are 48-bit and they know nothing about 32-bit IP addresses.
- How do IP addresses get mapped onto the data link layer address.
  - The upper layer software builds a packet with 192.31.65.5 as destination address and gives it to IP software to transmit.
  - The IP software can look at the address to see whether it is local, but it needs the corresponding Ethernet address.
  - One solution is to have a configuration file to map IP addresses to LAN addresses, but it is not practical for large number of hosts.
  - Another solution is to broadcast a packet onto the LAN asking who own the address 192.31.65.5?
  - The destination responds with its LANS address and the source learns the destination LAN address. This is called ARP.
- At this point the IP software builds an Ethernet frame addressed to the destination, puts the IP packet in the payload field and dumps it on to the Ethernet. The destination detects the frame, reorganize it. The Ethernet driver extract the IP packet from the payload and passes it to the IP software.

- One optimization is to cache the address in case it will be needed soon.
- Another optimization is to have every machine broadcast its mapping when it boots.
- For remote LAN access, ARP fails, there are two solutions:
  - The local router could be configured to respond to ARP request to other LANs. This is called *proxy ARP*.
  - Have the source send all nonlocal traffic to a default LAN when ARP fails locally.

The Reverse Address Resolution Protocol, RARP

- ARP solves the problem of finding an Ethernet address from an IP address.
- Sometime the reverse problem has to solved; finding the IP address from the Ethernet address(booting a diskless workstation).
- This protocol allows a newly-booted workstation to broadcast its 48-bit Ethernet address and ask: "Does anyone out there know my IP address?"
- The RARP server sees this request, looks up the Ethernet address in its configuration file and sends back the corresponding IP address.
- A RARP server is needed on each network.
- An alternative protocol is called BOOTP (bootstrap) protocol that uses UDP(user data protocol) messages which are forwarded over routers.
- It also provide a diskless workstation with additional information, including the IP address of the file server holding the memory image, the IP address of the default router.

Internet Control Message Protocol

- Echo (ping)
- Redirect (from router to source host)
- Destination unreachable (protocol, port, or host)
- TTL exceeded (so datagrams don't cycle forever)
- Checksum failed
- Reassembly failed
- Cannot fragment
- The Internet operations is closely monitored by the routers.
- All unexpected events are reported by the ICMP (Internet Control Message Protocol), which is used to test the Internet.
- About a dozen types of ICMP messages are defined.

The principal ICMP message types

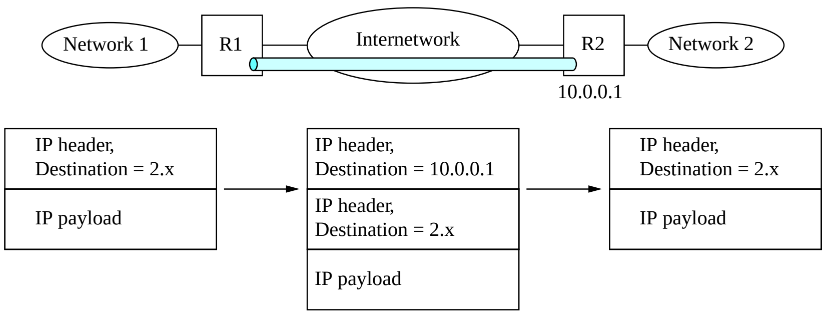
Message type	Description
Destination unreachable	Packet could not be delivered
Time exceeded	Time to live hit 0
Parameter problem	Invalid header field
Source quench	Choke packets
Redirect	Teach a router about geography
Echo request	Ask a machine if it is alive
Echo reply	Yes, I am alive
Timestamp request	Same as Echo request, but with timestamp
Timestamp reply	Same as Echo reply, but with timestamp

Dynamic Host Configuration Protocol (DHCP)

- Allow automatic configuration from DHCP sever of:
  - IP address (can be static in table indexed by hardware address OR dynamically assigned from pool (periodic renewal required))
  - default router
- DHCP server identification
  - host broadcasts DHCP DISCOVER message
  - carried in UDP packet
  - if DHCP server local replies
  - otherwise relayed by relay agent

Virtual Networks & Tunnels

- implement VPN using IP
- allow only members of VPN to access
- tunnel is established between routers
- router encapsulates packet in IP datagram with destination address of router at other end of tunnel



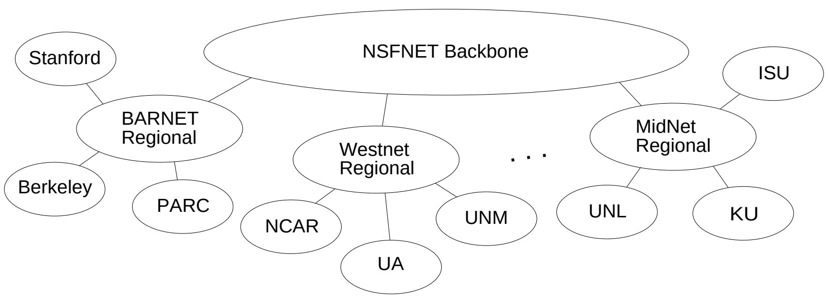
Network Number	NextHop
1	Interface 0
2	Interface 0
Default	Interface 1

- Why?
  - Security
  - connect routers with enhanced capability (mulitcast MBone)
  - carry non-Ip packets (IPX)
  - make machines at both ends seem like on same network

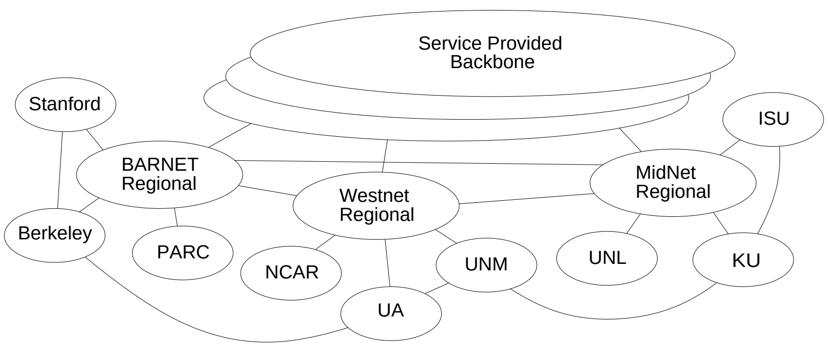
Global Internet

Internet Structure

⟹ Recent Past



⟹ Today



Scalability Issues

⟹ IP "hides" hosts in address hierarchy, but...

- Inefficient use of address space
  - class C network with 2 hosts (2/255 = 0.78% efficient)
  - class B network with 256 hosts (256/65535 = 0.39% efficient)
- Too many networks
  - today's Internet has tens of thousands of networks
  - routing tables do not scale
  - route propagation protocols do not scale

Subnetting

- Add another level to address/routing hierarchy: *subnet*
- *Subnet masks* define variable partition of host part
- Subnets visible only within site

Network Number	Host Number

Class B address

111111111111111111111111	00000000

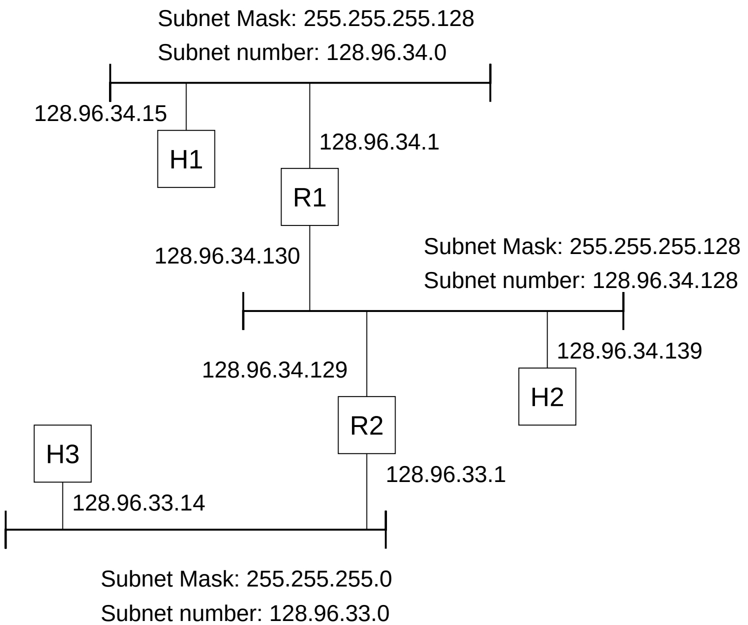
Subnet Mask (255.255.255.0)

Network Number	Subnet ID	Host ID

Subnetted Address

Subnet Example

- Consider the following configuration



- with the following routing table for R1

Subnet Number	Subnet Mask	Next Hop
128.96.34.0	255.255.255.128	interface 0
128.96.34.128	255.255.255.128	interface 1
128.96.33.0	255.255.255.0	R2

How to Send a Packet

- The host performs bitwise & between its subnet mask and the destination IP address
  - If the result is its subnet number ⟹ local subnet
  - If not, the packet is sent to a router
- Suppose H1 is sending to H2 where H1 and H2 belong to the same subnet

```
H2 = 10000000 01100000 00100010 10001011 =128.96.34.139
M1 = 11111111 11111111 11111111 10000000 =255.255.255.128
--------------------------------------------------------
D1 = 10000000 01100000 00100010 10000000 =128.96.34.128
```

- This does not match the subnet number (128.96.34.128) for H1 (128.96.34.0)
- H1 knows that H2 is on different network ⟹ it sends it to R1
- R1 has more work to do when Subnetting
- table entries now (`subnet number , subnet mask, next hop`)
- R1 ANDs the H2 IP address (28.96.34.139) with the subnet mask for each entry e.g. (255.255.255.128)
  - The result (128.96.34.128) is compared with the network entry (128.96.34.0) ⟹ no match
  - But it is matched with the second entry entry of the table
  - Forwarded to the interface 1 connected to R1

Forwarding Algorithm

```
D = destination IP address
for each entry ⟨SubnetNum, SubnetMask, NextHop⟩
   D1 = SubnetMask & D
   if D1 = SubnetNum
      if NextHop is an interface
         deliver datagram directly to destination
      else
         deliver datagram to NextHop (a router)
```

Notes

- Would use a default router if nothing matches
- Not necessary for all ones in subnet mask to be contiguous
- Can put multiple subnets on one physical network
- Subnets not visible from the rest of the Internet

Classless InterDomain Routing, CIDR: Superneting

- IP has been extremely successful with its exponential growth, but it is running out of address space.
- In principle, over 2 billion addresses exist, but in practice millions of them are wasted by classes.
- For most organizations, class A with 16 million addresses is too big and class C with 256 addresses is too small.
- A class B network with 65,536, is just right.
- Studies have shown that more than half of all class have fewer than 50 hosts.
- Another problem is table explosion. Routers do not have to know about all the host, but they know about other networks.
- Having half a million class C networks, every router would require a table with half million entries.
- Another problem is the complexity of various algorithms for management of the tables that grows faster than linear.
- Design choices made a decade ago with only 1000 network is far from optimal.
- The routing table problem can be solved by going to a deeper hierarchy(like telephone), but it requires more than 32-bit for IP addresses.
- Most solutions solve one problem but create new ones.
- One solution currently being implemented is CIDR (Classless InterDomain Routing)

- The basic idea behind CIDR is to allocate the remaining class C networks (almost 2 million) in variable-sized blocks.
  - If a site needs 2000 addresses, it is given 2048 addresses (8 contiguous class C networks), and not a full class B address.
- In addition to using contiguous blocks, the allocation rule were also changed. The world was partitioned into four zones.
  - Europe: 194.0.0.0 to 195.255.255.255
  - North America: 198.0.0.0 to 199.255.255.255
  - Central and South America: 200.0.0.0 to 201.255.255.255
  - Asia and Pacific: 202.0.0.0 to 203.255.255.255
- Each region was given 32 million addresses, with another 320 million class C addresses from 204.255.255.255 to 223.255.255.255 reserved for future use.
- Within each block allocate sub-block to ISP. ISP then allocates to customers.
- Restrict block sizes to powers of 2
- Use a bit mask (CIDR mask) to identify block size
- All routers must understand CIDR addressing

Route Propagation

- Impose a second hierarchy on the network that limits what routers talk to each other.
- The first hierarchy is the address hierarchy that governs how packets are forwarded.
- Idea: Know a smarter router
  - hosts know a local router
  - local routers know site routers
  - site routers know core router
  - core routers know everything
- Autonomous System (AS)
  - corresponds to an administrative domain
  - examples: University, company, backbone network
  - assign each AS a 16-bit number
- Two-level route propagation hierarchy
  - interior gateway protocol (each AS selects its own)
  - exterior gateway protocol (Internet-wide standard)

Popular Interior Gateway Protocols

- RIP: Route Information Protocol
  - developed for XNS
  - distributed with Unix
  - distance-vector algorithm
  - based on hop-count
- OSPF: Open Shortest Path First
  - recent Internet standard
  - uses link-state algorithm
  - supports load balancing
  - supports authentication

EGP: Exterior Gateway Protocol

- Overview
  - designed for tree-structured Internet
  - concerned with *reachability*, not optimal routes
- Protocol messages
  - neighbor acquisition: one router requests that another be its peer; peers exchange reachability information
  - neighbor reachability: one router periodically tests to see if the other router is still reachable; exchange HELLO/ACK messages;
  - routing updates: peers periodically exchange their routing tables (distance-vector)

BGP-4: Border Gateway Protocol

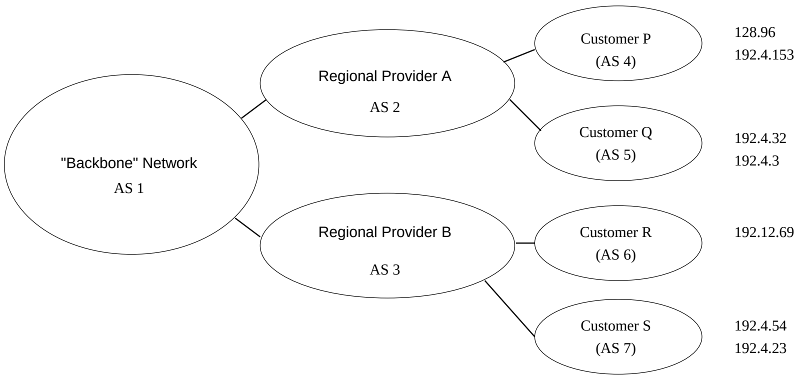
Assumes the Internet is an arbitrarily interconnected set of AS's. Define*local traffic* as traffic that originates at or terminates on nodes within an AS, and *transit traffic* as traffic that passes through an AS, we can classify AS's into three types:

- Stub AS: an AS that has only a single connection to one other AS; such an AS will only carry local traffic.
- Multihomed AS: an AS that has connections to more than one other AS, but refuses to carry transit traffic.
- Transit AS: an AS that has connections to more than one other AS, and is designed to carry both transit and local traffic.

Each AS has:

- One or more border routers (gateways)
- One BGP *speaker* that advertises:
  - local networks
  - other reachable networks (transit AS only)
  - gives *path* information
- BGP advertises complete paths as enumerated lists of ASs to reach network

BGP Example



- Speaker for AS 2 advertises reachability to P and Q

  Network 128.96, 192.4.153, 192.4.32, and 192.4.3, can be reached directly from AS 2.
- Speaker for backbone network then advertises

  Networks 128.96, 192.4.153, 192.4.32, and 192.4.3 can be reached along the path ⟨AS 1, AS 2⟩.
- Speaker can also cancel previously advertised paths
- BGP prevents looping by carrying complete path
- As numbers unique 16 bit numbers assigned by a central authority

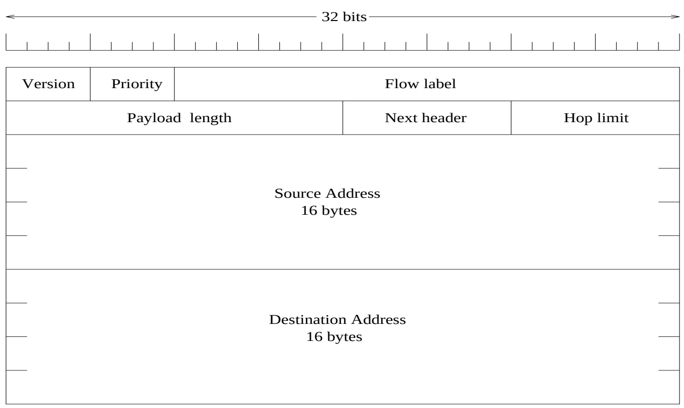
Next Generation IP (IPv6)

- CIDR may last for a few years, but everyone realizes that the days of IP in its current form (IPv4) are numbered.
- Besides growing number of Mobile stations, it may not be long before every TV set is an Internet node, producing billion machines.
- IETF has started working on a new version of IP, which would never run out of addresses, and solving a variety of other problems.
- Its major goals were to
  - Supports billions of hosts, even with inefficient address space allocation.
  - Reduce the size of the routing tables.
  - Simplify the protocol to allow routers to process packets faster.
  - Provide better security (authentication and privacy) than current IP.
  - Pay more attention to type of service, particularly for real-time data.
  - Aid multicasting by allowing scopes to be specified.
  - Make it possible for a host to roam without changing its address.
  - Allow the protocol to evolve in the future.
  - Permit the old and new protocols to coexist for years.

Major Features

- 128-bit addresses (3.4×10^{38} addresses)
- Autoconfiguration
- Multicast
- Real-time service
- Authentication and security
- Auto-configuration
- End-to-end fragmentation
- Protocol extensions

The Main IPv6 Header



The IPv6 fixed header

- 40-byte "base" header
- Extension headers (fixed order, mostly fixed length)
  - fragmentation
  - source routing
  - authentication and security
  - other options
- The Version field is always 6 for IPv6 and 4 for IPv4.
- The Priority field is used to distinguish between packets whose sources can be flow controlled and those that cannot.
  - 0-7 are capable of slowing down in the event of congestion. lower numbers are less important (1 for news, 4 for FTP, (6 for Telnet, ..).
  - 8-15 are for real-time traffic(audio, video).
- The Flow label is still experimental, but will be used to allow to set up particular properties between source and destination.
- The Payload length field tells how many bytes follow the 40-byte header
- The Next header field tells which of the (currently) six extension headers follows this one. If this header is last IP header the next header would be transport layer (TCP, UDP, etc.)
- The Hop limit field is used to keep packets from living forever. In IPv4 this was time.
- The Source and Destination fields are fixed-length 16-byte addresses.

Extension Headers

- IPv6 has introduced the concept of an (optional) extension header that can be used to provide extra information.

Extension header	Description
Hop-by-hop options	Miscellaneous information for routers
Routing	Full or partial route to follow
Fragmentation	Management of datagram fragments
Authentication	Verification of the sender's identity
Encrypted security payload	Information about encrypted contents
Destination options	Additional information for the destination

IPv6 Addresses

- Classless addressing/routing (similar to CIDR)
- Notation: x:x:x:x:x:x:x:x (x = 16-bit hex number)
  - one set of contiguous 0s are compressed: 47CD::A456:0124
  - Addresses with 80 0s are reserved for IPv4.
  - IPv4 compatible IPv6 address: ::128.42.1.87
  - IPv4 mapped IPv6 address: ::00FF:128.42.1.87
- Address assignment - a number of techniques
  - Aggretable Global Unicast Addresses - like classless IPv4
  - provider-based : Separate prefixes are assigned to different network providers.
  - Problems: changing providers, two providers
  - geographic
  - Autoconfiguration option - use interface ID that is unique on link + address prefix (from router?)

Address prefixes

Prefix	Use
0000 0000	Reserved
0000 0001	Reserved for NSAP (OSI)
0000 001	Reserved for IPX
001	Aggretable Global Unicats Addresses
1111 1110 10	Link local use addresses
1111 1110 11	Site local use addresses
1111 1111	Multicast addresses
others	Unassigned (see Table 4.11)

3	m	n	o	p	125−m−n−o−p
010	Registry ID	Provider ID	Subscriber ID	Subnet ID	Interface ID

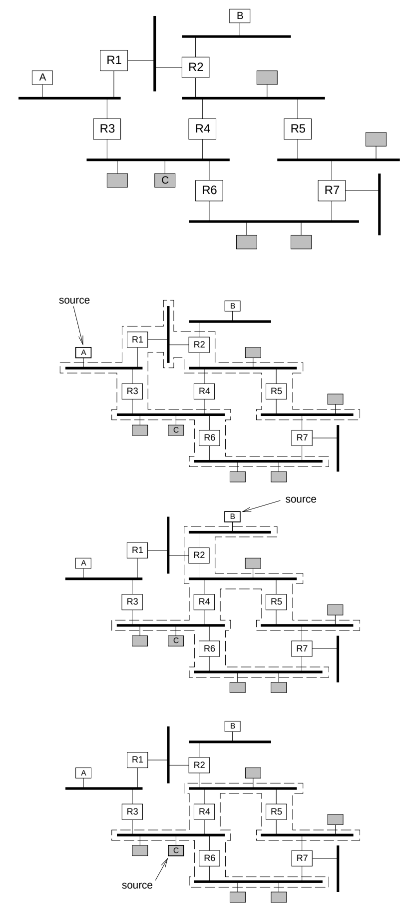
Internet Multicasting

- IP-V4 supports multicasting using class D addresses
- demonstrated with MBone
- 28 bits are available for identifying groups, so over 250 million groups can exist at the same time.
- problem is making it scale
- When a process sends a packet to a class D address, it is delivered to all the members of the group addressed, but no guarantees are given
- Two kinds of group addresses are supported
  - Permanent addresses: are always there; does not have to be set up
  - Temporary addresses: must be created before they can be used
- Multicasting is implemented by special multicast routers
- Once a minute, each multicast router sends a hardware multicast to the hosts on its LAN asking them to report back on the group their processes currently belong to
- Each host sends back responses for all the class D addresses it is interested in
- The query and response packets use a protocol called IGMP (Internet group management protocol)
- Router to host handled by network level multicast

Link-State Multicast

- Routers know entire topology
- Each host on a LAN periodically announces the groups it belongs to (IGMP).
- Augment update message (or Link state packet LSP) includes set of groups that have members on a particular LAN.
- Each router uses Dijkstra's algorithm to compute shortest-path *multicast spanning tree* for each source/group pair.
- Each router caches tree for currently active source/group pairs.

Example



Distance-Vector Multicast

Reverse Path Broadcast (RPB)

- Each router already knows that shortest path to destination S goes through router N.
- When a router receives multicast packet from S, forwards it on all outgoing links (except the one on which the packet arrived), iff packet arrived from N.
- Eliminate duplicate broadcast packets by only letting "parent" for LAN (relative to S) forward
  - shortest path to S (learn via distance vector)
  - smallest address to break ties

Reverse Path Multicast (RPM)

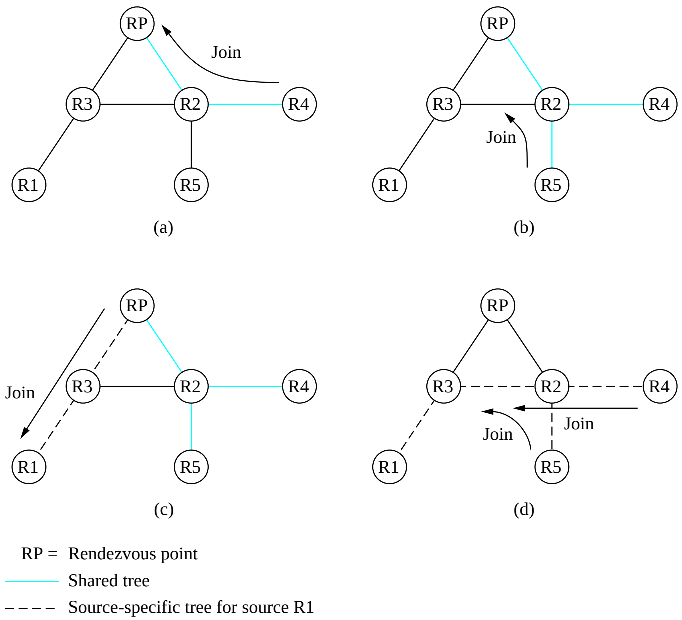
- Goal: Prune networks that have no hosts in group G
- Step 1: Determine of LAN is a *leaf* with no members in G
  - leaf if parent is only router on the LAN
  - determine if any hosts are members of G using IGMP
- Step 2: Propagate "no members of G here" information
  - augment ⟨`Destination, Cost`⟩ update sent to neighbors with set of groups for which this network is interested in receiving multicast packets.
  - only happens when multicast address becomes active.

Protocol Independent Multicast (PIM)

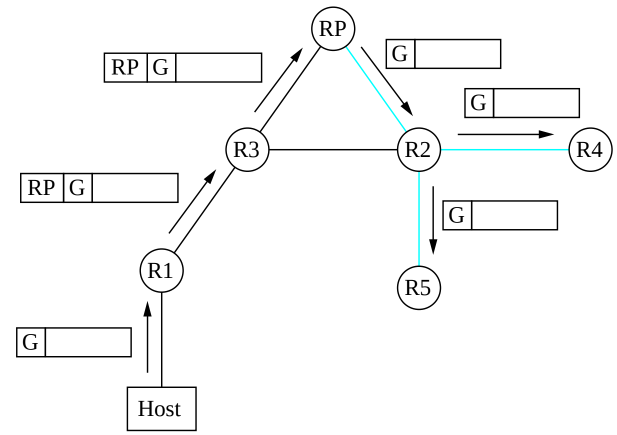
- Solve scaliing problems
- Sparse mode : few receivers
- Dense mode : many receivers

Sparse Mode PIM

- Routers explicitly Join/Prune (leave)
- Send to Rendezvous Points (RPs)
- create Multicast Forwarding Tree
  - shared (per group) (see a, b)
  - source specific (per sender - only created if data rate warrants) (see c,d)



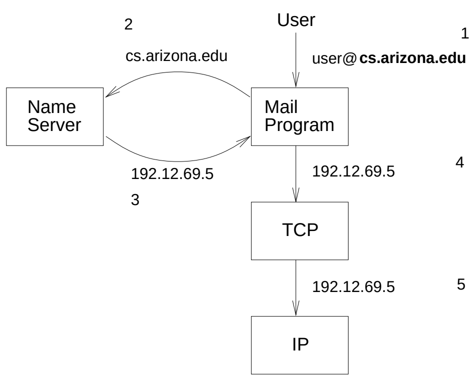
- (a) R4 sends Join to RP and joins shared tree
- (b) R5 joins shared tree
- (c) RP builds source specific tree to R1 by sending Join to R1
- (d) R4 and R5 build source specific tree to R1 by sending Joins to R1



Host Names (DNS)

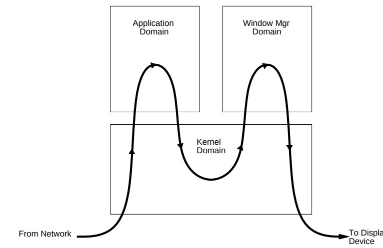
Overview

- Names versus Addresses
  - names are variable length, mnemonic, easy for humans to remember
  - addresses are fixed length, tied to routing, and easy for computers to process
- Name Space
  - defines set of possible names
  - flat versus hierarchical
  - consists of a set of name to value *bindings*



Domain Hierarchy

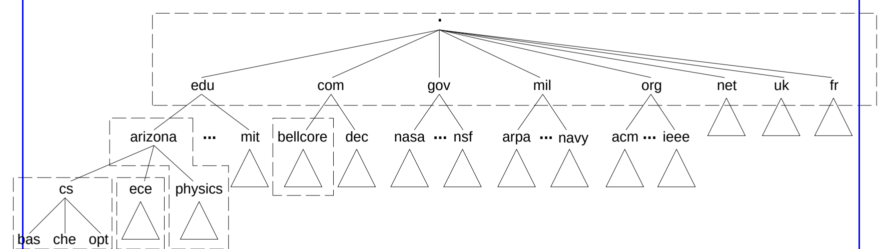
Example hierarchy



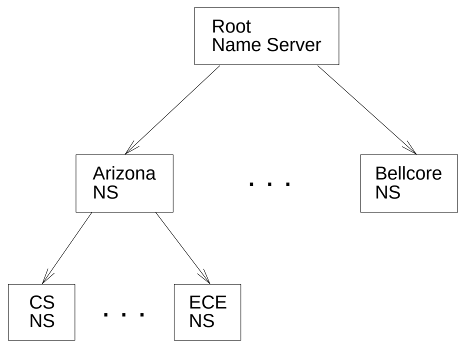
Example name: `cheltenham.cs.arizona.edu`

Name Servers

Partition hierarchy into *zones*



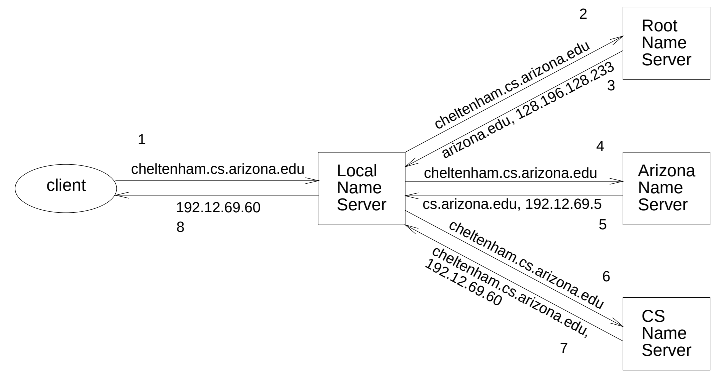
Each zone implemented by two or more *name servers* , a primary name server and one or more secondary name servers



Resource Records

- Each name server maintains a collection of *resource records*
  ⟨`Name, Value, Type, Class, TTL`⟩
- `Name/Value`: not necessarily host names to IP addresses
- `Type`
  - `NS`: the `Value` field gives the domain name for a host running a name server that knows how to resolve names within the specified domain.
  - `CNAME`: the `Value` field gives the canonical name for a particular host; it is used to define aliases.
  - `MX`: the `Value` field gives the domain name for a host running a mail server that accepts messages for the specified domain.
- `Class`: allow other entities to define types
- `TTL`: how long the resource record is valid

Name Resolution



- Strategies
  - forward
  - iterative
  - recursive
- Clients know local name server
- Local server queries other servers
- Authoritative and non-authoritative answers
  - need to know root at only one place (not each host)
  - site-wide cache

Mobile IP

- Many Internet users have portable computers
- Every IP address contains 3 fields: class, network number, and host number
- Given the class and network number, routers all over the world know how to get to the LAN
- By moving a machine to another LAN, the routers would still send packets to the old destination
- Giving a new IP address for a new location is not realistic since a large number of people, programs, databases should be informed about this change
- Another solution is to use the complete IP address (rather than class and network number) which requires routers to have millions of table entries(astronomical cost to the Internet)
- IETF formulated a number of goals:
  - Each mobile host must be able to use its home IP address anywhere
  - Software change to the fixed hosts were not permitted
  - Changes to router software and tables were permitted
  - Most packets for mobile host should not make detours
  - No overhead should be incurred when a mobile host is at home.
- The solution was chosen foreign and home agents.

- Home Agent (HA) - router on home network
  - Mobile Host (M) registers initially with it
- Foreign Agent (FA)
  - M registers with it when moved
  - gives home IP address and hardware address
  - FA contacts HA giving care-of address
- Issues to be resoloved
- How does HA intercept packets for M?
  - uses proxy ARP
- How does HA deliver to FA?
  - use tunneling
- How does FA deliver to M?
  - using hardware address
- M can be its own FA if it can dynamically acquire an IP address (e.g. using DHCP)