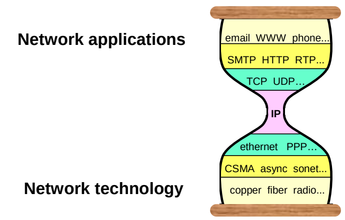
15-441 Computer Networking

Lecture 8 – IP Addressing and Forwarding

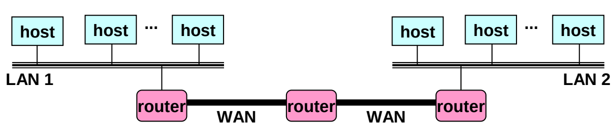
Internet Protocol (IP)

- Hour Glass Model
  - Create abstraction layer that hides underlying technology from network application software
  - Make as minimal as possible
  - Allows range of current & future technologies
  - Can support many different types of applications



What is an Internetwork?

- Multiple incompatible LANs can be physically connected by specialized computers called *routers*
- The connected networks are called an *internetwork*
  - The "*Internet*" is one (very big & successful) example of an internetwork



LAN 1 and LAN 2 might be completely different, totally incompatible LANs (e.g., Ethernet and ATM)

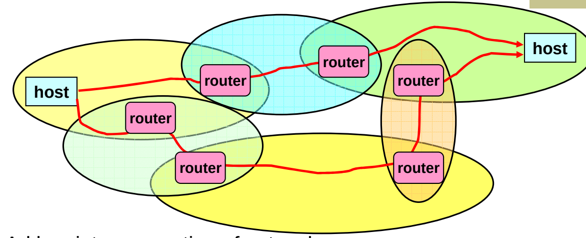
Designing an Internetwork

- How do I designate a distant host?
  - Addressing / naming
- How do I send information to a distant host?
  - Underlying service model
    - What gets sent?
    - How fast will it go?
    - What happens if it doesn't get there?
  - Routing
- Challenges
  - Heterogeneity
    - Assembly from variety of different networks
  - Scalability
    - Ensure ability to grow to worldwide scale

Outline

- Methods for packet forwarding
- Traditional IP addressing
- CIDR IP addressing
- Forwarding examples

Logical Structure of Internet



- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router forms bridge from one network to another
  - Different packets may take different routes

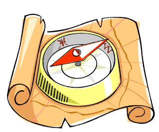
Getting to a Destination

- How do you get driving directions?
  - Intersections → routers
  - Roads → links/networks
  - Roads change slowly


- Road signs
- Detailed directions


Directions
1. Start out going WEST on FORBES AVE toward S CRAIG ST.
2. Turn RIGHT onto S BELLEFIELD AVE.
3. Turn LEFT onto 5TH AVE.
4. Turn LEFT onto CRAFT AVE.
5. Turn RIGHT onto FORBES AVE.
6. Turn SLIGHT RIGHT onto BOULEVARD OF THE ALLIES/PA-885 N.
7. Take the I-376 W ramp toward DOWNTOWN/FORT PITT BRIDGE.
8. Merge onto US-22 W/US-30 W.
9. US-22 W/US-30 W becomes PA-60 N.

- Maps



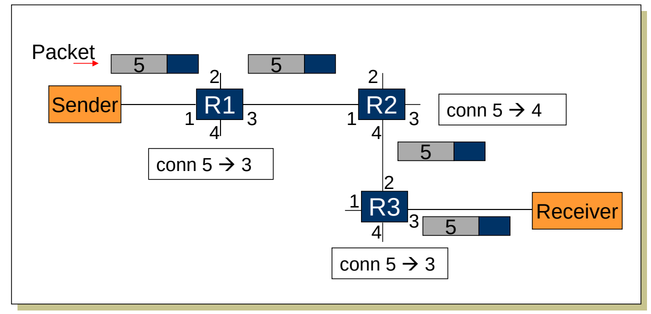
Forwarding Packets

- Table of virtual circuits
  - Connection routed through network to setup state
  - Packets forwarded using connection state
- Source routing
  - Packet carries path
- Table of global addresses (IP)
  - Routers keep next hop for destination
  - Packets carry destination address

Simplified Virtual Circuits

- Connection setup phase
  - Use other means to route setup request
  - Each router allocates flow ID on local link
- Each packet carries connection ID
  - Sent from source with 1st hop connection ID
- Router processing
  - Lookup flow ID – simple table lookup
  - Replace flow ID with outgoing flow ID
  - Forward to output port

Simplified Virtual Circuits Example



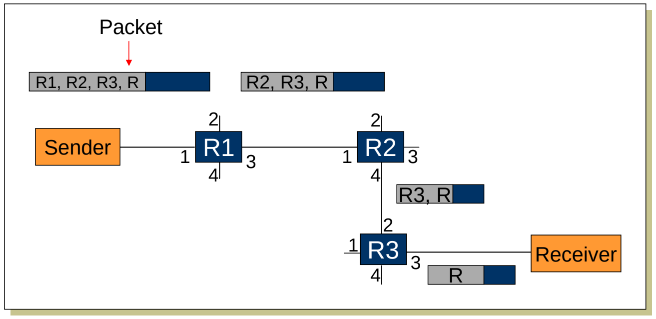
Virtual Circuits

- Advantages
  - Efficient lookup (simple table lookup)
  - More flexible (different path for each flow)
  - Can reserve bandwidth at connection setup
  - Easier for hardware implementations
- Disadvantages
  - Still need to route connection setup request
  - More complex failure recovery – must recreate connection state
- Typical use → fast router implementations
  - ATM – combined with fix sized cells
  - MPLS – tag switching for IP networks

Source Routing

- List entire path in packet
  - Driving directions (north 3 hops, east, etc..)
- Router processing
  - Strip first step from packet
  - Examine next step in directions
  - Forward to next step

Source Routing Example



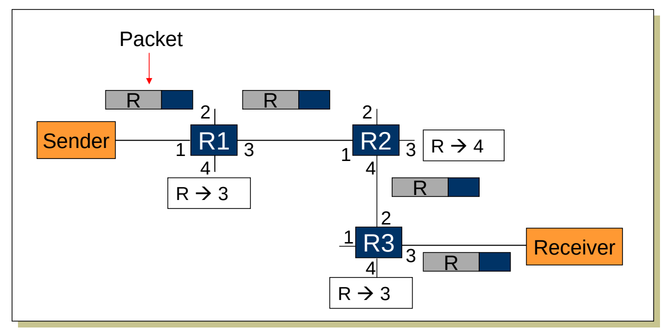
Source Routing

- Advantages
  - Switches can be very simple and fast
- Disadvantages
  - Variable (unbounded) header size
  - Sources must know or discover topology (e.g., failures)
- Typical uses
  - Ad-hoc networks (DSR)
  - Machine room networks (Myrinet)

Global Addresses (IP)

- Each packet has destination address
- Each router has forwarding table of destination → next hop
  - At v and x: destination → east
  - At w and y: destination → south
  - At z: destination → north
- Distributed routing algorithm for calculating forwarding tables

Global Address Example



Global Addresses

- Advantages
  - Stateless – simple error recovery
- Disadvantages
  - Every switch knows about every destination
    - Potentially large tables
  - All packets to destination take same route
  - Need routing protocol to fill table

Router Table Size

- One entry for every host on the Internet
  - 300M entries,doubling every 18 months
- One entry for every LAN
  - Every host on LAN shares prefix
  - Still too many and growing quickly
- One entry for every organization
  - Every host in organization shares prefix
  - Requires careful address allocation

Comparison

	Source Routing	Global Addresses	Virtual Circuits
Header Size	Worst	OK – Large address	Best
Router Table Size	None	Number of hosts (prefixes)	Number of circuits
Forward Overhead	Best	Prefix matching	Pretty Good
Setup Overhead	None	None	Connection Setup
Error Recovery	Tell all hosts	Tell all routers	Tell all routers and Tear down circuit and re-route

Outline

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Addressing in IP

- IP addresses are names of interfaces
  - E.g., 128.2.1.1
- Domain Name System (DNS) names are names of hosts
  - E.g., www.cmu.edu
- DNS binds host names to interfaces
- Routing binds interface names to paths

Addressing Considerations

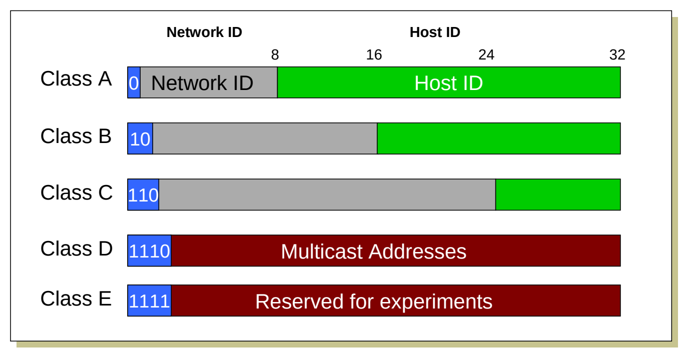
- Hierarchical vs. flat
  - Pennsylvania / Pittsburgh / Oakland / CMU / Seshan
    vs.
    Srinivasan Seshan:123-45-6789
- What information would routers need to route to Ethernet addresses?
  - Need hierarchical structure for designing scalable binding from interface name to route!
- What type of Hierarchy?
  - How many levels?
  - Same hierarchy depth for everyone?
  - Same segment size for similar partition?

IP Addresses

- Fixed length: 32 bits
- Initial classful structure (1981)
- Total IP address size: 4 billion
  - Class A: 128 networks, 16M hosts
  - Class B: 16K networks, 64K hosts
  - Class C: 2M networks, 256 hosts

High Order Bits	Format	Class
0	7 bits of net, 24 bits of host	A
10	14 bits of net, 16 bits of host	B
110	21 bits of net, 8 bits of host	C

IP Address Classes
(Some are Obsolete)



Original IP Route Lookup

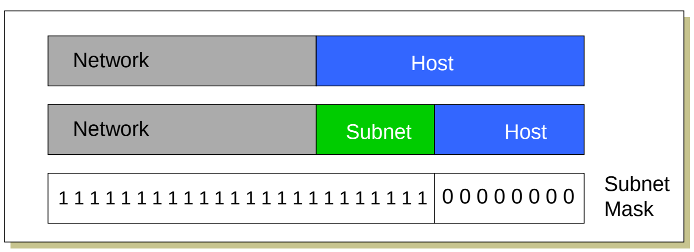
- Address would specify prefix for forwarding table
  - Simple lookup
- www.cmu.edu address 128.2.11.43
  - Class B address – class + network is 128.2
  - Lookup 128.2 in forwarding table
  - Prefix – part of address that really matters for routing
- Forwarding table contains
  - List of class+network entries
  - A few fixed prefix lengths (8/16/24)
- Large tables
  - 2 Million class C networks

Subnet Addressing RFC917 (1984)

- Class A & B networks too big
  - Very few LANs have close to 64K hosts
  - For electrical/LAN limitations, performance or administrative reasons
- Need simple way to get multiple "networks"
  - Use bridging, multiple IP networks or split up single network address ranges (subnet)
- CMU case study in RFC
  - Chose not to adopt – concern that it would not be widely supported ☺

Subnetting

- Add another layer to hierarchy
- Variable length subnet masks
  - Could subnet a class B into several chunks

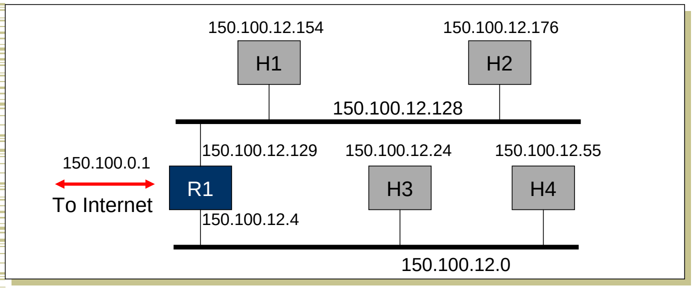


Subnetting Example

- Assume an organization was assigned address 150.100
- Assume < 100 hosts per subnet
- How many host bits do we need?
  - Seven
- What is the network mask?
  - 11111111 11111111 11111111 10000000
  - 255.255.255.128

Forwarding Example

- Assume a packet arrives with address 150.100.12.176
- Step 1: AND address with class + subnet mask



Aside: Interaction with Link Layer

- How does one find the Ethernet address of a IP host?
- ARP
  - Broadcast search for IP address
    - E.g., "who-has 128.2.184.45 tell 128.2.206.138" sent to Ethernet broadcast (all FF address)
  - Destination responds (only to requester using unicast) with appropriate 48-bit Ethernet address
    - E.g, "reply 128.2.184.45 is-at 0:d0:bc:f2:18:58" sent to 0:c0:4f:d:ed:c6

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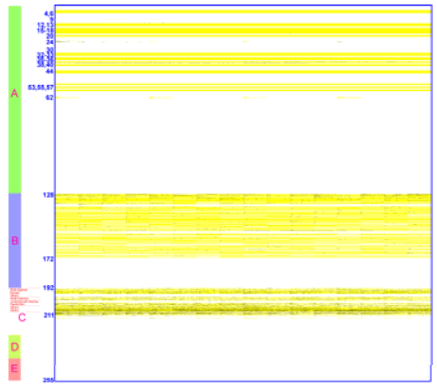
IP Address Problem (1991)

- Address space depletion
  - In danger of running out of classes A and B
  - Why?
    - Class C too small for most domains
    - Very few class A – very careful about giving them out
    - Class B – greatest problem
- Class B sparsely populated
  - But people refuse to give it back
- Large forwarding tables
  - 2 Million possible class C groups

IP Address Utilization ('97)



http://www.caida.org/outreach/resources/learn/ipv4space/

Classless Inter-Domain Routing (CIDR) – RFC1338

- Allows arbitrary split between network & host part of address
  - Do not use classes to determine network ID
  - Use common part of address as network number
  - E.g., addresses 192.4.16 - 192.4.31 have the first 20 bits in common. Thus, we use these 20 bits as the network number → 192.4.16/20
- Enables more efficient usage of address space (and router tables) → How?
  - Use single entry for range in forwarding tables
  - Combined forwarding entries when possible

CIDR Example

- Network is allocated 8 class C chunks, 200.10.0.0 to 200.10.7.255
  - Allocation uses 3 bits of class C space
  - Remaining 20 bits are network number, written as 201.10.0.0/21
- Replaces 8 class C routing entries with 1 combined entry
  - Routing protocols carry prefix with destination network address
  - Longest prefix match for forwarding

IP Addresses: How to Get One?

Network (network portion):

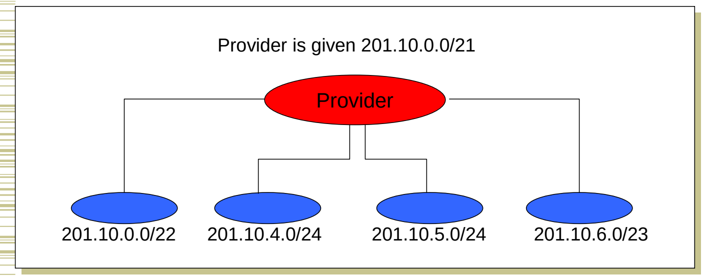
- Get allocated portion of ISP's address space:

ISP's block	11001000 00010111 00010000	00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000	00000000	200.23.16.0/23
Organization 1	11001000 00010111 00010010	00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100	00000000	200.23.20.0/23
...	.....	....	....
Organization 7	11001000 00010111 00011110	00000000	200.23.30.0/23

IP Addresses: How to Get One?

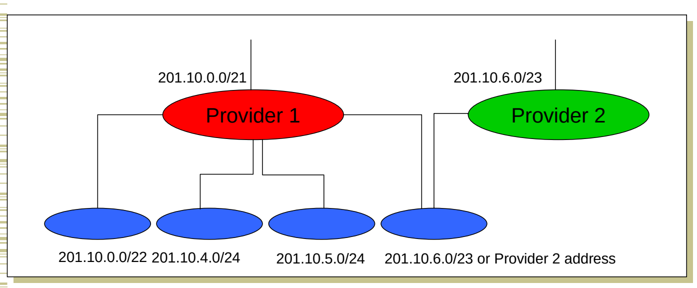
- How does an ISP get block of addresses?
  - From **Regional Internet Registries** (RIRs)
    - ARIN (North America, Southern Africa), APNIC (Asia-Pacific), RIPE (Europe, Northern Africa), LACNIC (South America)
- How about a single host?
  - Hard-coded by system admin in a file
  - DHCP: Dynamic Host Configuration Protocol: dynamically get address: "plug-and-play"
    - Host broadcasts "DHCP discover" msg
    - DHCP server responds with "DHCP offer" msg
    - Host requests IP address: "DHCP request" msg
    - DHCP server sends address: "DHCP ack" msg

CIDR Illustration



CIDR Implications

- Longest prefix match!!



Important Concepts

- Hierarchical addressing critical for scalable system
  - Don't require everyone to know everyone else
  - Reduces amount of updating when something changes
- Non-uniform hierarchy useful for heterogeneous networks
  - Initial class-based addressing too coarse
  - CIDR helps

Outline

- Methods for packet forwarding
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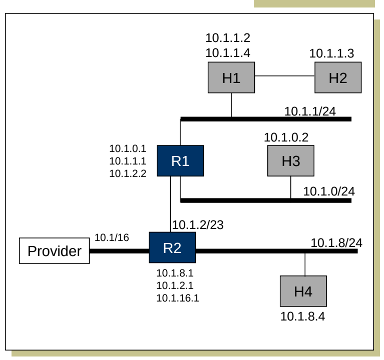
Host Routing Table Example

```
Destination     Gateway         Genmask         Iface
128.2.209.100   0.0.0.0         255.255.255.255 eth0
128.2.0.0       0.0.0.0         255.255.0.0     eth0
127.0.0.0       0.0.0.0         255.0.0.0       lo
0.0.0.0         128.2.254.36    0.0.0.0         eth0
```

- Host 128.2.209.100 when plugged into CS ethernet
- Dest 128.2.209.100 → routing to same machine
- Dest 128.2.0.0 → other hosts on same ethernet
- Dest 127.0.0.0 → special loopback address
- Dest 0.0.0.0 → default route to rest of Internet
  - Main CS router: gigrouter.net.cs.cmu.edu (128.2.254.36)

Routing to the Network

- Packet to 10.1.1.3 arrives
- Path is R2 – R1 – H1 – H2

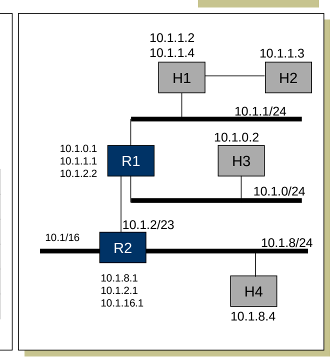


Routing Within the Subnet

- Packet to 10.1.1.3
- Matches 10.1.0.0/23

Routing table at R2

Destination	Next Hop	Interface
127.0.0.1	127.0.0.1	lo0
Default or 0/0	provider	10.1.16.1
10.1.8.0/24	10.1.8.1	10.1.8.1
10.1.2.0/23	10.1.2.1	10.1.2.1
10.1.0.0/23	10.1.2.2	10.1.2.1

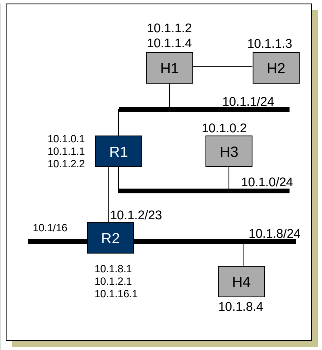


Routing Within the Subnet

- Packet to 10.1.1.3
- Matches 10.1.1.1/31
  - Longest prefix match

Routing table at R1

Destination	Next Hop	Interface
127.0.0.1	127.0.0.1	lo0
Default or 0/0	10.1.2.1	10.1.2.2
10.1.0.0/24	10.1.0.1	10.1.0.1
10.1.1.0/24	10.1.1.1	10.1.1.4
10.1.2.0/23	10.1.2.2	10.1.2.2
10.1.1.2/31	10.1.1.2	10.1.1.2

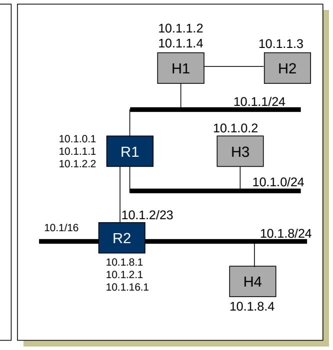


Routing Within the Subnet

- Packet to 10.1.1.3
- Direct route
  - Longest prefix match

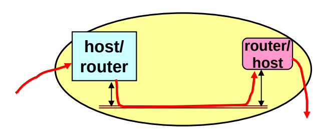
Routing table at H1

Destination	Next Hop	Interface
127.0.0.1	127.0.0.1	lo0
Default or 0/0	10.1.1.1	10.1.1.2
10.1.1.0/24	10.1.1.2	10.1.1.1
10.1.1.3/31	10.1.1.2	10.1.1.2



EXTRA SLIDES

Routing Through Single Network



- Path Consists of Series of Hops
  - Source – Router
  - Router – Router (typically high-speed, point-to-point link)
  - Router – Destination
- Each Hop Uses Link-Layer Protocol
  - Determine hop destination
    - Based on destination
  - Send over local network
    - Put on header giving MAC address of intermediate router (or final destination)

How is IP Design Standardized?

- IETF
  - Voluntary organization
  - Meeting every 4 months
  - Working groups and email discussions
- "We reject kings, presidents, and voting; we believe in rough consensus and running code" (Dave Clark 1992)
  - Need 2 independent, interoperable implementations for standard

Addressing Considerations

- Fixed length or variable length?
- Issues:
  - Flexibility
  - Processing costs
  - Header size
- Engineering choice: IP uses fixed length addresses

Virtual Circuits/Tag Switching

- Connection setup phase
  - Use other means to route setup request
  - Each router allocates flow ID on local link
  - Creates mapping of inbound flow ID/port to outbound flow ID/port
- Each packet carries connection ID
  - Sent from source with 1st hop connection ID
- Router processing
  - Lookup flow ID – simple table lookup
  - Replace flow ID with outgoing flow ID
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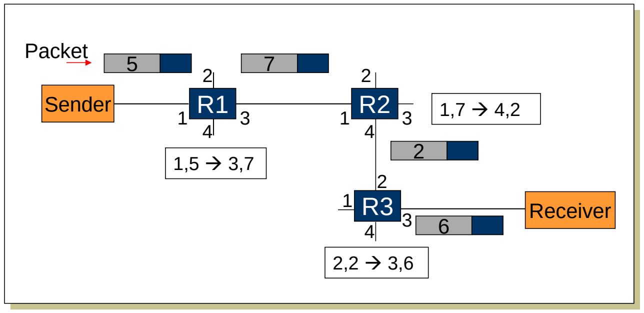
Virtual Circuits Examples



Virtual Circuits

- Advantages
  - More efficient lookup (simple table lookup)
  - More flexible (different path for each flow)
  - Can reserve bandwidth at connection setup
  - Easier for hardware implementations
- Disadvantages
  - Still need to route connection setup request
  - More complex failure recovery – must recreate connection state
- Typical uses
  - ATM – combined with fix sized cells
  - MPLS – tag switching for IP networks

Hierarchical Addressing Details

- Flat → would need router table entry for every single host… way too big
- Hierarchy → much like phone system…
- Hierarchy
  - Address broken into segments of increasing specificity
    - 412 (Pittsburgh area) 268 (Oakland exchange) 8734 (Seshan's office)
    - Pennsylvania / Pittsburgh / Oakland / CMU / Seshan
  - Route to general region and then work toward specific destination
  - As people and organizations shift, only update affected routing tables

Hierarchical Addressing Details

- Uniform Hierarchy
  - Segment sizes same for everyone
    - 412 (Pittsburgh area) 268 (Oakland exchange) 8734 (Seshan's office)
  - System is more homogeneous and easier to control
    - Requires more centralized planning
- Nonuniform Hierarchy
  - Number & sizes of segments vary according to destination
    - Pennsylvania / Pittsburgh / Oakland / CMU / Seshan
    - Delaware / Smallville / Bob Jones
  - System is more heterogenous & decentralized
    - Allows more local autonomy

Some Special IP Addresses

- 127.0.0.1: local host (a.k.a. the loopback address
- Host bits all set to 0: network address
- Host bits all set to 1: broadcast address

CIDR

- Supernets
  - Assign adjacent net addresses to same org
  - Classless routing (CIDR)
- How does this help routing table?
  - Combine forwarding table entries whenever all nodes with same prefix share same hop

Aggregation with CIDR

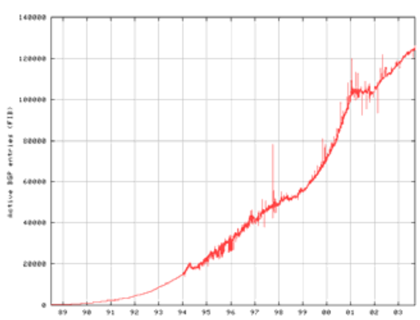
- Original Use: Aggregate Class C Addresses
- One organization assigned contiguous range of class C's
  - e.g., Microsoft given all addresses 207.46.192.X -- 207.46.255.X
  - Specify as CIDR address 207.46.192.0/18

0	8	16	24 31	
207	46	192	0	Decimal
cf	2e	c0	00	Hexadecimal
1100 1111	0010 1110	11xx xxxx	xxxx xxxx	Binary

Upper 18 bits frozen **Lower 14 bits arbitrary**

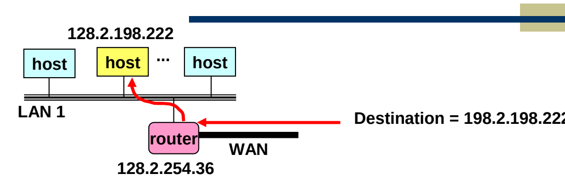
  - Represents 2^6 = 64 class C networks
- Use single entry in routing table
  - Just as if were single network address

Size of Complete Routing Table



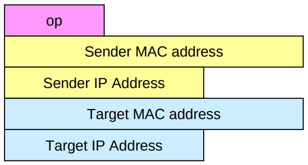
- Source: www.cidr-report.org
- Shows that CIDR has kept # table entries in check
  - Currently require 124,894 entries for a complete table
  - Only required by backbone routers

Finding a Local Machine



- Routing Gets Packet to Correct Local Network
  - Based on IP address
  - Router sees that destination address is of local machine
- Still Need to Get Packet to Host
  - Using link-layer protocol
  - Need to know hardware address
- Same Issue for Any Local Communication
  - Find local machine, given its IP address

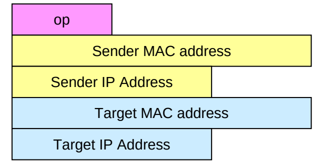
Address Resolution Protocol (ARP)



- op: Operation
  - 1: request
  - 2: reply
- Sender
  - Host sending ARP message
- Target
  - Intended receiver of message

  - Diagrammed for Ethernet (6-byte MAC addresses)
- Low-Level Protocol
  - Operates only within local network
  - Determines mapping from IP address to hardware (MAC) address
  - Mapping determined dynamically
    - No need to statically configure tables
    - Only requirement is that each host know its own IP address

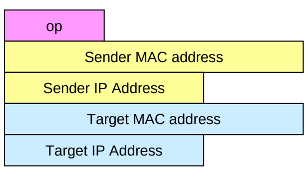
ARP Request



- op: Operation
  - 1: request
- Sender
  - Host that wants to determine MAC address of another machine
- Target
  - Other machine

- Requestor
  - Fills in own IP and MAC address as “sender”
    - Why include its MAC address?
- Mapping
  - Fills desired host IP address in target IP address
- Sending
  - Send to MAC address `ff:ff:ff:ff:ff:ff`
    - Ethernet broadcast

ARP Reply



- op: Operation
  - 2: reply
- Sender
  - Host with desired IP address
- Target
  - Original requestor

- Responder becomes “sender”
  - Fill in own IP and MAC address
  - Set requestor as target
  - Send to requestor’s MAC address

ARP Example

Time	Source MAC	Dest MAC
09:37:53.729185	**0:2:b3:8a:35:bf**	**ff:ff:ff:ff:ff:ff 0806 60:**
arp who-has 128.2.222.198 tell 128.2.194.66		
09:37:53.729202	**0:3:47:b8:e5:f3**	**0:2:b3:8a:35:bf 0806 42:**
arp reply 128.2.222.198 is-at 0:3:47:b8:e5:f3		

- Exchange Captured with windump
  - Windows version of tcpdump
- Requestor:
  - blackhole-ad.scs.cs.cmu.edu (128.2.194.66)
  - MAC address 0:2:b3:8a:35:bf
- Desired host:
  - bryant-tp2.vlsi.cs.cmu.edu (128.2.222.198)
  - MAC address 0:3:47:b8:e5:f3

Caching ARP Entries

- Efficiency Concern
  - Would be very inefficient to use ARP request/reply every time need to send IP message to machine
- Each Host Maintains Cache of ARP Entries
  - Add entry to cache whenever get ARP response
  - Set timeout of ~20 minutes

ARP Cache Example

- Show using command “arp -a”

Interface: 128.2.222.198 on Interface 0x1000003

Internet Address	Physical Address	Type
128.2.20.218	00-b0-8e-83-df-50	dynamic
128.2.102.129	00-b0-8e-83-df-50	dynamic
128.2.194.66	00-02-b3-8a-35-bf	dynamic
128.2.198.34	00-06-5b-f3-5f-42	dynamic
128.2.203.3	00-90-27-3c-41-11	dynamic
128.2.203.61	08-00-20-a6-ba-2b	dynamic
128.2.205.192	00-60-08-1e-9b-fd	dynamic
128.2.206.125	00-d0-b7-c5-b3-f3	dynamic
128.2.206.139	00-a0-c9-98-2c-46	dynamic
128.2.222.180	08-00-20-a6-ba-c3	dynamic
128.2.242.182	08-00-20-a7-19-73	dynamic
128.2.254.36	00-b0-8e-83-df-50	dynamic

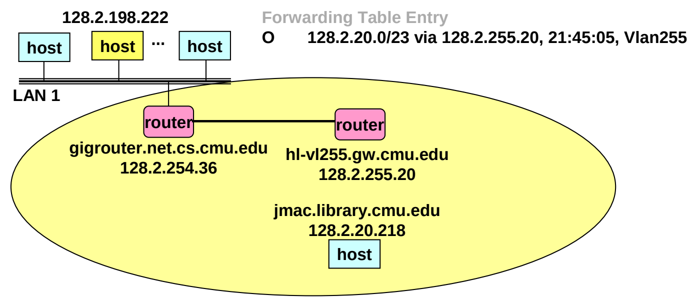
ARP Cache Surprise

- How come 3 machines have the same MAC address?

Interface: 128.2.222.198 on Interface 0x1000003

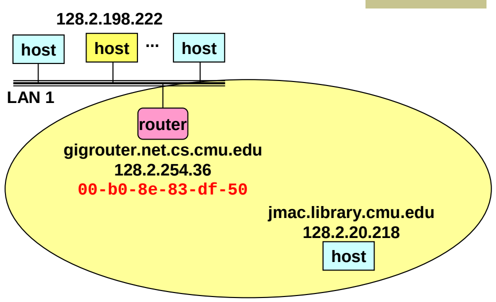
Internet Address	Physical Address	Type
128.2.20.218	*00-b0-8e-83-df-50*	*dynamic*
128.2.102.129	*00-b0-8e-83-df-50*	*dynamic*
128.2.194.66	00-02-b3-8a-35-bf	dynamic
128.2.198.34	00-06-5b-f3-5f-42	dynamic
128.2.203.3	00-90-27-3c-41-11	dynamic
128.2.203.61	08-00-20-a6-ba-2b	dynamic
128.2.205.192	00-60-08-1e-9b-fd	dynamic
128.2.206.125	00-d0-b7-c5-b3-f3	dynamic
128.2.206.139	00-a0-c9-98-2c-46	dynamic
128.2.222.180	08-00-20-a6-ba-c3	dynamic
128.2.242.182	08-00-20-a7-19-73	dynamic
128.2.254.36	*00-b0-8e-83-df-50*	*dynamic*

CMU’s Internal Network Structure



- CMU Uses Routing Internally
  - Maintains forwarding tables using OSPF
  - Most CMU hosts cannot be reached at link layer

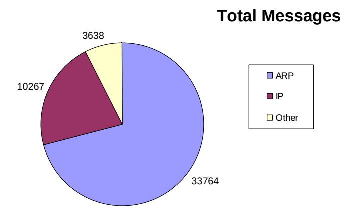
Proxy ARP



- Provides Link-Layer Connectivity Using IP Routing
  - Local router (gigrouter) sees ARP request
  - Uses IP addressing to locate host
  - Becomes “Proxy” for remote host
    - Using own MAC address
  - Requestor thinks that it is communicating directly with remote host

Monitoring Packet Traffic

- Experiment
  - Ran windump for 15 minutes connected to CMU network
  - No applications running
    - But many background processes use network
  - Lots of ARP traffic (71% of total)
    - Average 37 ARP requests / second (why all from CS hosts?)
    - Only see responses from own machine (why?)



Monitoring Packet Traffic

- Other Traffic
  - Mostly UDP
    - Encode low-level protocols such as bootp
  - Nothing very exciting (why?)
- Answers for UDP and ARP
  - On a switched network you only see broadcast traffic or traffic sent to/from you
  - TCP is never sent broadcast