CMSE 346 Computer Networks
Fall 2022

Internetworking
Part 2

Reading: Peterson and Davie, §3.2, 4.1

Aim and Problems

- Aim: Build networks connecting millions of users around the globe spanning networks based on any technology
- Problems: heterogeneity and scalability
  – heterogeneity: need to support different LANs, point-to-point technologies, switched networks, different addressing formats
  – scalability: addressing (management and configuration) and routing must be able to handle millions of hosts
- We will examine the (original) IP protocol (IPv4), IP addressing, packet forwarding, subnetting, and IPv6.

Outline

- Internet architecture
- IP service model
- IP forwarding
- Address translation (ARP)
- Automatic host configuration (DHCP) and error reporting (ICMP)
- Virtual Private Networks (VPNs)
- Subnetting
- Supernetting: Classless routing (CIDR)
- IPv6

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The Internet and IP

Terminology

– network = network based on one technology
– internet = "network of networks"
–The Internet = internet using IP
– routers = nodes connecting networks
– IP = Internet Protocol, current version IPv4 (IP Version 4)

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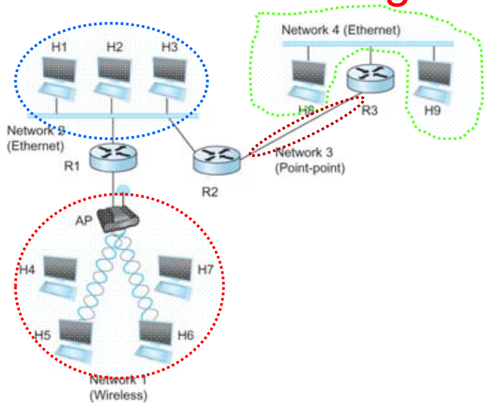
Internetworking



- Internetwork: An arbitrary collection of networks interconnected to provide some sort of host-host to packet delivery service

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IP principles

- Each host
  - has a globally unique IP address
  - must be reachable by everyone and from everywhere
- Simple packet forwarding
  - Network nodes simply forward packets
  - Keeping the routers as simple as possible was one of the original design goals of IP

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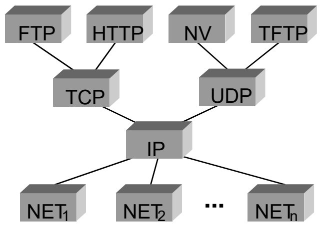
Internet architecture

- Recall Internet architecture from Chapter 1
  - Application layer: FTP, HTTP, …(Last Chapter)
  - Transport layer: TCP (reliable byte transfer) and UDP (unreliable datagram delivery) provide logical channels to applications (Next Chapter)
  - Network or IP layer: IP protocol interconnects multiple networks into a single logical network (This Chapter)
  - “Link” layer: wide variety of LAN and point-to-point protocols



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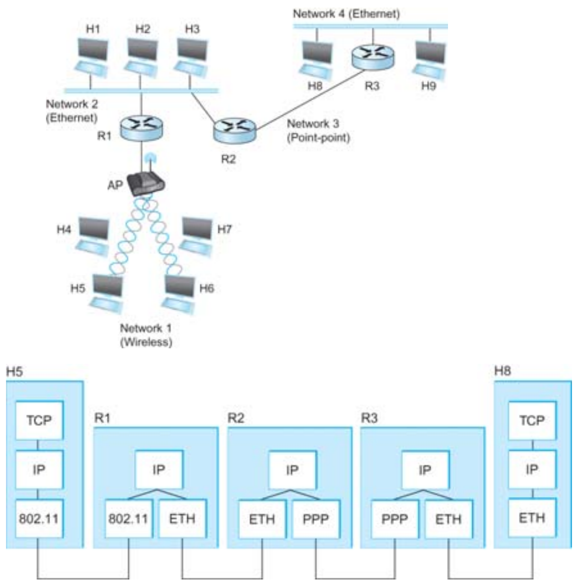
Protocol stack



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IP service model

- Main idea in the Internet service model:
  - Make it undemanding enough that IP can be run over anything
- This model is the major reason for the success of IP technology
- Service model consists of 2 parts:
  - Data delivery model
  - Global addressing scheme

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Data delivery model

- Data delivery in the Internet
  - IP network connectionless (datagram-based)
  - IP network offers best-effort delivery (unreliable service)
    - packets may be lost
    - packets may be delivered out of order
    - duplicate copies of a packet may be delivered
    - packets can be delayed for a long time
    - “intelligence” implemented at the end hosts
  - datagram format (next slide)

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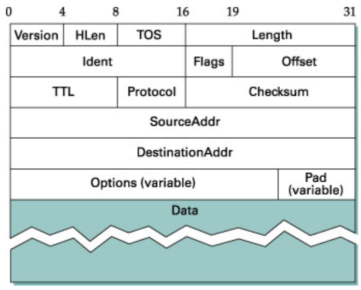
IP datagram format

Format aligned at 32 bit words
– simplifies packet processing in software

Header fields
– Version: version 4 (IPv4) or version 6 (IPv6)
– HLen: header length, in 32-bit words (min 5)
– TOS: type of service, used to give priorities to packets (QoS issue)
– Length: data+header length, in bytes
– 2nd word for fragmentation/reassembly (next slide)
– TTL: time to live, no of times packet allowed to be forwarded (no of hops), default 64, detects packets caught in routing loop
– Protocol: identifies upper layer protocols, TCP (6), UDP (17)
– Checksum: erroneous packets discarded
– Addresses: global Internet addresses
– Options: rarely used



Max. length of IP packet = (2^16) – 1= 65535 bytes

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Fragmentation/reassembly

- Each network has an MTU (Maximum Transmission Unit)
  – e.g., Ethernet 1500 bytes, PPP 532 bytes
- Strategy
  – Fragment when necessary (MTU < datagram length)
  – In general, try to avoid fragmentation: Hosts are encouraged to perform "path MTU discovery"
- Fragments are self-contained datagrams
  – each fragment contains a common identifier in Ident field
  – Flags (M-bit) and Offset used to guide fragmentation process
  – Offset measured in 8 byte units
  – Fragmented packet can be again re-fragmented
- Reassembly is performed only at destination host
- Reassembly does not try to recover lost fragments

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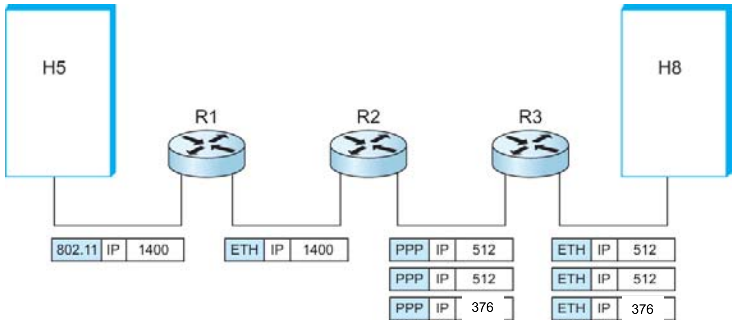
Fragmentation/reassembly example

- Assume H5 wants to send a 1400 byte datagram to H8 (see slide 8): 1400 bytes + 20 bytes (IP header)
- MTU: 802.11 and Ethernet 1500 bytes, PPP 532 bytes



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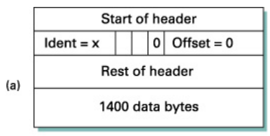
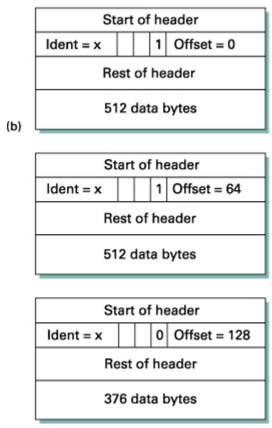
Example (continued)



(a) Unfragmented packet: H5→R1→R2



(b) Fragmented packets: R2→R3→H8

Can you think of a strategy that will abuse fragmentation to carry out a denial-of-service attack?
How can one prevent such an attack?

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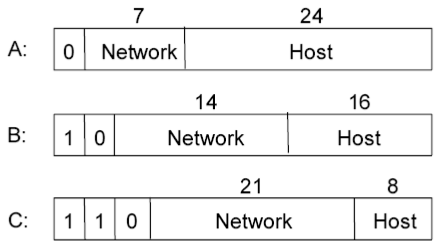
IP global addressing

- Properties
  - globally unique, 32 bits
  - hierarchical:
    network part + host part
  - address identifies interface
    - end host has one interface
    - router has many interfaces
  - IP address ≠ domain name
- Original classful addressing
  - class A, B and C networks
  - defines different sized networks
  - idea: small no of WANs, modest no of campus networks, large no of LANs
- Dotted Decimal Notation
  - 32 bit addresses represented as groups of 8 bit integers
  - e.g., **12.34.158.5** → 00001100 | 00100010 | 10011110 | 00000101



A : 1.0.0.0 to 127.255.255.255
B : 128.0.0.0 to 191.255.255.255
C : 192.0.0.0 to 223.255.255.255

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Forwarding vs. routing

- Forwarding:
  - Process of taking a packet from input interface, looking at its destination address, consulting a forwarding table, and sending the packet over an output interface determined by that table
- Routing:
  - Process by which forwarding tables are constructed
  - Routing must create optimal or efficient paths that the packets should follow

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IP forwarding

- Preliminaries
  - Every datagram contains destination's address
  - Every router has a forwarding table
  - Each host has a default router configured
  - Routers maintain forwarding tables with multiple entries (constructed via routing process)
  - Forwarding table maps network number into next hop router number or local interface number
- Strategy
  - A router receiving a packet checks destination network address of datagram and
  - if directly connected to destination network, then forwards directly to host
    - need to map IP address to physical LAN address (ARP)
  - if not directly connected to destination network, then forwards to next hop router

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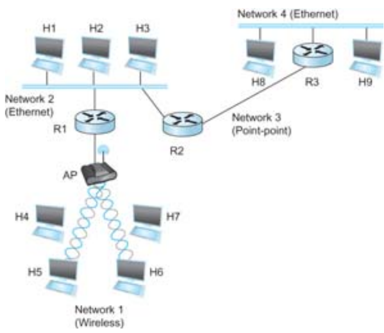
IP forwarding example

H1→H3: forwarding on the same network

H5→H8: forwarding via R1 and R2



Router R2

NetworkNum	NextHop
1	R1
2	Interface 1
3	Interface 0
4	R3

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Routers vs. bridges

Bridges are used for interconnecting LANs of the same type whereas routers interconnect networks of different (or the same) types

- Bridge (+/-)
  - + bridge operation is simple, requires less processing
  - + transparent (no configuration needed when new nodes added to LAN)
  - – restricted topology (forwarding determined by a spanning tree)
  - – LANs use a flat addressing space (no hierarchical network structure)
- Router (+/-)
  - + arbitrary topologies, enables use of efficient routing algorithms for distributing traffic (helps traffic management)
  - + hierarchical addressing enables scalability:
    - scalability requires minimization of address info stored in routers
    - routing based on network numbers ⇒ forwarding tables contain info on all networks, not all nodes
  - – requires IP address configuration
  - – packet processing more demanding
- Summary: bridges do well in small (~ 100 hosts) networks while routers are used in large networks (1000s of hosts)

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Address translation

What to do when router/host notes that it is connected directly to the network where an arriving packet is destined ?

- Need to map IP addresses into physical LAN addresses
  - – destination host
  - – next hop router
- Techniques
  - – encode physical LAN address in host part of IP address ⇒ not scalable! (not implemented)
  - – table-based (maintain IP address, PHY address pairs) ⇒ARP

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ARP details

- ARP (Address Resolution Protocol)
  - utilizes LAN's broadcast capabilities
  - each node maintains table of IP to physical LAN address bindings
  - broadcast request if address not in table
  - target machine responds with its physical LAN address
- ARP request contains also source addresses (physical and IP)
  - all "interested" parties can learn the source address
- Node (host/router) actions:
  - table entries timeout in about 10 minutes
  - if node already has an entry for source, refresh timer
  - if node is the target, reply and update table with source info
  - if node not target and does not have entry for the source, ignore source info

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ARP packet format

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

0	8	16 31
Hardware type = 1		ProtocolType = 0x0800
HLen = 48	PLen = 32	Operation
SourceHardwareAddr (bytes 0–3)		
SourceHardwareAddr (bytes 4–5)		SourceProtocolAddr (bytes 0–1)
SourceProtocolAddr (bytes 2–3)		TargetHardwareAddr (bytes 0–1)
TargetHardwareAddr (bytes 2–5)		
TargetProtocolAddr (bytes 0–3)		

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Need for automatic configuration!

- IP addresses need to be reconfigurable
  - Ethernet addresses hardwired onto the network adapter
  - IP address consists of network and host part
  - hosts can move between networks ⇒host gets new address in each network
- Need for automated host configuration
  - hosts need other configuration info, e.g., the default router
  - configuration manually impossible (too much work and errors)
  - ⇒Dynamic Host Configuration Protocol (DHCP)
- DHCP server
  - at least one DHCP server for each administrative domain
  - centralized repository for configuration info
  - two operation modes:
    - ◊ administrator chooses host addresses and configures them to DHCP
    - ◊ DHCP manages the addresses by allocating addresses dynamically from a pool of available addresses (more sophisticated)

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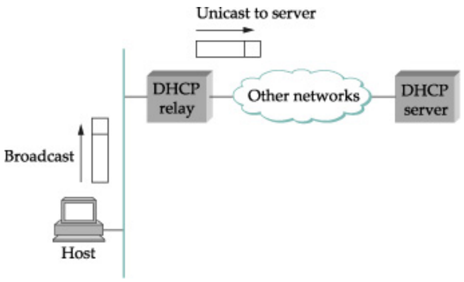
DHCP operation

- Server discovery: host sends DHCPDISCOVER msg to IP broadcast address (255.255.255.255)
- Msg broadcasted only on same network
- If server on same network, host receives its IP address
- If not, msg picked up by DHCP relay agent



- Relay agent knows address of DHCP server, forwards the msg to DHCP server and host receives its IP address
- Use of DHCP relay agent makes it possible to have fewer DHCP servers (relay agent configuration simpler than DHCP server configuration)

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Internet Control Message Protocol

- ICMP used for reporting errors in Internet
- Messages
  - Echo (ping)
  - Redirect (from router to source host if router knows of a better route to packet's destination)
  - Destination unreachable (protocol, port, or host)
  - TTL exceeded (so datagrams don't cycle forever)
  - Checksum failed
  - Reassembly failed
  - Cannot fragment

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Virtual private networks (VPN)

- Problem:
  - group of isolated networks
  - geographically distant from each other
  - need to connect different networks together into a "private" network securely
  - e.g., company with many branch offices
- Solution: VPN
- Methods
  - Build a private network from leased lines (not shared)
  - Create a virtual private network which is overlaid on top of public networks
    - ATM and Frame Relay: Use virtual circuits
    - IP: Use IP tunneling (usually coupled with secure IPsec)

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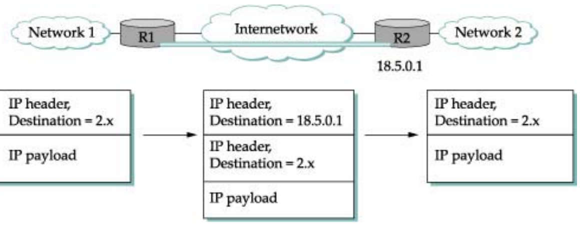
VPN and IP tunneling



• Problem with IP:
  - not possible to connect to Internet via router without the whole Internet also knowing about your network.

• Tunneling
  – virtual point-to-point link between two nodes separated by arbitrary no of networks
  – created at R1 by providing it with address of R2
  – R1 encapsulates original packet in a new packet addressed to R2
  – packet forwarded normally inside IP network
  – R2 receives packet and strips off packet header and notices payload contains an encapsulated packet addressed to some host inside network 2

Global Internet

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 (1)

- Problem 1: Any network with more than 255 hosts, needs class B addresses, or should get many class C addresses
- Problem 2: Each new network implies additional entry in forwarding table → large table
- Solution:
  - Share one network number between several networks. ⇒ another level is added to address/routing hierarchy : *subnet*

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Subnetting (2)

- Makes most sense for large corporations or campuses
- Corporation networks share 1 network number
- Number of other networks *within* the corporation, using subnet masks
  - E.g., a class B address, is shared among 8 networks, by using a 19-bit "subnet mask" (255.255.224.0 = 11111111 11111111 11100000 00000000)
  - I.e., subnet addresses are defined by first 19 bits of the IP address. → Host part now has a "subnet" part in it.
- Class B network address continues to be advertised to the rest of the Internet, subnetting only used "within campus" (i.e. Subnets visible only within site).

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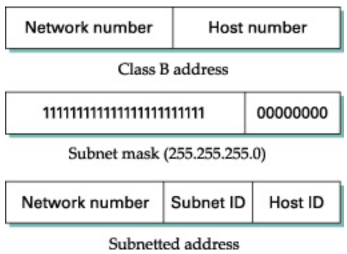
Subnetting (3)

- Another example: a class B address, is shared among 256 networks, by using a 24-bit "subnet mask" :

(255.255.255.0 = 11111111 11111111 11111111 00000000)



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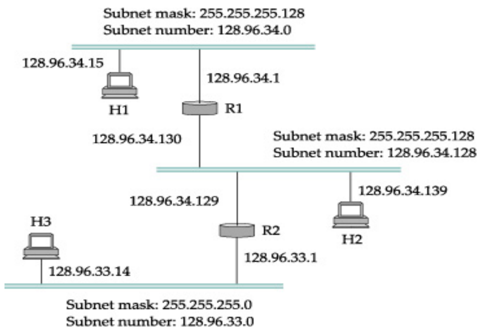
Subnet example



Forwarding table at 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

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Forwarding algorithm with subnetting

```
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)
```

Q: Apply the algorithm when H1 is sending to H2 and H3.

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

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Subnetting Example

- Where does the router forward packets addressed to:
  - 128.96.39.10 –> If0
  - 128.96.40.12 –> R2
  - 128.96.40.151 –> R4
  - 192.4.153.17 –> R3
  - 192.4.153.90 –> R4

Subnet Number	Subnet Mask	Next Hop
128.96.39.0	255.255.255.128	Interface 0
128.96.39.128	255.255.255.128	Interface 1
128.96.40.0	255.255.255.128	R2
192.4.153.0	255.255.255.192	R3
<default>		R4

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Supernetting (CIDR) (1)

- Classful addressing:
  - inefficient use of address space, address space exhaustion
  - subnetting does not get around the fact that a network with more than 255 hosts requires a class B address
  - class B net allocate addresses for 65K hosts, even if only 2K hosts in that network
- CIDR: Classless InterDomain Routing
  - network portion of address of arbitrary length
  - address format: a.b.c.d/x, where x is # bits in network portion of address

network part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

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Supernetting (CIDR) (2)

- Assign block of contiguous network numbers to near-by networks ⇒ helps to aggregate routers ⇒ less entries in the forwarding tables
- Restrict block sizes to powers of 2
- E.g. Consider an *Autonomous system* with 16 class C network numbers (192.4.16 to192.4.31)⇒ the top 20 bits are same ⇒ 20-bit network number (a single network prefix) can be used in forwarding tables. Something between class B and class C ⇒ classless!

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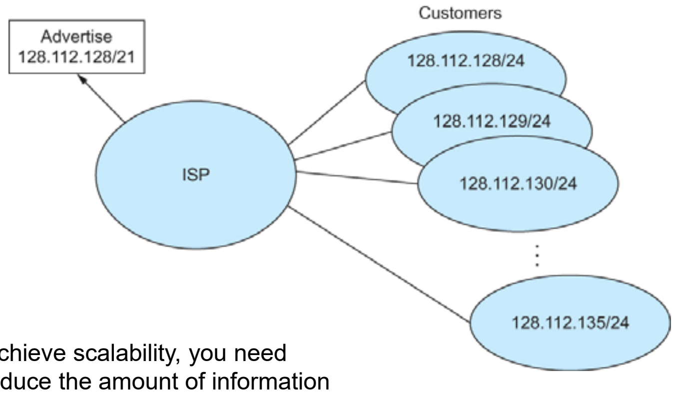
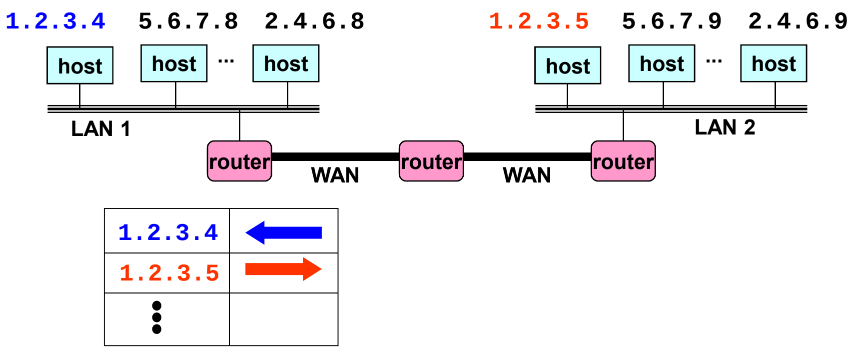
Route aggregation



To achieve scalability, you need
to reduce the amount of information
stored in routers
Hierarchical aggregation:
IP has a two-level hierarcy (network+host)

A simple example

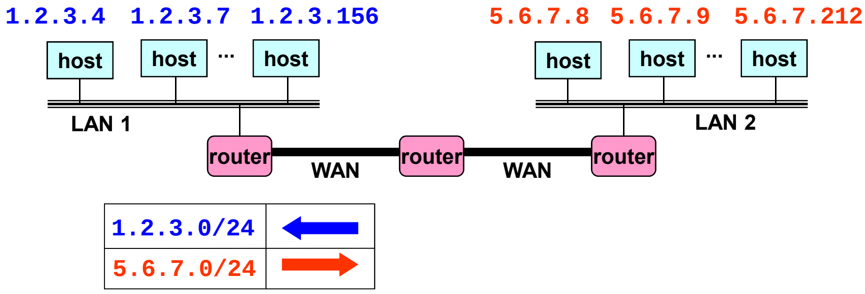
- Suppose hosts had arbitrary addresses
  - Then every router would need a lot of information
  - …to know how to direct packets toward the host



forwarding table

Example continued..

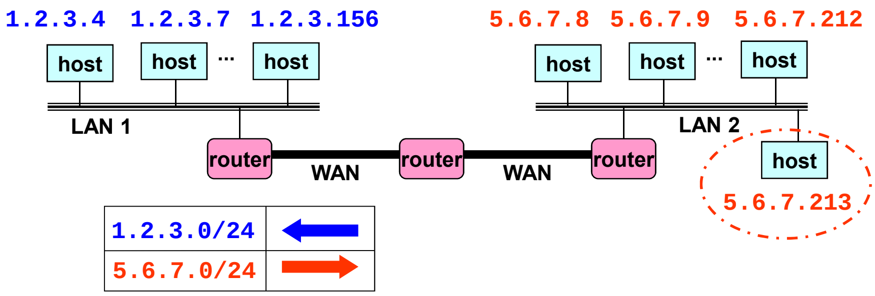
- Number related hosts from a common subnet
  - 1.2.3.0/24 on the left LAN
  - 5.6.7.0/24 on the right LAN



forwarding table

Example continued..

- Easy to add a new host
- No need to update the routers
  - E.g., adding a new host 5.6.7.213 on the right
  - Doesn't require adding a new forwarding entry



forwarding table

Longest Prefix Match

- With CIDR, prefixes may be of any length and may overlap
- For example, suppose we have the following in the forwarding table at a router:
  - 171.69 (a 16-bit prefix)
  - 171.69.10 (a 24-bit prefix)
- A packet with destination address 171.69.10.5 matches both prefixes
- The rule is to choose the longest prefix to forward to
- Consider also 171.69.20.5. The longest match would be 171.69
- Efficient algorithms are required for finding the longest match in a forwarding table

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CIDR Example

- Suppose the router does the longest-prefix match. Where does the router forward packets addressed (in hex) to:
  - C4.5E.13.87 –> B
  - C4.5E.22.09 –> A
  - C3.41.80.02 –> E
  - 5E.43.91.12 –> F
  - C4.6D.31.2E –> C
  - C4.6B.31.2E –> D

Net / Mask Length	Next Hop
C4.50.0.0 / 12	A
C4.5E.10.0 / 20	B
C4.60.0.0 / 12	C
C4.68.0.0 / 14	D
80.0.0.0 / 1	E
40.0.0.0 / 2	F
00.0.0.0 / 2	G

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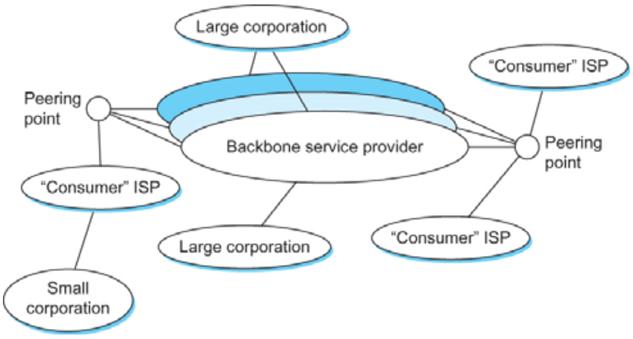
Today's Internet

- Sites are connected arbitrarily rather than as a tree-like structure as was the case in 1990s
- Some large corporations connect with each other. This is called peering



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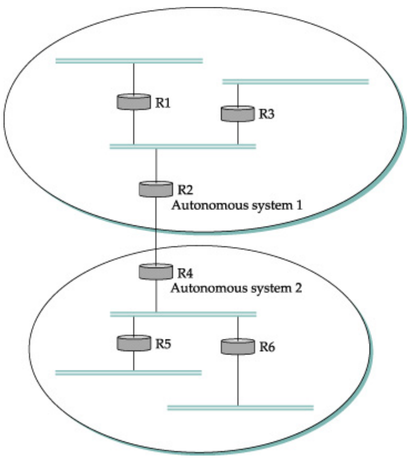
Routing in the Internet (1)

- The Global Internet consists of Autonomous Systems (AS) interconnected with each other.
- AS:
  – corresponds to an administrative domain
  – examples: University, company, backbone network
  – Each AS is assigned a 16-bit number



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Routing in the Internet (2)

- We can classify ASs into three types:
  - **Stub AS**: small corporation: a single connection to one other AS. Traffic originates or terminates in it ⇒ only carry local traffic
  - **Multihomed AS**: large corporation: multiple connections to other AS's. (no transit, i.e. refuses to carry others traffic)
  - **Transit AS**: provider, hooking many AS's together
  - Q: Which ASes are Stub, Multihomed and Transit in Slide 40?
- Two-level routing:
  - **Intra-AS:** administrator responsible for choice of routing algorithm within network
  - **Inter-AS:** unique standard for inter-AS routing: BGP

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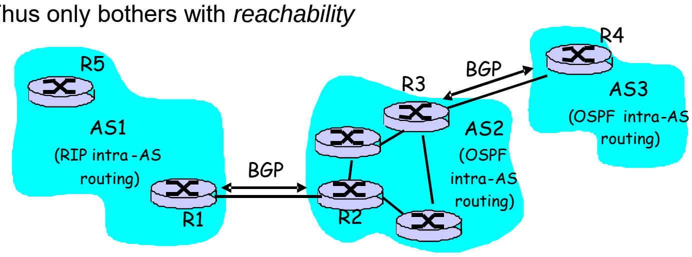
Intra-AS, Inter-AS routing

- Most common Intra-AS routing protocols:
  - RIP: Routing Information Protocol
  - OSPF: Open Shortest Path First
  - IGRP: Interior Gateway Routing Protocol
- Most common Inter-AS routing protocol is Border Gateway Protocol (BGP)

  - Leave “optimality” aside. Just *find* a loop-free path

  - Thus only bothers with *reachability*



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IPv6 (1)

Major Features

- 128-bit addresses
- Multicast
- Real-time service
- Authentication and security
- Autoconfiguration
- End-to-end fragmentation
- Protocol extensions

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IPv6 (2)

IPv6 addresses

- Classless addressing/routing (similar to CIDR)
- Notation: x:x:x:x:x:x:x:x (x = 16-bit hex number)
  - – contiguous 0s are compressed: 47CD::A456:0124
  - – IPv6 compatible IPv4 address: ::128.42.1.87
- Address assignment
  - – provider-based
  - – geographic

3	m	n	o	p	125–m–n–o–p
010	RegistryID	ProviderID	SubscriberID	SubnetID	InterfaceID

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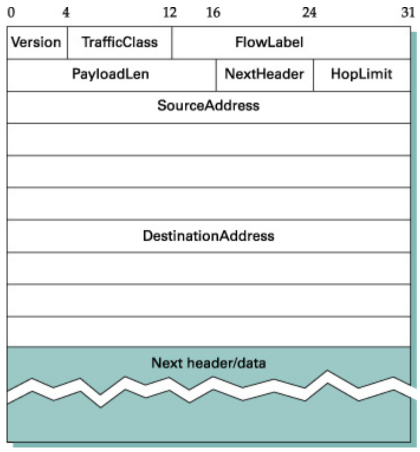
IPv6 Header

- 40-byte "base" header
- Extension headers (fixed order, mostly fixed length)
  - fragmentation
  - source routing
  - authentication and security
  - other options



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