Internet Technology

07. Network Layer

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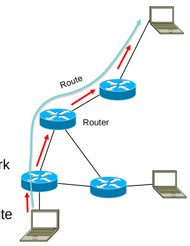
Network Layer

- Transport Layer (Layer 4)
  - Application-to-application communication
- Network Layer (Layer 3)
  - Host-to-host communication
- **Route**
  - The path that a packet takes through the network
- **Routing**
  - The process of moving the packet along the route
- **Forwarding**
  - Transferring a packet from an incoming link to an outgoing link
- **Router**
  - The device that forwards packets (datagrams)



Forwarding vs. Routing

- **Routing**
  - Responsibility over the path
  - Routing algorithms figure out the path a packet should take
- **Forwarding**
  - A router consults a forwarding table
  - Examines data in a packets header & uses the table to determine the outgoing link for the packet
  - Routing algorithms configure forwarding tables
- **Switches vs. Routers**
  - Packet switches: transfer data between links based on link layer data (e.g., Ethernet)
  - Routers: transfer data between links based on network layer data (e.g., IP)

Network service models: our wish list

What would we like from a network?

- Guaranteed delivery (no loss)
- Bounded (maximum) delay
- In-order packet delivery
- Guaranteed constant or minimum bandwidth
- Maximum jitter
  - Jitter = variation in latency
- Endpoint authentication & encrypted delivery

Network service models: what do we get?

- IP gives us none of this
  - Best-effort = no guarantees on delivery, delay, order
- Other network architectures provide some of these items
  - E.g., ATM (Asynchronous Transfer Mode)
  - ATM CBR (Constant Bit Rate)
    - Connection setup specifies bandwidth
    - Network provides constraints on jitter and packet loss
    - Network guarantees in-order delivery
  - ATM ABR (Available Bit Rate)
    - In-order delivery
    - Guaranteed minimum bandwidth but higher rates if resources available
    - Feedback to sender if congestion is present

Virtual Circuit vs. Datagram Networks

- Virtual Circuit (VC) Networks
  - Connection service at the network layer
  - All routers in the path are involved in the connection
- Datagram Networks
  - Connectionless service at the network layer
  - Connection-oriented service provided at the transport layer
    - Only end systems are involved
    - Routers are oblivious

IP is a datagram network

Virtual Circuit Networks

- Connection setup
  - Set up route based on destination address
  - Each router commits resources
  - Each router builds enters the connection in its forwarding table
    - Routers maintain connection state information

Incoming interface	Incoming VC #	Outgoing Interface	Outgoing VC #
1	12	2	83
1	9	2	101
2	4	1	151

Forwarding Table

- Communication
  - Each packet contains a VC#
  - Forwarding table determines the next link and VC#
  - Destination address *not* needed on each packet; just the VC#
- Teardown
  - Clear connection from forwarding table on each router

Datagram Networks

- Packet identified with the destination address
- No setup; routers maintain no state information
- Routers
  - Use the destination address to forward the packet
  - Forwarding table maps destination address to output link
- IP addresses are 32 bits
  - We can't have a forwarding table with 2^{32} (4,294,967,296) entries!
  - Match a range of addresses by matching a prefix

Routing Protocols

192.168.*.* = Rutgers

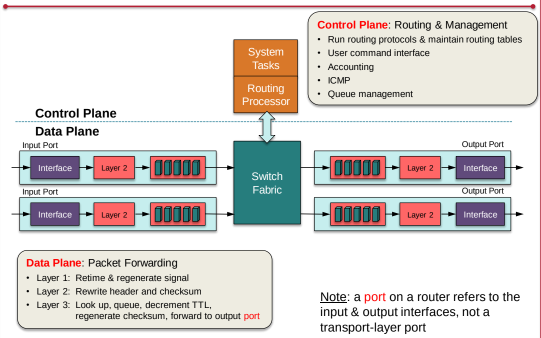
longest prefix matching rule: 15.[32-47].*.* = HP; 15.*.*.* = HP

Prefix	Outgoing Interface
1000 0000 0000 0110	2
0000 0111 0010	3
0000 0111	1

Forwarding Table = Routing Table

The Router

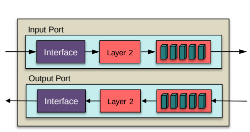
Router Architecture



Note: a port on a router refers to the input & output interfaces, not a transport-layer port

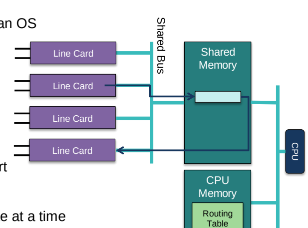
Router Architecture: line cards

A line card is responsible for I/O on a specific interface



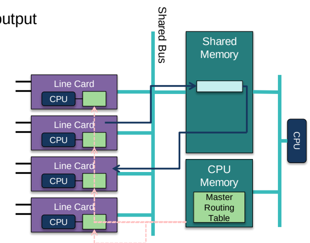
Shared Memory - Conventional

- Ports
  - Function as I/O devices in an OS
- Packet arrival
  - CPU interrupt
  - Copied to memory
- Routing
  - CPU determines route
  - Copies packet to output port
- Limitation
  - Only one memory read/write at a time
  - CPU & bus can be bottlenecks



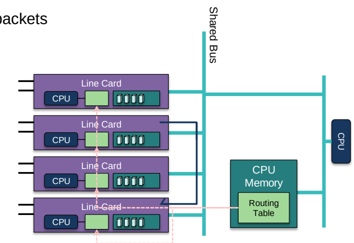
Shared Memory – Distributed CPUs

- CPU & copy of routing table in each line card
- Lookup and data copy to output port done by line card
- Limitation
  - Only one memory read/write at a time
  - Bus can be a bottleneck



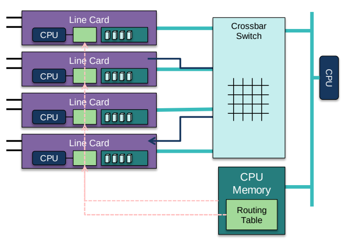
Shared Bus – No Shared Memory

- No shared memory
- Bus used to copy packets directly from one port to another
- Limitation
  - Shared bus can be a bottleneck



Non-shared Memory – Crossbar Data Path

- N×N crossbar switching fabric
- One port can move a packet to another port without blocking other ports
- Multiple switching fabrics can used to route packets to the same port
- Verdict
  - Fastest solution
  - $$$



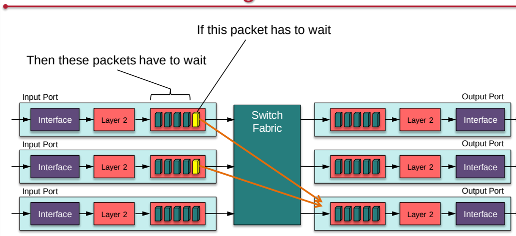
Output Port Queuing

- If there's a queue at an output port
  - A packet scheduler chooses one packet for transmission
  - This can be simple first-come-first-served (FCFS)
  - … or take other factors into account (source, destination, protocol, service level)
- If the output port queue is full
  - We have packet loss
  - A router can decide which packet to drop
  - Active Queue Management (AQM) algorithms: decide which packets to drop

Input Port Queuing

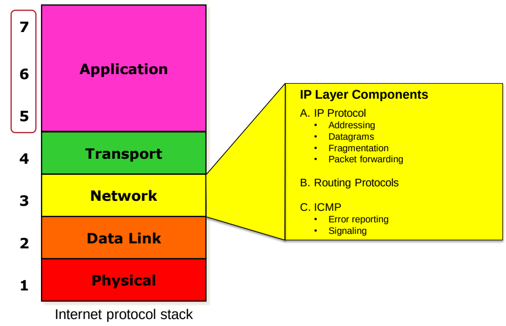
- If packets arrive faster than they could be switched
  - They need to be queued at input ports
  - If multiple queues have a packet for the same output port
    - Only one will be switched at a time
    - The others will be blocked … and the packets behind them will be blocked too!
    - Head-of-line blocking
- If the queue overflows
  - We have packet loss

Head-of-line blocking



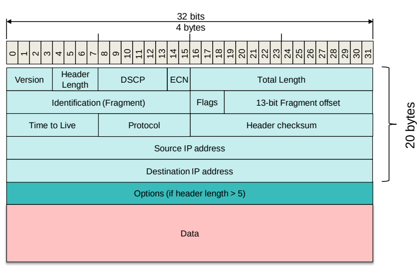
Internet Protocol

Internet Protocol: Layer 3 – IP



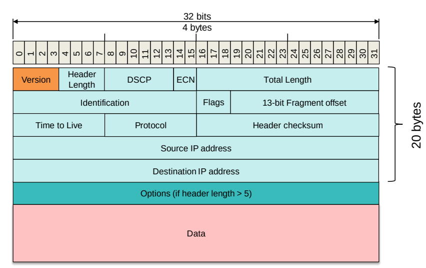
IP Datagram Structure

- 20 byte fixed part
- Variable-size options



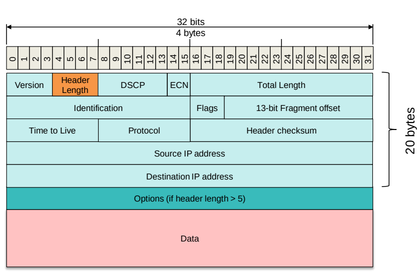
IP Datagram: Version

- 4-bit identification of the protocol used: 4 = IPv4



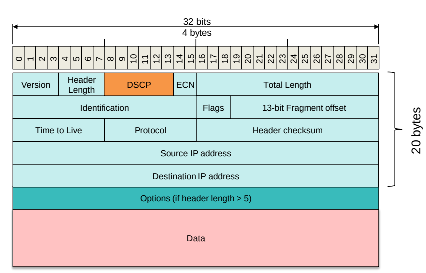
IP Datagram: Header Length

- 4-bit header length (in # of 32-bit words)
  - IP packets usually have no options, so this is usually 5



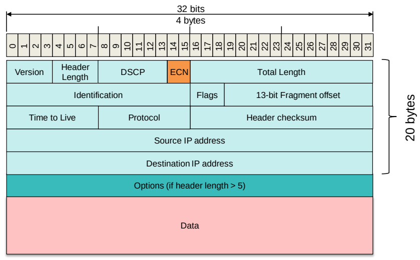
IP Datagram: DSCP

- Differentiated Services Control Point
  - Identifies class of service for QoS aware routers (e.g., VoIP)



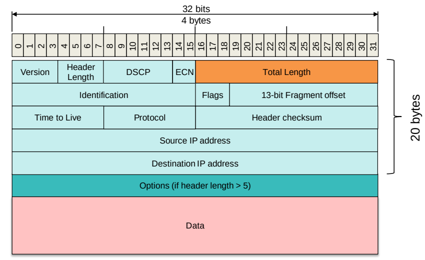
IP Datagram: ECN

- Explicit Congestion Notifications
  - Routers normally do not inform endpoints of congestion
  - ECN is an optional feature to allow them to do so



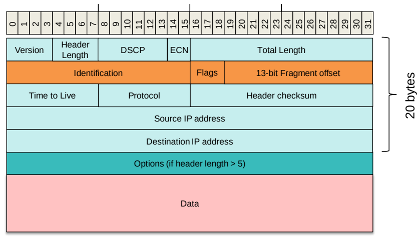
IP Datagram: Total Length

- 16-bit value of the entire datagram (including the 20-byte IP header)



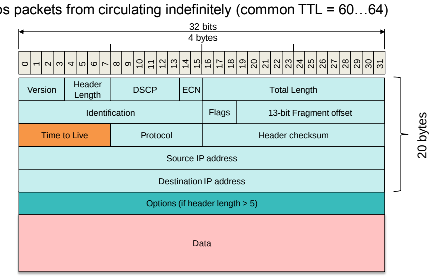
IP Datagram: Fragmentation

- Fragmentation
  - Identification: Identifies fragment of an original datagram
  - Flags: control fragmentation or identify if there are more fragments
  - Fragment offset: offset of fragment relative to original data



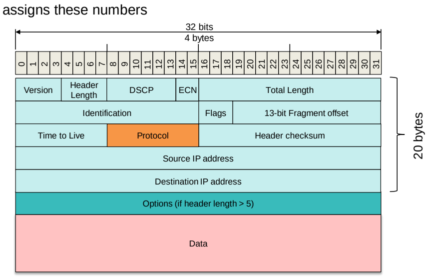
IP Datagram: Time-To-Live

- Hop count: decremented by 1 each time the datagram hits a router
  - If TTL == 0, discard the packet
  - Keeps packets from circulating indefinitely (common TTL = 60…64)



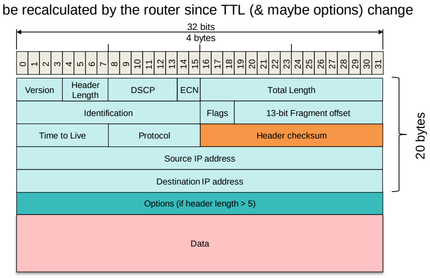
IP Datagram: Protocol

- Identifies the protocol in the data portion
  - TCP = 6, UDP = 17
  - IANA assigns these numbers



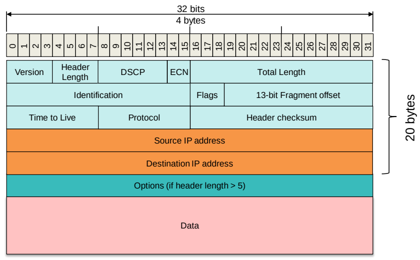
IP Datagram: Header Checksum

- 1s complement checksum of the header
  - Router discards packet if corrupt
  - Must be recalculated by the router since TTL (& maybe options) change



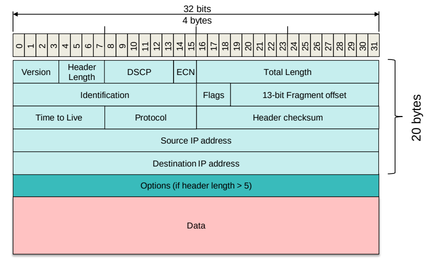
IP Datagram: Source & Destination

- Identifies source and destination IP addresses



IP Datagram: Options

- Extensions to the header – *rarely used*
- Options include: route to destination, record of route, IP timestamp

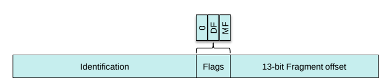


IP Fragmentation & Reassembly

- Remember MTU (Maximum Transmission Unit)?
  - Maximum size of payload that a link layer frame can carry
  - This limits the size of an IP datagram (and hence a TCP or UDP segment)
- What if a router needs to forward a packet that is larger than that link's MTU?
  - Break up the datagram into two or more fragments
  - Each fragment is a separate IP datagram
  - IP layer at the end system needs to reassemble the fragments before passing the data to the transport layer

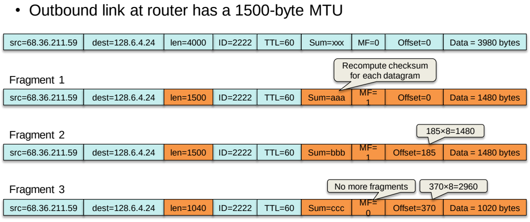
IP Fragmentation

- When an IP datagram is first created
  - Sender creates an ID number for each datagram (usually value of a counter)
  - DF bit ("Don't Fragment") set to 0: fragmenting is allowed
- When a router needs to fragment a datagram
  - Each fragment contains the same ID #, source address, destination address
  - Fragment offset
    - Identifies offset of the fragment relative to the original datagram in 8-byte blocks
    - First datagram Offset = 0
  - All fragments except for the last one have the MF ("More Fragments") bit set



IP Fragmentation

- Example: send 4,000 byte datagram
  - 20 bytes IP header + 3980 bytes data
- Outbound link at router has a 1500-byte MTU



IP Reassembly

- Identification
  - Receiver knows a packet is a fragment if MF is 1 and/or Fragment Offset is not 0
- Matching & Sequencing
  - Identification field is used to match fragments from the same datagram
  - Offsets identify the sequence of fragments
- Size of original
  - When the receiver gets the last fragment (MF==0, Offset != 0)
  - It knows the size of the datagram ((offset×8)+length)
- Giving up
  - If any parts are missing within a time limit, discard the packet
  - Linux: `/proc/sys/net/ipv4/ipfrag_time` (default 30 seconds)
- Once reassembled, pass to protocol that services this datagram

IP Addressing

IP Addressing

- IPv4 address: 32 bits expressed in dotted-decimal notation
  - www.rutgers.edu = `0x80064489` = 128.6.68.137
- Each interface needs to have an IP address
  - E.g., each link on a router has an address
  - If your laptop is connected via Ethernet and 802.11, you have 2 IP addresses
  - *Every interface at a router has its own address*

Route Aggregation: Subnets

- IP address = 32 bits = 2^{32} addresses
  - But addresses cannot be assigned randomly
  - Otherwise routing tables would have to be 2^{32} entries long!
  - … and maintaining them would be a nightmare
- Instead, assign groups of adjacent addresses to an organization
  - www.rutgers.edu = 128.6.68.137
  - All hosts in Rutgers start with 128.6
  - First 16 bits of the IP address identify a host at Rutgers
  - Routers need to know how to route to just 128.6 instead of all 65,536 (2^{16}) possible addresses
- Route aggregation = use one prefix to advertise routes to multiple devices or networks

Subnets

- Subnet (= subnetwork = network)
  - Group of IP addresses sharing a common prefix (*n* high-order bits)
  - A logical network connected to a router (LAN or collection of LANs)
- Rutgers subnet = 128.6.0.0/16 (Top 16 bits identify the subnetwork)
  - CIDR notation (Classless Inter-Domain Routing)
  - *A/N*: *N* most significant (leftmost) bits of address

www.rutgers.edu = 128.6.68.137

$\underbrace{\texttt{10000000 00000110}}_{\text{Network number}}\ \underbrace{\texttt{01000100 10001001}}_{\text{Host number}}$

Subnet Mask

- A subnet mask (or netmask)
  - A bit mask with 1s in the network number position
  - Address & netmask → strips away host bits
  - Address & ~netmask → strips away network bits
- For Rutgers, the netmask is

$\overbrace{\texttt{11111111 11111111}}^{\text{16 bits – network}}\ \overbrace{\texttt{00000000 00000000}}^{\text{16 bits – host}}$

255.255.0.0

- For a 221.2.1.0/26 network, the netmask is

$\overbrace{\texttt{11111111 11111111 11111111 11}}^{\text{26 bits – network}}\overbrace{\texttt{000000}}^{\text{6 bits – host}}$

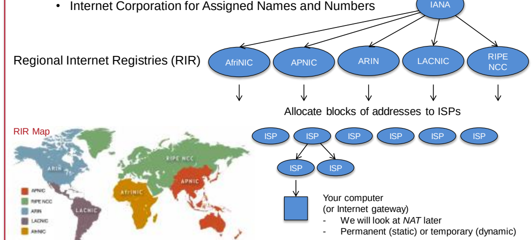
255.255.255.192

How are IP addresses assigned?

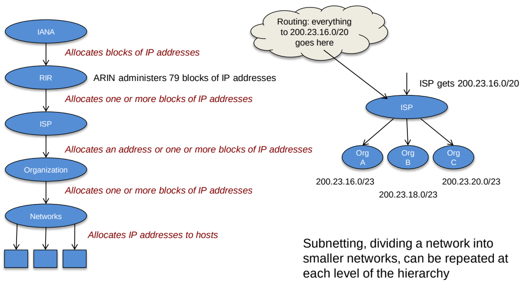
From Lecture 3: DNS

IP addresses are distributed hierarchically

- Internet Assigned Numbers Authority (IANA) at the top
  - IANA is currently run by ICANN
    - Internet Corporation for Assigned Names and Numbers



Address allocation: it's a hierarchy



Subnet Mask Example Within Rutgers

- Rutgers = 128.6.0.0 – netmask is

16 bits – network | 16 bits – host

11111111 11111111 00000000 00000000

255.255.0.0

IP address range: 128.6.0.0 – 128.6.255.255

- Rutgers iLab systems are on a subnet within Rutgers

25 bits – network | 7 bits – host

11111111 11111111 11111111 11000000

255.255.255.128

IP address range: 128.6.13.128 – 128.6.13.255

Special addresses

- **Network address**: all host bits 0
  - Rarely, if ever, used
  - Rutgers = 128.6.0.0
- **Limited broadcast address**: all bits 1
  - Broadcast address for *this network*, the local network.
  - Datagrams are not forwarded by routers to other networks
- **Directed broadcast address**: all host bits 1
  - All hosts on the specified subnet get datagrams sent to this address
  - Routers may or may not forward broadcasts (no for outside an organization)
  - Rutgers iLab systems = 128.6.13.255 (network=128.6.13.128)
- **Loopback address**: 127.0.0.1 = `localhost`
  - Communicate with your own device
  - Uses the loopback network interface

Host Configuration

- How do you assign an address to a host?
  - Manually, configure the device with its
    - IP address
    - Subnet mask, so it knows what addresses are local
    - Gateway: default address for non-local addresses not in a routing table
      - Router that connects the LAN to another network
    - DNS server addresses(s), so it can look up addresses
  - Automatically, via the Dynamic Host Configuration Protocol (DHCP)

Dynamic Host Configuration Protocol

- Protocol for client to get an IP address and network parameters
- It has to work before the client has a valid address on the network!
  - Use IP broadcasts
- DHCP server must be running on the same network link (LAN)
  - Else each link must run a *DHCP Relay Agent* that forwards the request to a DHCP server

DHCP: Three mechanisms for allocation

1. Automatic allocation
   - DHCP assigns an permanent IP address to a client
   - This association remains fixed until the administrator changes it
2. Dynamic allocation
   - DHCP assigns an IP address to a client for a limited period of time
   - *Allows automatic reuse of an address that is no longer needed by the client*
3. Manual allocation
   - A client IP address is assigned by the network administrator

DHCP: The Protocol

Client | **Server**

Discover

Client broadcasts DHCP Discover
- Client sends a limited broadcast *DHCP Discover* UDP message to port 67
- Contains random transaction identifier

Offer

Server responds with an offer
- *Server sends a limited broadcast DHCP Offer UDP message to port 68*
- *Response contains*
  - *Matching transaction identifier*
  - *Proposed IP address*
  - *Subnet mask*
  - *Lease time*

Request

Client broadcasts DHCP Request
- Sends back a DHCP message with a copy of the parameters
- This performs *selection* (if multiple offers), *confirmation of data*, *extension of lease*

ACK

Server sends DHCP ACK
- Sends configuration parameters, including committed IP address

D-O-R-A

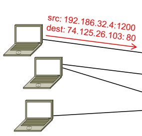
NAT: Network Address Translation

- Every device on the Internet needs an IP address
  - Every address has to be unique

    … otherwise, how do you address a host?
- IP addresses are not plentiful
  - Does an organization with 10,000 IP hosts really need 10,000 addresses?

NAT: Network Address Translation

- Private IP address space in the organization
- One external IP address
- NAT Translation Table
  - Map source address:port in outgoing IP requests to a unique external address:port
  - Inverse mapping for incoming requests
- A NAT-enabled router looks like a single device with one IP address

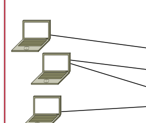


Internal		External	
Host	Port	Host	Port
192.168.32.4	1200	68.36.210.55	4000
192.168.32.6	1200	68.36.210.55	4001
192.168.32.6	1102	68.36.210.55	4002
192.168.32.11	9000	68.36.210.55	4003

Translation Table in a NAT-Enabled Router

NAT: Network Address Translation

- NAT requires a router to look at the transport layer!
  - Source port (outgoing) & destination port (incoming) changes
  - TCP/UDP checksum recomputed



Internal		External	
Host	Port	Host	Port
192.168.32.4	1200	68.36.210.55	4000
192.168.32.6	1200	68.36.210.55	4001
192.168.32.6	1102	68.36.210.55	4002
192.168.32.11	9000	68.36.210.55	4003

Translation Table in a NAT-Enabled Router

NAT: Private Addresses

- We cannot use IP addresses of valid external hosts locally

  … how will we distinguish local vs. external hosts?
- RFC 1918: Address Allocation for Private Internets
  - Defines unregistered, non-routable addresses for internal networks

Address Range	# addresses	CIDR block
10.0.0.0 – 10.255.255.255	16,777,216	10.0.0.0/8
172.16.0.0 – 172.31.255.255	1,048,576	172.16.0.0/12
192.168.0.0 – 192.168.255.255	65,536	192.168.0.0/16

NAT variants

- Static NAT
  - One-to-one mapping between internal and external addresses
- Dynamic NAT
  - Maps an unregistered (internal) IP address to one of several registered IP addresses
- Overloading, or Port Address Translation (PAT)
  - A form of dynamic NAT that maps multiple internal IP addresses to a single registered address by using different ports

Advantages of NAT

- Internal address space can be much larger than the addresses allocated by the ISP
- No need to change internal addresses if ISP changes your address
- Enhanced security
  - A computer on an external network cannot contact an internal computer
    - Unless the internal computer initiated the communication
    - But can only contact the computer on that specific port (this is where active mode FTP had problems)

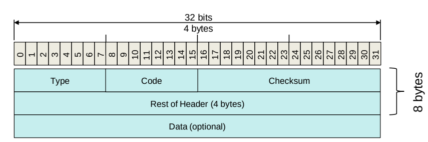
ICMP

Internet Control Message Protocol (ICMP)

- Network-layer protocol to allow hosts & routers to communicate network-related information
- ICMP information is carried as IP payload

ICMP Segment Structure

- Variable-size segment; 8-byte minimum
- Type: command or status report ID
- Code: status code for the type
- Checksum: Checksum from ICMP header & data
- Rest of header: depends on *type*
  - Error reports contain the IP header & first 8 bytes of original datagram's data



Some ICMP Message Types

Type	Description
0	Echo reply (ping)
3	Destination unreachable
4	Source quench
5	Redirect message
8	Echo request
9	Router advertisement
10	Router solicitation
11	TTL exceeded
12	Bad IP header
13	Timestamp
14	Timestamp reply
17	Address mask request
18	Address mask reply

Ping program

- Get a network ping (echo) from a requested host
  - Test network reachability
  - Measure round-trip time
  - Optionally specify packet size
- Request/response protocol
  - Ping Client
    - Create socket (AF_INET, SOCK_RAW, IPPROTO_ICMP)
    - Set IP header fields & ICMP header fields
    - Send it to a destination via *sendto()*
    - Wait for a response from the destination address via *recvfrom()*

Ping program

- Request
  - Send ICMP type=8 (echo request), code 0 (no options to echo)

Type = 8	Code = 0	Checksum
Identifier		Sequence number
Timestamp		Data
Data		

Associate replies with requests

- Reply
  - Destination responds back with an ICMP type=0 (echo reply), code=0

Type = 0	Code = 0	Checksum
Same identifier		Same sequence number
same timestamp		Same data
Same data		

Traceroute program

- Traceroute – trace a route to a specific host
  - Send a series of UDP segments with a bogus destination port
    - 33434 to 33534 on Linux systems
  - First IP datagram has TTL=1
  - Second IP datagram has TTL=2, and so on
  - Keep a timer for each datagram sent
- At a router
  - When the TTL expires, a router sends an ICMP warning message
  - Type 11, code 0 = TTL expired
  - ICMP message includes the name of the router and its IP address
- At the final destination
  - The destination sends an ICMP warning message
  - Type 3 code 3 = Destination port unreachable

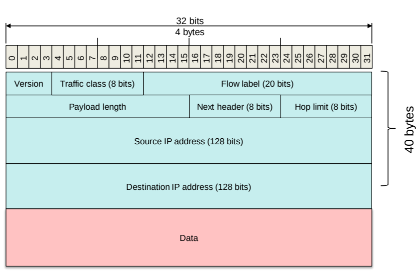
IPv6

- We've been rapidly using up IPv4 addresses ever more rapidly
  - Growth of the web
  - Always-on IP devices
  - Set-top boxes and phones
  - Inefficient network allocation
- We dealt with it with
  - NAT
  - Name-based web hosting
  - Reallocation of network allocation & subnetting
- Those solutions helped a lot … but not enough
  - We're out of IPv4 addresses in parts of the world
    - ARIN's free pool of IPv4 address space was depleted on September 24, 2015
  - IPv6 to the rescue!

Highlights

- Huge address space
  - 128-bit addresses: 3.4×10^{38} addresses (>7.9×10^{28} more than IPv4)
- Simplified 40-byte header
  - Longer addresses but far fewer fields
  - Focus is to simplify routing
- Anycast address
  - Allows a datagram to be delivered to one of a group of interfaces
  - Usually used to identify the nearest host of several hosts
- Flow label
  - Allows related packets that require specific levels of service to be identified
  - E.g., voice, video
  - Not well defined yet

IP Datagram Structure



IP datagram structure

- Version: protocol version = 6
- Traffic class: defines a category of service
- Flow label: identification tag for related flows
- Payload length: # bytes following the 40-byte datagram
- Next header: identifies higher-level protocol (e.g., TCP or UDP)
  - Same as in IPv4
  - Also permits extensions to IPv6, such as fragmentation, authentication
- Hop limit: TTL; decremented at each router
- Source & destination addresses
- Data
- No fragmentation – need to use IPv6 extension headers
  - Routers will never fragment IPv6 datagrams!
- No header checksum! Ethernet does it; so do TCP and UDP

Transitioning

- IPv6 systems can bridge to IPv4 networks
  - IPv4 addresses are a subset of IPv6 addresses
- Dual-stack systems
  - Hosts with both IPv4 and IPv6 network stacks to communicate with both protocols
  - DNS can identify if a given domain is IPv6 capable or not
- IPv4 systems cannot communicate with IPv6 systems
  - Migrating to IPv6 results in a loss of global visibility in the IPv4 network
- Initial transition is not visible to end users
  - Cable modems, set-top boxes, VoIP MTAs
  - IPv6 access

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The end

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