Computer Networks

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Course Content

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4. **Internet Network Layer (IPv4, IPv6)**
5. Internet Routing (RIP, OSPF, BGP)
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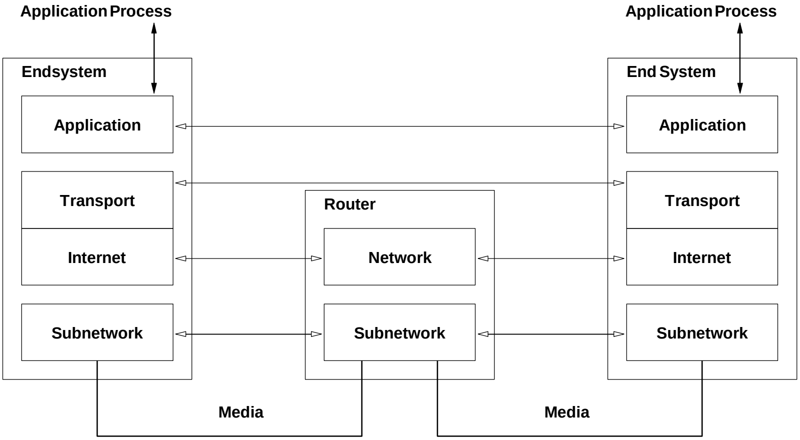
10. External Data Representation (XDR)
11. Augmented Backus Naur Form (ABNF)
12. Electronic Mail (SMTP, IMAP)
13. Document Access and Transfer (HTTP, FTP)

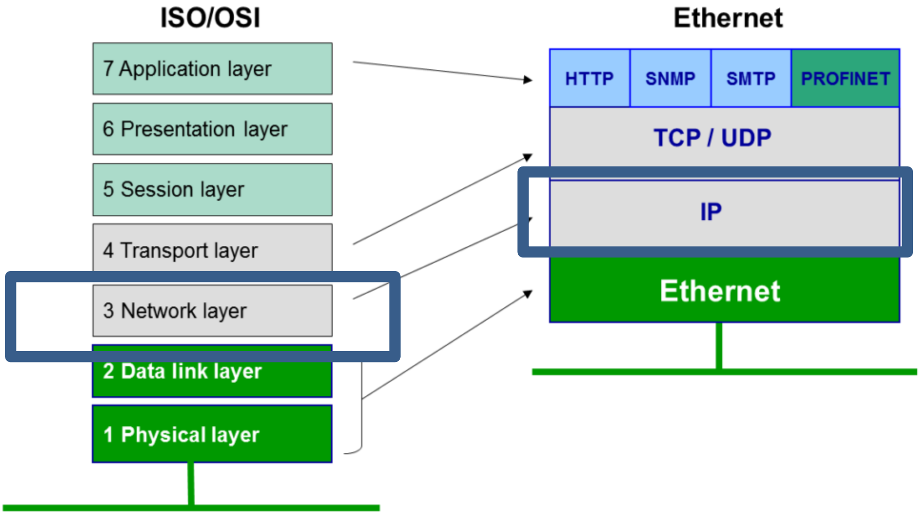
Part 4: Internet Network Layer

Section 18: Concepts and Terminology

Internet Reference Model



Internet Reference Model – Our Focus



Terminology (1/2)

- A *node* is a device which implements an Internet Protocol (such as IPv4 or IPv6).
- A *router* is a node that forwards IP packets not addressed to itself.
- A *host* is any node which is not a router.
- A *link* is a communication channel below the IP layer which allows nodes to communicate with each other (e.g., an Ethernet).
- The *neighbors* is the set of all nodes attached to the same link.
- An *interface* is a node's attachement to a link.
- An *IP address* identifies an interface or a set of interfaces.

Terminology (2/2)

- An *IP prefix* is the initial part of an IP address identifying an IP network. The IP prefix is commonly defined by the number of the initial bits of an IP address that are identifying an IP network, the so called *prefix length*.
- An *interface identifier* is the portion of an IP address that identifies an interface in a certain IP network.
- An *IP packet* is a bit sequence consisting of an IP header and the payload.
- The *link MTU* is the maximum transmission unit, i.e., maximum packet size in octets, that can be conveyed over a link.
- The *path MTU* is the the minimum link MTU of all the links in a path between a source node and a destination node.

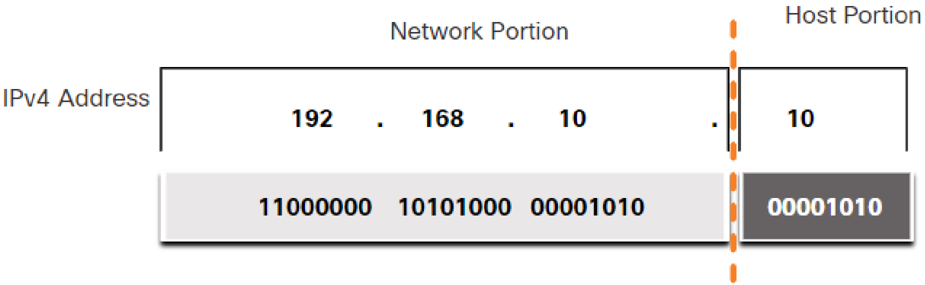
Internet Address / Prefix Assignment

- Manual: A network administrator assigns an IP prefix manually to an interface.
- System: A networking stack automatically assigns a prefix to an interface (e.g., 127.0.0.1/8 or ::1/128 for a loopback interface).
- Stateless automatic configuration: A networking stack automatically calculates and assigns an IP prefix (e.g., deriving an interface identifier from a lower-layer address and combining it with a learned prefix).
- Stateful automatic configuration: A networking stack obtains an prefix from a service providing IP addresses on request (e.g., DHCP).
- Temporary addresses: A networking stack generates temporary addresses from a know prefix in order to enhance privacy.

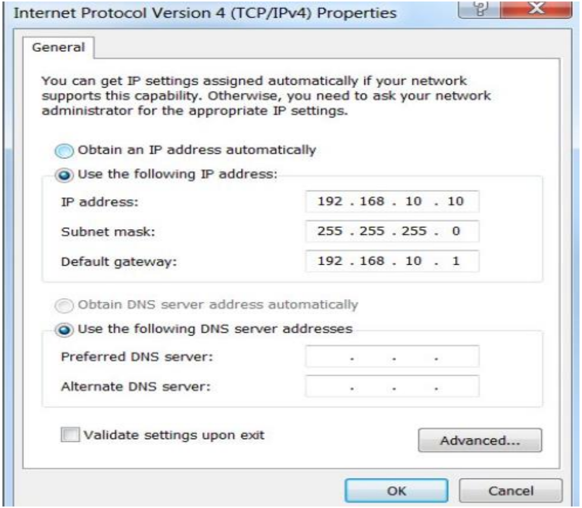
IPv4 Address Structure

Network and Host Portions

- An IPv4 address is a 32-bit hierarchical address that is made up of a network portion and a host portion.
- When determining the network portion versus the host portion, you must look at the 32-bit stream.



The Subnet Mask (1-2)



The Subnet Mask (2-2)

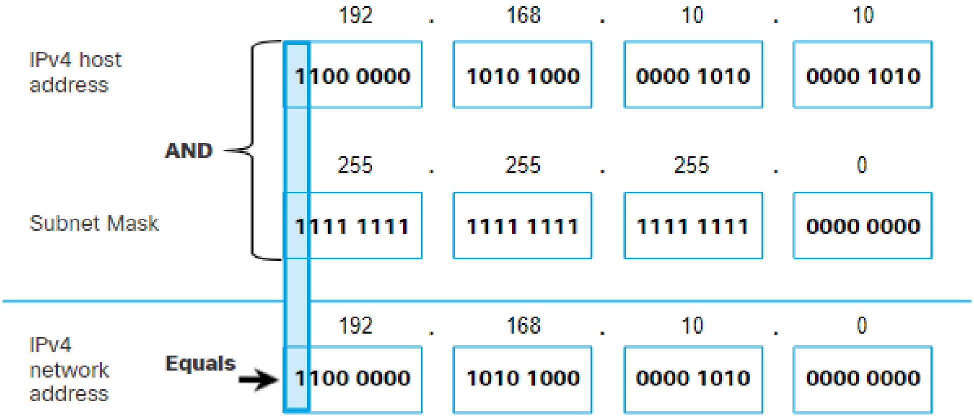
The 32-bit subnet mask in dotted decimal and binary formats.

Subnet Mask	255	.	255	.	255	.	0
	11111111		11111111		11111111		00000000

Prefix Length

Subnet Mask	32-bit Address	Prefix Length
255.0.0.0	11111111.00000000.00000000.00000000	/8
255.255.0.0	11111111.11111111.00000000.00000000	/16
255.255.255.0	11111111.11111111.11111111.00000000	/24
255.255.255.128	11111111.11111111.11111111.10000000	/25
255.255.255.192	11111111.11111111.11111111.11000000	/26
255.255.255.224	11111111.11111111.11111111.11100000	/27
255.255.255.240	11111111.11111111.11111111.11110000	/28
255.255.255.248	11111111.11111111.11111111.11111000	/29
255.255.255.252	11111111.11111111.11111111.11111100	/30

Determining the Network: Logical AND



Jacobs University's IP Networks

- Jacobs University currently uses the global IPv4 address blocks 212.201.44.0/22 and 212.201.48.0/23. How many IPv4 addresses can be used in these two address spaces?
- 212.201.44.0/22: $2^{32-22} - 2 = 2^{10} - 2 = 1022$
  212.201.48.0/23: $2^{32-23} - 2 = 2^{9} - 2 = 510$
- Jacobs University currently uses the global IPv6 address block 2001:638:709::/48. How many IPv6 addresses can be used?
- 2001:638:709::/48: $2^{128-48} - 2 = 2^{80} - 2$ which is 1208925819614629174706174.
- If you equally distribute the addresses over the campus area ($30 \cdot 10^4 m^2$), what is the space covered per address?

Internet Network Layer Protocols

IPv4 VS **IPv6**

Example: 127.255.255.255

Example: *2001:0db8:85a3:0000:0000:8a2e:0370:7334*

- IPv6:
  - The *Internet Protocol version 6* (IPv6) provides for transmitting datagrams from sources to destinations using 16 byte IPv6 addresses
  - The *Internet Control Message Protocol version 6* (ICMPv6) is used for IPv6 error reporting, testing, auto-configuration and address resolution
- IPv4:
  - The *Internet Protocol version 4* (IPv4) provides for transmitting datagrams from sources to destinations using 4 byte IPv4 addresses
  - The *Internet Control Message Protocol version 4* (ICMPv4) is used for IPv4 error reporting and testing

    The *Address Resolution Protocol* (ARP) maps IPv4 addresses to IEEE 802 addresses

IP Forwarding

- IP addresses can be divided into a part which identifies a network (the network prefix) and a part which identifies an interface of a node within that network (the interface identifier).
- The *forwarding table* realizes a mapping of the network prefix to the next node (next hop) closer to the destination and the local interface used to reach the next node.
- For every IP packet, the entry in the forwarding table with the longest matching prefix for the destination address has to be found (longest prefix match).
- A default forwarding table entry (if it exists) uses a zero-length prefix, that is either 0.0.0.0/0 (IPv4) or ::/0 (IPv6).

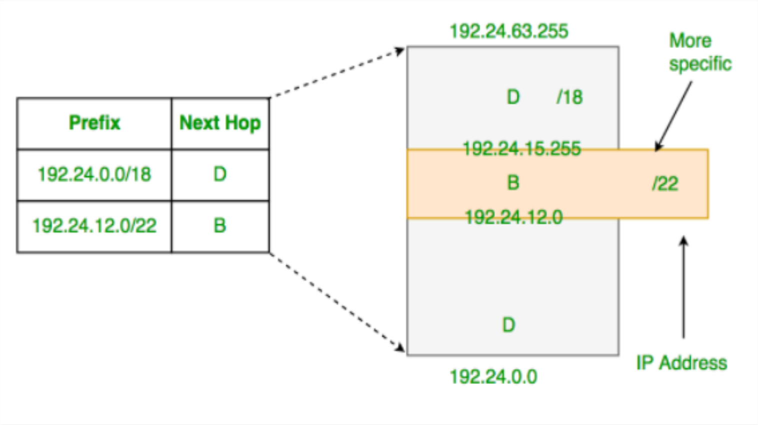
Displaying the Routing Table

Administrator: Command Prompt

```
IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0      192.168.0.1    192.168.0.101     25
        127.0.0.0        255.0.0.0         On-link         127.0.0.1    306
        127.0.0.1  255.255.255.255         On-link         127.0.0.1    306
  127.255.255.255  255.255.255.255         On-link         127.0.0.1    306
      192.168.0.0    255.255.255.0         On-link     192.168.0.101    281
    192.168.0.101  255.255.255.255         On-link     192.168.0.101    281
    192.168.0.255  255.255.255.255         On-link     192.168.0.101    281
     192.168.56.0    255.255.255.0         On-link      192.168.56.1    266
     192.168.56.1  255.255.255.255         On-link      192.168.56.1    266
   192.168.56.255  255.255.255.255         On-link      192.168.56.1    266
        224.0.0.0        240.0.0.0         On-link         127.0.0.1    306
        224.0.0.0        240.0.0.0         On-link      192.168.56.1    266
        224.0.0.0        240.0.0.0         On-link     192.168.0.101    281
  255.255.255.255  255.255.255.255         On-link         127.0.0.1    306
  255.255.255.255  255.255.255.255         On-link      192.168.56.1    266
  255.255.255.255  255.255.255.255         On-link     192.168.0.101    281
===========================================================================
Persistent Routes:
  Network Address          Netmask  Gateway Address  Metric
          0.0.0.0          0.0.0.0    192.168.80.251  Default
```

Longest Prefix Matching in Routers

Prefix	Next Hop
192.24.0.0/18	D
192.24.12.0/22	B



IP Forwarding Table Management

Destination	Subnet mask	Interface
128.75.43.0	255.255.255.0	Eth0
128.75.43.0	255.255.255.128	Eth1
192.12.17.5	255.255.255.255	Eth3
default		Eth2

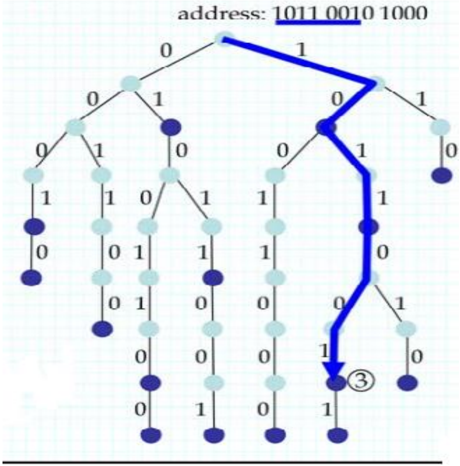
- Entries of the IP forwarding table may be created by different entities:
  - Manual: A network administrator creates entries in the IP forwarding table manually.
  - System: A networking stack automatically creates forwarding entries (e.g., when assigning a prefix to a network interface).
  - Automatic Configuration Protocols: Protocols discovering valid prefixes or obtaining IP addresses and prefixes dynamically from a pool may create suitable IP forwarding table entries.
  - Routing Protocols: Distributed routing protocols create and maintain one or more routing tables that these routing tables feed data into the IP forwarding table.
- Some implementations support multiple forwarding tables that can be selected by certain packet properties.

Longest Prefix Match: Binary Trie

routing table

prefix	next hop
10*	7
01*	5
110*	3
1011*	5
0001*	0
0101 1*	7
0001 0*	1
0011 00*	2
1011 001*	3
1011 010*	5
0100 110*	6
0100 1100*	4
~~1011 0011*~~	8
1001 1000*	10
0101 1001*	9

address: 1011 0010 1000

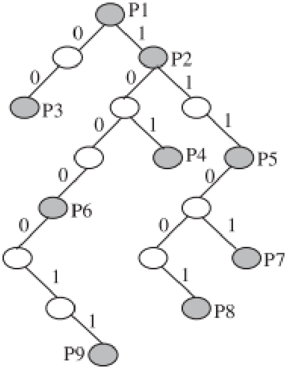


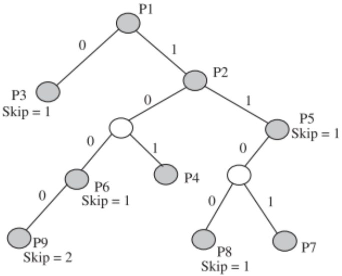
- A binary trie is the representation of the binary prefixes in a tree.

Longest Prefix Match: Path Compressed Trie

Prefix database

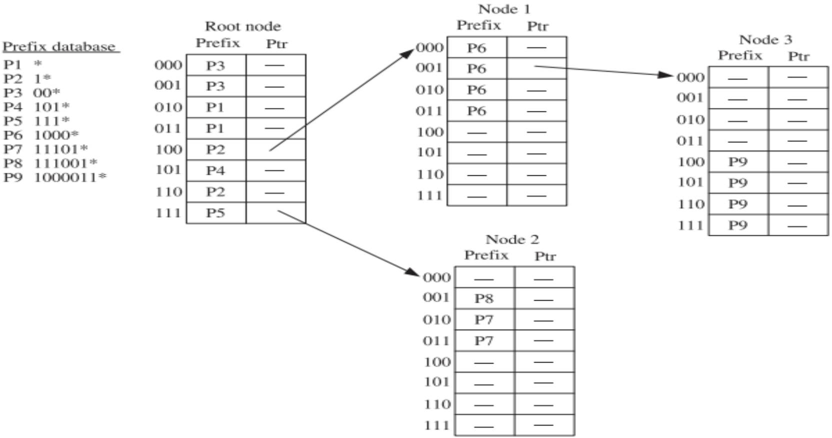
P1	*
P2	1*
P3	00*
P4	101*
P5	111*
P6	1000*
P7	11101*
P8	111001*
P9	1000011*





- A path compressed trie is obtained by collapsing all one-way branch nodes.
- The number attached to nodes indicates the next (absolute) bit to inspect.
- While walking down the tree, you verify in each step that the prefix still matches the prefix stored at each node.

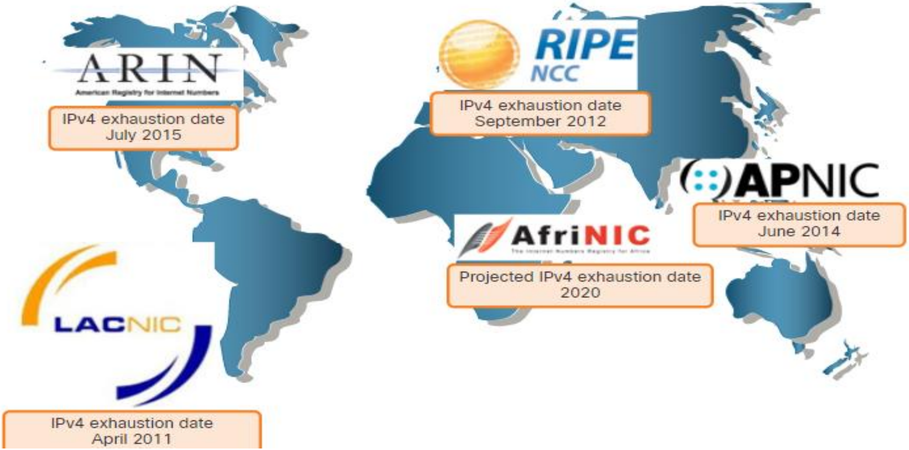
Longest Prefix Match: Two-bit stride multibit Trie



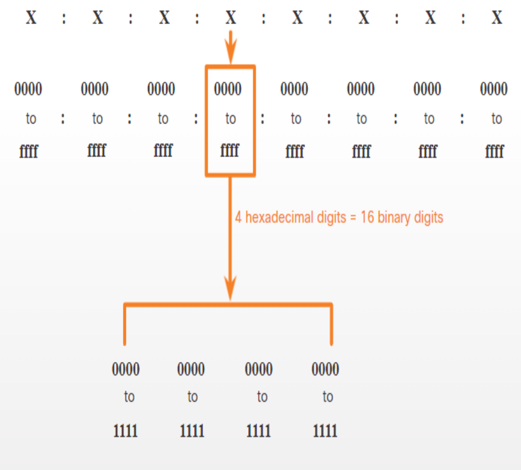
- A two-bit multibit trie reduces the number of memory accesses.

Section 19: Internet Protocol Version 6

Need for IPv6



IPv6 Addressing Formats (1/3)



2001 : 0db8 : 0000 : 1111 : 0000 : 0000 : 0000: 0200
2001 : 0db8 : 0000 : 00a3 : abcd : 0000 : 0000: 1234
2001 : 0db8 : 000a : 0001 : c012 : 9aff : fe9a: 19ac
2001 : 0db8 : aaaa : 0001 : 0000 : 0000 : 0000: 0000
fe80 : 0000 : 0000 : 0000 : 0123 : 4567 : 89ab: cdef
fe80 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0001
fe80 : 0000 : 0000 : 0000 : c012 : 9aff : fe9a: 19ac
fe80 : 0000 : 0000 : 0000 : 0123 : 4567 : 89ab: cdef
0000 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0001
0000 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0000

IPv6 Addressing Formats (2/3) -Omit Leading Zeros

Omitting Leading 0s

Type	Format
Preferred	2001 : 0db8 : 0000 : 1111 : 0000 : 0000 : 0000 : 0200
No leading 0s	2001 : db8 : 0 : 1111 : 0 : 0 : 0 : 200
Preferred	2001 : 0db8 : 0000 : 00a3 : ab00 : 0ab0 : 00ab : 1234
No leading 0s	2001 : db8 : 0 : a3 : ab00 : ab0 : ab : 1234
Preferred	2001 : 0db8 : 000a : 0001 : c012 : 90ff : fe90 : 0001
No leading 0s	2001 : db8 : a : 1 : c012 : 90ff : fe90 : 1

IPv6 Addressing Formats (3/3) -Double Colon

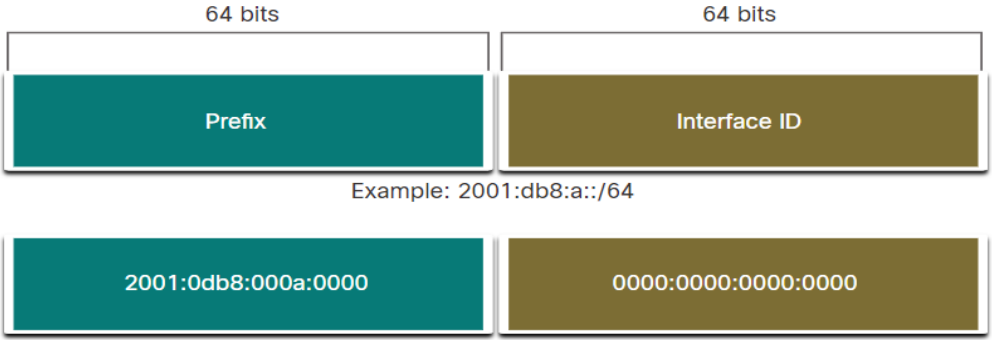
Omitting Leading 0s and All 0 Segments

Type	Format
Preferred	2001 : 0db8 : 0000 : 1111 : 0000 : 0000 : 0000 : 0200
Compressed/spaces	2001 : db8 : 0 : 1111 : : 200
Compressed	2001:db8:0:1111::200
Preferred	2001 : 0db8 : 0000 : 0000 : ab00 : 0000 : 0000 : 0000
Compressed/spaces	2001 : db8 : 0 : 0 : ab00 ::
Compressed	2001:db8:0:0:ab00::
Preferred	2001 : 0db8 : aaaa : 0001 : 0000 : 0000 : 0000 : 0000
Compressed/spaces	2001 : db8 : aaaa : 1 ::
Compressed	2001:db8:aaaa:1::

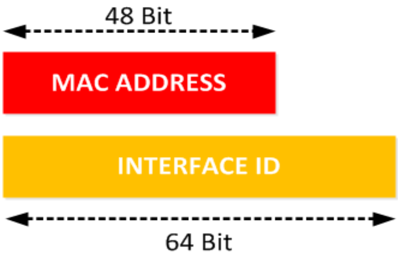
IPv6 Interface Identifier

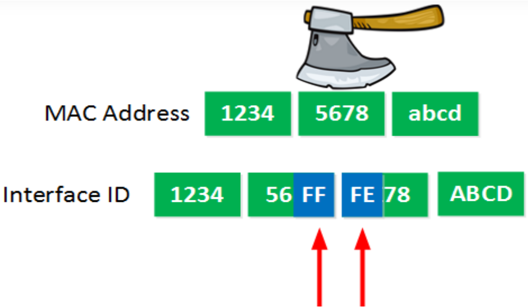
- Interface identifiers in IPv6 unicast addresses are used to uniquely indentify interfaces on a link.
- For unicast addresses, except those that start with binary 000, interface identifiers are generally required to be 64 bits long.
- Combination of the interface identifier with a network prefix leads to an IPv6 address.
- Link local unicast addresses have the prefix fe80::/10.
- Interface identifier may be obtained from an IEEE 802 MAC address using a modified EUI-64 format, but this has privacy issues.
- Alternatively, it is possible to use temporary interface identifiers that keep changing.

IPv6 prefix length



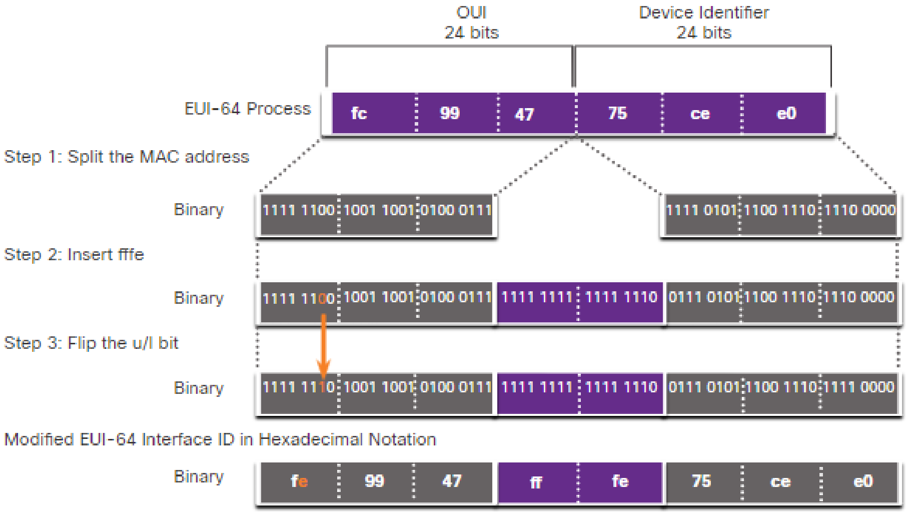
Modified EUI-64 Format (1/2)





- Modified EUI-64 format can be obtained from IEEE 802 MAC addresses.
- Warning: Ipv6 addresses derived from MAC addresses can be used to track mobile nodes used in different networks.
- Solution: Temporary addresses with interface identifiers based on time-varying random bit strings and relatively short lifetimes.

Modified EUI-64 Format (2/2)



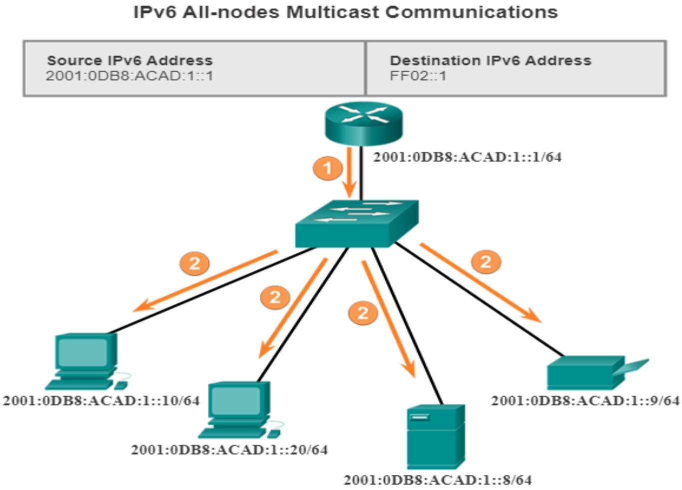
IPv6 Multicast Addresses

8 bits	4 bits	4 bits	112 bits
FF	Flags	Scope	Group ID

Address	Description
ff02::1	All nodes on the local link.
ff02::2	All routers on the local link.
ff02::3	All hosts on the local link.
ff02::1:2	All DHCP servers and relay agents on a local link.
ff02::fb	All multicast DNS servers on a local link.

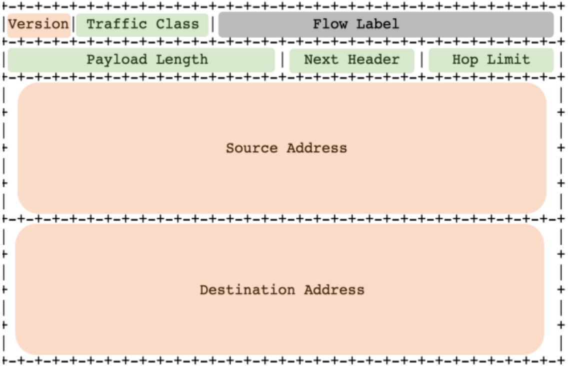
- IPv6 multicast addresses use the prefix ff00::/8.
- The addresses listed above are some of the well-known multicast addresses.
- Applications can, of course, allocate additional multicast addresses.

IPv6 Multicast Addresses



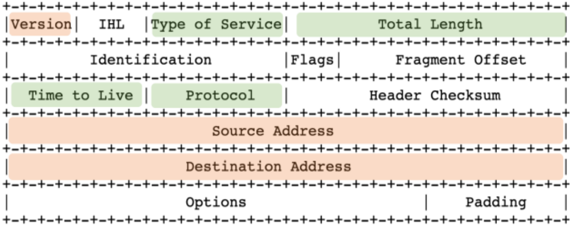
IPv6 Packet Format (RFC 8200)

IPv6 Header

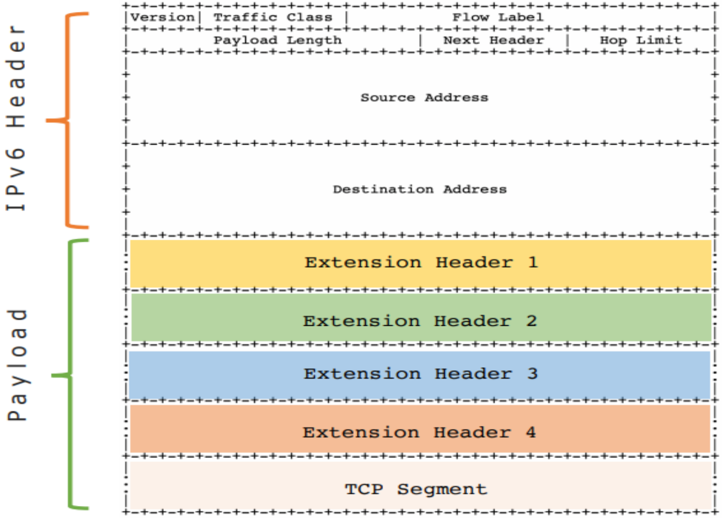


- Keep the same name -- 3 parts
- Different names with similar functions -- 4 parts
- New function – 1 part

IPv4 Header

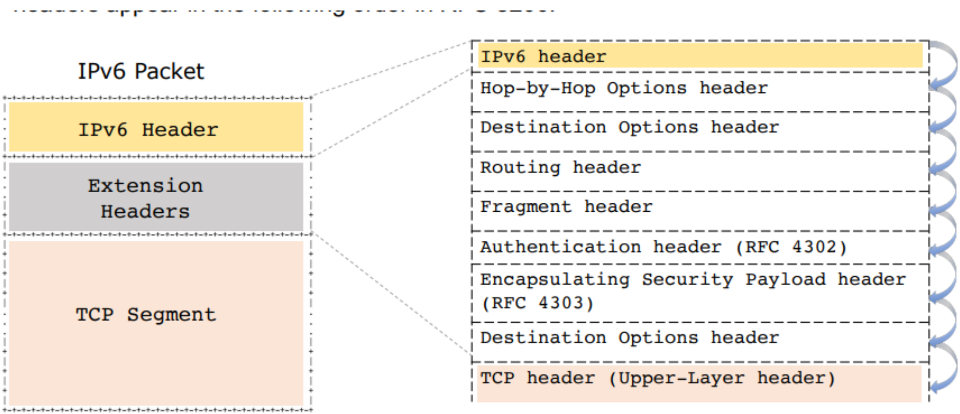


IPv6 Extension Header



Maybe the payload is composed of several extension headers and the TCP segment.

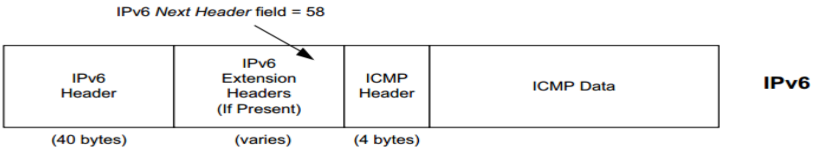
IPv6 Extension Header

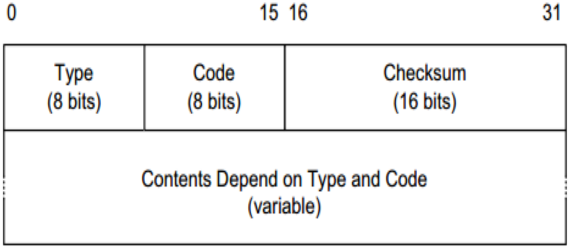


IPv6 Forwarding

- IPv6 packets are forwarded using the longest prefix match algorithm.
- IPv6 addresses have relatively long prefixes, which allows network operators to achieve better address aggregation, which reduces the number of forwarding table entries needed in the backbone infrastructure.
- Due to the length of the prefixes, it is crucial to use a longest prefix match algorithm whose complexity does not dependent on the number of entries in the forwarding table or the average prefix length.
- Due to better aggregation possibilities, IPv6 forwarding tables can be expected to be shorter than IPv4 forwarding tables

IPv6 Error Handling (ICMPv6) (RFC 4443)





- The Internet Control Message Protocol Version 6 (ICMPv6) is used
  - to report error situations,
  - to run diagnostic tests,
  - to auto-configure IPv6 nodes, and
  - to supports the resolution of IPv6 addresses to link-layer addresses.

IPv6 Neighbor Discovery (RFC 4861)

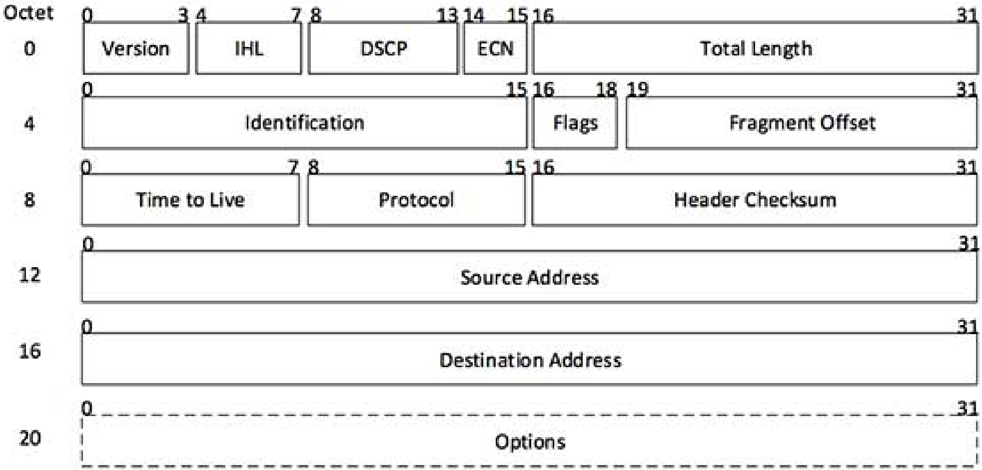
- Discovery of the routers attached to a link.
- Discovery of the prefixes used on a link.
- Discovery of parameters such as the link MTU or the hop limit for outgoing packets.
- Automatic configuration of IPv6 addresses.
- Resolution of IPv6 addresses to link-layer addresses.
- Determination of next-hop addresses for IPv6 destination addresses.
- Detection of unreachable nodes which are attached to the same link.
- Detection of conflicts during address generation.
- Discovery of better alternatives to forward packets.

IPv6 over IEEE 802.3 (RFC 2464)

- Frames containing IPv6 packets are identified by the value 0x86dd in the IEEE 802.3 type field.
- The link MTU is 1500 bytes, which corresponds to the IEEE 802.3 maximum frame size of 1500 byte.
- The mapping of IPv6 addresses to IEEE 802.3 addresses is table driven. Entries in so called address translation tables can be either statically configured or dynamically learned using the neighbor discovery protocol.
- IPv6 over IEEE 802.3 does not use IEEE LLC encapsulation.

Section 20: Internet Protocol Version 4

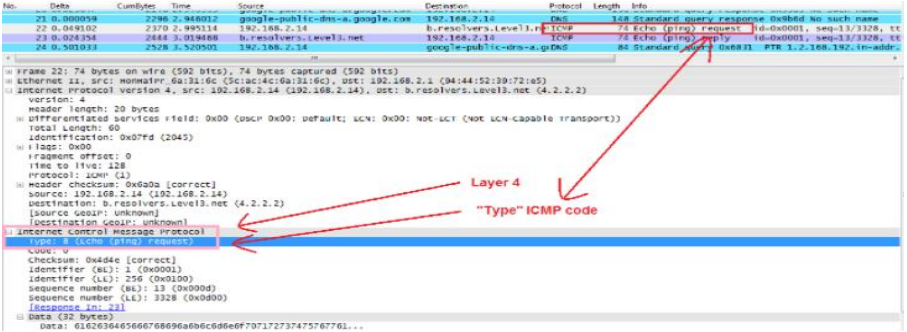
IPv4 Packet Format (RFC 791)



IPv4 Error Handling (ICMPv4)

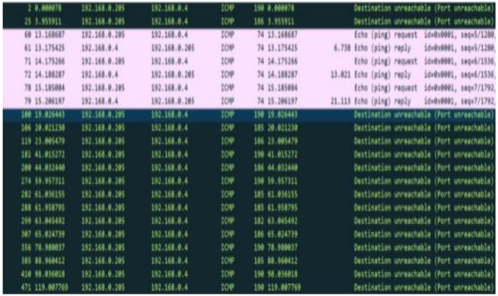
- The Internet Control Message Protocol (ICMP) is used to inform nodes about problems encountered while forwarding IP packets.
  - Echo Request/Reply messages are used to test connectivity.
  - Unreachable Destination messages are used to report why a destination is not reachable.
  - Redirect messages are used to inform the sender of a better (shorter) path.
- Can be used to trace routes to hosts:
  - Send messages with increasing TTL starting with one and interpret the ICMP response message.
  - Pack additional data into the request to measure latency.
- ICMPv4 is an integral part of IPv4 (even though it is a different protocol).

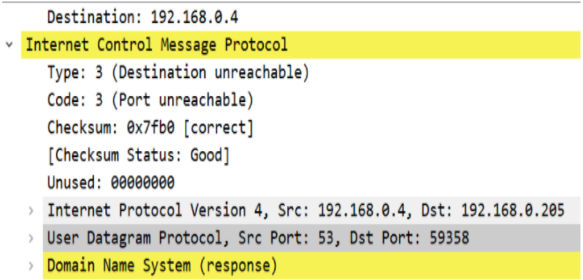
ICMPv4 Echo Request/Reply



- The ICMP echo request message (type = 8, code = 0) asks the destination node to return an echo reply message (type = 0, code = 0).
- The Identifier and Sequence Numberfields are used to correlate incoming replies with outstanding requests.
- The data field may contain any additional data.

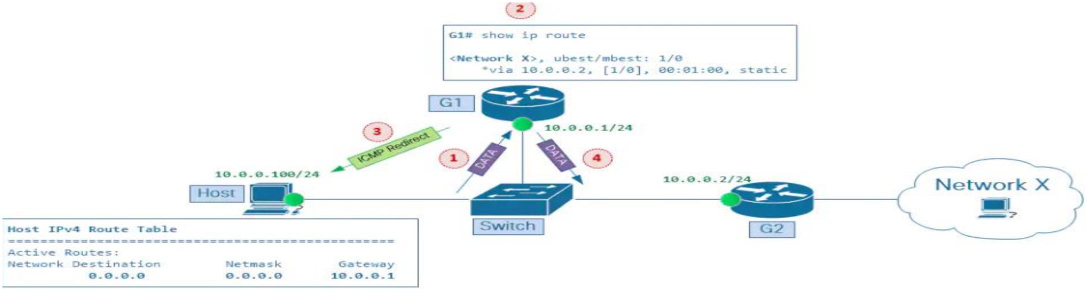
ICMPv4 Unreachable Destinations





- The Type field has the value 3 for all unreachable destination messages.
- The Code field indicates why a certain destination is not reachable.
- The data field contains the beginning of the packet which caused the ICMP unreachable destination message.

ICMPv4 Redirect



- The Type field has the value 5 for redirect messages.
- The Code field indicates which type of packets should be redirected.
- The Router Internet Address field identifies the IP router to which packets should be redirected.
- The data field contains the beginning of the packet which caused the ICMP redirect message.

IPv4 Fragmentation

- IPv4 packets that do not fit the outgoing link MTU will get fragmented into smaller packets that fit the link MTU.
  - The Identification field contains the same value for all fragments of an IPv4 packet.
  - The Fragment Offset field contains the relative position of a fragment of an IPv4 packet (counted in 64-bit words).
  - The flag More Fragments (MF) is set if more fragments follow.
- The Don’t Fragment (DF) flag can be set to indicate that a packet should not be fragmented.
- IPv4 allows fragments to be further fragmented without intermediate reassembly.

Fragmentation Considered

- The receiver must buffer fragments until all fragments have been received. However, it is not useful to keep fragments in a buffer indefinitely. Hence, the TTL field of all buffered packets will be decremented once per second and fragments are dropped when the TTL field becomes zero.
- The loss of a fragment causes in most cases the sender to resend the original IP packet which in most cases gets fragmented as well. Hence, the probability of transmitting a large IP packet successfully goes quickly down if the loss rate of the network goes up.
- Since the Identification field identifies fragments that belong together and the number space is limited, one cannot fragment an arbitrary large number of packets.

MTU Path Discovery (RFC 1191)

- The sender sends IPv4 packets with the DF flag set.
- A router which has to fragment a packet with the DF flag turned on drops the packet and sends an ICMP message back to the sender which also includes the local maximum link MTU.
- Upon receiving the ICMP message, the sender adapts his estimate of the path MTU and retries.
- Since the path MTU can change dynamically (since the path can change), a once learned path MTU should be verified and adjusted periodically.
- Not all routers send necessarily the local link MTU. In this cases, the sender tries typical MTU values, which is usually faster than doing a binary search.

IPv4 over IEEE 802.3 (RFC 894)

- IPv4 packets are identified by the value 0x800 in the IEEE 802.3 type field.
- According to the maximum length of IEEE 802.3 frames, the maximum link MTU is 1500 byte.
- The mapping of IPv4 addresses to IEEE 802.3 addresses is table driven. Entries in so called mapping tables (sometimes also called address translation tables) can either be statically configured or dynamically learned.
- Note that the RFC 894 approach does not provide an assurance that the mapping is actually correct...

IPv4 Address Translation (RFC 826)

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Hardware Type         |         Protocol Type         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     HLEN      |     PLEN      |           Operation           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                 Sender Hardware Address (SHA)                 =
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
= Sender Hardware Address (SHA) |    Sender IP Address (SIP)    =
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
=    Sender IP Address (SIP)    | Target Hardware Address (THA) =
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
=                 Target Hardware Address (THA)                 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Target IP Address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- The Address Resolution Protocol (ARP) resolved IPv4 addresses to link-layer addresses of neighboring nodes.

ARP and RARP

- The Hardware Type field identifies the address type used on the link-layer (the value 1 is used for IEEE 802.3 MAC addresses).
- The Protocol Type field identifies the network layer address type (the value 0x800 is used for IPv4).
- ARP/RARP packets use the 802.3 type value 0x806.
- The Operation field contains the message type: ARP Request (1), ARP Response (2), RARP Request (3), RARP Response (4).
- The sender fills, depending on the request type, either the Target IP Address field (ARP) or the Target Hardware Address field (RARP).
- The responding node swaps the Sender/Target fields and fills the empty fields with the requested information.

DHCP Version 4

- The Dynamic Host Configuration Protocol (DHCP) allows nodes to retrieve configuration parameters from a central configuration server.
- A binding is a collection of configuration parameters, including at least an IP address, associated with or bound to a DHCP client.
- Bindings are managed by DHCP servers.
- Bindings are typically valid only for a limited lifetime.
- See RFC 2131 for the details and the message formats.
- See RFC 3118 for security aspects due to lack of authentication.

DHCPv4 Message

- The DHCPDISCOVER message is a broadcast message which is sent by DHCPclients to locate DHCP servers.
- The DHCPOFFER message is sent from a DHCP server to offer a client a set of configuration parameters.
- The DHCPREQUEST is sent from the client to a DHCP server as a response to a previous DHCPOFFER message, to verify a previously allocated binding or to extend the lease of a binding.
- The DHCPACK message is sent by a DHCP server with some additional parameters to the client as a positive acknowledgement to a DHCPREQUEST.
- The DHCPNAKmessage is sent by a DHCP server to indicate that the client's notion of a configuration binding is incorrect.

DHCPv4 Message Types

- The DHCPDECLINE message is sent by a DHCP client to indicate that parameters are already in use.
- The DHCPRELEASE message is sent by a DHCP client to inform the DHCP server that configuration parameters are no longer used.
- The DHCPINFORM message is sent from the DHCP client to inform the DHCP server that only local configuration parameters are needed.

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