Chapter 4
Network Layer:

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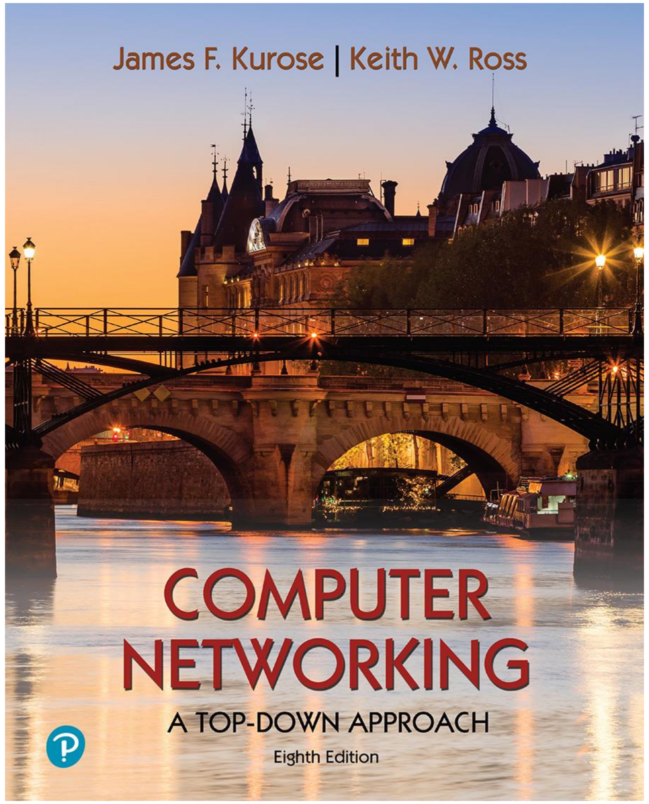


Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Network layer: our goals

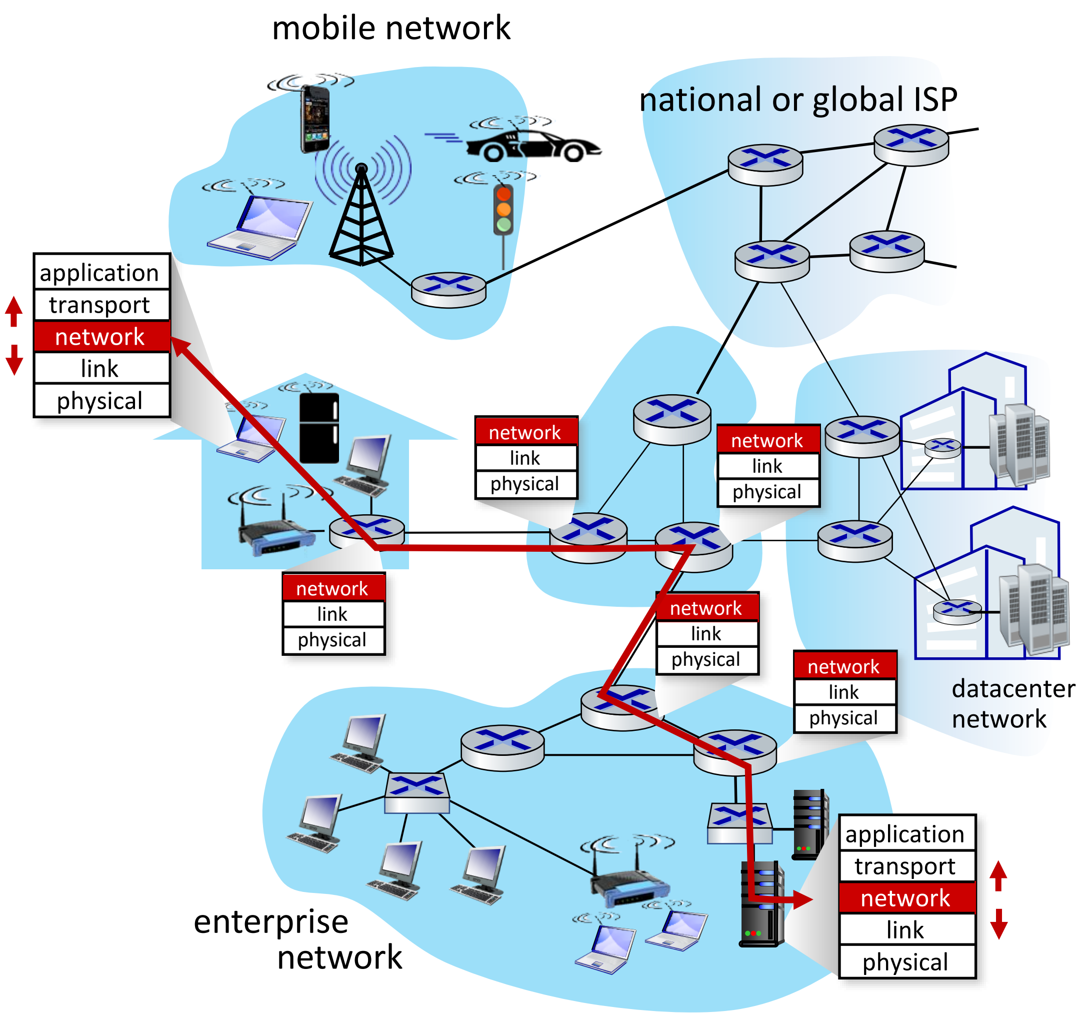
- understand principles behind network layer services, focusing on data plane:
  - network layer service models
  - forwarding versus routing
  - how a router works
  - addressing
  - generalized forwarding
  - Internet architecture
- instantiation, implementation in the Internet
  - IP protocol
  - NAT, middleboxes

Network layer: “data plane” roadmap

- Network layer: overview
  - data plane
  - control plane
- What’s inside a router
  - input ports, switching, output ports
  - buffer management, scheduling
- IP: the Internet Protocol
  - **datagram format**
  - **addressing**
  - network address translation
  - IPv6

Network-layer services and protocols

- transport segment from sending to receiving host
  - sender: encapsulates segments into datagrams, passes to link layer
  - receiver: delivers segments to transport layer protocol
- network layer protocols in *every Internet device*: hosts, routers
- routers:
  - examines header fields in all IP datagrams passing through it
  - moves datagrams from input ports to output ports to transfer datagrams along end-end path



Two key network-layer functions

network-layer functions:

- *forwarding:* move packets from a router's input link to appropriate router output link
- *routing:* determine route taken by packets from source to destination
  - *routing algorithms*

analogy: taking a trip

- *forwarding:* process of getting through single interchange
- *routing:* process of planning trip from source to destination

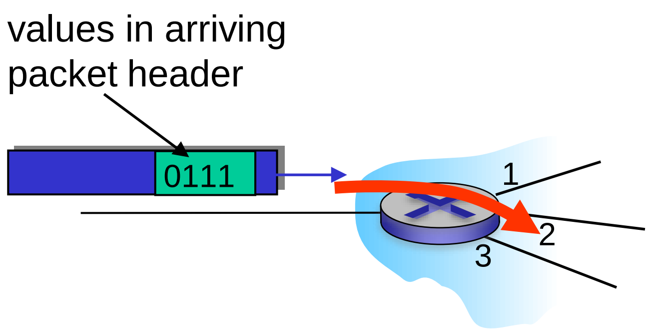
forwarding

routing

Network layer: data plane, control plane

Data plane:

- *local*, per-router function
- determines how datagram arriving on router input port is forwarded to router output port

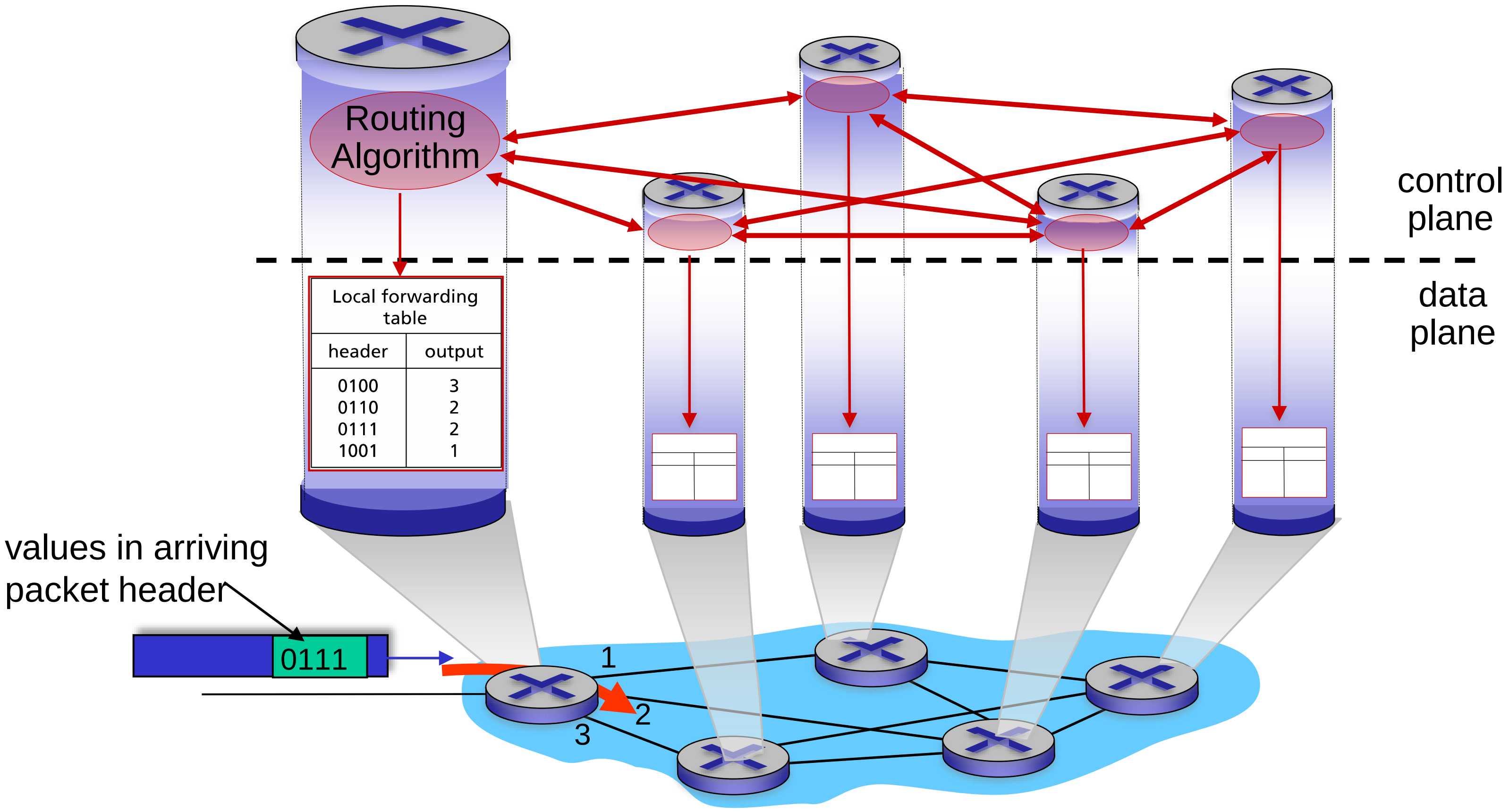


Control plane

- *network-wide* logic
- determines how datagram is routed among routers along end-end path from source host to destination host
- two control-plane approaches:
  - *traditional routing algorithms:* implemented in routers
  - *software-defined networking (SDN)*: implemented in (remote) servers

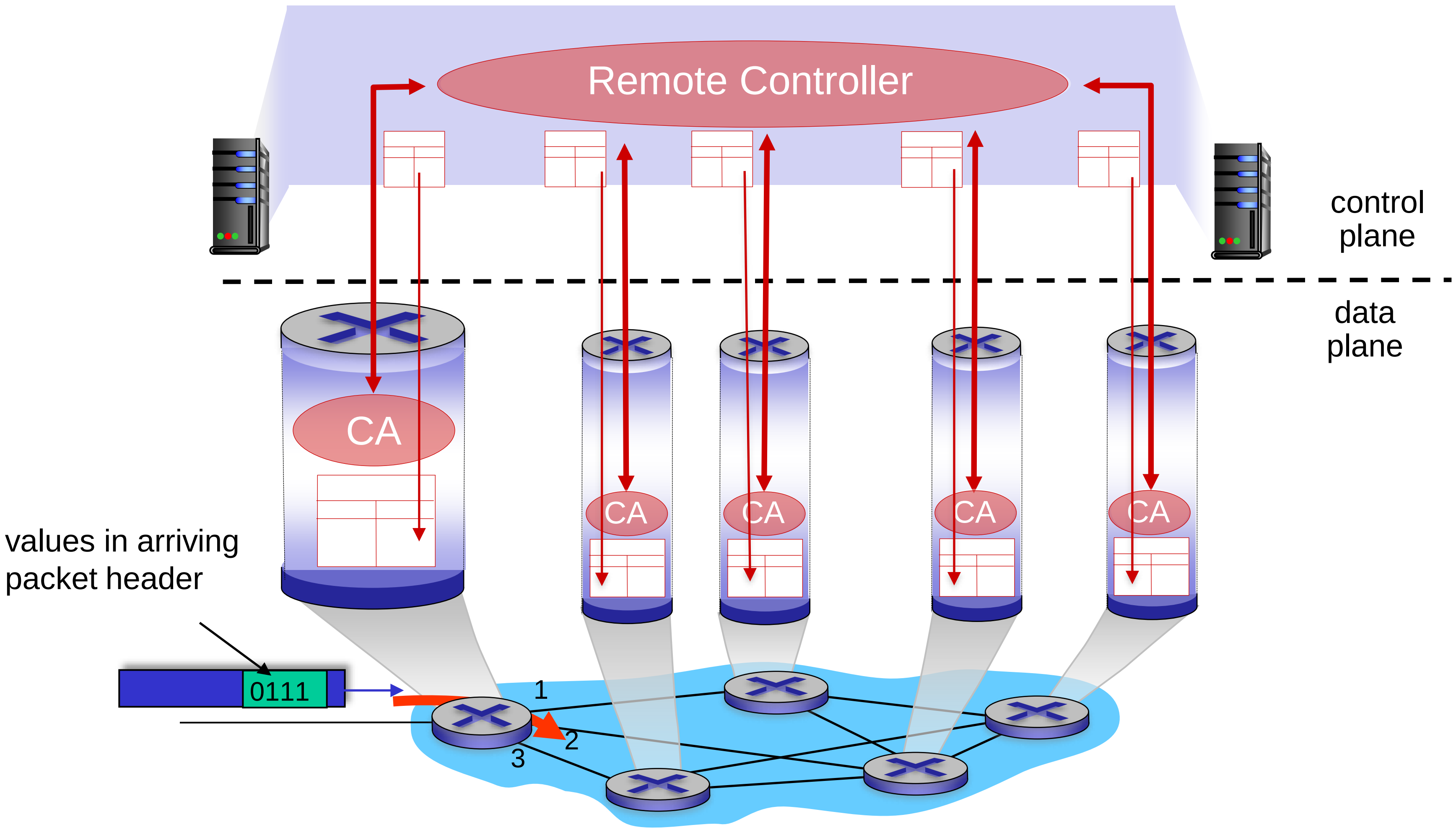
Per-router control plane

Individual routing algorithm components *in each and every router* interact in the control plane



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers



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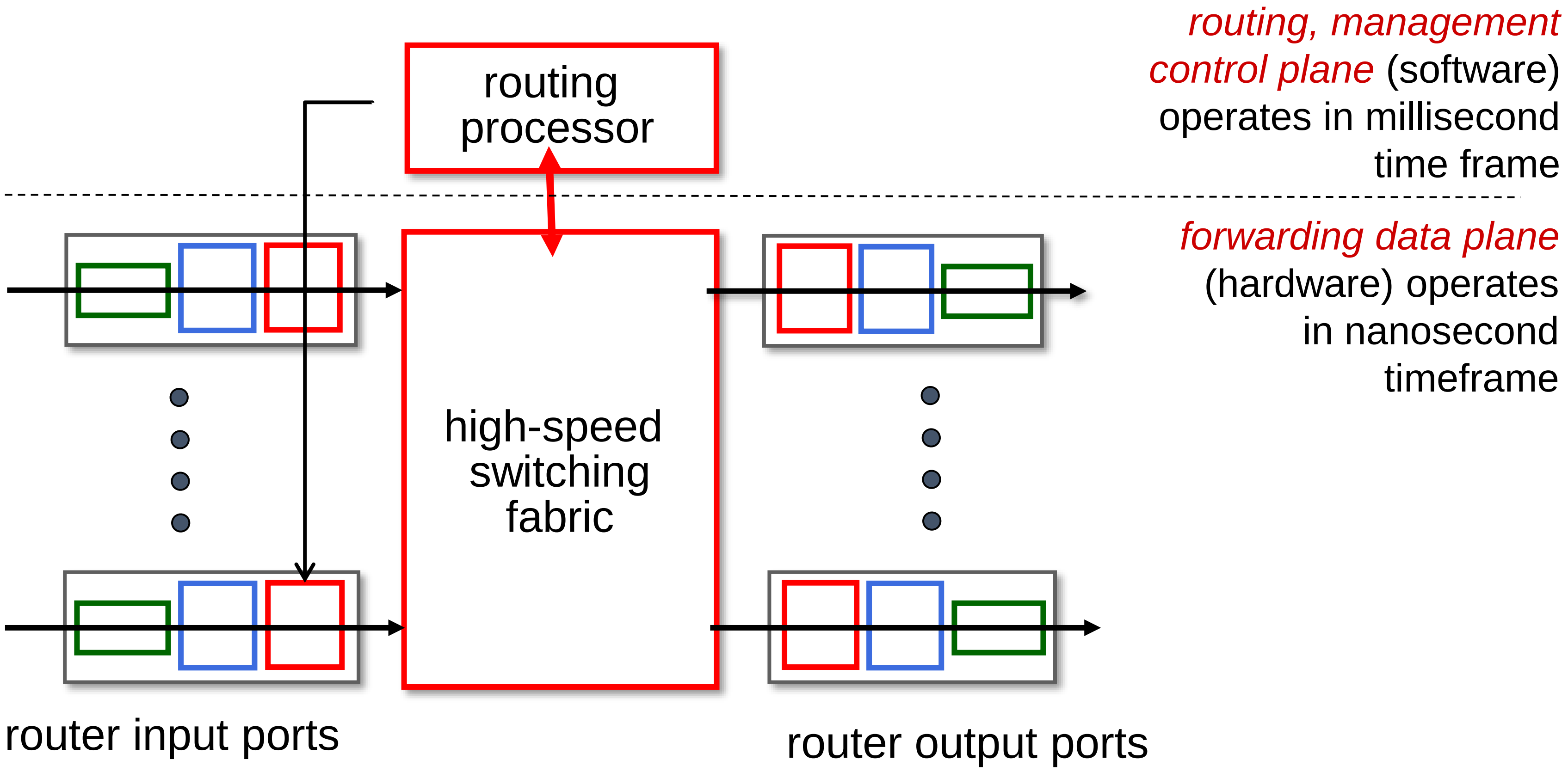
  - IPv6

Router architecture overview

high-level view of generic router architecture:



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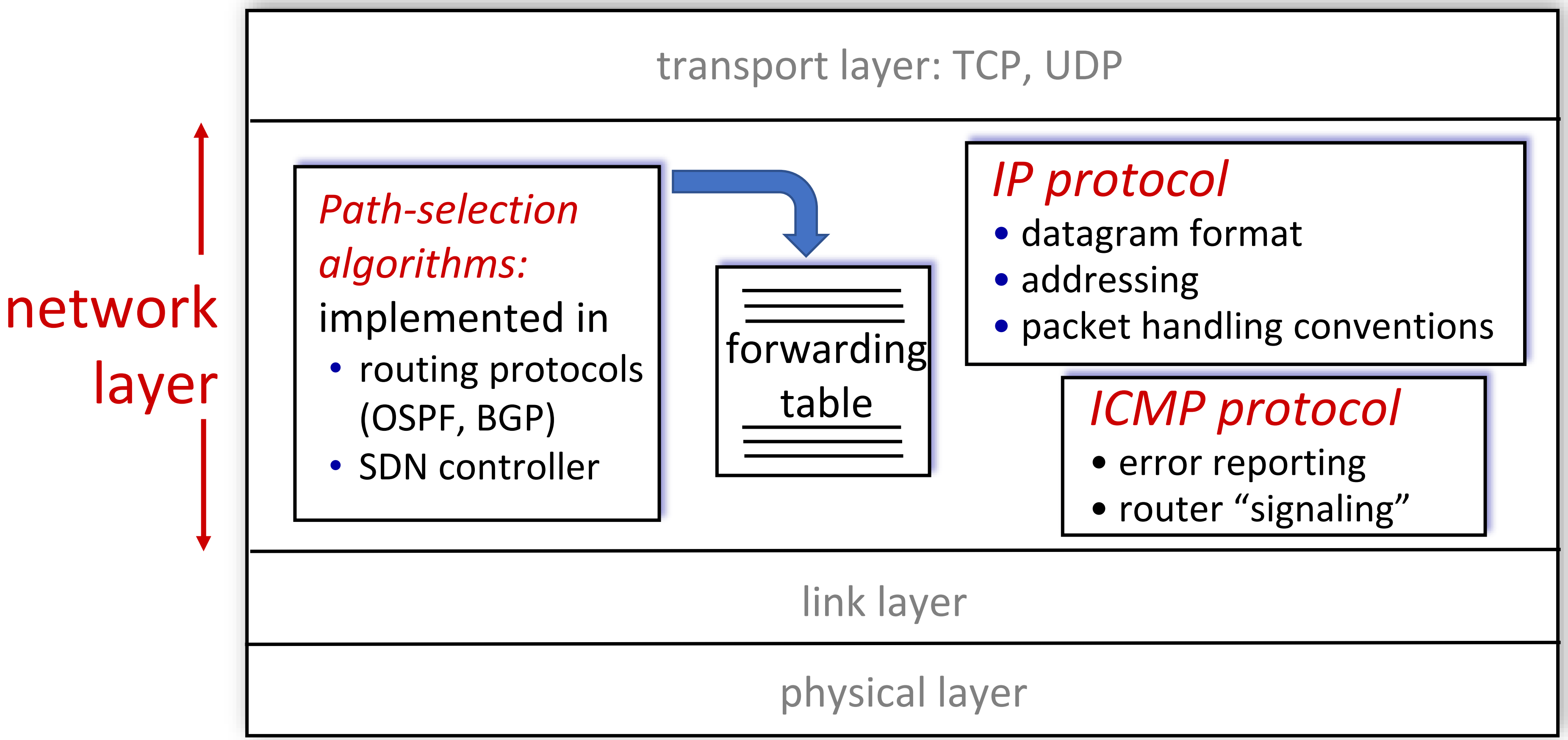
- Generalized Forwarding, SDN
  - match+action
  - OpenFlow: match+action in action
- Middleboxes

Network Layer: Internet

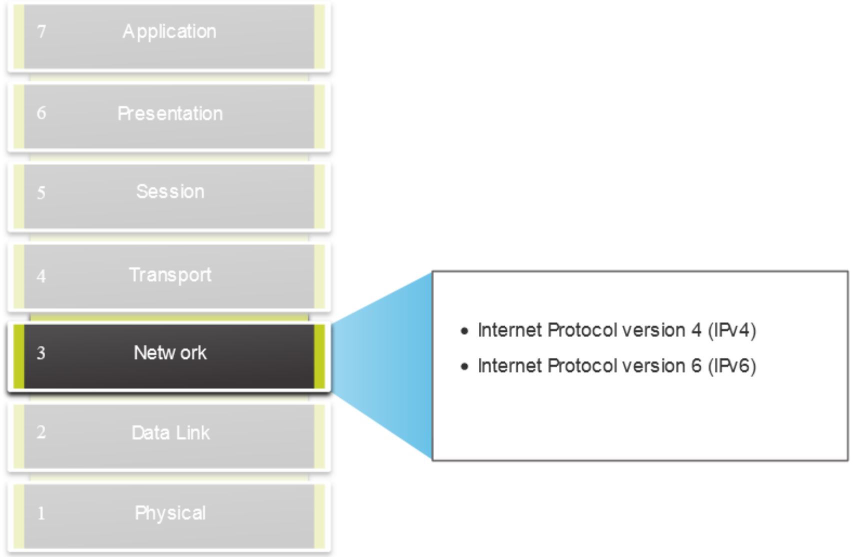
host, router network layer functions:

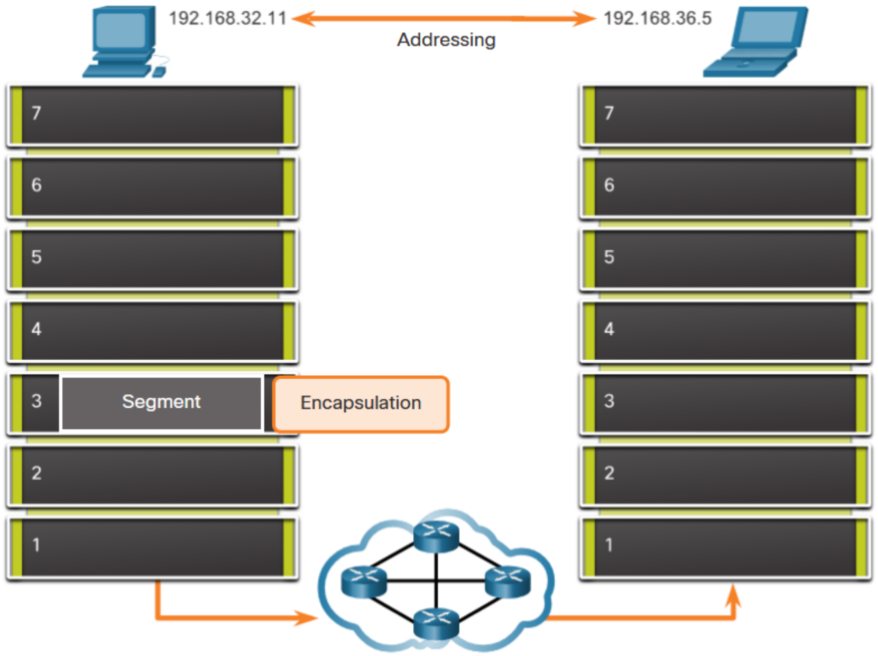


Network Layer Characteristics

The Network Layer

- Provides services to allow end devices to exchange data
- IP version 4 (IPv4) and IP version 6 (IPv6) are the principle network layer communication protocols.
- The network layer performs four basic operations:
  - Addressing end devices
  - Encapsulation
  - Routing
  - De-encapsulation



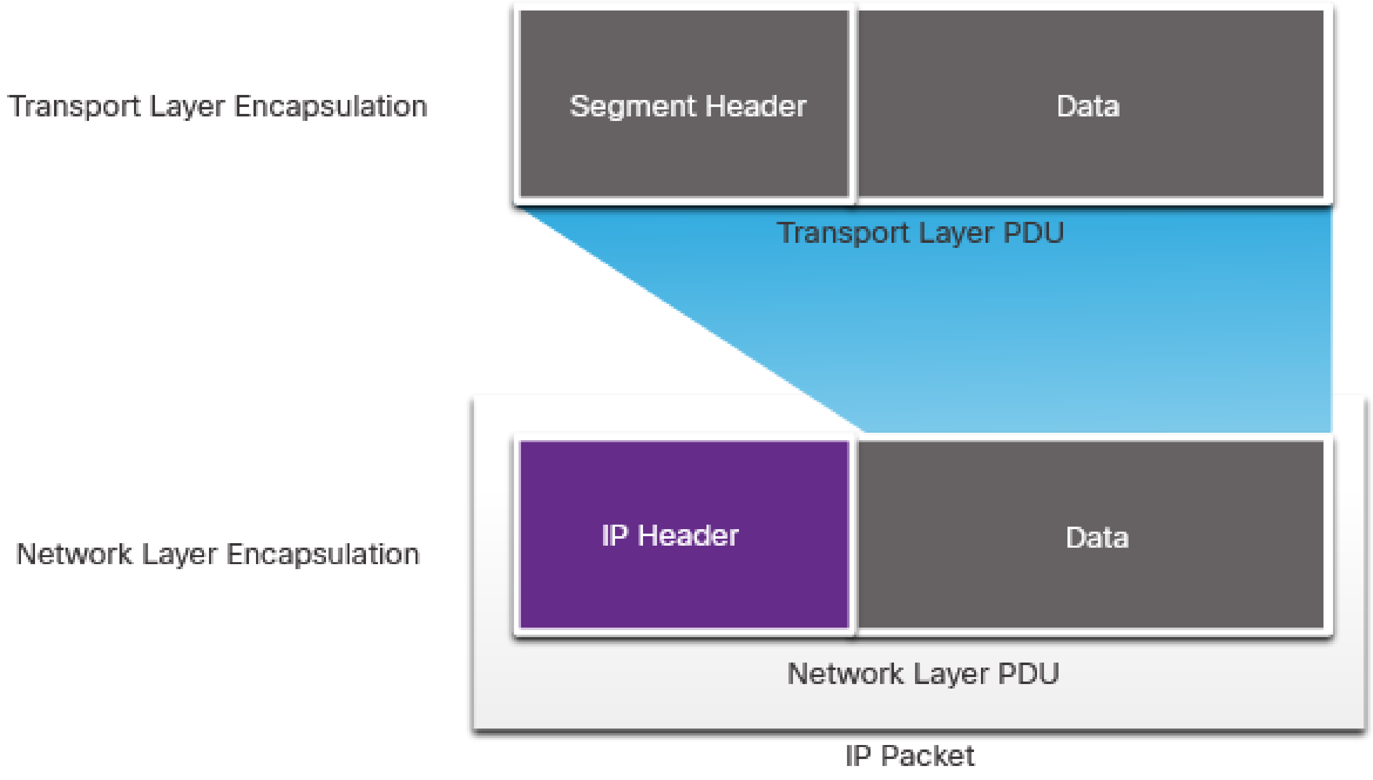


Network layer protocols forward transport layer PDUs between hosts.

IP Encapsulation

- IP encapsulates the transport layer segment.
- IP can use either an IPv4 or IPv6 packet and not impact the layer 4 segment.
- IP packet will be examined by all layer 3 devices as it traverses the network.
- The IP addressing does not change from source to destination.

Note: NAT will change addressing, but will be discussed in a later module.



Characteristics of IP

IP is meant to have low overhead and may be described as:

- Connectionless
- Best Effort
- Media Independent

Connectionless

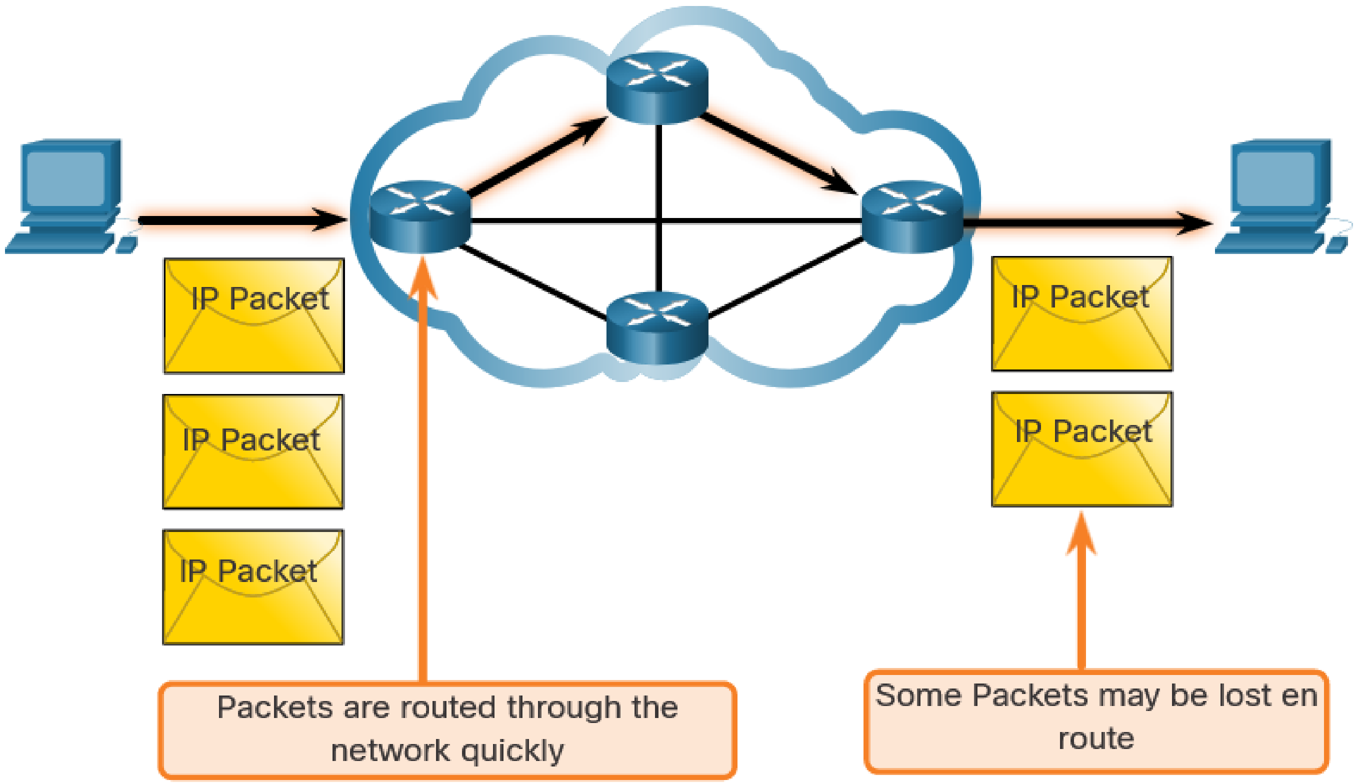
IP is Connectionless

- IP does not establish a connection with the destination before sending the packet.
- There is no control information needed (synchronizations, acknowledgments, etc.).
- The destination will receive the packet when it arrives, but no pre-notifications are sent by IP.
- If there is a need for connection-oriented traffic, then another protocol will handle this (typically TCP at the transport layer).

Best Effort

IP is Best Effort

- IP will not guarantee delivery of the packet.
- IP has reduced overhead since there is no mechanism to resend data that is not received.
- IP does not expect acknowledgments.
- IP does not know if the other device is operational or if it received the packet.



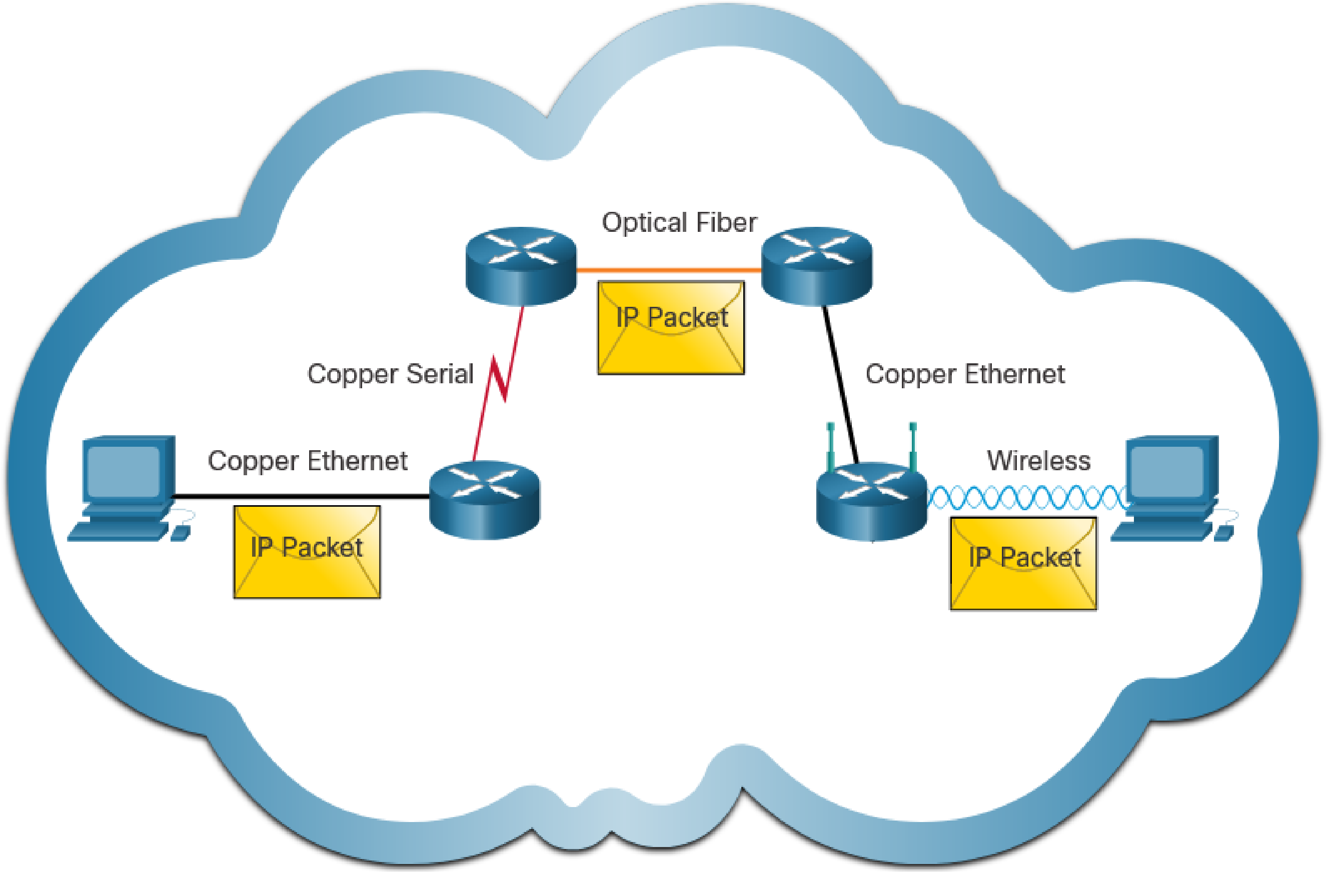
Media Independent

IP is unreliable:

- It cannot manage or fix undelivered or corrupt packets.
- IP cannot retransmit after an error.
- IP cannot realign out of sequence packets.
- IP must rely on other protocols for these functions.

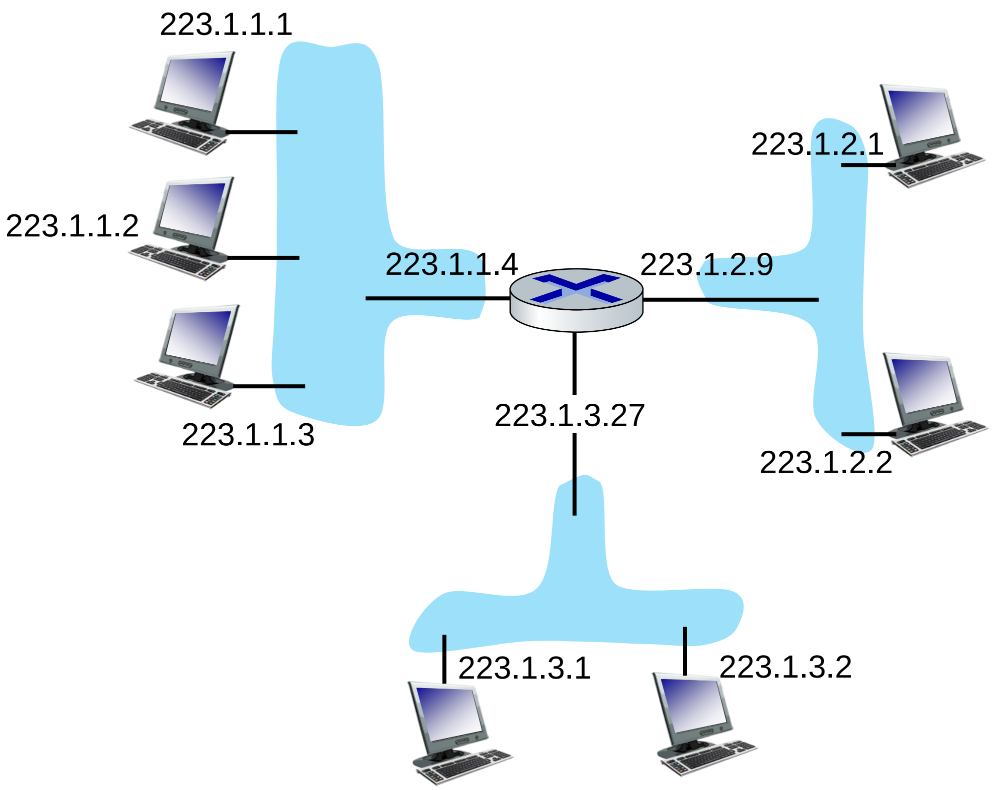
IP is media Independent:

- IP does not concern itself with the type of frame required at the data link layer or the media type at the physical layer.
- IP can be sent over any media type: copper, fiber, or wireless.



IP addressing: introduction

- IP address: 32-bit identifier associated with each host or router *interface*
- interface: connection between host/router and physical link
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)



dotted-decimal IP address notation:

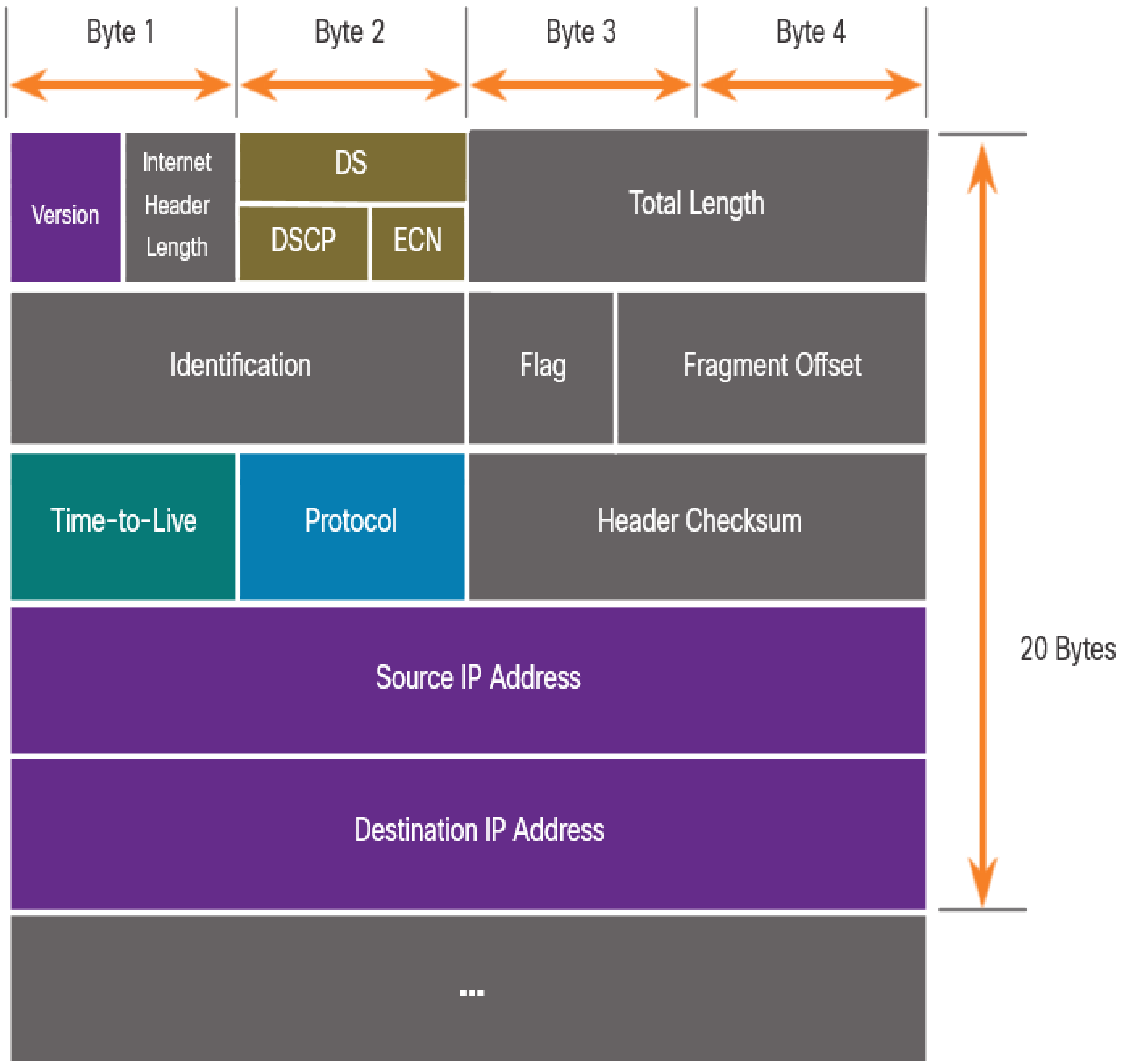
$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

IPv4 Packet Header Fields

The IPv4 network header characteristics:

- It is in binary.
- Contains several fields of information
- Diagram is read from left to right, 4 bytes per line
- The two most important fields are the source and destination.

Protocols may have may have one or more functions.

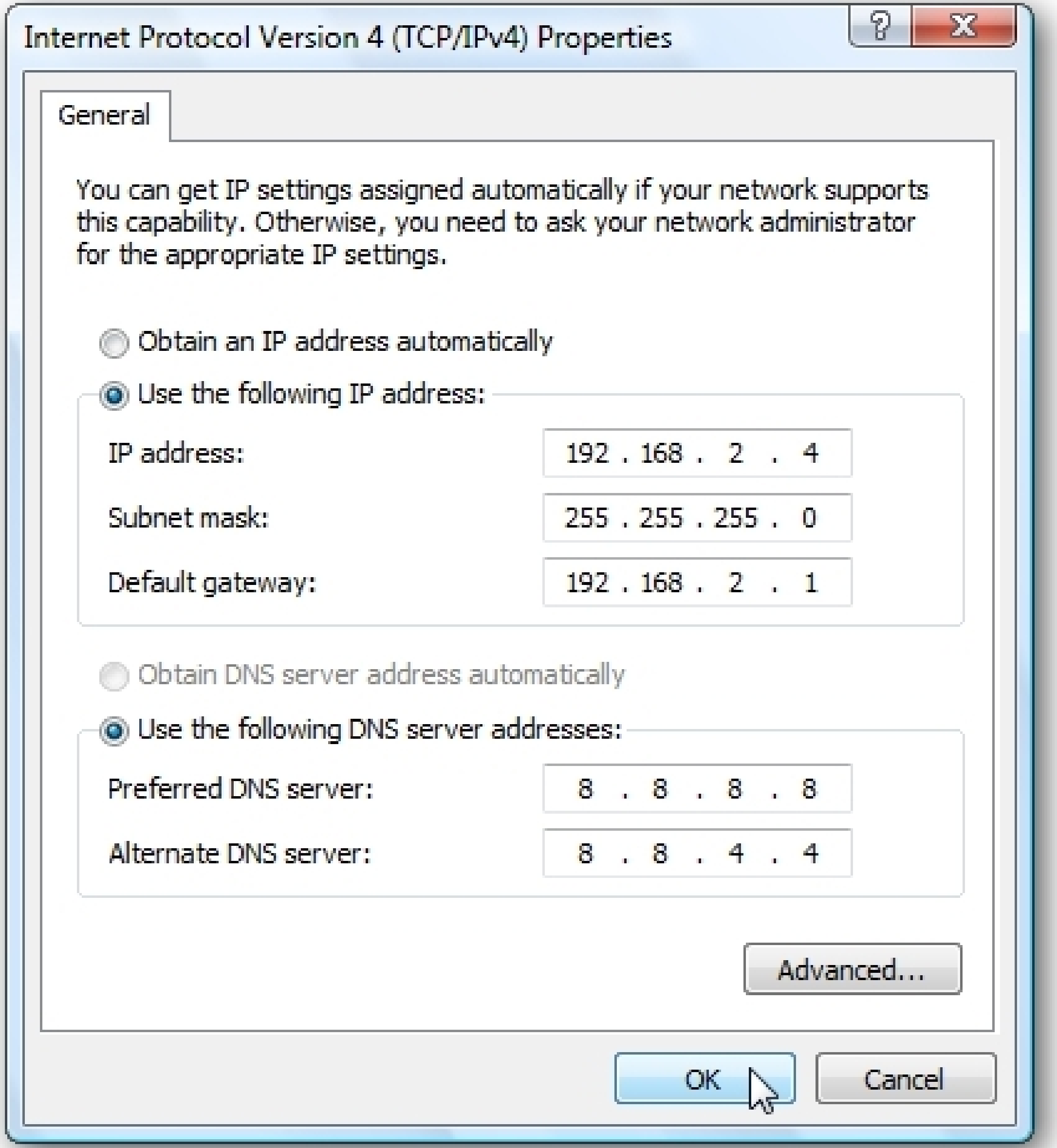


IPv4 Packet Header Fields

Significant fields in the IPv4 header:

Function	Description
Version	This will be for v4, as opposed to v6, a 4 bit field= 0100
Differentiated Services	Used for QoS: DiffServ – DS field or the older IntServ – ToS or Type of Service
Header Checksum	Detect corruption in the IPv4 header
Time to Live (TTL)	Layer 3 hop count. When it becomes zero the router will discard the packet.
Protocol	I.D.s next level protocol: ICMP, TCP, UDP, etc.
Source IPv4 Address	32 bit source address
Destination IPV4 Address	32 bit destination address

IPv4 Address

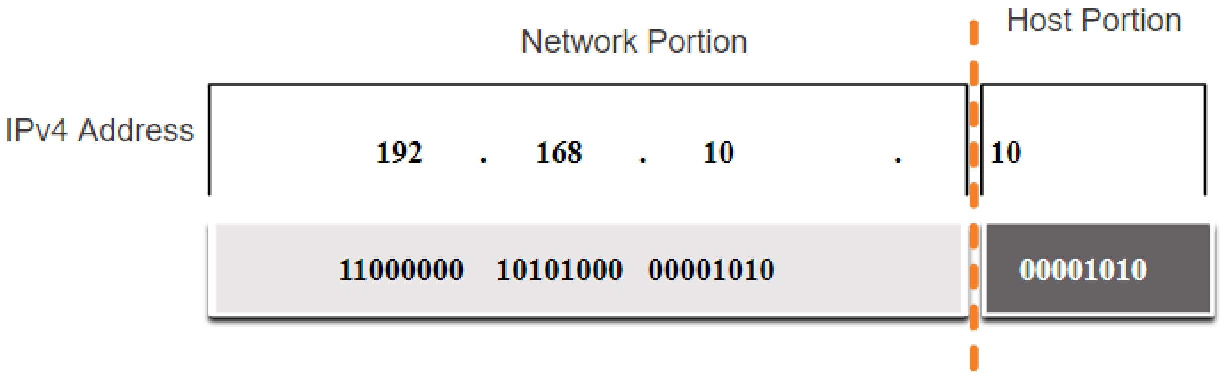


IPv4 Address Structure

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.

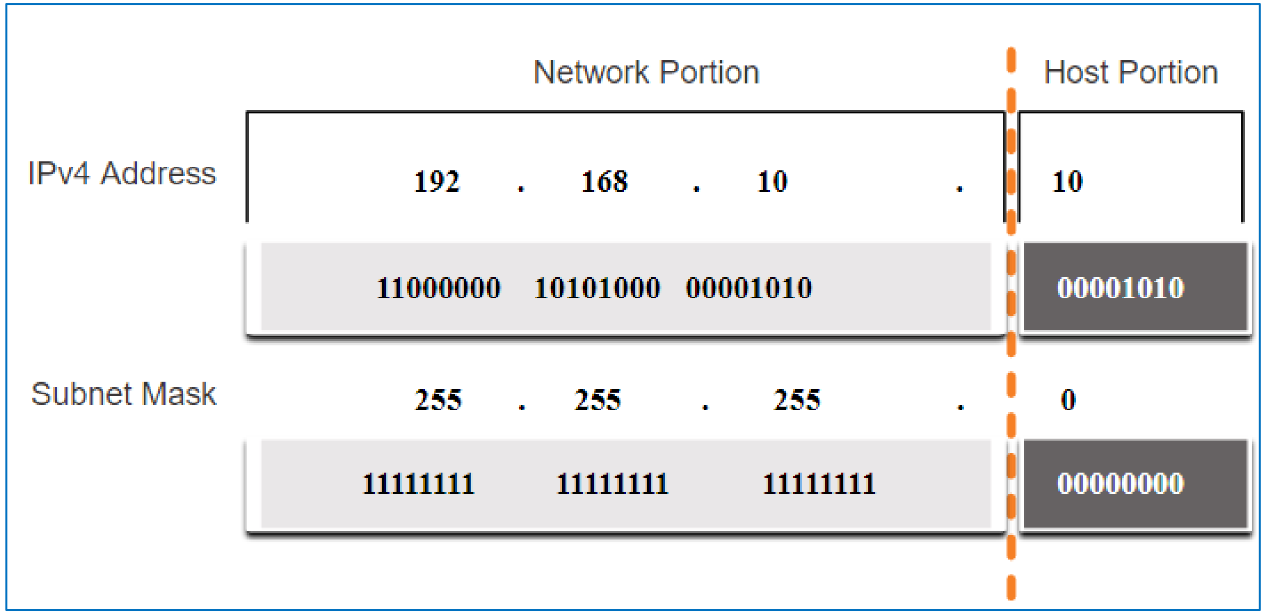
- When determining the network portion versus the host portion, you must look at the 32-bit stream.
- A subnet mask is used to determine the network and host portions.



The Subnet Mask

- To identify the network and host portions of an IPv4 address, the subnet mask is compared to the IPv4 address bit for bit, from left to right.

- The actual process used to identify the network and host portions is called ANDing.



IPv4 Address Structure

The Prefix Length

- A prefix length is a less cumbersome method used to identify a subnet mask address.

- The prefix length is the number of bits set to 1 in the subnet mask.

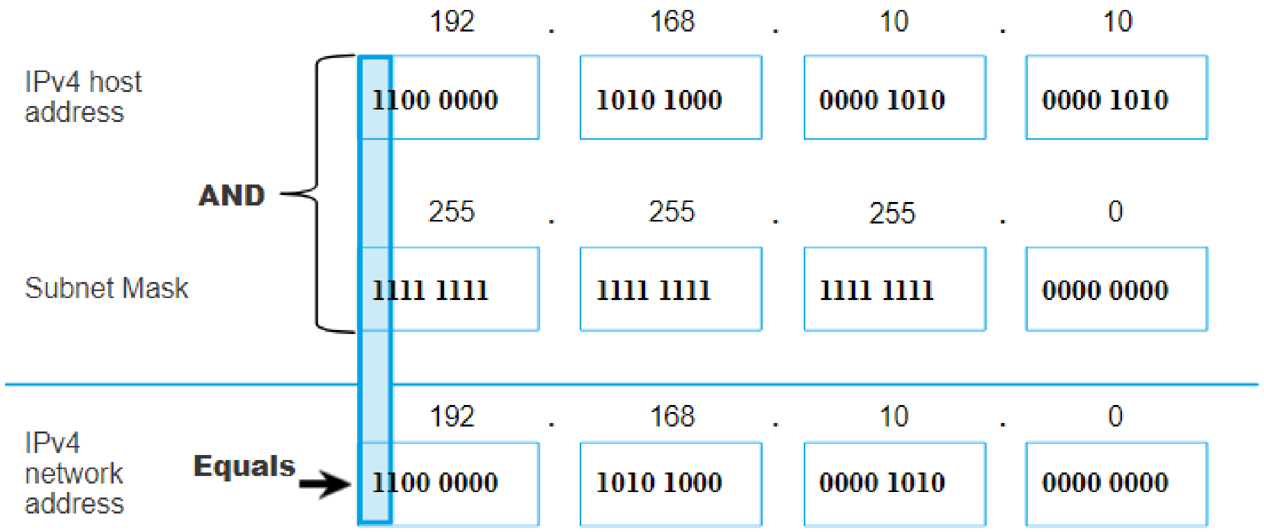
- It is written in “slash notation” therefore, count the number of bits in the subnet mask and prepend it with a slash.

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

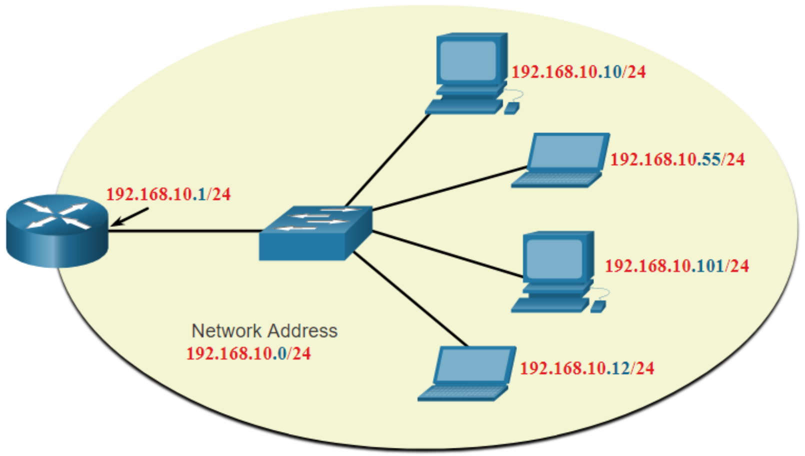
- A logical AND Boolean operation is used in determining the network address.
  - Logical AND is the comparison of two bits where only a 1 AND 1 produces a 1 and any other combination results in a 0.
  - 1 AND 1 = 1, 0 AND 1 = 0, 1 AND 0 = 0, 0 AND 0 = 0
  - 1 = True and 0 = False

- To identify the network address, the host IPv4 address is logically ANDed, bit by bit, with the subnet mask to identify the network address.



Network, Host, and Broadcast Addresses

- Within each network are three types of IP addresses:
  - Network address
  - Host addresses
  - Broadcast address

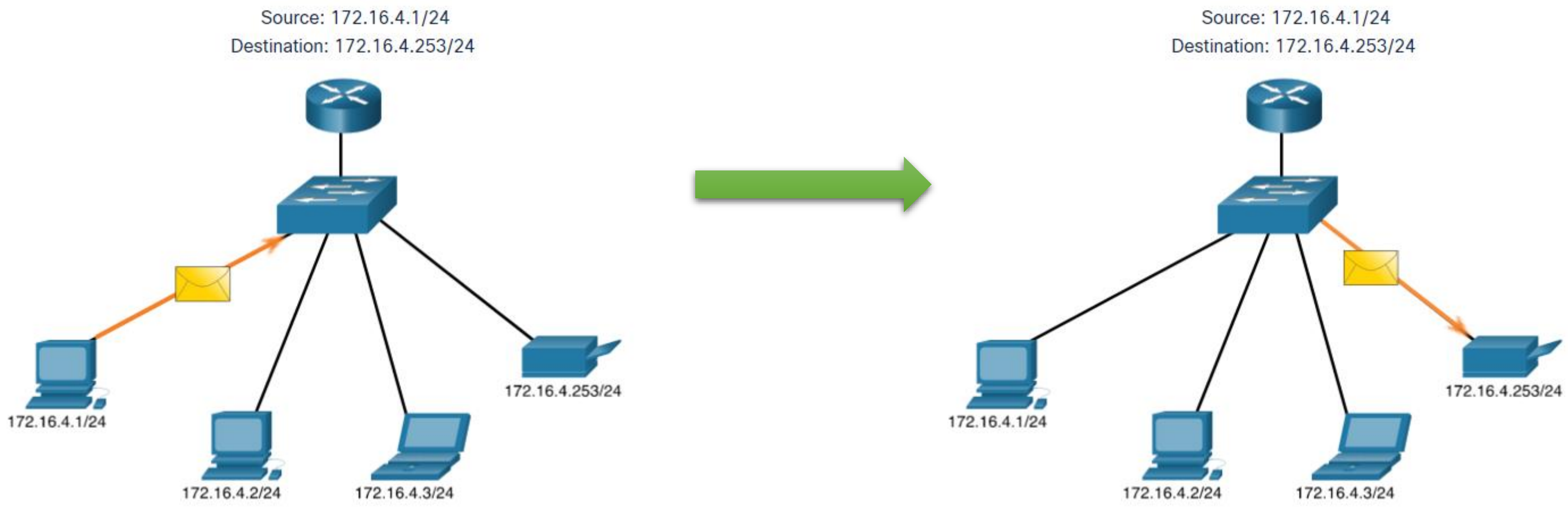


	Network Portion			Host Portion	Host Bits
Subnet mask **255.255.255.0 or /24**	255 11111111	255 11111111	255 11111111	0 00000000	
Network address **192.168.10.0 or /24**	192 11000000	168 10100000	10 00001010	0 00000000	All 0s
First address **192.168.10.1 or /24**	192 11000000	168 10100000	10 00001010	1 00000001	All 0s and a 1
Last address **192.168.10.254 or /24**	192 11000000	168 10100000	10 00001010	254 11111110	All 1s and a 0
Broadcast address **192.168.10.255 or /24**	192 11000000	168 10100000	10 00001010	255 11111111	All 1s

IPv4 Unicast, Broadcast, and Multicast

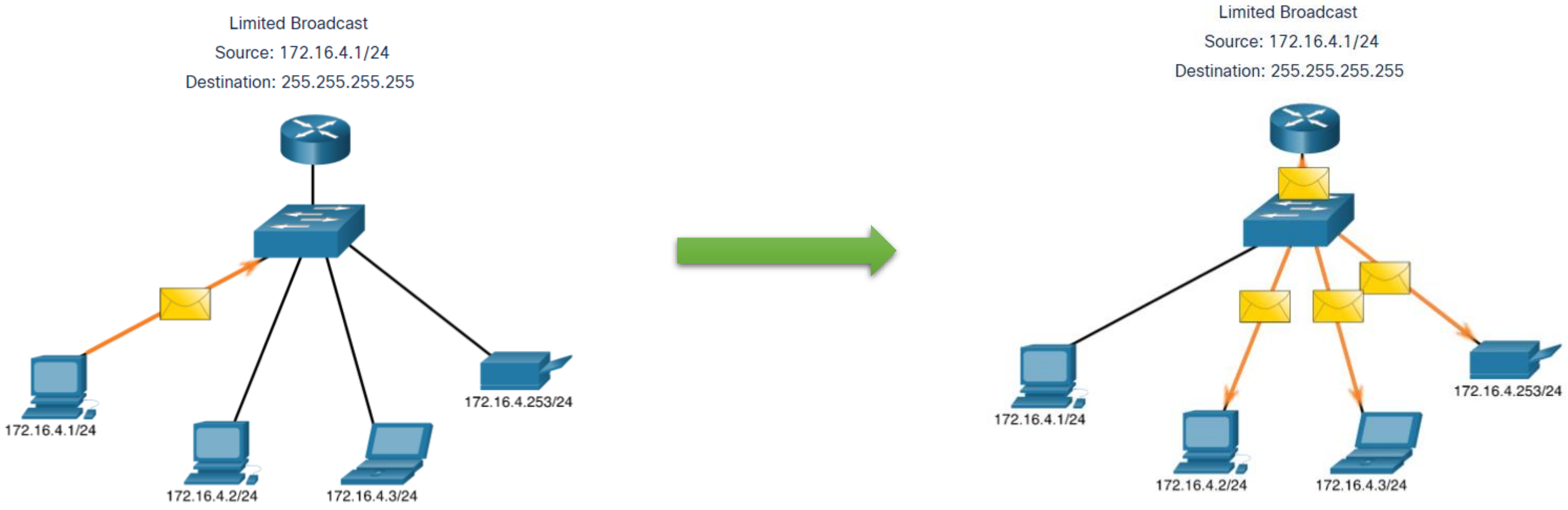
Unicast

- Unicast transmission is sending a packet to one destination IP address.
- For example, the PC at 172.16.4.1 sends a unicast packet to the printer at 172.16.4.253.



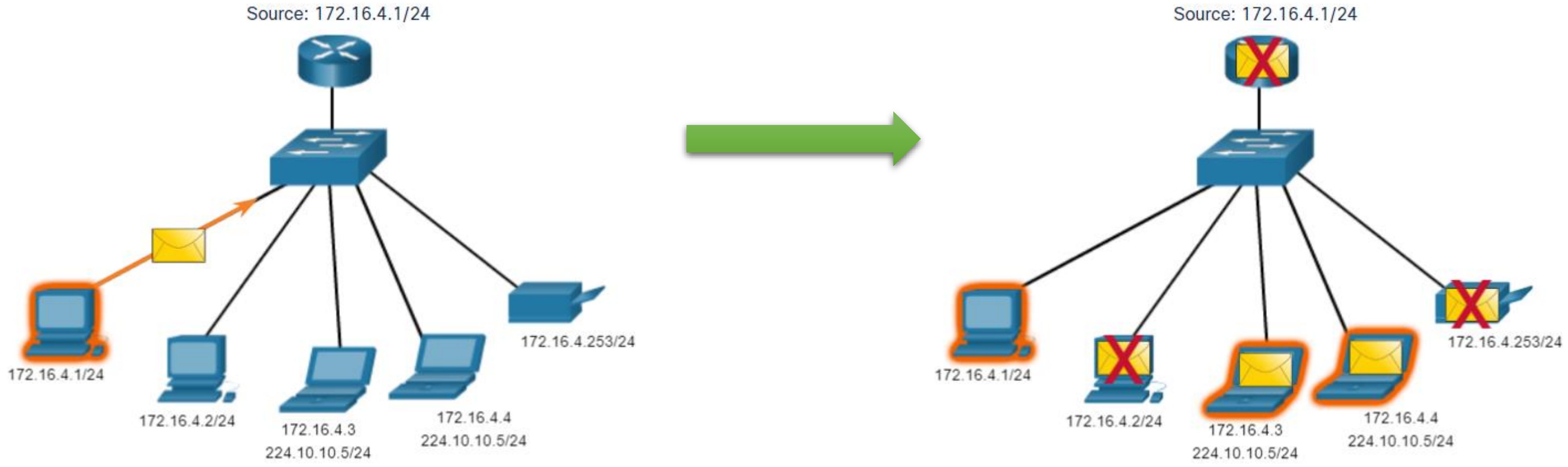
Broadcast

- Broadcast transmission is sending a packet to all other destination IP addresses.
- For example, the PC at 172.16.4.1 sends a broadcast packet to all IPv4 hosts.



Multicast

- Multicast transmission is sending a packet to a multicast address group.
- For example, the PC at 172.16.4.1 sends a multicast packet to the multicast group address 224.10.10.5.



Types of IPv4 Addresses

Public and Private IPv4 Addresses

- As defined in in RFC 1918, public IPv4 addresses are globally routed between internet service provider (ISP) routers.

- Private addresses are common blocks of addresses used by most organizations to assign IPv4 addresses to internal hosts.

- Private IPv4 addresses are not unique and can be used internally within any network.

Network Address and Prefix	RFC 1918 Private Address Range
10.0.0.0/8	10.0.0.0 - 10.255.255.255
172.16.0.0/12	172.16.0.0 - 172.31.255.255
192.168.0.0/16	192.168.0.0 - 192.168.255.255

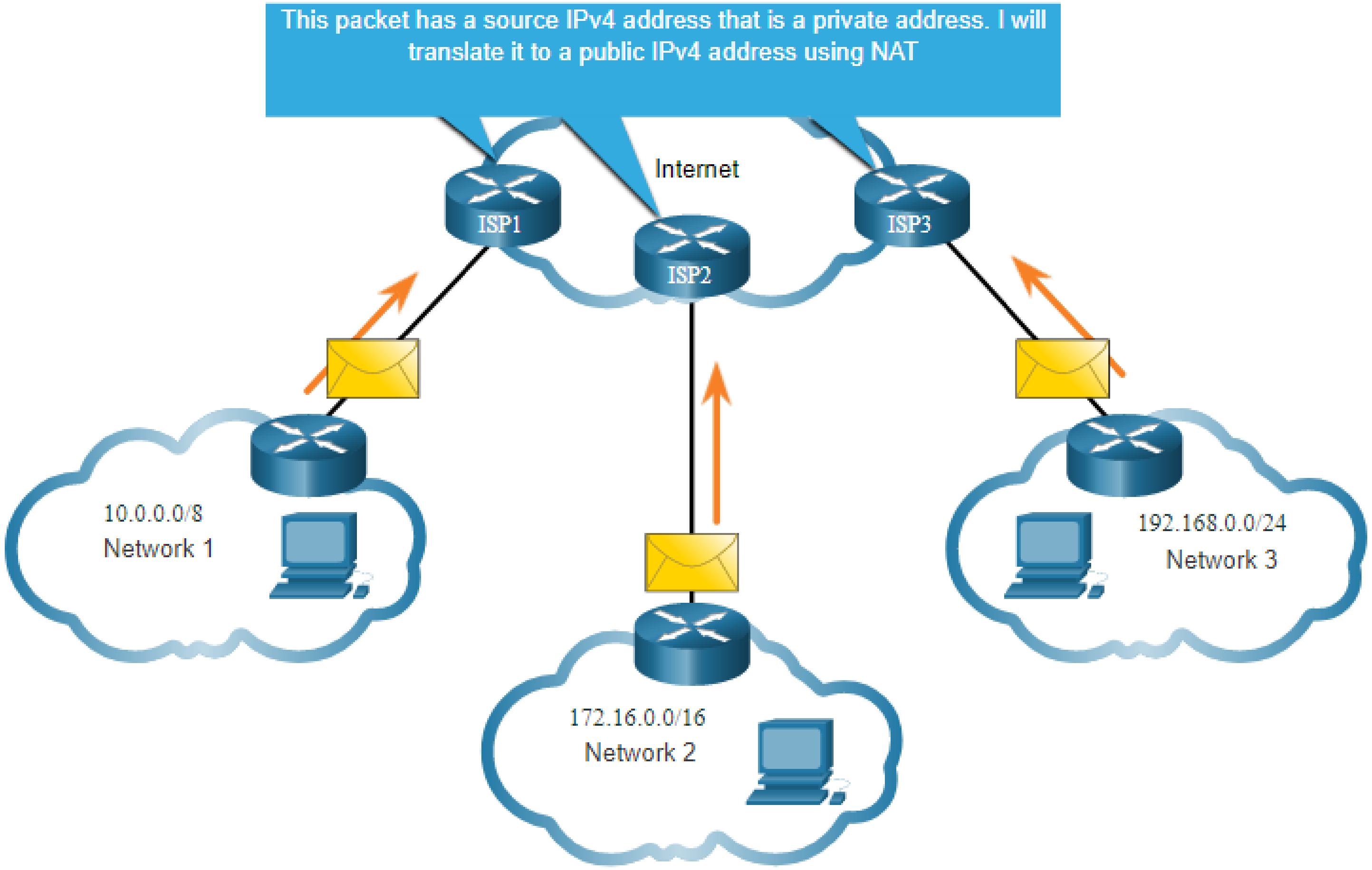
- However, private addresses are not globally routable.

Routing to the Internet

- Network Address Translation (NAT) translates private IPv4 addresses to public IPv4 addresses.

- NAT is typically enabled on the edge router connecting to the internet.

- It translates the internal private address to a public global IP address.



Types of IPv4 Addresses

Special Use IPv4 Addresses

Loopback addresses

- 127.0.0.0 /8 (127.0.0.1 to 127.255.255.254)
- Commonly identified as only 127.0.0.1
- Used on a host to test if TCP/IP is operational.

```
C:\Users\NetAcad> ping 127.0.0.1
Pinging 127.0.0.1 with 32 bytes of data:
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
```

Link-Local addresses

- 169.254.0.0 /16 (169.254.0.1 to 169.254.255.254)
- Commonly known as the Automatic Private IP Addressing (APIPA) addresses or self-assigned addresses.
- Used by Windows DHCP clients to self-configure when no DHCP servers are available.

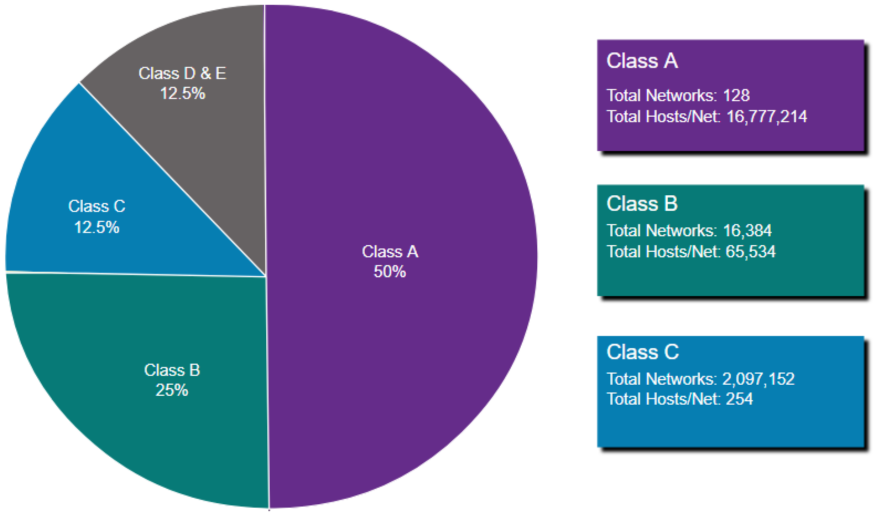
Legacy Classful Addressing

RFC 790 (1981) allocated IPv4 addresses in classes

- Class A (0.0.0.0/8 to 127.0.0.0/8)
- Class B (128.0.0.0 /16 – 191.255.0.0 /16)
- Class C (192.0.0.0 /24 – 223.255.255.0 /24)
- Class D (224.0.0.0 to 239.0.0.0)
- Class E (240.0.0.0 – 255.0.0.0)

- Classful addressing wasted many IPv4 addresses.

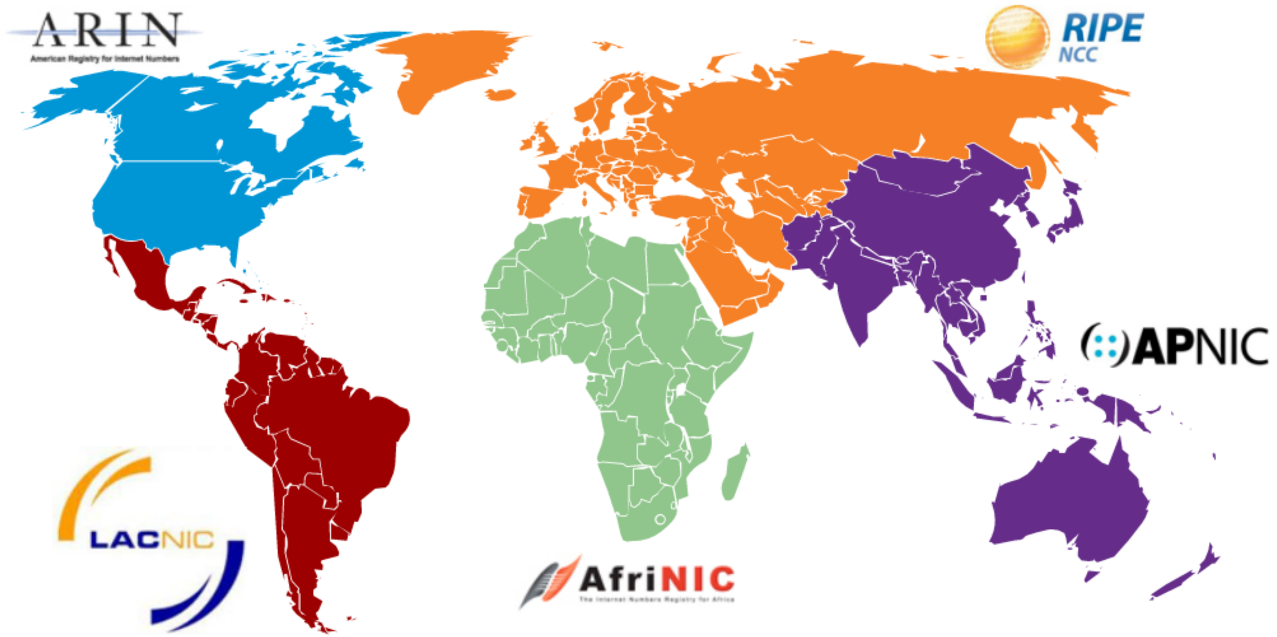
Classful address allocation was replaced with classless addressing which ignores the rules of classes (A, B, C).



Assignment of IP Addresses

- The Internet Assigned Numbers Authority (IANA) manages and allocates blocks of IPv4 and IPv6 addresses to five Regional Internet Registries (RIRs).

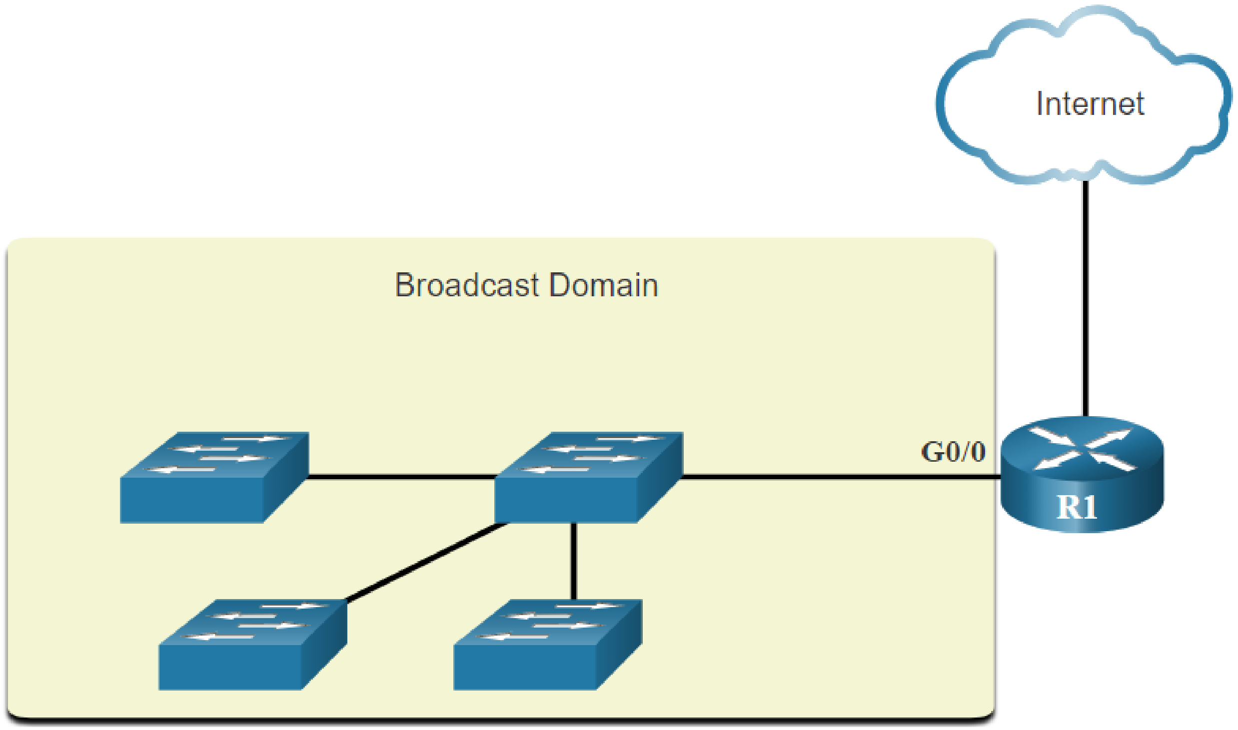
- RIRs are responsible for allocating IP addresses to ISPs who provide IPv4 address blocks to smaller ISPs and organizations.



Network Segmentation

Broadcast Domains and Segmentation

- Many protocols use broadcasts or multicasts (e.g., ARP use broadcasts to locate other devices, hosts send DHCP discover broadcasts to locate a DHCP server.)
- Switches propagate broadcasts out all interfaces except the interface on which it was received.



- The only device that stops broadcasts is a router.
- Routers do not propagate broadcasts.
- Each router interface connects to a broadcast domain and broadcasts are only propagated within that specific broadcast domain.

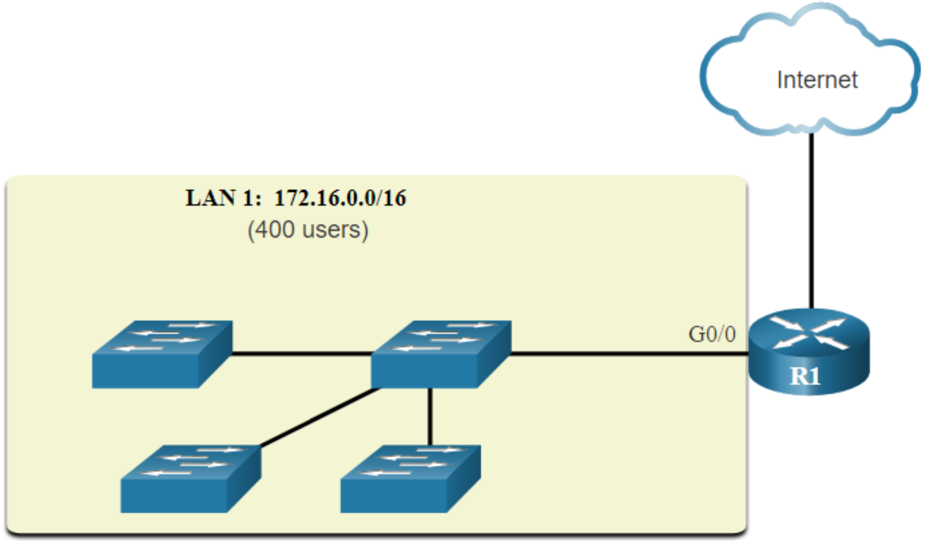
Network Segmentation

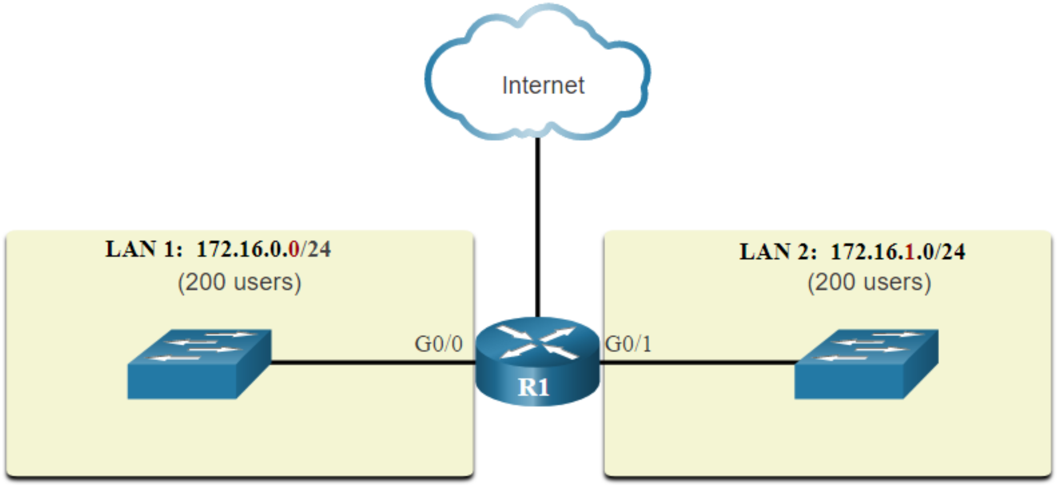
Problems with Large Broadcast Domains

- A problem with a large broadcast domain is that these hosts can generate excessive broadcasts and negatively affect the network.

- The solution is to reduce the size of the network to create smaller broadcast domains in a process called subnetting.

- Dividing the network address 172.16.0.0 /16 into two subnets of 200 users each: 172.16.0.0 /24 and 172.16.1.0 /24.
- Broadcasts are only propagated within the smaller broadcast domains.



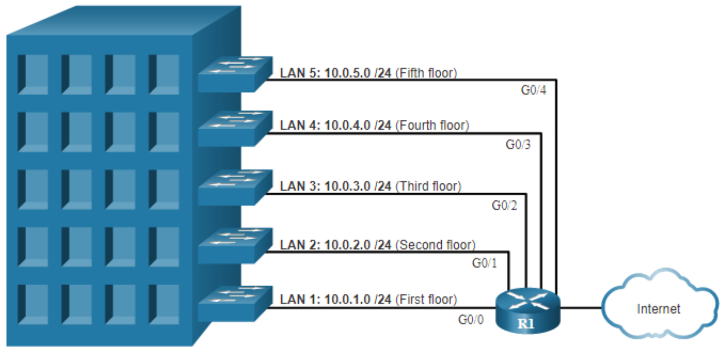


Reasons for Segmenting Networks

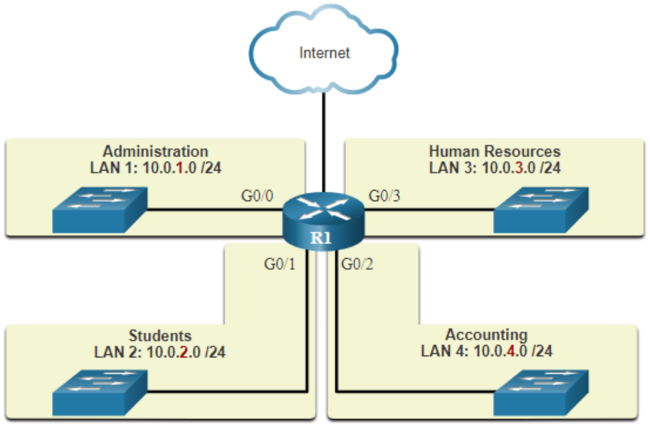
- Subnetting reduces overall network traffic and improves network performance.
- It can be used to implement security policies between subnets.
- Subnetting reduces the number of devices affected by abnormal broadcast traffic.

- Subnets are used for a variety of reasons including by:

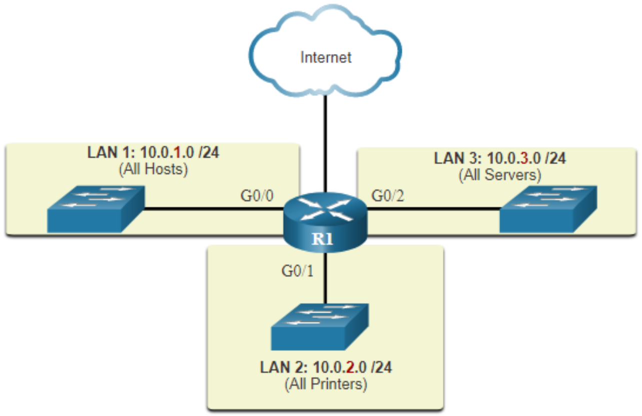
Location



Group or Function

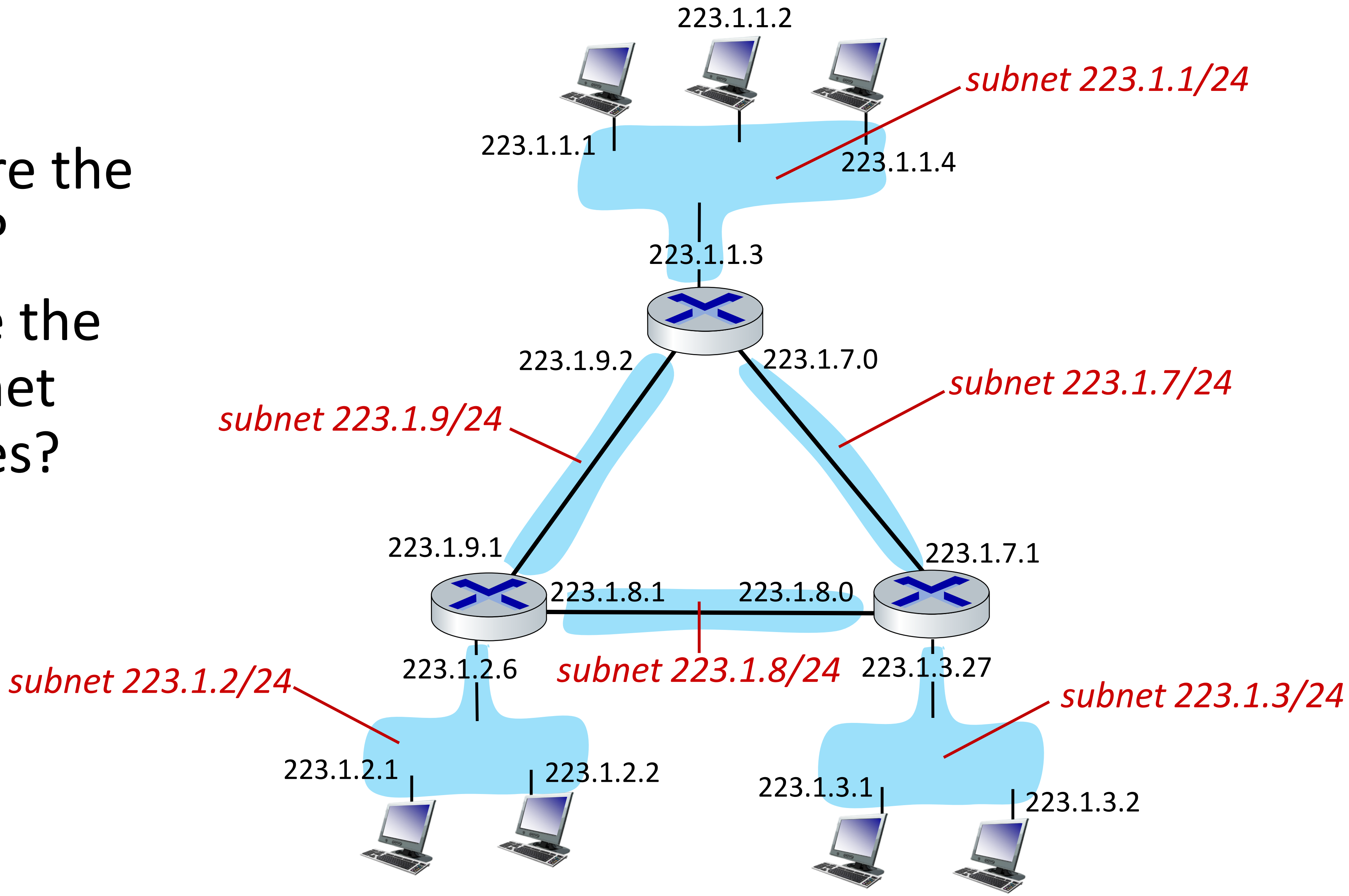


Device Type



Subnets

- where are the subnets?
- what are the /24 subnet addresses?



IP addressing: CIDR

CIDR: Classless InterDomain Routing (pronounced “cider”)

- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address

subnet part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

Subnet on an Octet Boundary

- Networks are most easily subnetted at the octet boundary of /8, /16, and /24.
- Notice that using longer prefix lengths decreases the number of hosts per subnet.

Prefix Length	Subnet Mask	Subnet Mask in Binary (n = network, h = host)	# of hosts
/8	**255**.0.0.0	**nnnnnnnn**.hhhhhhhh.hhhhhhhh.hhhhhhhh **11111111**.00000000.00000000.00000000	16,777,214
/16	**255.255**.0.0	**nnnnnnnn.nnnnnnnn**.hhhhhhhh.hhhhhhhh **11111111.11111111**.00000000.00000000	65,534
/24	**255.255.255**.0	**nnnnnnnn.nnnnnnnn.nnnnnnnn**.hhhhhhhh **11111111.11111111.11111111**.00000000	254

Subnet on an Octet Boundary (Cont.)

- In the first table 10.0.0.0/8 is subnetted using /16 and in the second table, a /24 mask.

Subnet Address (256 Possible Subnets)	**Host Range** (65,534 possible hosts per subnet)	**Broadcast**
10.0.0.0**/16**	**10.0**.0.1 - **10.0**.255.254	**10.0**.255.255
10.1.0.0**/16**	**10.1**.0.1 - **10.1**.255.254	**10.1**.255.255
10.2.0.0**/16**	**10.2**.0.1 - **10.2**.255.254	**10.2**.255.255
10.3.0.0**/16**	**10.3**.0.1 - **10.3**.255.254	**10.3**.255.255
10.4.0.0**/16**	**10.4**.0.1 - **10.4**.255.254	**10.4**.255.255
10.5.0.0**/16**	**10.5**.0.1 - **10.5**.255.254	**10.5**.255.255
10.6.0.0**/16**	**10.6**.0.1 - **10.6**.255.254	**10.6**.255.255
10.7.0.0**/16**	**10.7**.0.1 - **10.7**.255.254	**10.7**.255.255
...	...	...
10.255.0.0**/16**	**10.255**.0.1 - **10.255**.255.254	**10.255**.255.255

Subnet Address (65,536 Possible Subnets)	**Host Range** (254 possible hosts per subnet)	**Broadcast**
10.0.0.0**/24**	**10.0.0**.1 - **10.0.0**.254	**10.0.0**.255
10.0.1.0**/24**	**10.0.1**.1 - **10.0.1**.254	**10.0.1**.255
10.0.2.0**/24**	**10.0.2**.1 - **10.0.2**.254	**10.0.2**.255
...	...	...
10.0.255.0**/24**	**10.0.255**.1 - **10.0.255**.254	**10.0.255**.255
10.1.0.0**/24**	**10.1.0**.1 - **10.1.0**.254	**10.1.0**.255
10.1.1.0**/24**	**10.1.1**.1 - **10.1.1**.254	**10.1.1**.255
10.1.2.0**/24**	**10.1.2**.1 - **10.1.2**.254	**10.1.2**.255
...	...	...
10.100.0.0**/24**	**10.100.0**.1 - **10.100.0**.254	**10.100.0**.255
...	...	...
10.255.255.0**/24**	**10.255.255**.1 - **10.2255.255**.254	**10.255.255**.255

Subnet within an Octet Boundary

- Refer to the table to see six ways to subnet a /24 network.

Prefix Length	Subnet Mask	Subnet Mask in Binary (n = network, h = host)	# of subnets	# of hosts
/25	255.255.255.128	nnnnnnnn.nnnnnnnn.nnnnnnnn.**n**hhhhhhh 11111111.11111111.11111111.**1**0000000	**2**	126
/26	255.255.255.192	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nn**hhhhhh 11111111.11111111.11111111.**11**000000	**4**	62
/27	255.255.255.224	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnn**hhhhh 11111111.11111111.11111111.**111**00000	**8**	30
/28	255.255.255.240	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnn**hhhh 11111111.11111111.11111111.**1111**0000	**16**	14
/29	255.255.255.248	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnnn**hhh 11111111.11111111.11111111.**11111**000	**32**	6
/30	255.255.255.252	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnnnn**hh 11111111.11111111.11111111.**111111**00	**64**	2

Create Subnets with a Slash 16 prefix

- The table highlights all the possible scenarios for subnetting a /16 prefix.

Prefix Length	Subnet Mask	Network Address (n = network, h = host)	# of subnets	# of hosts
/17	255.255.**128**.0	nnnnnnnn.nnnnnnnn.**n**hhhhhhh.hhhhhhhh 11111111.11111111.**1**0000000.00000000	**2**	32766
/18	255.255.**192**.0	nnnnnnnn.nnnnnnnn.**nn**hhhhhh.hhhhhhhh 11111111.11111111.**11**000000.00000000	**4**	16382
/19	255.255.**224**.0	nnnnnnnn.nnnnnnnn.**nnn**hhhhh.hhhhhhhh 11111111.11111111.**111**00000.00000000	**8**	8190
/20	255.255.**240**.0	nnnnnnnn.nnnnnnnn.**nnnn**hhhh.hhhhhhhh 11111111.11111111.**1111**0000.00000000	**16**	4094
/21	255.255.**248**.0	nnnnnnnn.nnnnnnnn.**nnnnn**hhh.hhhhhhhh 11111111.11111111.**11111**000.00000000	**32**	2046
/22	255.255.**252**.0	nnnnnnnn.nnnnnnnn.**nnnnnn**hh.hhhhhhhh 11111111.11111111.**111111**00.00000000	**64**	1022
/23	255.255.**254**.0	nnnnnnnn.nnnnnnnn.**nnnnnnn**h.hhhhhhhh 11111111.11111111.**1111111**0.00000000	**128**	510
/24	255.255.**255.0**	nnnnnnnn.nnnnnnnn.**nnnnnnnn**.hhhhhhhh 11111111.11111111.**11111111**.00000000	**256**	254
/25	255.255.**255.128**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.n**hhhhhhh 11111111.11111111.**11111111.1**0000000	**512**	126
/26	255.255.**255.192**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.nn**hhhhhh 11111111.11111111.**11111111.11**000000	**1024**	62
/27	255.255.**255.224**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.nnn**hhhhh 11111111.11111111.**11111111.111**00000	**2048**	30
/28	255.255.**255.240**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.nnnn**hhhh 11111111.11111111.**11111111.1111**0000	**4096**	14
/29	255.255.**255.248**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.nnnnn**hhh 11111111.11111111.**11111111.11111**000	**8192**	6
/30	255.255.**255.252**	nnnnnnnn.nnnnnnnn.**nnnnnnnn.nnnnnn**hh 11111111.11111111.**11111111.111111**00	**16384**	2

Create 100 Subnets with a Slash 16 prefix

Consider a large enterprise that requires at least 100 subnets and has chosen the private address 172.16.0.0/16 as its internal network address.

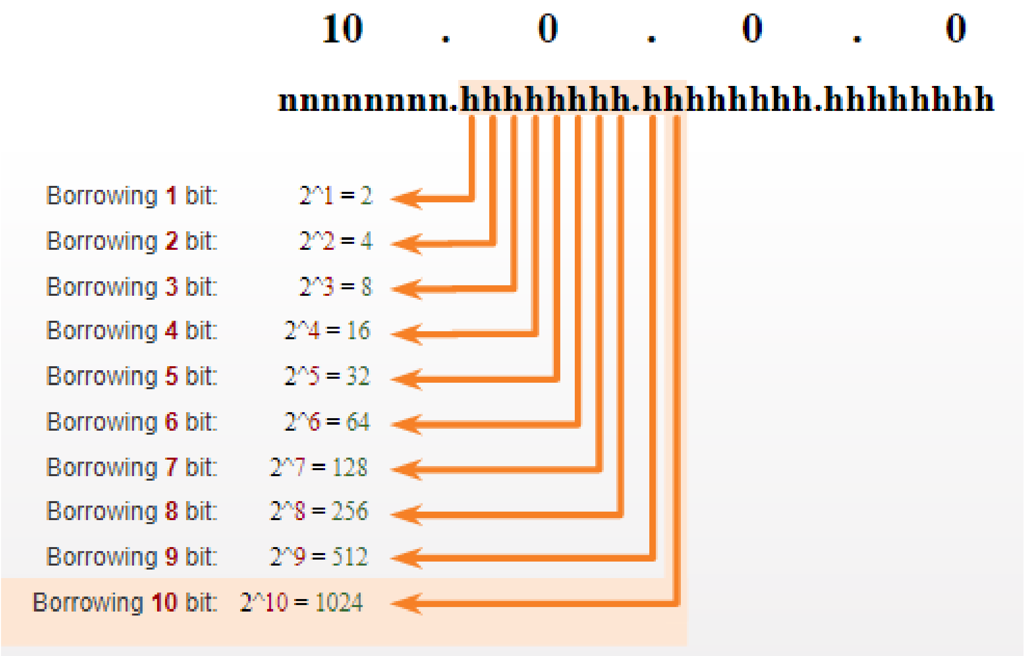
- The figure displays the number of subnets that can be created when borrowing bits from the third octet and the fourth octet.
- Notice there are now up to 14 host bits that can be borrowed (i.e., last two bits cannot be borrowed).

To satisfy the requirement of 100 subnets for the enterprise, 7 bits (i.e., 2^7 = 128 subnets) would need to be borrowed (for a total of 128 subnets).

Create 1000 Subnets with a Slash 8 prefix

Consider a small ISP that requires 1000 subnets for its clients using network address 10.0.0.0/8 which means there are 8 bits in the network portion and 24 host bits available to borrow toward subnetting.

- The figure displays the number of subnets that can be created when borrowing bits from the second and third.
- Notice there are now up to 22 host bits that can be borrowed (i.e., last two bits cannot be borrowed).

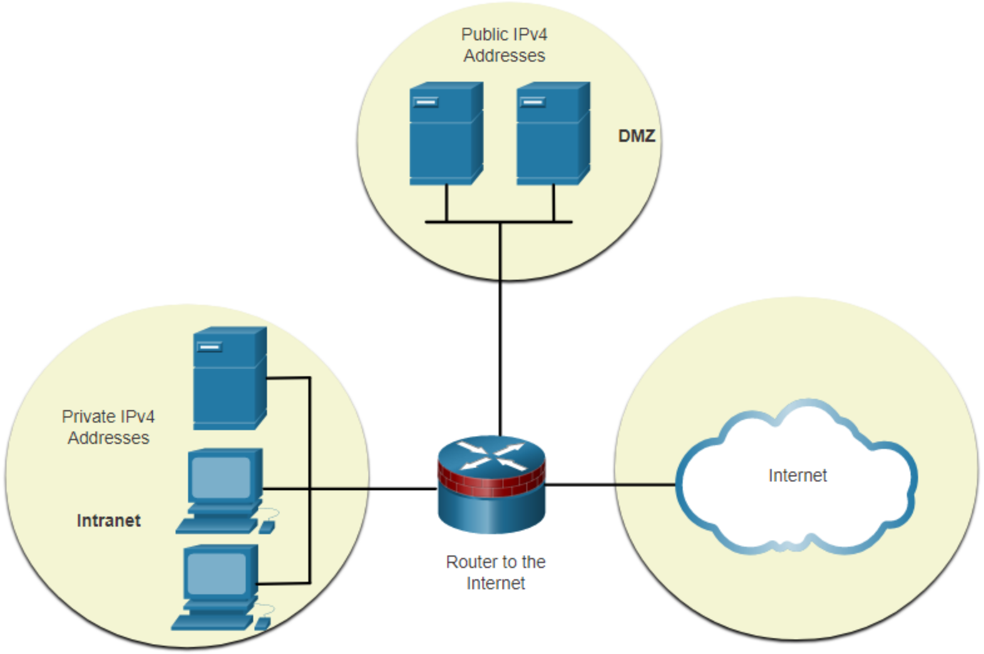


To satisfy the requirement of 1000 subnets for the enterprise, 10 bits (i.e., 2^{10}=1024 subnets) would need to be borrowed (for a total of 128 subnets)

Subnet Private versus Public IPv4 Address Space

Enterprise networks will have an:

- Intranet - A company’s internal network typically using private IPv4 addresses.
- DMZ – A companies internet facing servers. Devices in the DMZ use public IPv4 addresses.
- A company could use the 10.0.0.0/8 and subnet on the /16 or /24 network boundary.
- The DMZ devices would have to be configured with public IP addresses.



Subnet to Meet Requirements

Minimize Unused Host IPv4 Addresses and Maximize Subnets

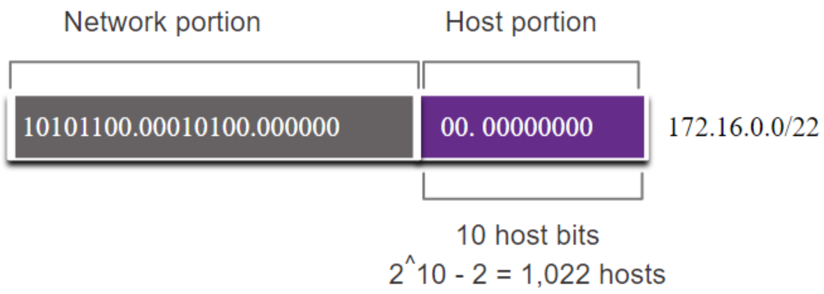
There are two considerations when planning subnets:

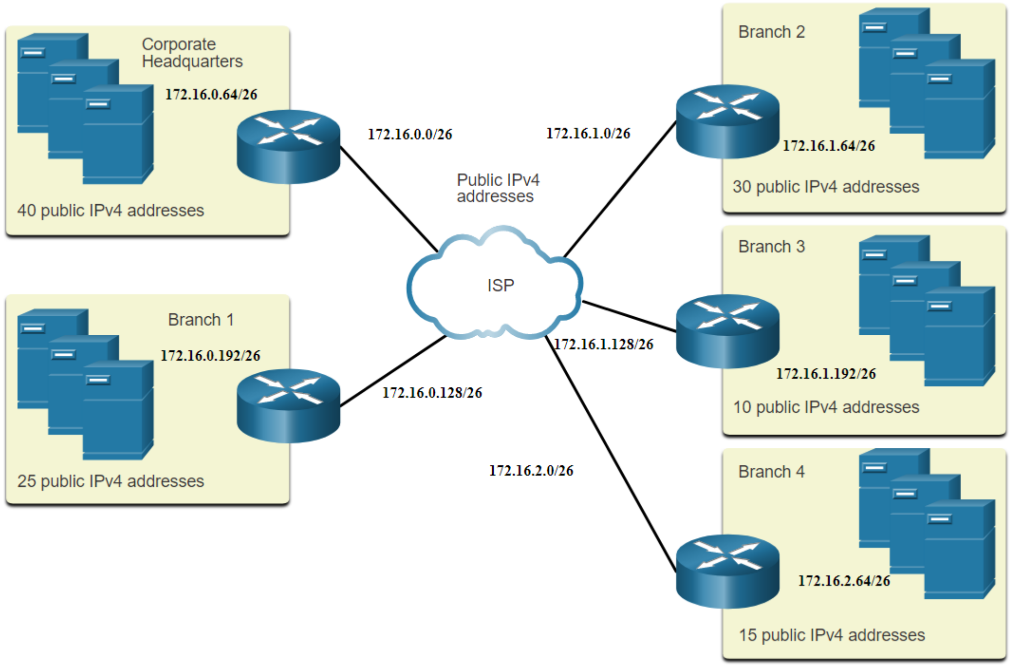
- The number of host addresses required for each network
- The number of individual subnets needed

Prefix Length	Subnet Mask	Subnet Mask in Binary (n = network, h = host)	# of subnets	# of hosts
/25	255.255.255.128	nnnnnnnn.nnnnnnnn.nnnnnnnn.**n**hhhhhhh 11111111.11111111.11111111.**1**0000000	**2**	126
/26	255.255.255.192	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nn**hhhhhh 11111111.11111111.11111111.**11**000000	**4**	62
/27	255.255.255.224	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnn**hhhhh 11111111.11111111.11111111.**111**00000	**8**	30
/28	255.255.255.240	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnn**hhhh 11111111.11111111.11111111.**1111**0000	**16**	14
/29	255.255.255.248	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnnn**hhh 11111111.11111111.11111111.**11111**000	**32**	6
/30	255.255.255.252	nnnnnnnn.nnnnnnnn.nnnnnnnn.**nnnnnn**hh 11111111.11111111.11111111.**111111**00	**64**	2

Example: Efficient IPv4 Subnetting

- In this example, corporate headquarters has been allocated a public network address of 172.16.0.0/22 (10 host bits) by its ISP providing 1,022 host addresses.
- There are five sites and therefore five internet connections which means the organization requires 10 subnets with the largest subnet requires 40 addresses.
- It allocated 10 subnets with a /26 (i.e., 255.255.255.192) subnet mask.





Practice

Problem 1:

Given:	
Host IP Address:	192.168.200.139
Original Subnet Mask	255.255.255.0
New Subnet Mask:	255.255.255.224

Find:	
Number of Subnet Bits	
Number of Subnets Created	
Number of Host Bits per Subnet	
Number of Hosts per Subnet	
Network Address of this Subnet	
IPv4 Address of First Host on this Subnet	
IPv4 Address of Last Host on this Subnet	
IPv4 Broadcast Address on this Subnet	

Practice

Problem 2:

Given:	
Host IP Address:	10.101.99.228
Original Subnet Mask	255.0.0.0
New Subnet Mask:	255.255.128.0

Find:	
Number of Subnet Bits	
Number of Subnets Created	
Number of Host Bits per Subnet	
Number of Hosts per Subnet	
Network Address of this Subnet	
IPv4 Address of First Host on this Subnet	
IPv4 Address of Last Host on this Subnet	
IPv4 Broadcast Address on this Subnet	

Practice

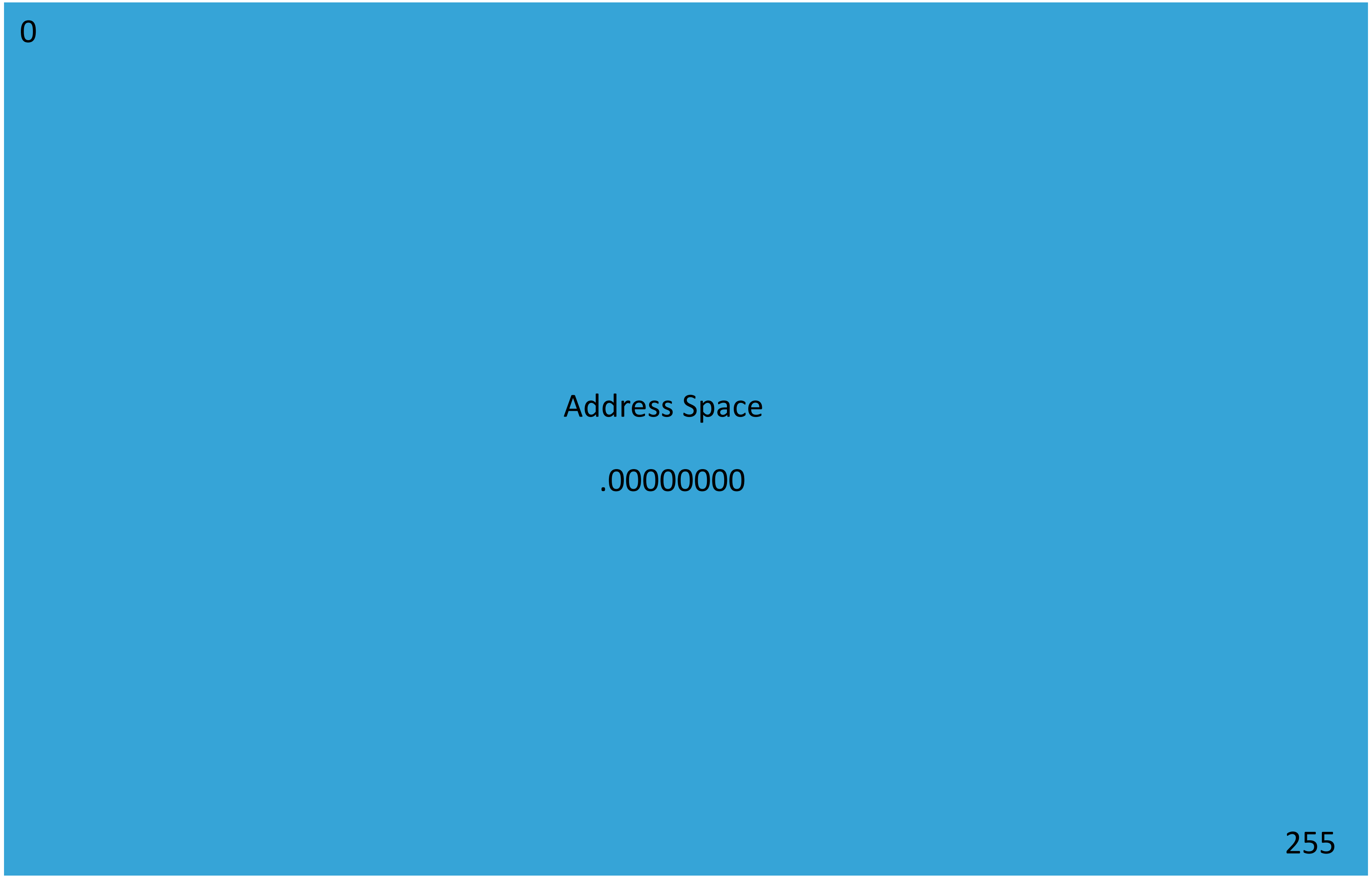
Problem 3:

Given:	
Host IP Address:	172.22.32.12
Original Subnet Mask	255.255.0.0
New Subnet Mask:	255.255.224.0

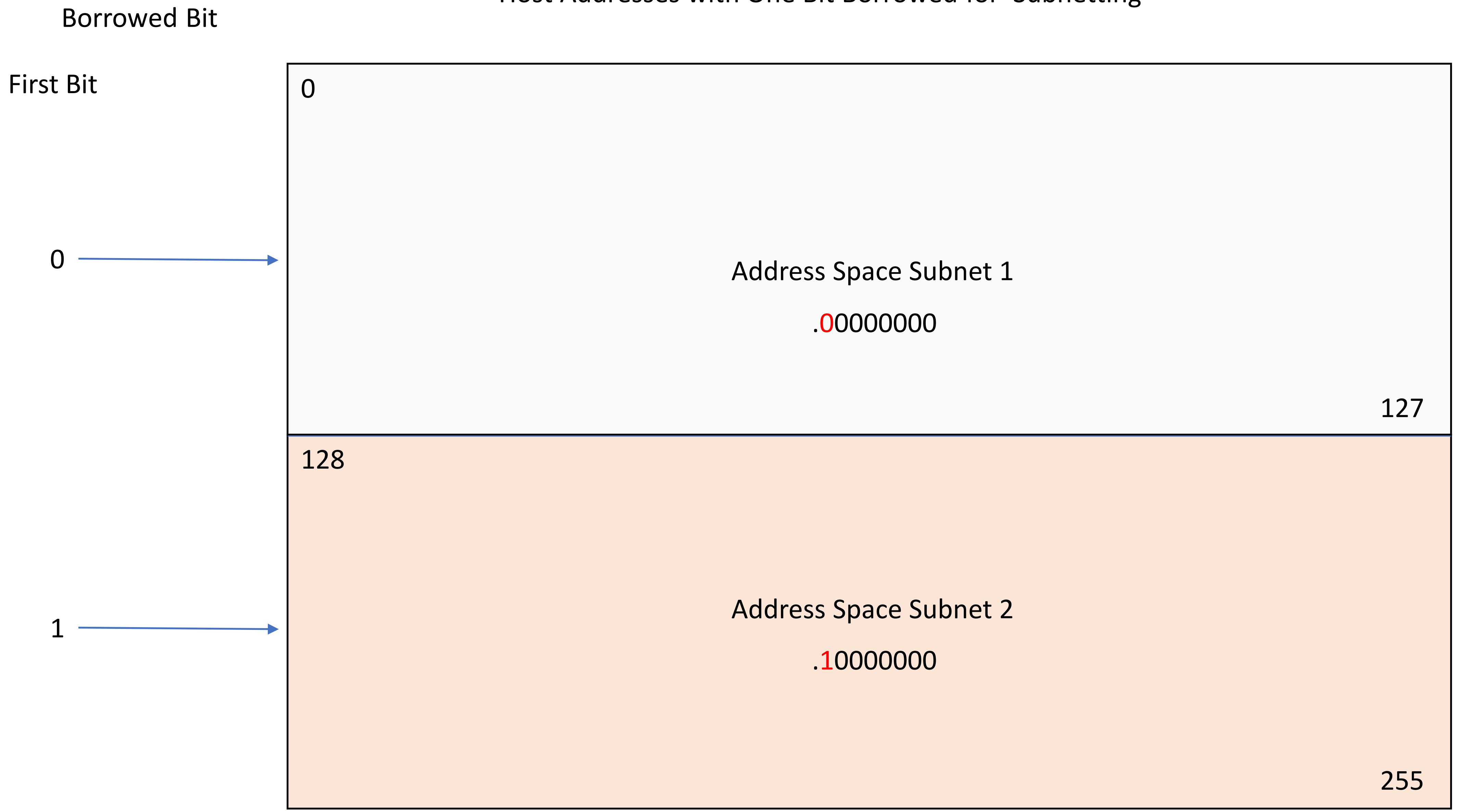
Find:	
Number of Subnet Bits	
Number of Subnets Created	
Number of Host Bits per Subnet	
Number of Hosts per Subnet	
Network Address of this Subnet	
IPv4 Address of First Host on this Subnet	
IPv4 Address of Last Host on this Subnet	
IPv4 Broadcast Address on this Subnet	

VLSM
(Variable-Length Subnet Mask)

Host Addresses without Subnetting

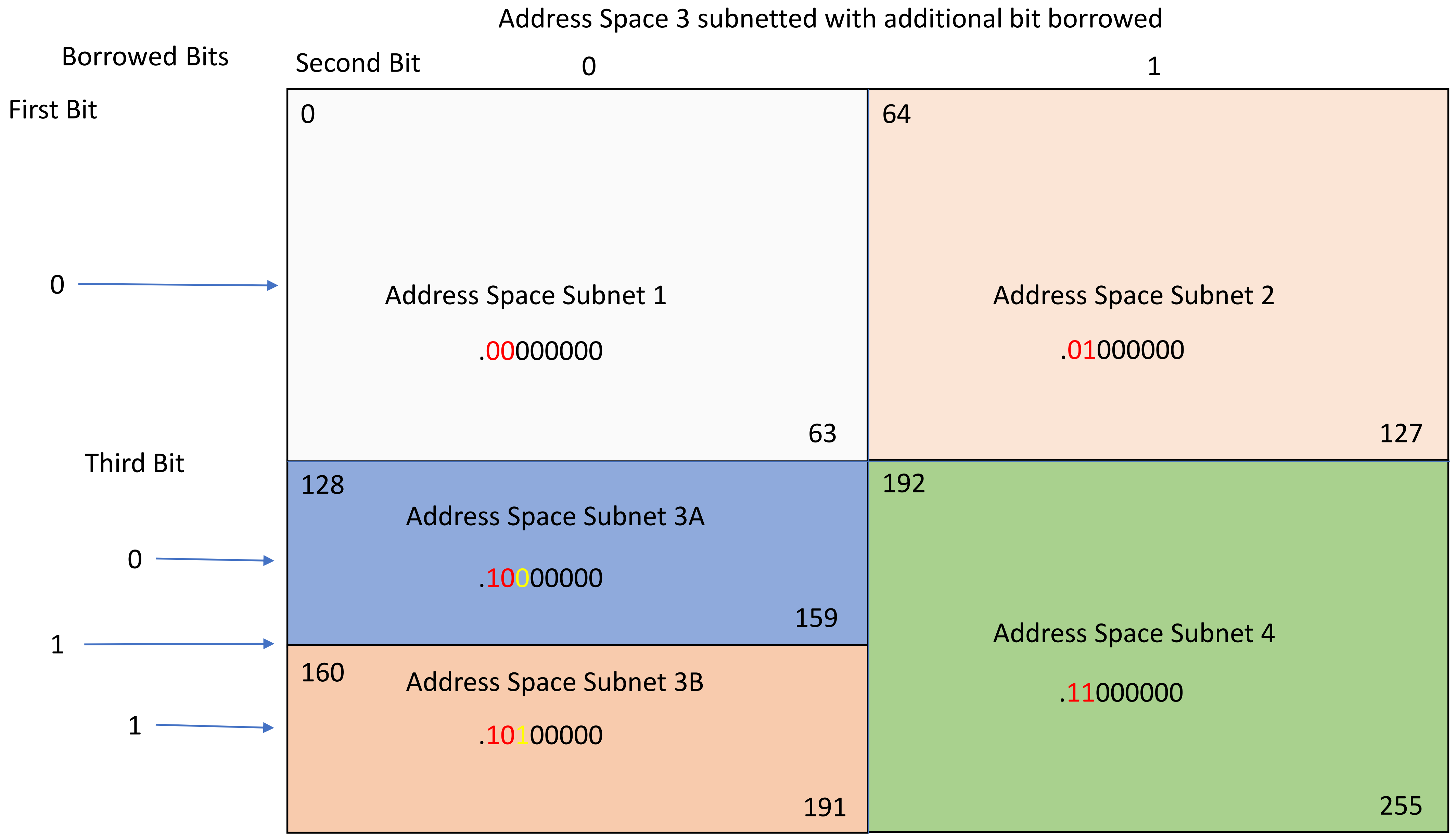


Host Addresses with One Bit Borrowed for Subnetting

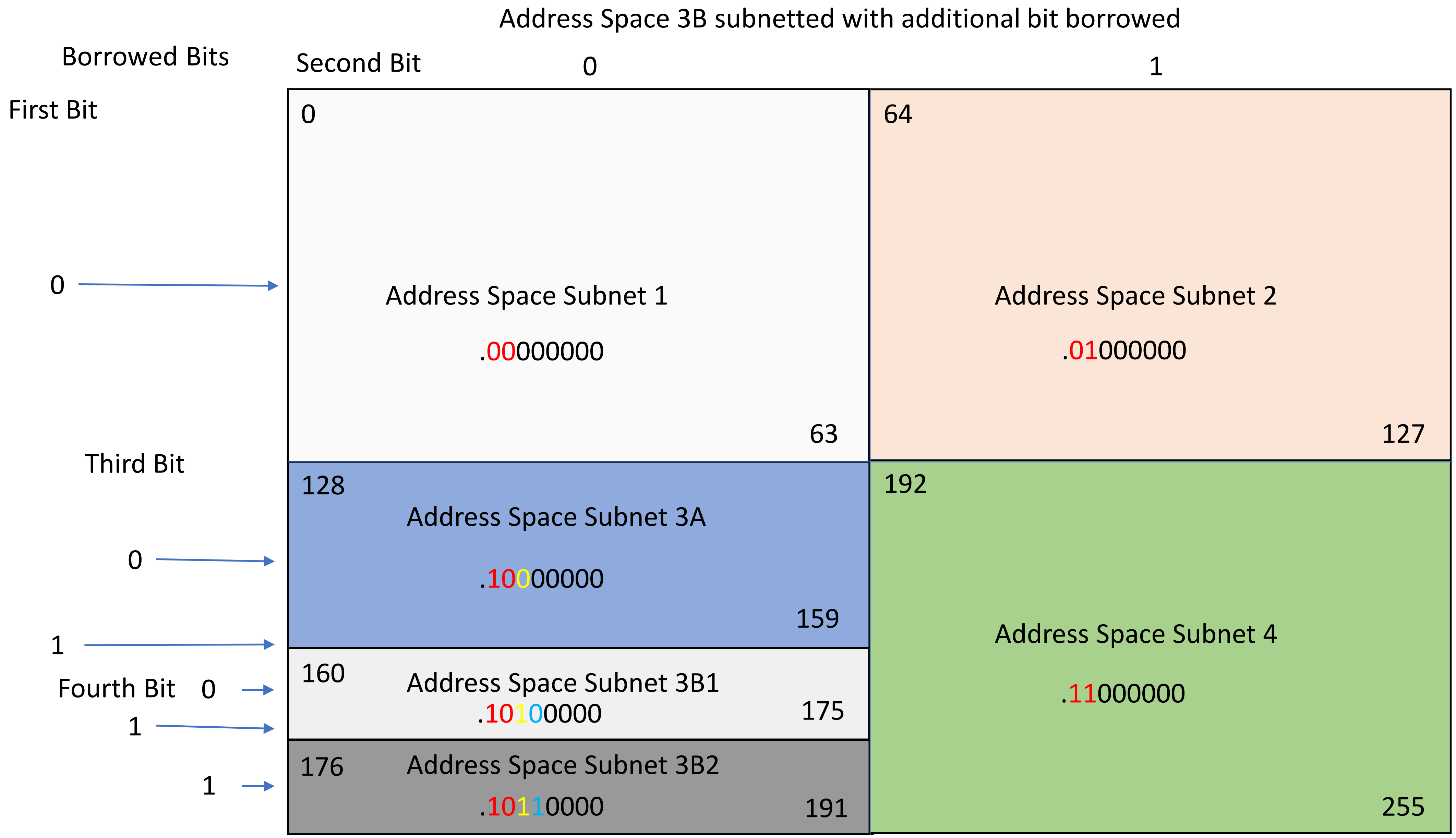


Host Addresses with Two Bits Borrowed for Subnetting

Borrowed Bits First Bit	Second Bit 0	Second Bit 1
0	0 Address Space Subnet 1 .00000000 63	64 Address Space Subnet 2 .01000000 127
1	128 Address Space Subnet 3 .10000000 191	192 Address Space Subnet 4 .11000000 255



Address Space 3 subnetted with additional bit borrowed
Borrowed Bits
Second Bit
0
1
First Bit
0
Third Bit
0
1
1
0
Address Space Subnet 1
.00000000
63
64
Address Space Subnet 2
.01000000
127
128
Address Space Subnet 3A
.10000000
159
160
Address Space Subnet 3B
.10100000
191
192
Address Space Subnet 4
.11000000
255

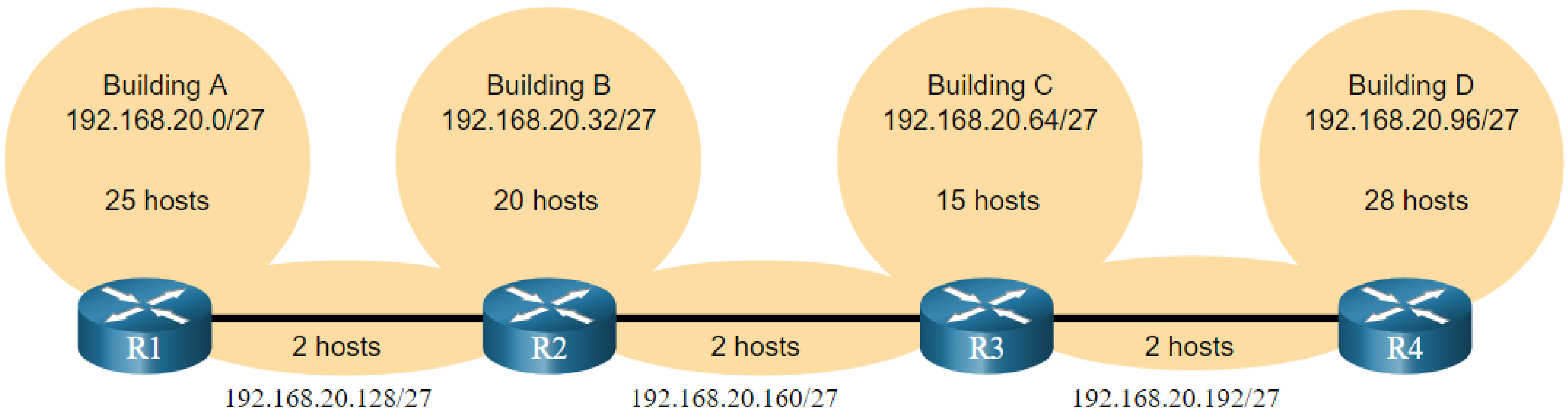


Address Space 3B subnetted with additional bit borrowed
Borrowed Bits
Second Bit
0
1
First Bit
0
Third Bit
0
1
Fourth Bit
0
1
1
0
Address Space Subnet 1
.00000000
63
64
Address Space Subnet 2
.01000000
127
128
Address Space Subnet 3A
.10000000
159
160
Address Space Subnet 3B1
.10100000
175
176
Address Space Subnet 3B2
.10110000
191
192
Address Space Subnet 4
.11000000
255

IPv4 Address Conservation

Given the topology, 7 subnets are required (i.e, four LANs and three WAN links) and the largest number of host is in Building D with 28 hosts.

- A /27 mask would provide 8 subnets of 30 host IP addresses and therefore support this topology.



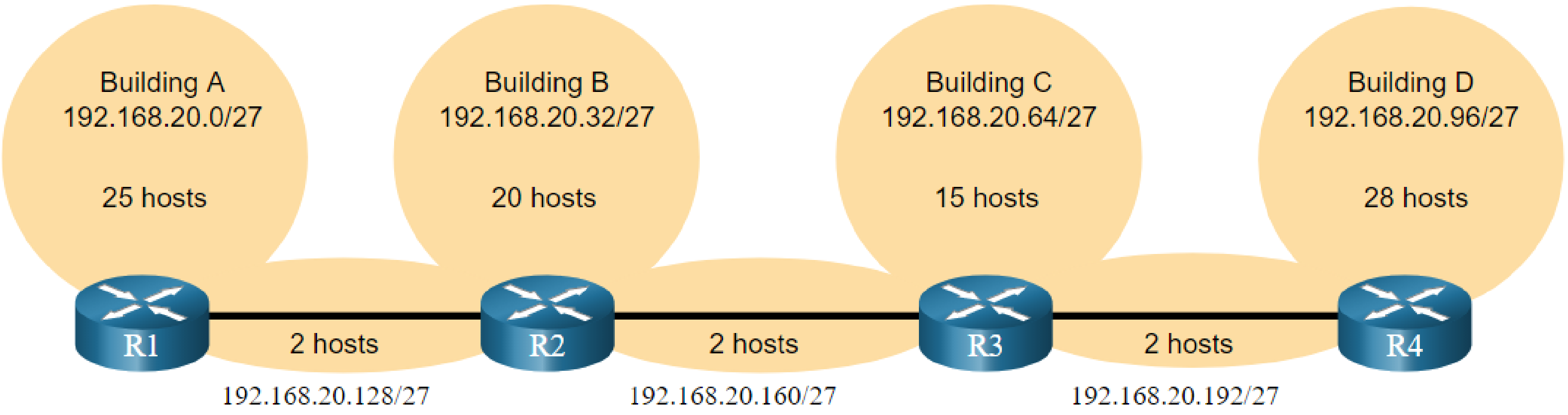
IPv4 Address Conservation (Cont.)

However, the point-to-point WAN links only require two addresses and therefore waste 28 addresses each for a total of 84 unused addresses.

Host portion
2^5 – 2 = 30 host IP addresses per subnet

30 – 2 = 28
Each WAN subnet wastes 28 addresses

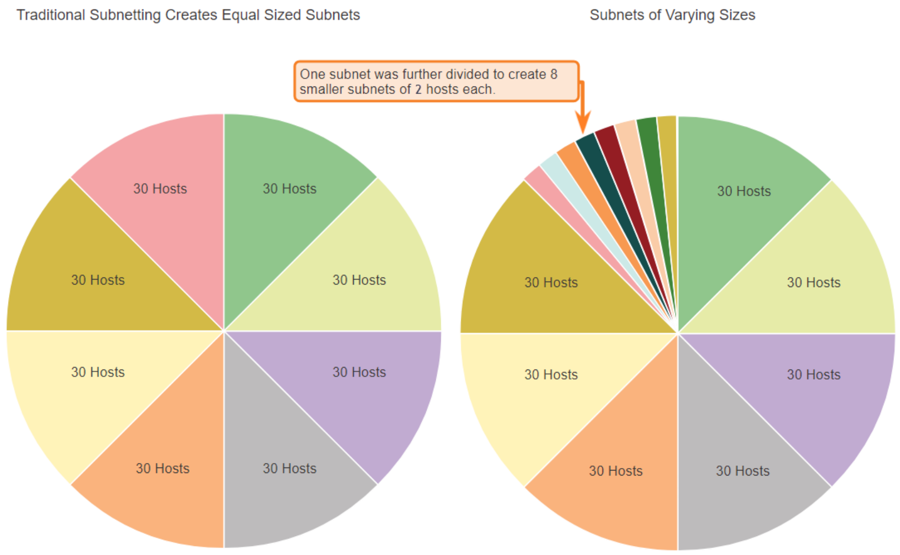
28 x 3 = 84
84 addresses are unused



- Applying a traditional subnetting scheme to this scenario is not very efficient and is wasteful.
- VLSM was developed to avoid wasting addresses by enabling us to subnet a subnet.

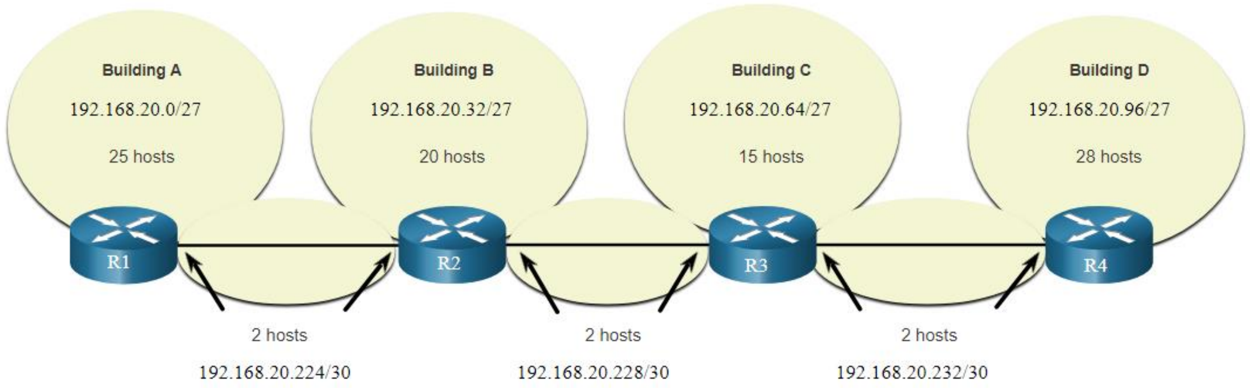
VLSM

- The left side displays the traditional subnetting scheme (i.e., the same subnet mask) while the right side illustrates how VLSM can be used to subnet a subnet and divided the last subnet into eight /30 subnets.



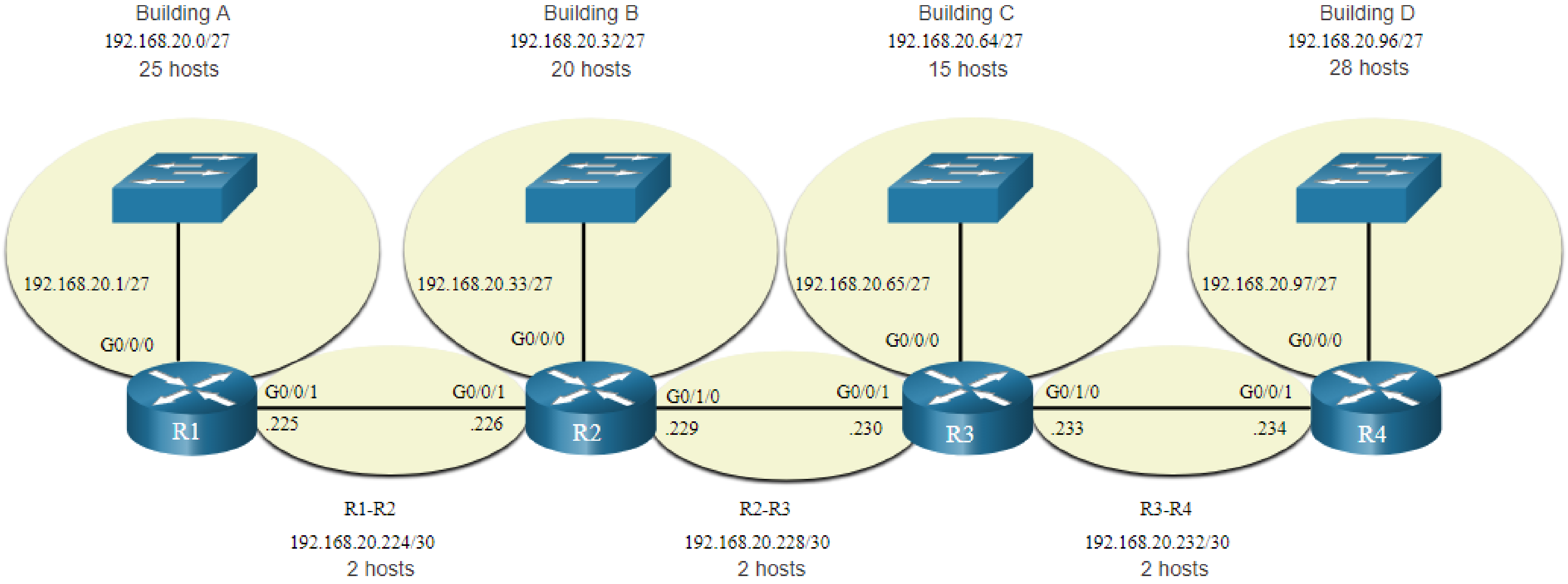
- When using VLSM, always begin by satisfying the host requirements of the largest subnet and continue subnetting until the host requirements of the smallest subnet are satisfied.

- The resulting topology with VLSM applied.



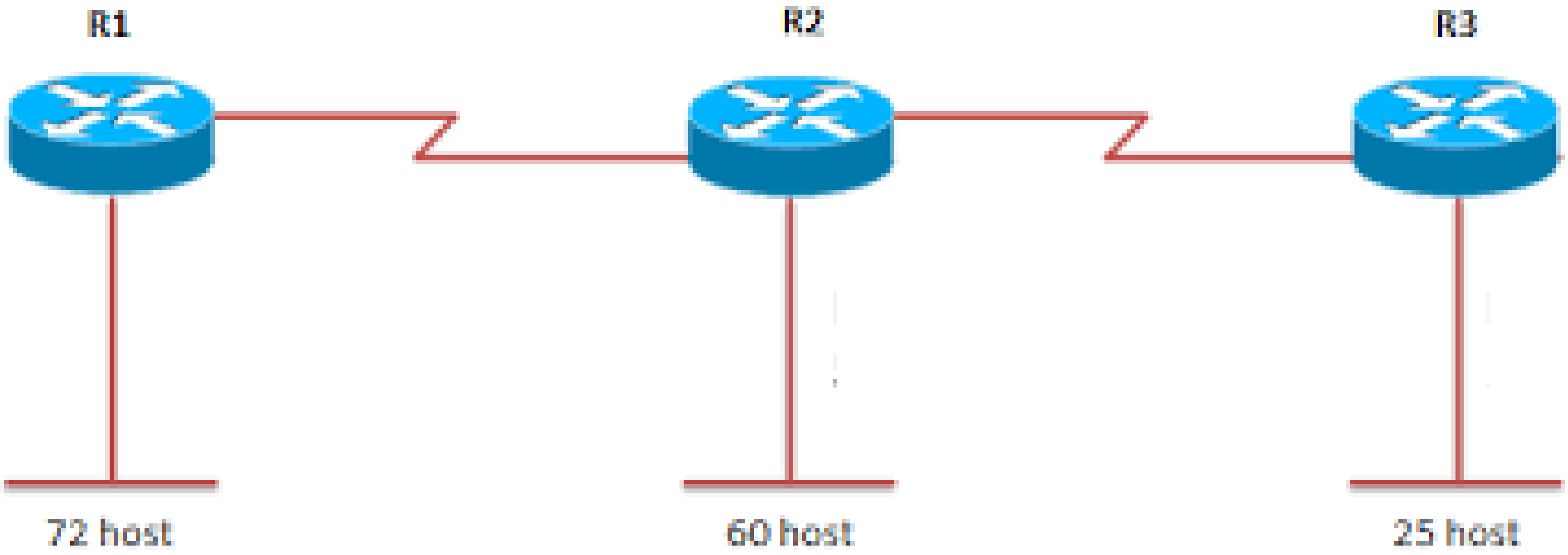
VLSM Topology Address Assignment

- Using VLSM subnets, the LAN and inter-router networks can be addressed without unnecessary waste as shown in the logical topology diagram.



Practice

Given a network address **192.168.100.0/24**. Use VLSM to divide subnet for the following topology.



IPv6 Packets

Limitations of IPv4

IPv4 has three major limitations:

- IPv4 address depletion – We have basically run out of IPv4 addressing.
- Lack of end-to-end connectivity – To make IPv4 survive this long, private addressing and NAT were created. This ended direct communications with public addressing.
- Increased network complexity – NAT was meant as temporary solution and creates issues on the network as a side effect of manipulating the network headers addressing. NAT causes latency and troubleshooting issues.

IPv6 Overview

- IPv6 was developed by Internet Engineering Task Force (IETF).
- IPv6 overcomes the limitations of IPv4.
- Improvements that IPv6 provides:
  - **Increased address space** – based on 128 bit address, not 32 bits
  - **Improved packet handling** – simplified header with fewer fields
  - **Eliminates the need for NAT** – since there is a huge amount of addressing, there is no need to use private addressing internally and be mapped to a shared public address

IPv4 and IPv6 Address Space Comparison

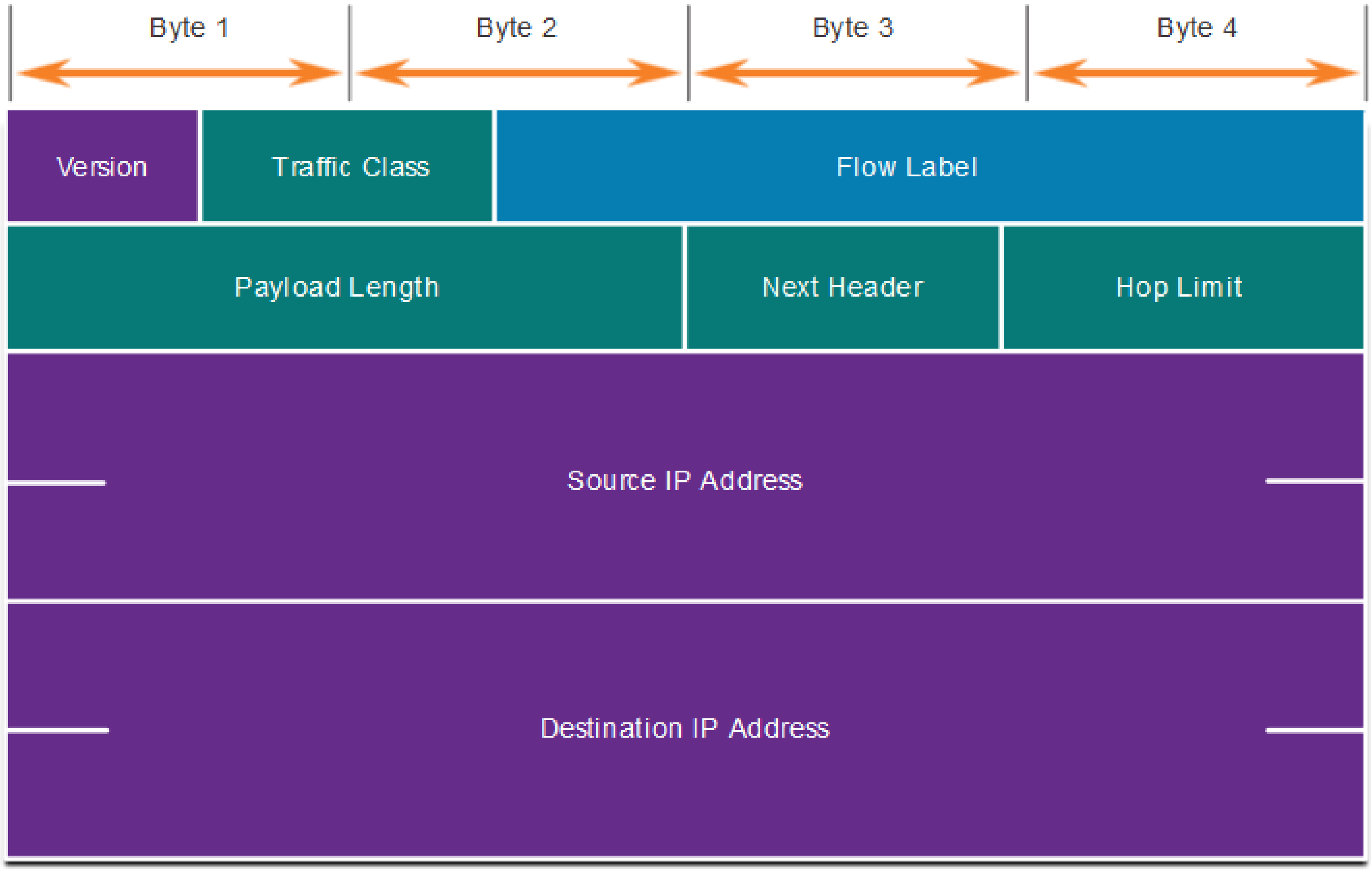
Number Name	Scientific Notation	Number of Zeros
1 Thousand	10^3	1,000
1 Million	10^6	1,000,000
1 Billion	10^9	1,000,000,000
1 Trillion	10^12	1,000,000,000,000
1 Quadrillion	10^15	1,000,000,000,000,000
1 Quintillion	10^18	1,000,000,000,000,000,000
1 Sextillion	10^21	1,000,000,000,000,000,000,000
1 Septillion	10^24	1,000,000,000,000,000,000,000,000
1 Octillion	10^27	1,000,000,000,000,000,000,000,000,000
1 Nonillion	10^30	1,000,000,000,000,000,000,000,000,000,000
1 Decillion	10^33	1,000,000,000,000,000,000,000,000,000,000,000
1 Undecillion	10^36	1,000,000,000,000,000,000,000,000,000,000,000,000

Legend

- There are 4 billion IPv4 addresses
- There are 340 undecillion IPv6 addresses

IPv4 Packet Header Fields in the IPv6 Packet Header

- The IPv6 header is simplified, but not smaller.
- The header is fixed at 40 Bytes or octets long.
- Several IPv4 fields were removed to improve performance.
- Some IPv4 fields were removed to improve performance:
  - Flag
  - Fragment Offset
  - Header Checksum



IPv6 Packet Header

Significant fields in the IPv6 header:

Function	Description
Version	This will be for v6, as opposed to v4, a 4 bit field= 0110
Traffic Class	Used for QoS: Equivalent to DiffServ – DS field
Flow Label	Informs device to handle identical flow labels the same way, 20 bit field
Payload Length	This 16-bit field indicates the length of the data portion or payload of the IPv6 packet
Next Header	I.D.s next level protocol: ICMP, TCP, UDP, etc.
Hop Limit	Replaces TTL field Layer 3 hop count
Source IPv4 Address	128 bit source address
Destination IPV4	128 bit destination address

IPv6 Packet Header (Cont.)

IPv6 packet may also contain extension headers (EH).

EH headers characteristics:

- provide optional network layer information
- are optional
- are placed between IPv6 header and the payload
- may be used for fragmentation, security, mobility support, etc.

Note: Unlike IPv4, routers do not fragment IPv6 packets.

IPv4 and IPv6 Coexistence

Both IPv4 and IPv6 will coexist in the near future and the transition will take several years.

The IETF has created various protocols and tools to help network administrators migrate their networks to IPv6. These migration techniques can be divided into three categories:

- **Dual stack** -The devices run both IPv4 and IPv6 protocol stacks simultaneously.
- **Tunneling** – A method of transporting an IPv6 packet over an IPv4 network. The IPv6 packet is encapsulated inside an IPv4 packet.
- **Translation** - Network Address Translation 64 (NAT64) allows IPv6-enabled devices to communicate with IPv4-enabled devices using a translation technique similar to NAT for IPv4.

Note: Tunneling and translation are for transitioning to native IPv6 and should only be used where needed. The goal should be native IPv6 communications from source to destination.

12.2 IPv6 Address Representation

IPv6 Addressing Formats

- IPv6 addresses are 128 bits in length and written in hexadecimal.
- IPv6 addresses are not case-sensitive and can be written in either lowercase or uppercase.
- The preferred format for writing an IPv6 address is x:x:x:x:x:x:x:x, with each “x” consisting of four hexadecimal values.
- In IPv6, a hextet is the unofficial term used to refer to a segment of 16 bits, or four hexadecimal values.
- Examples of IPv6 addresses in the preferred format:

```
2001:0db8:0000:1111:0000:0000:0000:0200
2001:0db8:0000:00a3:abcd:0000:0000:1234
```

IPv6 Address Representation

Rule 1 – Omit Leading Zero

The first rule to help reduce the notation of IPv6 addresses is to omit any leading 0s (zeros).

Examples:

- 01ab can be represented as 1ab
- 09f0 can be represented as 9f0
- 0a00 can be represented as a00
- 00ab can be represented as ab

Note: This rule only applies to leading 0s, NOT to trailing 0s, otherwise the address would be ambiguous.

Type	Format
Preferred	2001 : **0**db8 : **000**0 : 1111 : **000**0 : **000**0 : **000**0 : **0**200
No leading zeros	2001 : db8 : 0 : 1111 : 0 : 0 : 0 : 200

IPv6 Address Representation

Rule 2 – Double Colon

A double colon (::) can replace any single, contiguous string of one or more 16-bit hextets consisting of all zeros.

Example:

- 2001:db8:cafe:1:0:0:0:1 (leading 0s omitted) could be represented as 2001:db8:cafe:1::1

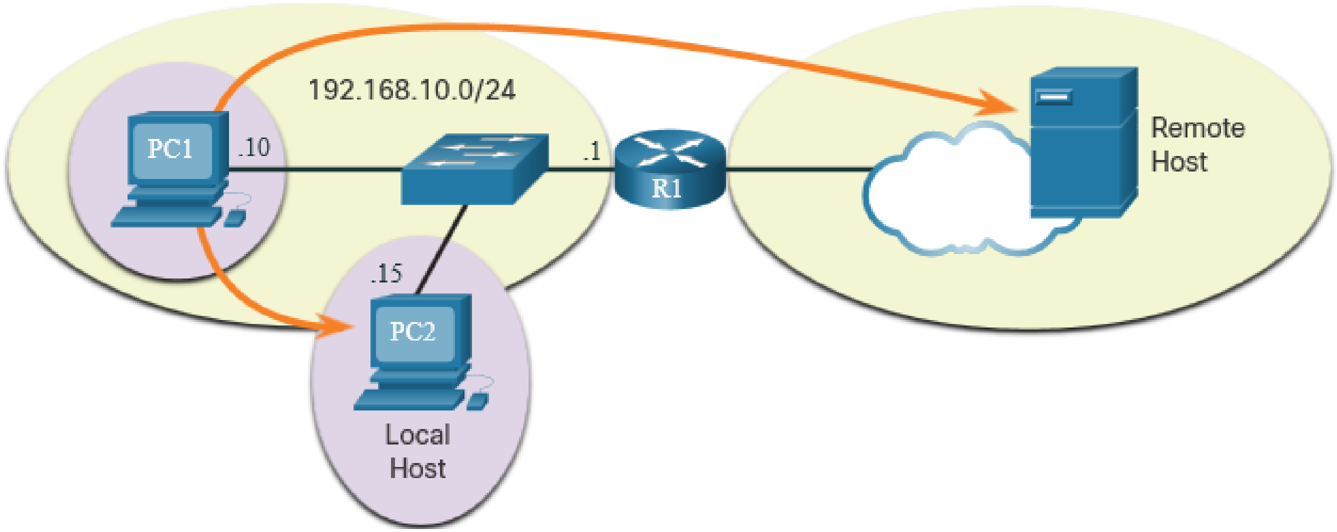
Note: The double colon (::) can only be used once within an address, otherwise there would be more than one possible resulting address.

Type	Format
Preferred	2001 : **0**db8 : **000**0 : 1111 : **0000** : **0000** : **0000** : **0**200
Compressed	2001:db8:0:1111::200

How a Host Routes

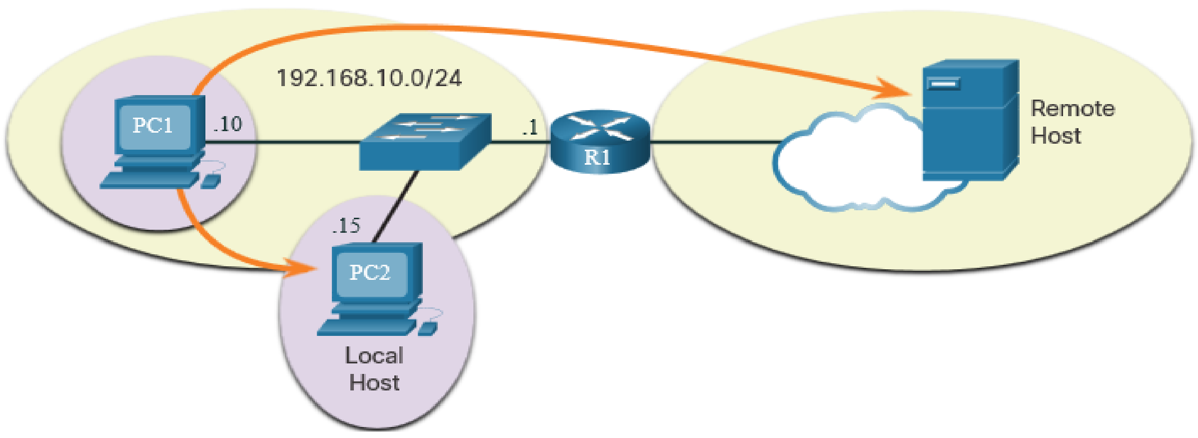
Host Forwarding Decision

- Packets are always created at the source.
- Each host devices creates their own routing table.
- A host can send packets to the following:
  - Itself – 127.0.0.1 (IPv4), ::1 (IPv6)
  - Local Hosts – destination is on the same LAN
  - Remote Hosts – devices are not on the same LAN



Host Forwarding Decision (Cont.)

- The Source device determines whether the destination is local or remote
- Method of determination:
  - IPv4 – Source uses its own IP address and Subnet mask, along with the destination IP address
  - IPv6 – Source uses the network address and prefix advertised by the local router
- Local traffic is dumped out the host interface to be handled by an intermediary device.
- Remote traffic is forwarded directly to the default gateway on the LAN.



Default Gateway

A router or layer 3 switch can be a default-gateway.

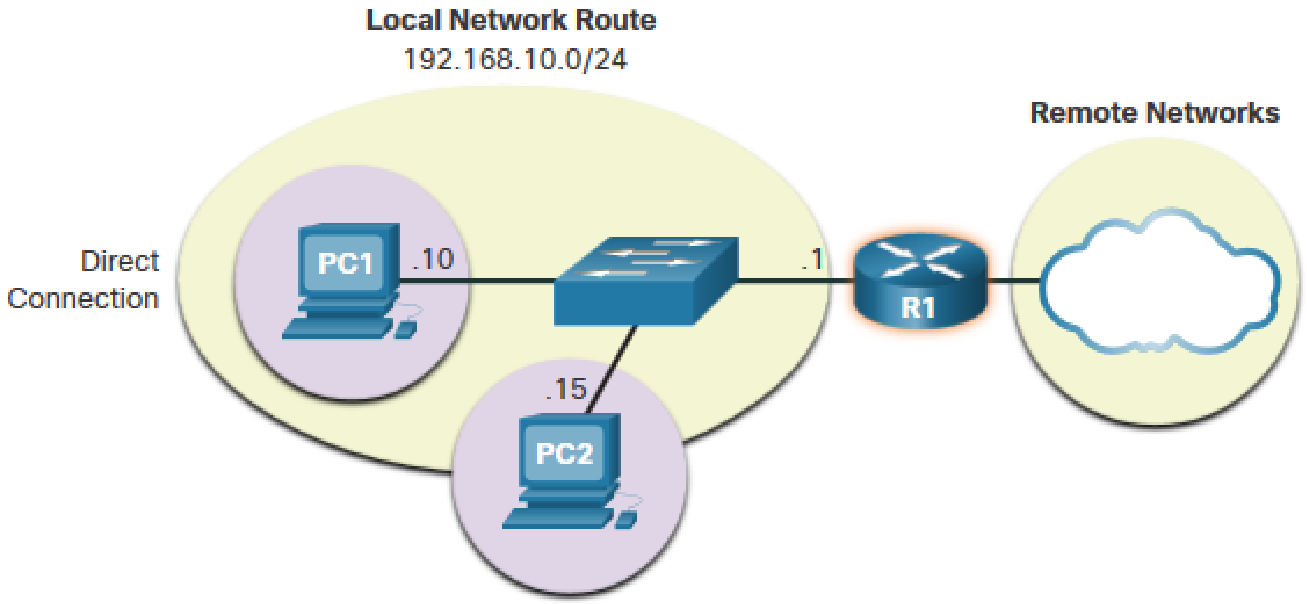
Features of a default gateway (DGW):

- It must have an IP address in the same range as the rest of the LAN.
- It can accept data from the LAN and is capable of forwarding traffic off of the LAN.
- It can route to other networks.

If a device has no default gateway or a bad default gateway, its traffic will not be able to leave the LAN.

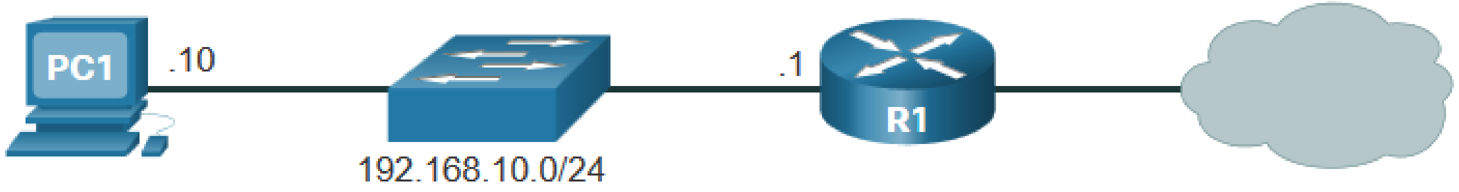
A Host Routes to the Default Gateway

- The host will know the default gateway (DGW) either statically or through DHCP in IPv4.
- IPv6 sends the DGW through a router solicitation (RS) or can be configured manually.
- A DGW is static route which will be a last resort route in the routing table.
- All device on the LAN will need the DGW of the router if they intend to send traffic remotely.



Host Routing Tables

- On Windows, route print or netstat -r to display the PC routing table
- Three sections displayed by these two commands:
  - Interface List – all potential interfaces and MAC addressing
  - IPv4 Routing Table
  - IPv6 Routing Table



IPv4 Routing Table for PC1

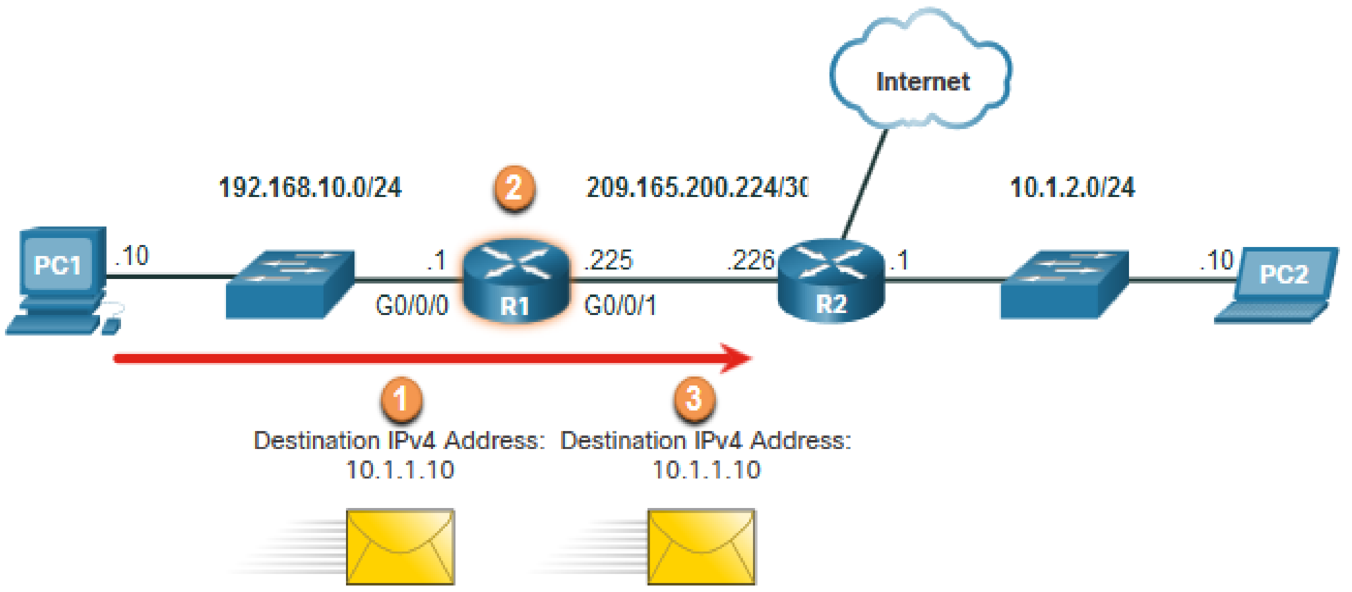
```
C:\Users\PC1> netstat -r

IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0     192.168.10.1    192.168.10.10     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
     192.168.10.0    255.255.255.0         On-link     192.168.10.10    281
    192.168.10.10  255.255.255.255         On-link     192.168.10.10    281
   192.168.10.255  255.255.255.255         On-link     192.168.10.10    281
        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     192.168.10.10    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     192.168.10.10    281
```

Introduction to Routing

Router Packet Forwarding Decision

What happens when the router receives the frame from the host device?



R1 Routing Table

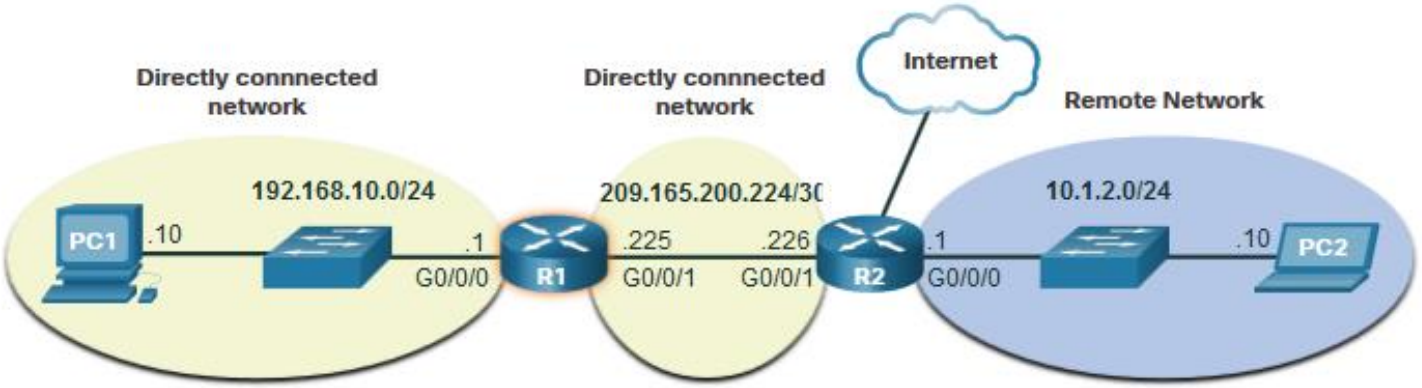
Route	Next Hop or Exit Interface
192.168.10.0 /24	G0/0/0
209.165.200.224/30	G0/0/1
10.1.1.0/24	**via R2**
Default Route 0.0.0.0/0	via R2

1. Packet arrives on the Gigabit Ethernet 0/0/0 interface of router R1. R1 de-encapsulates the Layer 2 Ethernet header and trailer.
2. Router R1 examines the destination IPv4 address of the packet and searches for the best match in its IPv4 routing table. The route entry indicates that this packet is to be forwarded to router R2.
3. Router R1 encapsulates the packet into a new Ethernet header and trailer, and forwards the packet to the next hop router R2.

IP Router Routing Table

There three types of routes in a router's routing table:

- **Directly Connected** – These routes are automatically added by the router, provided the interface is active and has addressing.
- **Remote** – These are the routes the router does not have a direct connection and may be learned:
  - Manually – with a static route
  - Dynamically – by using a routing protocol to have the routers share their information with each other
- **Default Route** – this forwards all traffic to a specific direction when there is not a match in the routing table

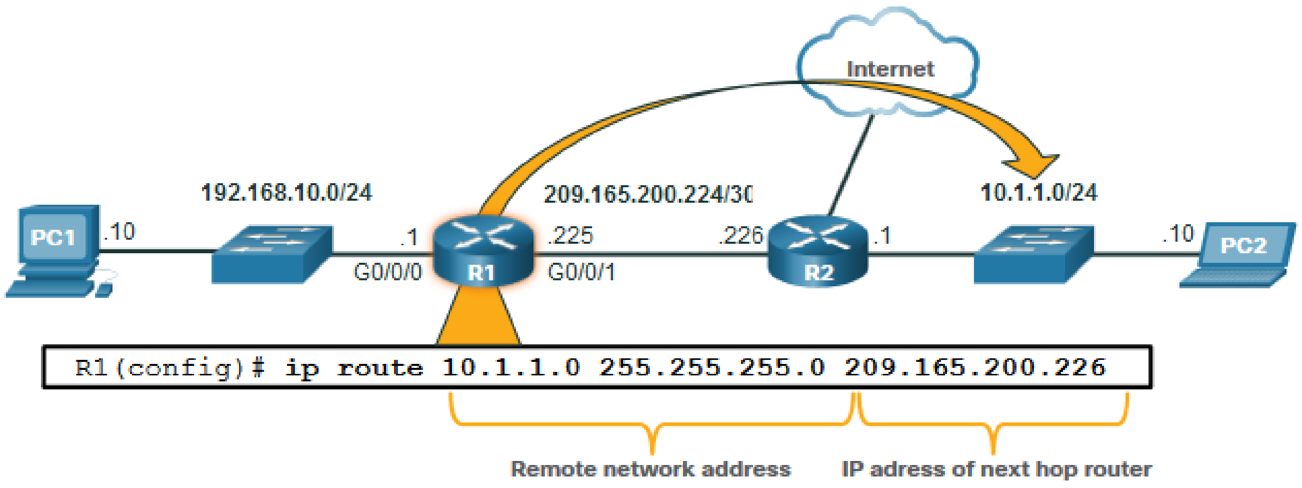


Introduction to Routing

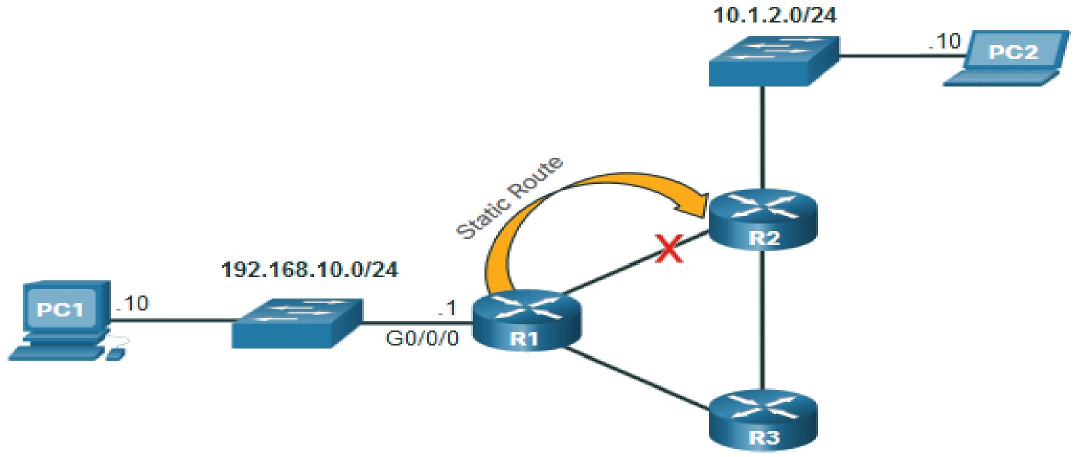
Static Routing

Static Route Characteristics:

- Must be configured manually
- Must be adjusted manually by the administrator when there is a change in the topology
- Good for small non-redundant networks
- Often used in conjunction with a dynamic routing protocol for configuring a default route



R1 is manually configured with a static route to reach the 10.1.1.0/24 network. If this path changes, R1 will require a new static route.



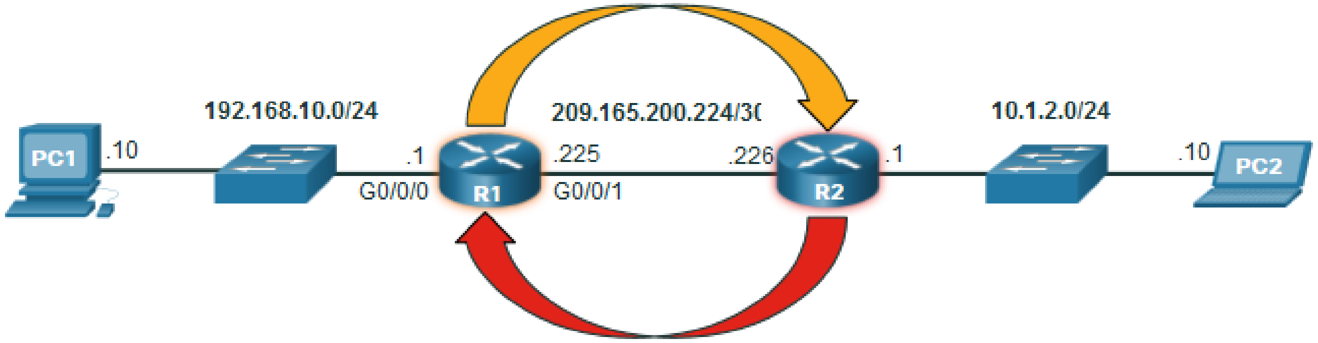
If the route from R1 via R2 is no longer available, a new static route via R3 would need to be configured. A static route does not automatically adjust for topology changes.

Dynamic Routing

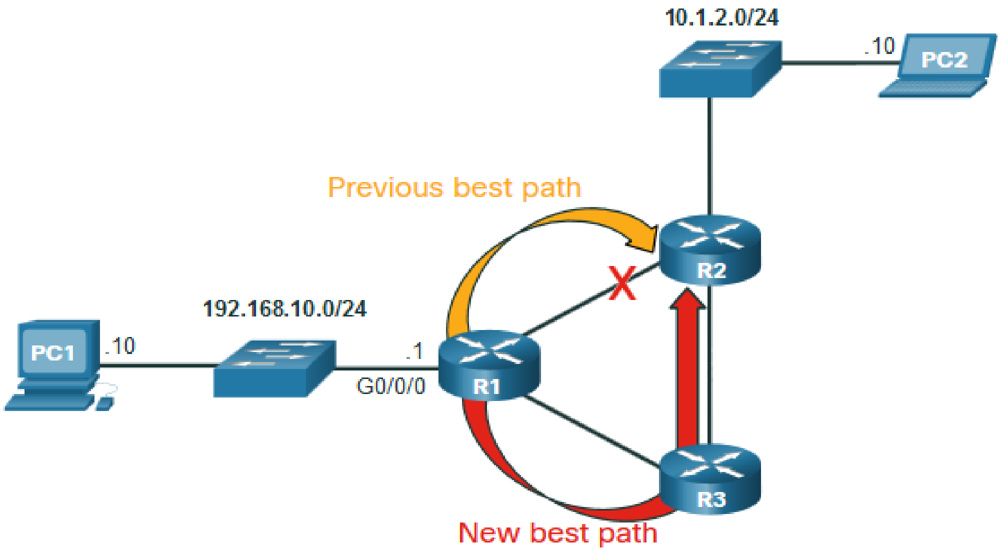
Dynamic Routes Automatically:

- Discover remote networks
- Maintain up-to-date information
- Choose the best path to the destination
- Find new best paths when there is a topology change

Dynamic routing can also share static default routes with the other routers.



- R1 is using the routing protocol OSPF to let R2 know about the 192.168.10.0/24 network.
- R2 is using the routing protocol OSPF to let R1 know about the 10.1.1.0/24 network.



R1, R2, and R3 are using the dynamic routing protocol OSPF. If there is a network topology change, they can automatically adjust to find a new best path.

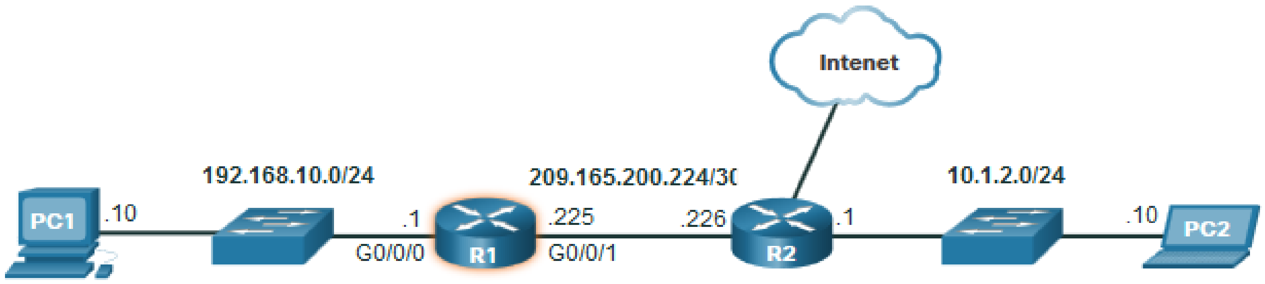
Introduction to an IPv4 Routing Table

The **show ip route** command shows the following route sources:

- **L** - Directly connected local interface IP address
- **C** – Directly connected network
- **S** – Static route was manually configured by an administrator
- **O** – OSPF
- **D** – EIGRP

This command shows types of routes:

- Directly Connected – C and L
- Remote Routes – O, D, etc.
- Default Routes – S*




```
R1# show ip route
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
       D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
       N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
       E1 - OSPF external type 1, E2 - OSPF external type 2
       i - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
       ia - IS-IS inter area, * - candidate default, U - per-user static route
       o - ODR, P - periodic downloaded static route, H - NHRP, l - LISP
       a - application route
       + - replicated route, % - next hop override, p - overrides from PfR
Gateway of last resort is 209.165.200.226 to network 0.0.0.0
S*    0.0.0.0/0 [1/0] via 209.165.200.226, GigabitEthernet0/0/1
      10.0.0.0/24 is subnetted, 1 subnets
O        10.1.1.0 [110/2] via 209.165.200.226, 00:02:45, GigabitEthernet0/0/1
      192.168.10.0/24 is variably subnetted, 2 subnets, 2 masks
C        192.168.10.0/24 is directly connected, GigabitEthernet0/0/0
L        192.168.10.1/32 is directly connected, GigabitEthernet0/0/0
      209.165.200.0/24 is variably subnetted, 2 subnets, 2 masks
C        209.165.200.224/30 is directly connected, GigabitEthernet0/0/1
L        209.165.200.225/32 is directly connected, GigabitEthernet0/0/1
R1#
```