Lecture 5 – Network Layer and IP Addressing

COMP1002 (Cybersecurity and Networks)

Overview

- Network layer (CCNA1 - ch8)
  - The role of the Network layer - describe communication from one end device to another end device.
  - Internet Protocol (IP) and its features for providing connectionless and best-effort service.
- Basic router configuration (ch10)
- IPv4 addressing (ch11)
  - The division, or grouping, of devices into networks.
  - Hierarchical addressing of devices and how this allows communication between networks.
  - The fundamentals of routes, next-hop addresses, and packet forwarding to a destination network.

Part 1: Network Layer

Aim and objectives

- Aim: the Network layer (OSI Layer 3) provides services to exchange the individual pieces of data over the network between identified end devices.
- Basic processes:
  - Addressing
  - Encapsulation
  - Routing
  - Decapsulation

Processes

- Addressing – provided addresses must be unique
- Encapsulation – add src/dst address to each network layer PDU (packet)
- Routing - provide services to direct the packets to their destination host
- Decapsulation – extract content of the packet at the destination host

Protocols

- Internet Protocol version 4 (IPv4)
- Internet Protocol version 6 (IPv6)

IPv4

- RFC791 – September 1981
- The standard for the current Internet
  - IPv6 - only isolated and encapsulated in IPv4
- IP - low overhead, only delivery of packets from source to destination over an interconnected network(s).
- Characteristics
  - Connectionless - No connection is established before sending data packets.
  - Best Effort (unreliable) - No overhead is used to guarantee packet delivery.
  - Media Independent - Operates independently of the medium carrying the data.

Characteristics

- Connectionless service = no prior notification of the recipient
  - No confirmation of arrival
  - Therefore, IP has:
    - No additional control fields in header
    - No control data
    - No knowledge of end-to-end delivery
- Media independence = no specific requirements for the link layer
  - No strict packet size
  - No single transport medium
- Best effort = No reliability
  - No guarantees about delivery
  - No capability to manage or recover from loss
  - Therefore, IP has no control fields in the header and no packet tracking

IPv4 header

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version|  IHL  |Type of Service|          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time to Live |    Protocol   |         Header Checksum       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

IPv4 fields

- IP Source / Destination Address (32b)
- Time-to-Live (TTL) (8b) - the remaining "life" of the packet.
  - Decreased by at least one each time the packet is processed by a router
  - When the value becomes zero, the router discards or drops the packet and it is removed from the network data flow.
  - This mechanism prevents routing loops

IPv4 fields (cont)

- Protocol (8b) - data payload type
  - Enables Network layer to pass data to appropriate upper-layer protocol.
  - e.g.: 01 ICMP, 06 TCP, 17 UDP
- Type-of-Service (TOS) (8b) – priority
  - To be used by Quality-of-Service (QoS)
- Fragment Offset (13b)
  - Router may fragment a packet when forwarding it from one medium to another medium that has a smaller MTU.
  - IPv4 uses Fragment Offset and the MF flag to reconstruct the packet at the destination host.
- More Fragments (MF) flag – (1b)
  - MF=1 - not the last fragment of a packet.
  - MF=0 – last fragment of a packet, reconstruct
- Don't Fragment flag
  - DF=1 – fragmentation is not allowed

Transport across networks

- If communication is between hosts in different networks, the local network delivers the packet from the source to its gateway router
- Router examines the network portion of destination address and forwards the packet to the appropriate interface.
  - If destination network is directly connected, the packet is forwarded directly to that host.
  - If the destination network is not directly connected, the packet is forwarded to a second router (next-hop router)
- At each hop, the forwarding decisions are based on the information in the IP packet header

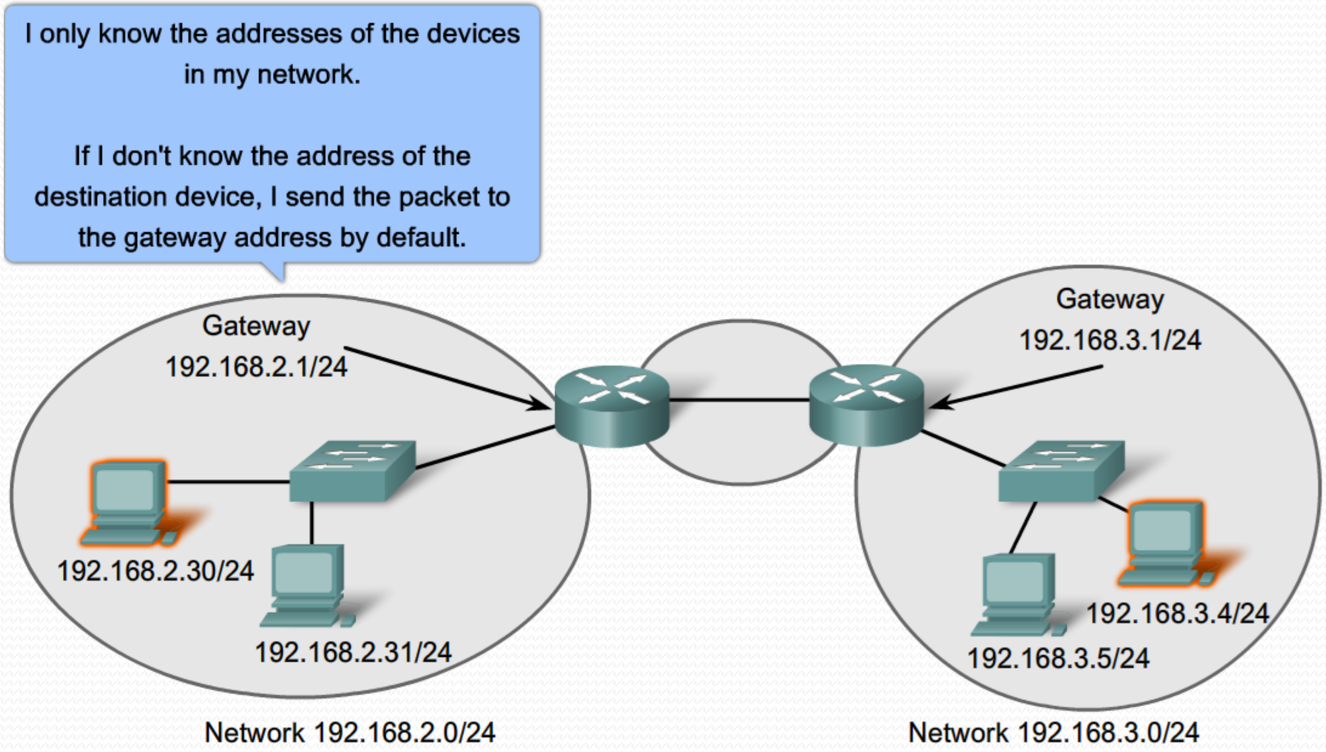
Routing

- No packet can be forwarded without a route - the device must have a route to identify where to forward the packet.
- A host must either forward a packet to the host on the local network or to the gateway, as appropriate
  - The host must have routes that represent these destinations.
- A router makes a forwarding decision for each packet that arrives at the gateway interface.
  - This forwarding process is referred to as routing.
- The destination network may be a number of routers or hops away from the gateway.
  - The route only indicates the next-hop router, not the final router.

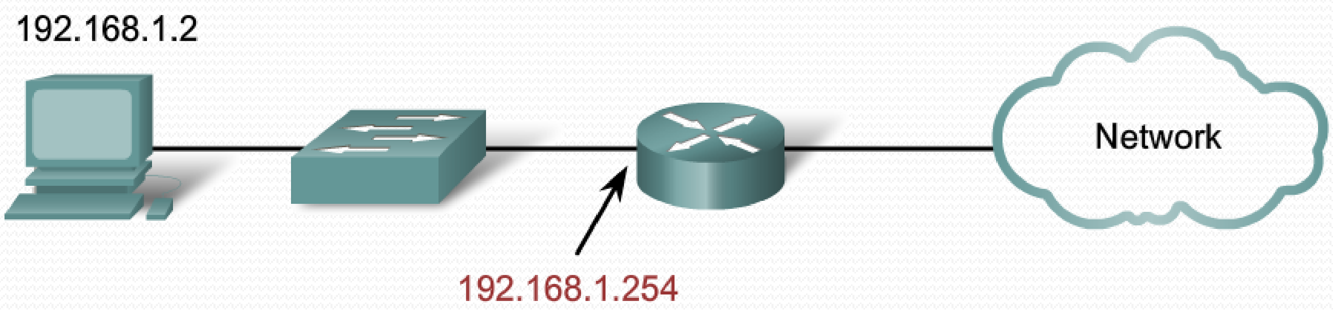
Forwarding process

- Routing - packet-by-packet and hop-by-hop.
- Each packet is treated independently in each router along the path.
  - Examine destination IP address and check routing table for forwarding information.
- The router will either:
  - Forward packet to the next-hop router
  - Forward packet to the destination host
  - Drop packet

Using the gateway



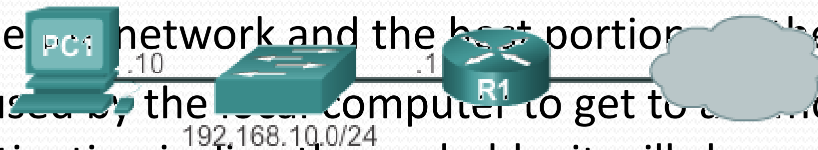
IPv4 routing table – host




```
Interface List
0x2 ...00 0f fe 26 f7 7b ...  Gigabit Ethernet - Packet Scheduler Miniport
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0    192.168.1.254     192.168.1.2      20
      192.168.1.0    255.255.255.0      192.168.1.2     192.168.1.2      20
Default Gateway:     192.168.1.254
// output omitted //
===========================================================================
```

IPv4 routing table – host

- Network Destination - reachable networks.
- Netmask - determine network and the host portion e IP address.
- Gateway - address u the computer to get to ote network destination. If a destination is directly reachable, it will show as "on-link" in this column.
- Interface - a o the gateway that is used t
- Metric - cost a destination.

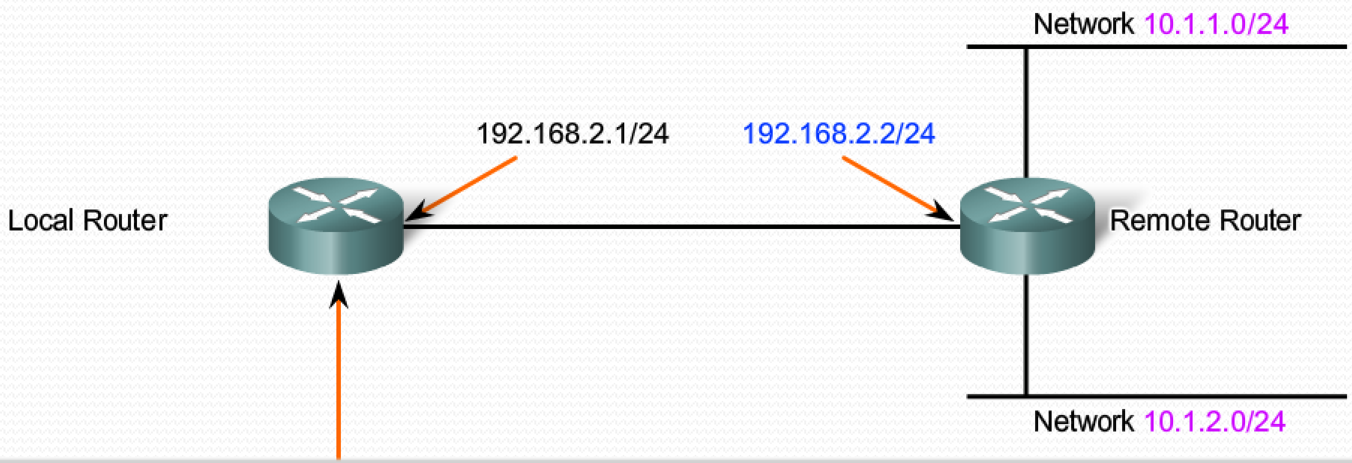



```
C:\Users\PC1>netstat -r

<Output omitted>

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
===========================================================================

<Output omitted>
```

IPv4 routing table - host

- 0.0.0.0 - default route
- 127.0.0.0 – 127.255.255.255 – loopback
- 192.168.10.0 - 192.168.10.255 – local network
  - 192.168.10.0 - The local network route address
  - 192.168.10.10 - The address of the local host.
  - 192.168.10.255 - The network broadcast address
- 224.0.0.0 - multicast class D addresses
- 255.255.255.255 – limited broadcast IP address values for loopback interface (127.0.0.1) or the host IP address (192.168.10.10)

Routing tables

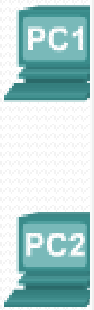


10.0.0.0/24 is subnetted, 2 subnets
R 10.1.1.0 [120/1] via 192.168.2.2, 00:00:08, FastEthernet0/0
R 10.1.2.0 [120/1] via 192.168.2.2, 00:00:08, FastEthernet0/0
C 192.168.2.0/24 is directly connected, FastEthernet0/0

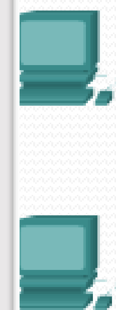
Routing table - router

- Directly-connected routes – from active router interfaces.
  - Added when an interface is configured/activated with an IP address
- Remote routes - from remote networks connected to other routers.
  - Either be manually configured on the local router by the network administrator or dynamically configured by enabling the local router to exchange routing information with other routers using dynamic routing protocols.

Routing table - router




```
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, E - EGP
       i - IS-IS, 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
Gateway of last resort is not set
     10.0.0.0/8 is variably subnetted, 2 subnets, 2 masks
D       10.1.1.0/24 [90/2170112] via 209.165.200.226, 00:00:05,
        Serial0/0/0
     192.168.10.0/24 is variably subnetted, 2 subnets, 3 masks
C       192.168.10.0/24 is directly connected, GigabitEthernet0/0
L       192.168.10.1/32 is directly connected, GigabitEthernet0/0
     192.168.11.0/24 is variably subnetted, 2 subnets, 3 masks
C       192.168.11.0/24 is directly connected, GigabitEthernet0/1
L       192.168.11.1/32 is directly connected, GigabitEthernet0/1
     209.165.200.0/24 is variably subnetted, 2 subnets, 3 masks
C       209.165.200.224/30 is directly connected, Serial0/0/0
L       209.165.200.225/32 is directly connected, Serial0/0/0
R1#
```

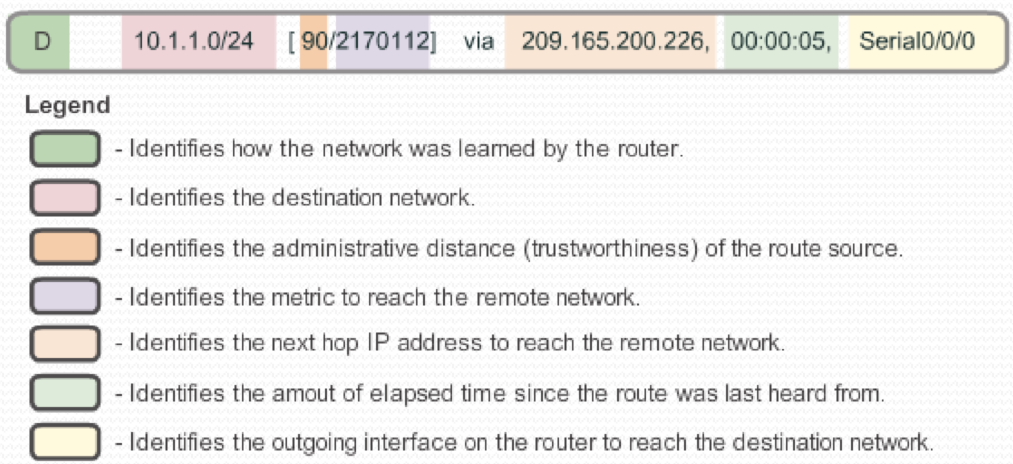


Routing table - router

- Directly connected interfaces
  - C - directly connected network, automatically created when an interface is configured with an IP address and activated.
  - L - link local route, automatically created when an interface is configured with an IP address and activated.
- Remote networks
  - S - route was manually created by an administrator to reach a specific network. This is known as a static route.
  - D - route was learned dynamically from another router using the Enhanced Interior Gateway Routing Protocol (EIGRP).
  - O - route was learned dynamically from another router using the Open Shortest Path First (OSPF) routing protocol.

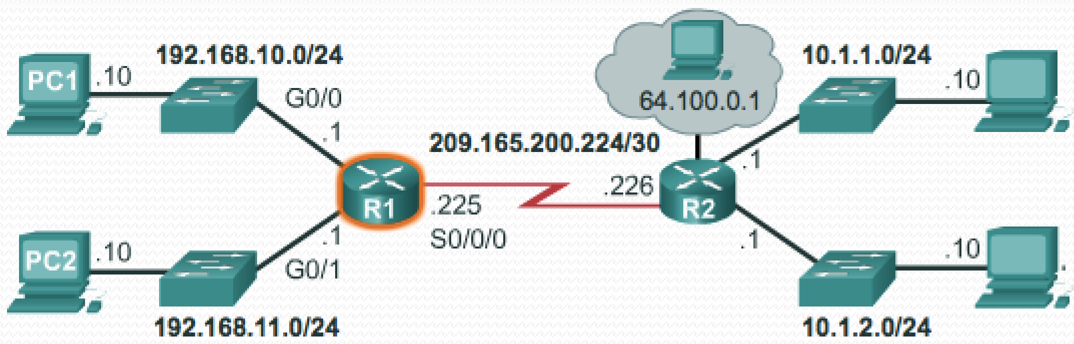
Routing table – router

- Route source - Identifies how the route was learned.
- Destination network - Identifies the address of the remote network.
- Administrative distance - Identifies the trustworthiness of the route source.
- Metric - value assigned to reach the remote network - lower values indicate preferred routes.
- Next-hop - Identifies the IP address of the next router to forward the packet.
- Route timestamp - Identifies when the route was last heard from
- Outgoing interface - exit interface to forward a packet to final destination.



Routing examples

- PC1 to 192.168.10.1
- PC1 to 192.168.11.10
- PC1 to 209.165.200.226
- PC1 to 10.1.1.10



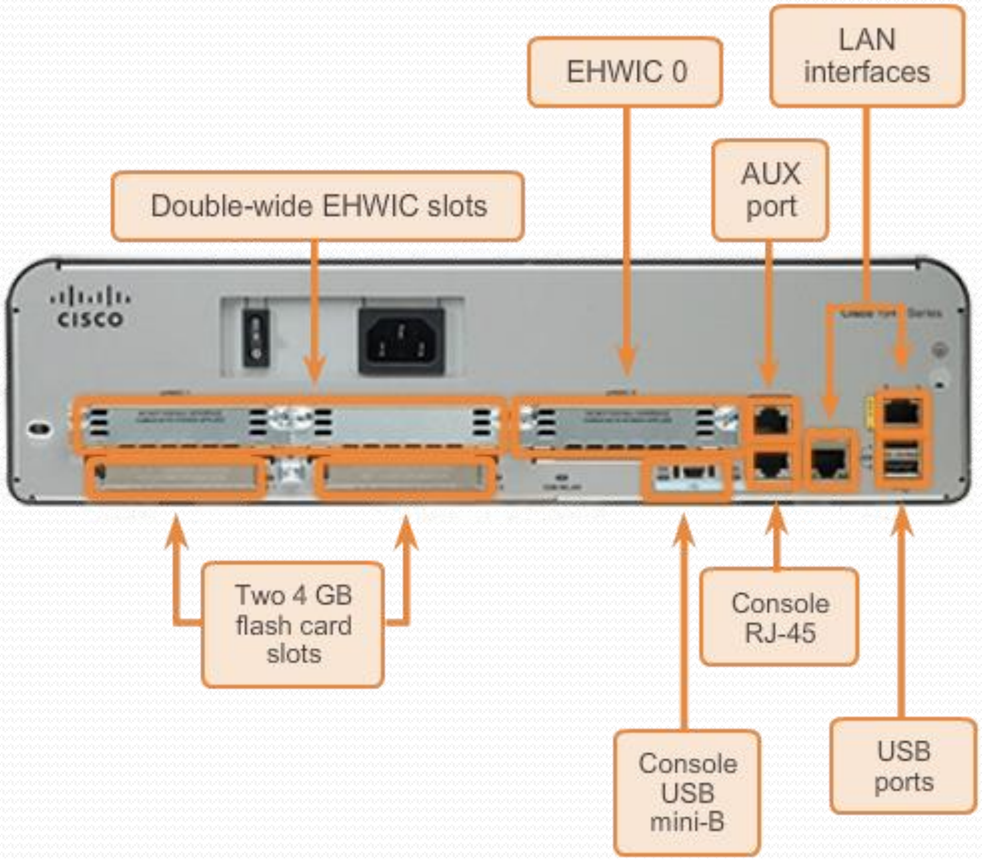
IOS

- Internetworking Operating System
  - used by Cisco in its routers
- Certain models include a GUI, but typical configuration is done via CLI
- At boot:
  - startup-config (NVRAM) is copied into RAM and stored as the running-config file.
  - IOS executes running-config.
  - Any changes are stored in running-config and are immediately implemented by the IOS

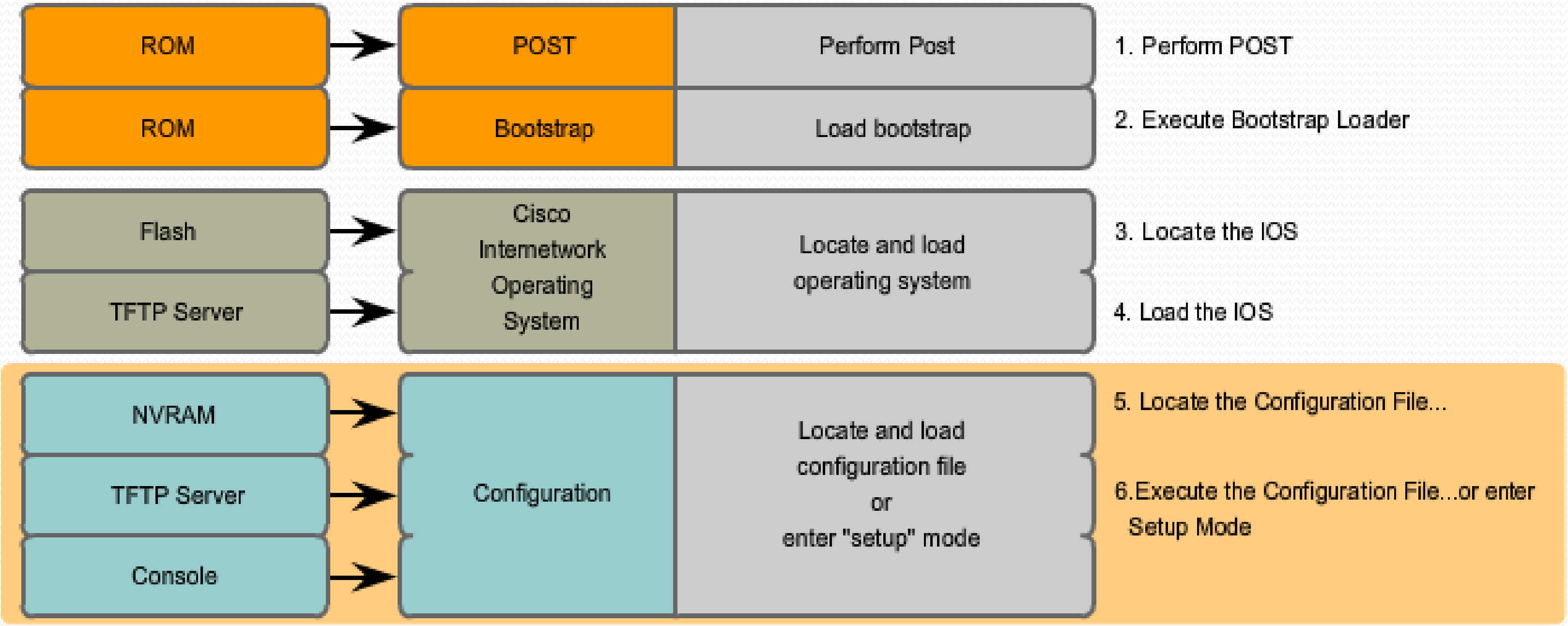
Interfaces

- Management ports
  - Console port – serial communication
  - Auxiliary port – similar to console, also modem
- Network ports
  - LAN - Ethernet/Fast Ethernet
  - Enhanced high-speed WAN interface card (EHWIC) slots - provide modularity and flexibility by enabling the router to support different types of interface modules, including Serial, digital subscriber line (DSL), switch port, and wireless.

Interfaces


EHWIC 0
LAN interfaces
AUX port
Double-wide EHWIC slots
Two 4 GB flash card slots
Console RJ-45
Console USB mini-B
USB ports

Boot process



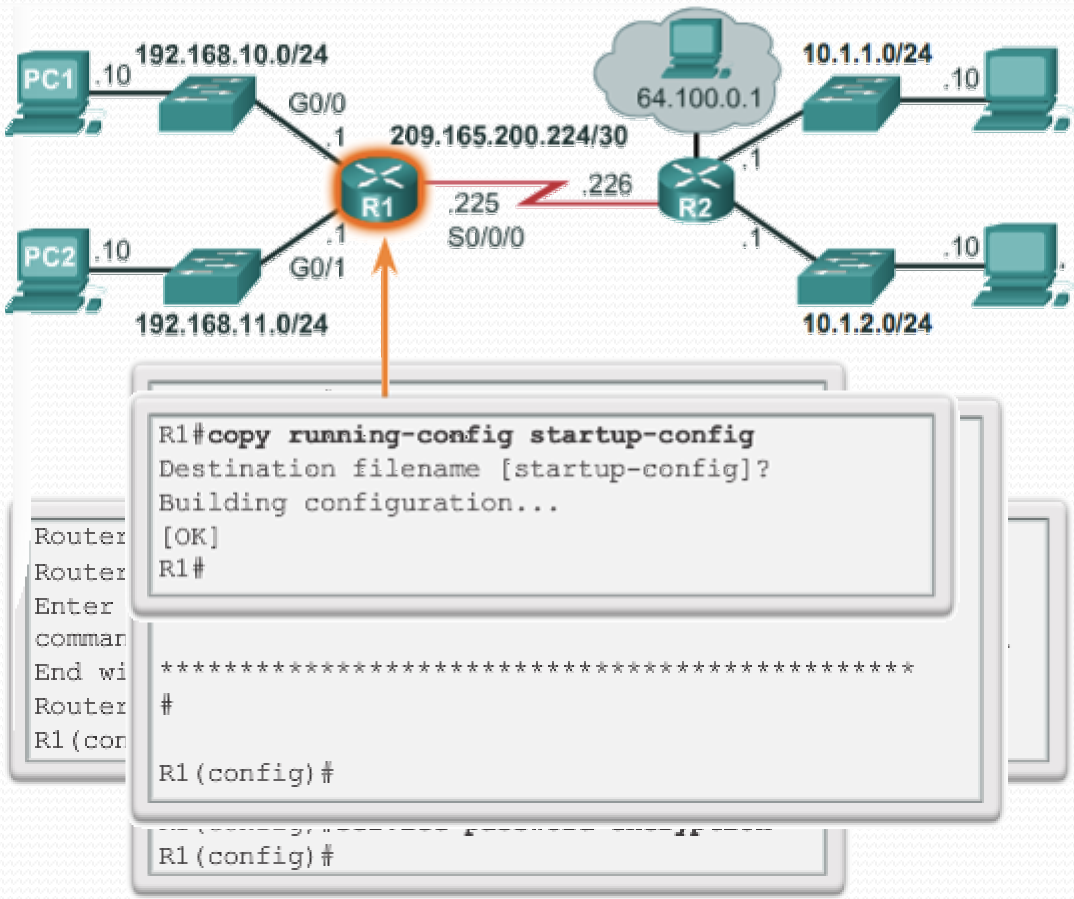
Boot process

- Performing POST (Power On Self Test)
  - Test router hardware
- Loading the bootstrap program
  - Copy bootstrap from ROM to RAM and execute
- Locate and load the Cisco IOS software
  - IOS can be stored on flash, tftp server, etc
  - Copy/extract IOS from flash into RAM
- Locate and load startup configuration
  - NVRAM, tftp server,etc
  - If not found – router may go into setup mode
- CLI (Command Line Interface)
- The content of the router may be seen using the **`show version`** command

Routing process

- Router examines the destination IP of each received packet and decides what to do with it based on a routing table
  - Match found
    - Directly connected to the network – send the packet to destination
    - Not directly connected – forward it to another router
  - No match found – drop the packet
- Routing – layer 3 (based on IP addresses)
  - Routers operate at layers 1,2, and 3

Basic router configuration



Interface configuration

Basic Router Configuration Command Syntax	
Configuring an interface	Router(config)#**interface** *type number*
	Router(config-if)#**ip address** *address mask*
	Router(config-if)#**description** *description*
	Router(config-if)#**no shutdown**
Saving changes on a router	Router#**copy running-config startup-config**
Examining the output of **show** commands	Router#**show running-config**
	Router#**show ip route**
	Router#**show ip interface brief**
	Router#**show interfaces**

View/verify configuration

- View running/startup config

  R1#show running-config

  R1#show startup-config

- Copy running config to startup config

  R1#copy running-config startup-config

- View current routing table and interface status

  R1#show ip route

  R1#show interfaces

  R1#show ip interface brief

Configure default gateway

- Host
  - Part of the interface configuration
- Switch

```
S1(config)# interface vlan1
S1(config-vlan)# ip address 192.168.10.50 255.255.255.0
S1(config-vlan)# no shut
S1(config)# ip default-gateway 192.168.10.1
```

Summary

- Network layer – carry data over the network
  - Routing table – core/essential
- IPv4
- Default gateway – connecting the network with the rest of the internet/Internet
- Router architecture – CPU, memory, storage, interfaces
- Basic configuration of a router

Lab activities

- 10.1.4 – Configure initial router settings

Go to **www.menti.com** and use the code **5652 3480**

Part 2: IP Addressing

Overview

- Explain the structure IP addressing
- Classify IPv4 addresses by type
- Explain how IP address are assigned to networks
- Determine the network portion of the host address and explain the role of the subnet mask in dividing networks.
- Calculate the appropriate addressing components, given IPv4 addressing information and design criteria,.
- Use common testing utilities to verify and test network connectivity and operational status of the IP protocol stack on a host.

Representation

- Binary (as in IP header)
  - 10101100000100000000010000010100
- Dotted decimal
  - 172.16.4.20
- Network and host portion (for a /16 netmask)
  - 172.16.4.20

Binary-decimal conversion

- The number: 245
  - a.k.a. 11110101
  - (a.k.a. f5)
- Decimal representation

  $245 = 2 \cdot 10^2 + 4 \cdot 10^1 + 5 \cdot 10^0$
- Binary representation

$11110101 = 1 \cdot 2^7 + 1 \cdot 2^6 + 1 \cdot 2^5 + 1 \cdot 2^4 + 0 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^{1\,+}\, 1 \cdot 2^0$

$= 128 + 64 + 32 + 16 + 4 + 1$

Binary-decimal conversion (cont)

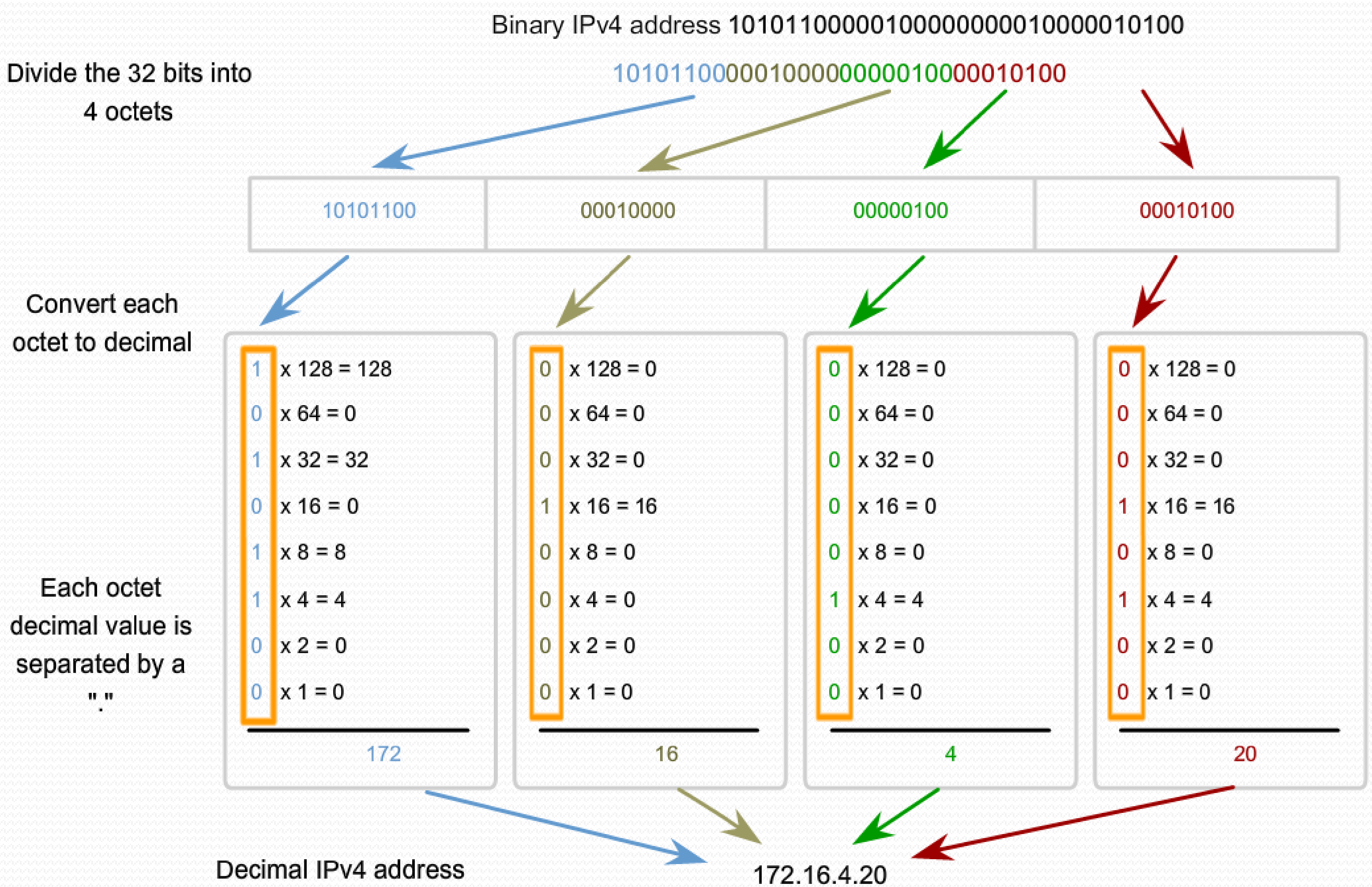
Exponent	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Position	128	64	32	16	8	4	2	1
Bits	1	1	1	1	0	1	0	1
	1 BYTE / 1 Octet							
Add these numbers together	128 + 64 + 32 + 16 + 0 + 4 + 0 + 1							
Decimal	245							

A 1 in this position means 64 is added to the total.

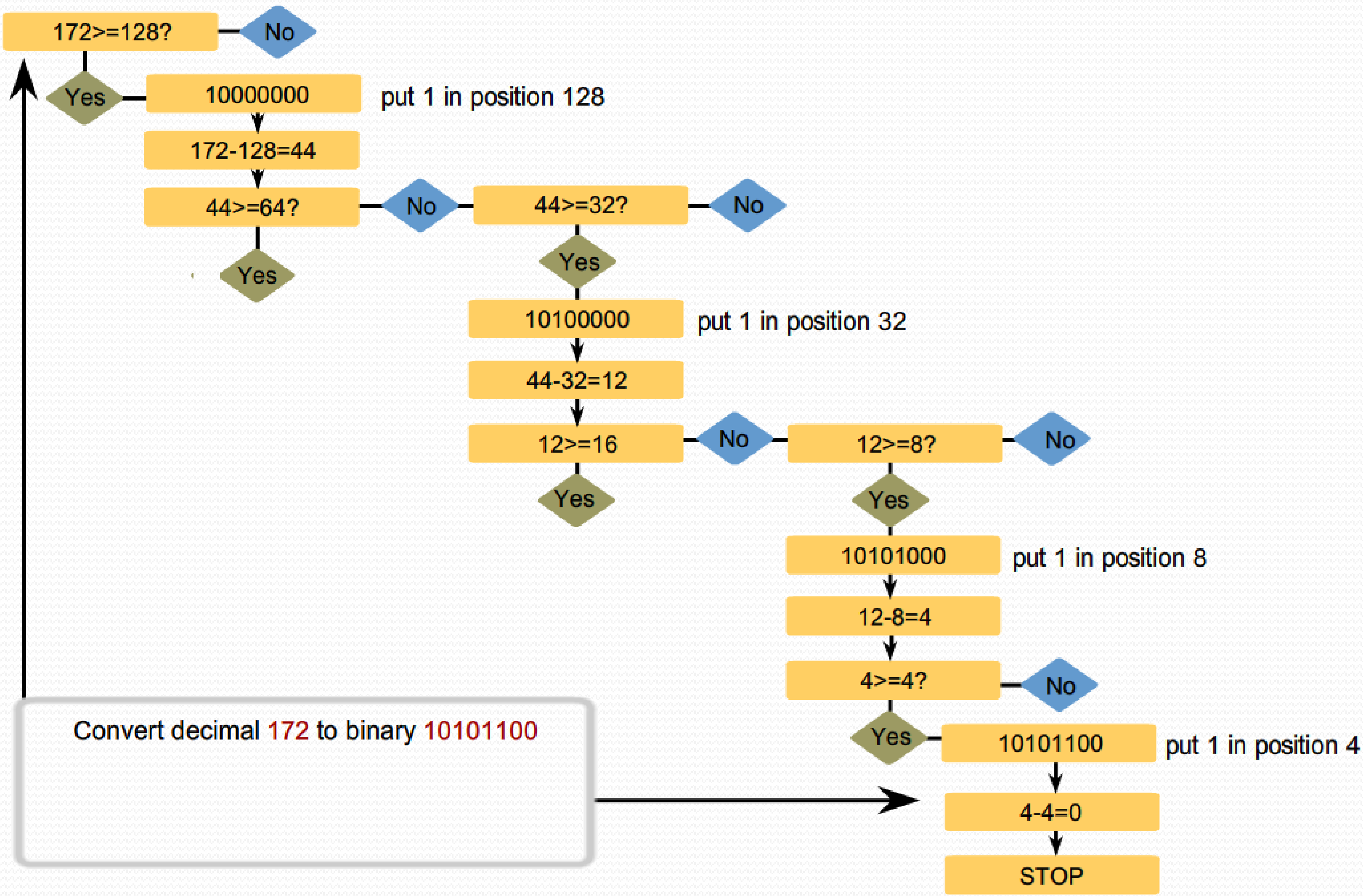
A 0 in any position means that 0 is added to the total.

11110101 in Binary = Decimal Number 245

Binary-decimal conversion (cont)



Binary-decimal conversion (cont)

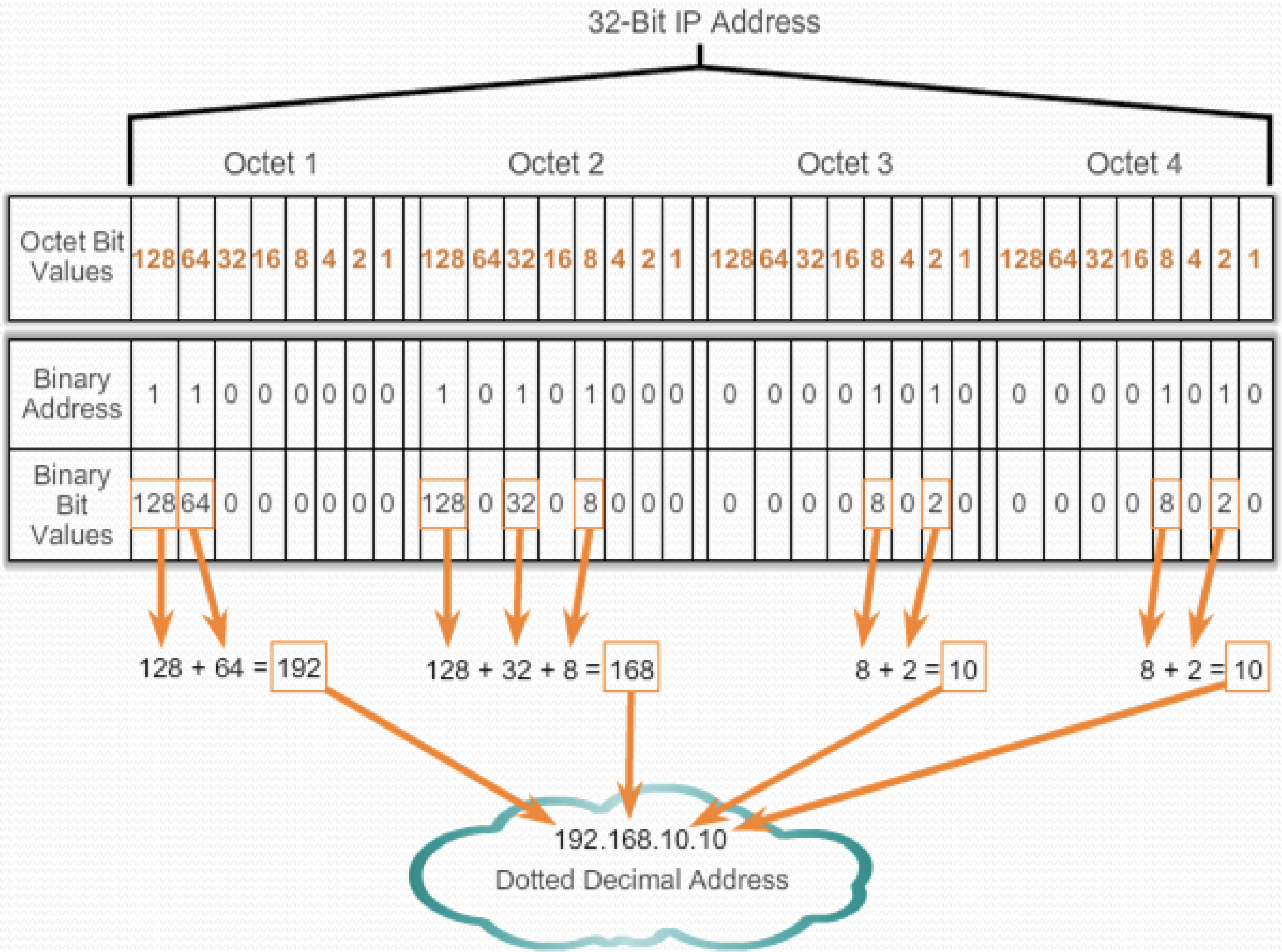


Addresses within a (sub)net

- Network address - The address by which we refer to the network
  - All host bits are 0
- Broadcast address - A special address used to send data to all hosts in the network
  - All host bits are 1
- Host addresses - The addresses assigned to the end devices in the network
  - From all-zeroes to all-ones

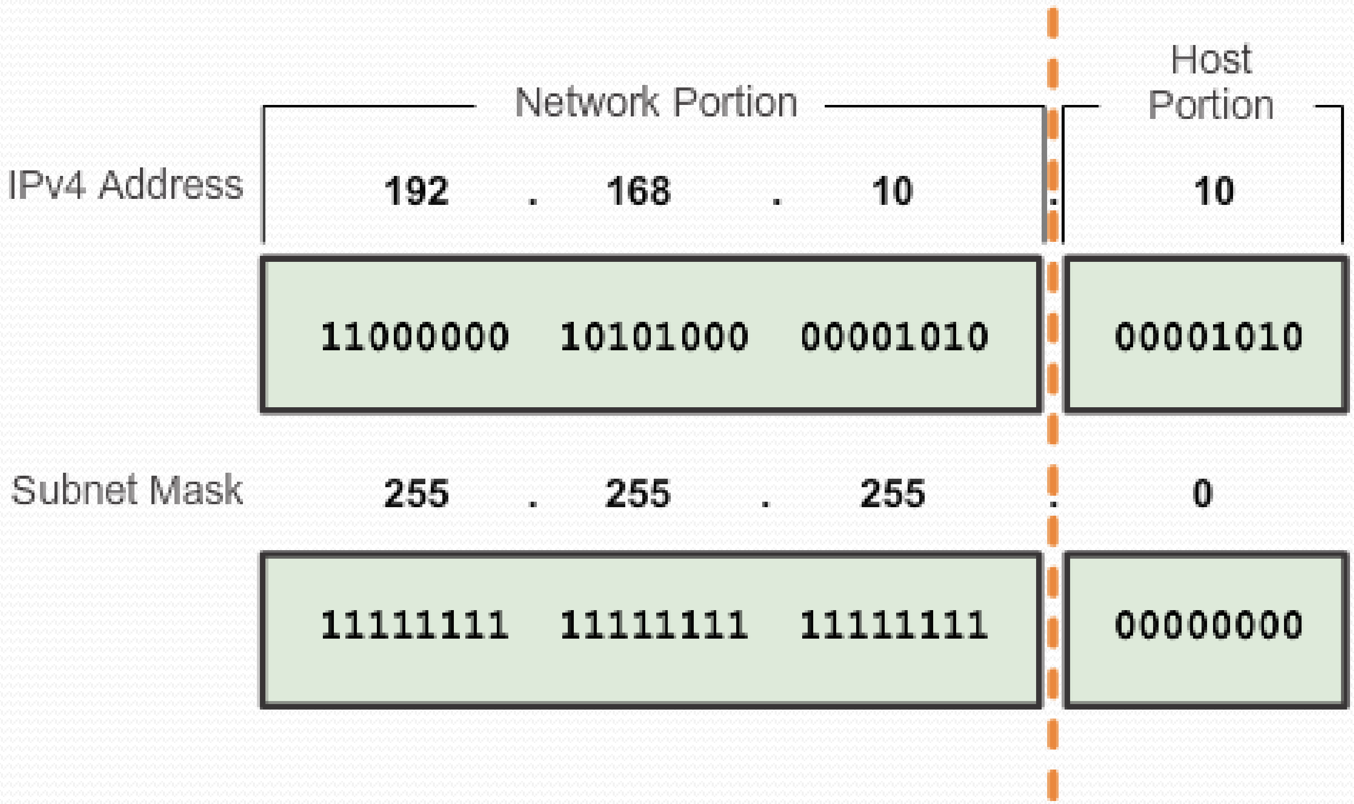
Network prefix: the number of bits in the address that gives us the network portion

Binary-decimal/octet conversion



Network and host part

- The network portion bits of the address - identical for all devices that reside in the same network.



Netmask

- Defines the size of the network part
  - 1…10…0
  - The 1s in the subnet mask represent the network portion; the 0s represent the host portion

Subnet Value	Bit Value 128	64	32	16	8	4	2	1
255	1	1	1	1	1	1	1	1
254	1	1	1	1	1	1	1	0
252	1	1	1	1	1	1	0	0
248	1	1	1	1	1	0	0	0
240	1	1	1	1	0	0	0	0
224	1	1	1	0	0	0	0	0
192	1	1	0	0	0	0	0	0
128	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0

Network prefixes

	Dotted Decimal	Significant bits shown in binary
Network Address	**10.1.1.0/24**	**10.1.1.00000000**
First Host Address	10.1.1.1	**10.1.1.00000001**
Last Host Address	10.1.1.254	**10.1.1.11111110**
Broadcast Address	10.1.1.255	**10.1.1.11111111**
Number of hosts: 2^8 – 2 = 254 hosts		

Network Address	**10.1.1.0/25**	**10.1.1.00000000**
First Host Address	10.1.1.**1**	**10.1.1.00000001**
Last Host Address	10.1.1.**126**	**10.1.1.01111110**
Broadcast Address	10.1.1.**127**	**10.1.1.01111111**
Number of hosts: 2^7 – 2 = 126 hosts		

Network Address	**10.1.1.0/26**	**10.1.1.00000000**
First Host Address	10.1.1.**1**	**10.1.1.00000001**
Last Host Address	10.1.1.**62**	**10.1.1.00111110**
Broadcast Address	10.1.1.**63**	**10.1.1.00111111**
Number of hosts: 2^6 – 2 = 62 hosts		

172.16.20.0/25

Network address

172 . 16. 20. 0/25

10101100.00010000.00010100.00000000

|--------------Network -------------|- host -|

0+0+0+0+0+0+0+0=0

Network address = 172.16.20.0

Step 1

First host address

172 . 16. 20. 1

10101100.00010000.00010100.00000001

|--------------Network -------------|- host -|

0+0+0+0+0+0+0+1=1

Lowest host address = 172.16.20.1

Step 2

Broadcast address

172 . 16. 20. 127

10101100.00010000.00010100.01111111

|--------------Network -------------|- host -|

0+64+32+16+8+4+2+1=127

Broadcast address = 172.16.20.127

Step 3

Last host address

172 . 16. 20. 126

10101100.00010000.00010100.01111110

|--------------Network -------------|- host -|

0+64+32+16+8+4+2+0=126

Highest host address = 172.16.20.126

Step 4

Identify network address - ANDing

IPv4 Address	192 .	168 .	10 .	10
	11000000	10101000	00001010	00001010
Subnet Mask	255 .	255 .	255 .	0
	11111111	11111111	11111111	00000000
Network Address	192 .	168 .	10 .	0
	11000000	10101000	00001010	00000000

Assigning IP addresses in a LAN

- Static – manual
- Dynamic - DHCP

Communication

- Unicast - one host to one host
  - Typical communication
- Broadcast - one host to all hosts in the network
  - Directed – can be used remotely – using the broadcast address
  - Limited – local network – using the 255.255.255.255 address
- Multicast - one host to a selected group of hosts
  - Reduce overall bandwidth (one packet for all listening hosts)
  - Multicast clients subscribe to a group
  - Uses (reserved) addresses: 224.0.0.0 – 239.255.255.255

Reserved IP ranges

- Multicast (RFC1700)
  - 224.0.0.0 – 239.255.255.255
- Experimental: (RFC1700, RFC3330)
  - 240.0.0.0 – 255.255.255.254
- Private/Network Address Translation (RFC1918)
  - 10.0.0.0 to 10.255.255.255 (10.0.0.0 /8)
  - 172.16.0.0 to 172.31.255.255 (172.16.0.0 /12)
  - 192.168.0.0 to 192.168.255.255 (192.168.0.0 /16)
- Link local
  - 169.254.0.0 to 169.254.255.255 (169.254.0.0/16)
- Test-net (teaching/learning)
  - 192.0.2.0 to 192.0.2.255 (192.0.2.0/24)

Special IPv4 addresses

- Network and broadcast addresses
  - All-zeroes and all-ones host bits
- Default route
  - 0.0.0.0
- Loopback
  - 127.0.0.1

Legacy IP addressing

Address Class	1st octet range (decimal)	1st octet bits (green bits do not change)	Network(N) and Host(H) parts of address	Default subnet mask (decimal and binary)	Number of possible networks and hosts per network
A	1-127**	00000000- 01111111	N.H.H.H	255.0.0.0	128 nets (2^7) 16,777,214 hosts per net (2^24-2)
B	128-191	10000000- 10111111	N.N.H.H	255.255.0.0	16,384 nets (2^14) 65,534 hosts per net (2^16-2)
C	192-223	11000000- 11011111	N.N.N.H	255.255.255.0	2,097,150 nets (2^21) 254 hosts per net (2^8-2)
D	224-239	11100000- 11101111	NA (multicast)		
E	240-255	11110000- 11111111	NA (experimental)		

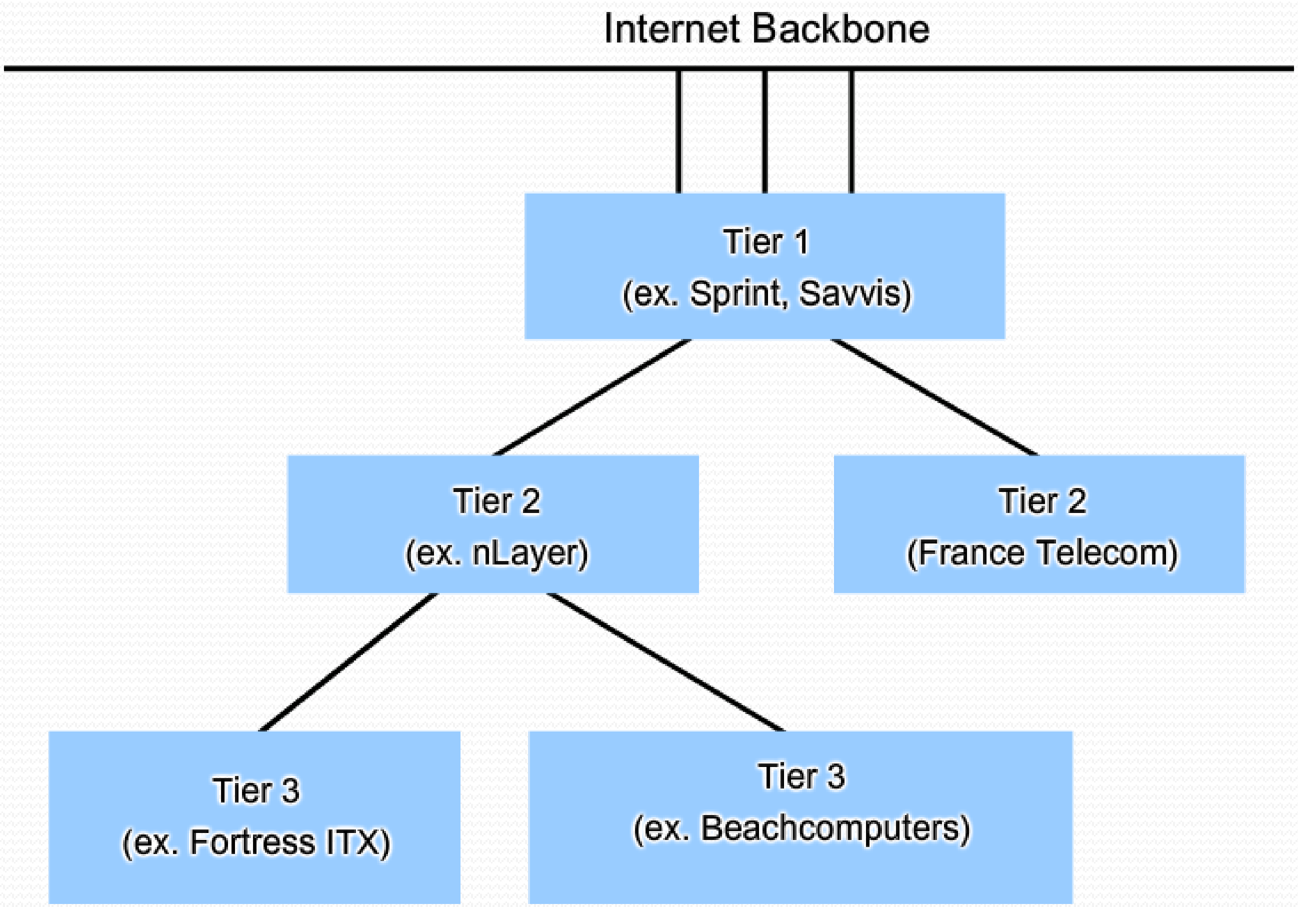
Network address planning

- Criteria:
  - Preventing duplication of addresses
  - Providing and controlling access
  - Monitoring security and performance
- Allocation
  - Static – manual
    - Servers and routers
  - Dynamic – automatic
    - Using DHCP

Assigning IP addresses

- Level 0: the Internet - IANA
- Level 1: Regional Internet Registries
- Level 3: ISPs
- Level 4: Network administrators

Internet tiers



Subnet mask

- Defines the network and host portions

IP Address	172	.	16	.	4	.	1
	10101100		00010000		00000100		00000001
Subnet Mask	255	.	255	.	255	.	0
	111111111		1111111111		111111111		00000000

Prefix /24 (24 high order bits)

Applying the subnet mask – ANDing

	High order bits Prefix /16		Low order bits	
	192 .	0 .	0 .	1
Host Address	11000000	00000000	00000000	00000001
Subnet Mask	255	255	0	0
	11111111	11111111	00000000	00000000
Network Address	11000000	00000000	00000000	00000000
Network	192 .	0 .	0 .	0

ANDing example

- Network address for host 172.16.132.70/20

Host Address	172	16	132	70
Binary Host Address	10101100	00010000	10000100	01000110
Binary Subnet Mask	11111111	11111111	11110000	00000000
Binary Network Address	10101100	00010000	10000000	00000000
Network Address	172	16	128	0

Ping and traceroute

- Loopback
- Local network
- Remote device

- Traceroute
  - Sends packets with increasing TTL values
  - Forces time exceeded replies from routers along the route

Activities

- 5.1.6 / 5.1.7 – Binary-decimal conversion
- https://learningcontent.cisco.com/games/binary/index.html
- 11.1.7 - ANDing to Determine the Network Address