Lecture 12: IP Addressing & Datagram Forwarding

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IPv4 Address

Each host is assigned a unique **32-bit IP address**, which is typically expressed in **dotted decimal notation**:

(8 bits).(8 bits).(8 bits).(8 bits)

Examples:

10.2.0.37	00001010.00000010.00000000.00100101
128.10.2.3	
128.128.255.1	10000000.10000000.11111111.00000001
129.52.6.2	
182.24.31.144	10110110. 00011000.00011111.10010000
192.5.48.3	

Range:

$00000000_b . 00000000_b . 00000000_b . 00000000_b - 11111111_b . 11111111_b . 11111111_b . 11111111_b$

$0_d . 0_d . 0_d . 0_d - 255_d . 255_d . 255_d . 255_d$

Total of 2^{32} = 4,294,967,296 addresses.

IPv4 Address

- An IP address does not actually refer to a host. It refers to a network interface, so if a host is connected to two networks, it must have two IP addresses (e.g., routers).
- IP addresses are hierarchical. They consist of: Network ID, which identifies the physical network to which the host is attached, and Host ID, which identifies the host (interface).
- The Host ID is unique to each host on one physical network, and the Network ID is unique for each physical network across the globe.
- This ensures uniqueness when assigning addresses, and reduces entries in router forwarding tables (i.e., simplifies IP packet forwarding). However, it can waste IP addresses (inefficient allocation).

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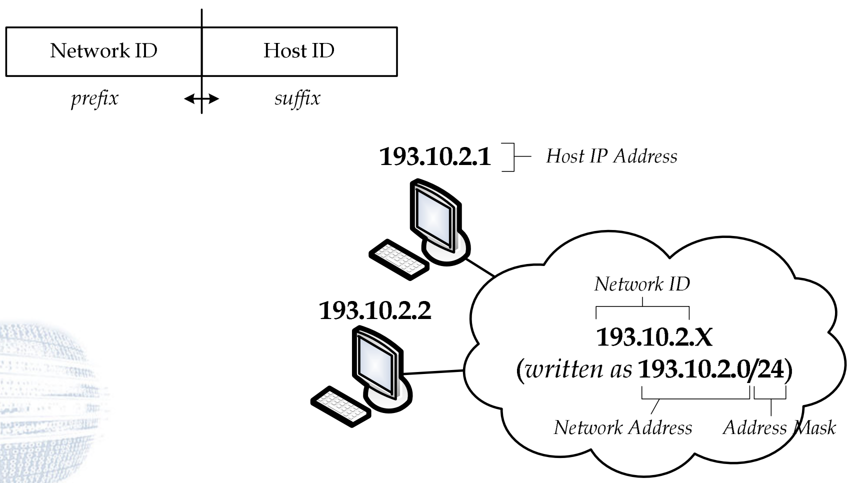
IPv4 Address Assignment



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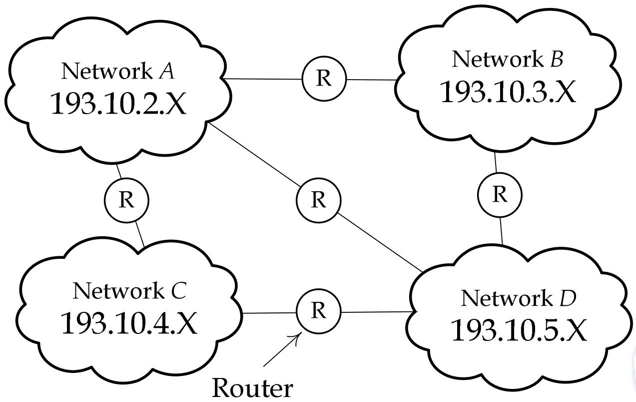
Network IDs are Unique Globally Host IDs are Unique Locally



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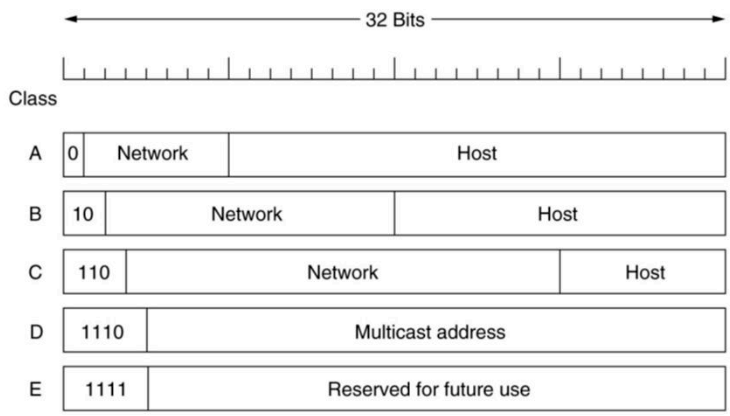
Classful IP Addresses: Classes A, B and C



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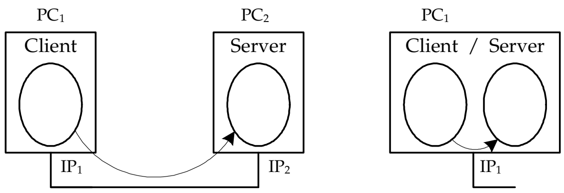
Ranges: Classes A, B and C

Class	Possible Network IDs	No. of Networks	Max Hosts per Network
A	1.X.Y.Z to 127.X.Y.Z	$2^7 - 1 = 127$	$2^{24} - 2 = 16{,}777{,}214$
B	128.0.X.Y to 191.255.X.Y	$2^{14} = 16{,}384$	$2^{16} - 2 = 65{,}534$
C	192.0.0.X to 223.255.255.X	$2^{21} = 2{,}097{,}152$	$2^8 - 2 = 254$
D	224.0.0.0 to 239.255.255.255		
E	240.0.0.0 to 255.255.255.254		
Broadcast	255.255.255.255		



Examples

- MIT (Massachusetts Institute of Technology), USA, network was assigned the IP class A address range 18.0.0.0/8 (18.0.0.1 – 18.255.255.254). Sold some later.
- The University of Kansas, USA, network is assigned the IP class B address range 129.237.0.0/16 (129.237.0.1 – 129.237.255.254).
- The University of Jordan, was assigned the class C network address 193.188.81.0/24 when it was first connected to the Internet through NIC (National Information Center, Jordan),
- But since JU switched to JUNet, they gave up this address range for the smaller range of 87.236.232.64/27 (87.236.232.65 – 87.236.232.95).
- Try whois utility or https://www.whois.com/whois.

Global Address Assignment

- Internet Assigned Numbers Authority (**IANA**): oversees global IP address allocation, autonomous system number allocation, root zone management in DNS, media types, and other IP-related symbols and numbers.
- IANA is a department operated by the Internet Corporation for Assigned Names and Numbers (**ICANN**).
- IANA hands out /8 address blocks to Regional Internet Registries (RIR):
  - RIPE NCC (Europe, Middle East, Russia, Central Asia)
  - APNIC (Asia Pacific)
  - ARIN (North America)
  - LACNIC (Latin America)
  - AfriNIC (African Region)
- (see http://www.iana.org/assignments/)
- ISPs obtain their network addresses from RIRs.
- End users and companies obtain their IP addresses form ISPs

Special IP Addresses

Network ID	0000000 0000000	Network Address
Network ID	1111111 1111111	Directed (Distant) Broadcast Address
11111111111111111111111111111111		Limited (Local) Broadcast Address
00000000000000000000000000000000		This Host Address
000...000	Host ID	Hosts on This Network
127	Anything	Loopback Addresses

Special IP Addresses

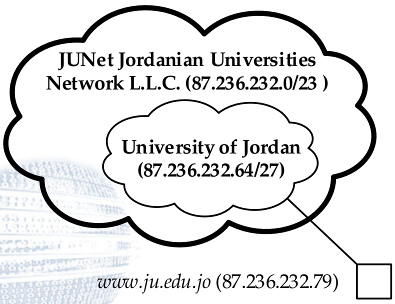
- **Network Address**: Refers to the network itself. For example 128.211.0.0 denotes the network that has been assigned the Network ID 128.211.X.X (or 128.211.0.0/16). The network address is not assigned to any of the hosts in the network, which means it should never appear as source or destination address in an IP packet. However, it is useful for routing (*see later*).
- **Directed (Distant) Broadcast Address**: When an IP packet is sent to a network's directed broadcast address, a single copy of the packet travels across the Internet until it reaches the specified network, and the packet is then delivered to all hosts on the network. This address is not assigned to any single host, so it can appear as destination address, but not as source address in an IP packet.
- **Limited (Local) Broadcast Address**: Using 255.255.255.255 as the destination address, the IP packet will be broadcast across the local network (i.e., all hosts on the physical network will read the packet). Typically sent inside L2 frame with FF:FF:FF:FF:FF:FF destination MAC address. Useful when a computer starts up, as it does not yet know the Network ID.

Special IP Addresses

- **This Host Address**: When a host is **not** assigned an IP address beforehand (e.g., when the computer boots up), it is allowed to use the address 0.0.0.0 temporarily as the source IP address to mean "This Computer" or "This Host". This is useful when executing certain protocols at startup such as DHCP.
- **Hosts on This Network**: Such addresses allow machines to refer to their own network without knowing its Network ID (but they have to know its class to know how many 0's to include).
- **Loopback Addresses**: Used to test network applications (i.e., for debugging). All IP addresses in the range 127.0.0.0/8 are loopback. The host address you choose within 127.0.0.0/8 is irrelevant since packets sent to any one of these IP addresses are not put onto the wire; instead they are recycled locally. The most popular loopback IP address is 127.0.0.1.

Classless IP Addresses (CIDR Addresses)

The original **class A** network address 11.0.0.0 **becomes** 11.0.0.0/8
The original **class B** network address 128.5.0.0 **becomes** 128.5.0.0/16
The original **class C** network address 192.6.1.0 **becomes** 192.6.1.0/24



87 . 236 . 232 .	64	/27	Allocation
87 . 236 . 232 . 010	00000		Network Address
87 . 236 . 232 . 010	00001		87.236.232.65 Host Address
	. . .		
87 . 236 . 232 . 010	11110		87.236.232.94 Host Address
87 . 236 . 232 . 010	11111		87.236.232.95 Directed Broadcast

Example

- If a network contains a maximum of 60 computers, only 6 bits of Host ID are needed ($2^6 - 2 = 62$).
- The remaining 26 bits are used for the Network ID, and the network address would be written with **/26** (e.g., **130.5.1.128/26**). Possible IP addresses within this network are 130.5.1.129 to 130.5.1.190.

10000010. 00000101. 00000001. 10	000001	130.5.1.129
	. . .	
	111110	130.5.1.190

Example (*Different Approach*)

- What is the Network Address?
- What is the Subnet Mask (Address Mask)?
- What is the Distant Broadcast Address?
- What is the maximum number of hosts that can be connected to this network?
- Is the host IP address 130.5.1.131 within this network?
- Is the host IP address 130.5.1.199 within this network?

Example (*Cont.*)

- The host IP address 130.5.1.131 is part of the network 130.5.1.128/26 because:
- (130.5.1.131) AND (/26) =
(130.5.1.131) AND (255.255.255.192) = 130.5.1.128

	10000010. 00000101. 00000001. 10000011	130.5.1.131
AND	11111111. 11111111. 11111111. 11000000	255.255.255.192
	10000010. 00000101. 00000001. 10000000	130.5.1.128

Example (*Cont.*)

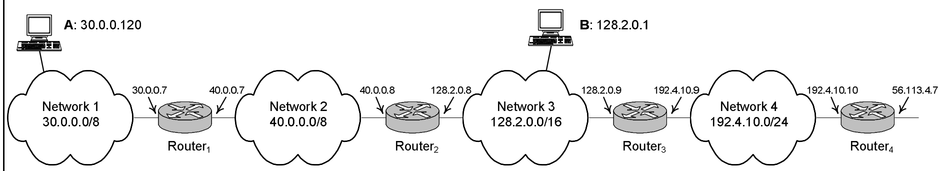
- The host IP address 130.5.1.199 is **not** part of this network 130.5.1.128/26 because:
- (130.5.1.199) AND (/26) = (130.5.1.199) AND (255.255.255.192) = 130.5.1.192

	10000010. 00000101. 00000001. 11000111	130.5.1.199
AND	11111111. 11111111. 11111111. 11000000	255.255.255.192
	10000010. 00000101. 00000001. 11000000	130.5.1.192

IP Datagram Forwarding

- A router forwards IP packets to the next hop until they reach their final destination. Called store-and-forward packet switching or next-hop forwarding.
- Router examines the destination IP address to select the next router that is closer to the destination, and then **forwards** the packet to that router.
- To allow selecting the next hop at each router, routers maintain a table (called a **routing table** or **forwarding table**) listing many possible networks in the Internet and the next router (hop) in the path to reach them.
- The routing table includes an entry for each network the router knows about, with each entry consisting of the triplet (Network Address, Address Mask, Next hop and its interface).
- Routers only need to know about network addresses and not specific host IP addresses. This reduces the size of the routing tables in routers.
- Building the routing tables is called **routing**, and is done via a routing protocol, such as RIP, OSPF, EIGRP, or BGP.

IP Datagram Forwarding/Example



Route Table at Router 1

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	Direct	6	Int0	other hosts on LAN
40.0.0.0	/8	Direct	6	Int1	other hosts on LAN
128.2.0.0	/16	40.0.0.8	6	Int1	next hop
192.4.10.0	/24	40.0.0.8	6	Int1	next hop
0.0.0.0	/0	40.0.0.8	6	Int1	default gateway
....					other entries

```
if( (DestIPAddress & AddressMask[i]) == DestinationNetwork[i])
     Forward to NextHop[i];
```


Route Table at Router 1

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	Direct	6	Int0	other hosts on LAN
40.0.0.0	/8	Direct	6	Int1	other hosts on LAN
128.2.0.0	/16	40.0.0.8	6	Int1	next hop
192.4.10.0	/24	40.0.0.8	6	Int1	next hop
0.0.0.0	/0	40.0.0.8	6	Int1	default gateway
....					other entries

Route Table at Router 2

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	40.0.0.7	6	Int0	next hop
40.0.0.0	/8	Direct	6	Int0	other hosts on LAN
128.2.0.0	/16	Direct	6	Int1	other hosts on LAN
192.4.10.0	/24	128.2.0.9	6	Int1	next hop
0.0.0.0	/0	128.2.0.9	6	Int1	default gateway
....					other entries

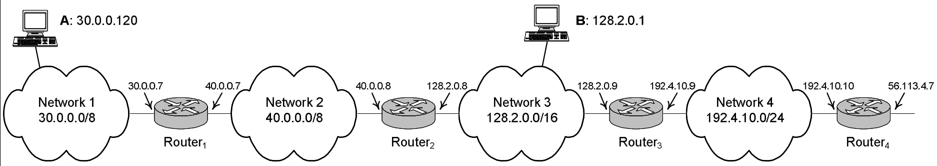
Route Table at Router 3

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	128.2.0.8	6	Int0	next hop
40.0.0.0	/8	128.2.0.8	6	Int0	next hop
128.2.0.0	/16	Direct	6	Int0	other hosts on LAN
192.4.10.0	/24	Direct	6	Int1	other hosts on LAN
0.0.0.0	/0	192.4.10.10	6	Int1	default gateway
....					other entries

Route Table at Router 4

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	192.4.10.9	6	Int0	next hop
40.0.0.0	/8	192.4.10.9	6	Int0	next hop
128.2.0.0	/16	192.4.10.9	6	Int0	next hop
192.4.10.0	/24	Direct	6	Int0	other hosts on LAN
0.0.0.0	/0	56.113.4.8	6	Int1	default gateway
....					other entries

IP Datagram Forwarding/Example

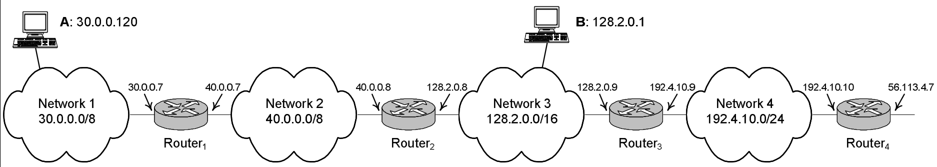


Route Table at Host 30.0.0.120

Network Destination	Netmask	Next Hop	Metric	Interface	Comments
127.0.0.0	/8	127.0.0.1	1	127.0.0.1	Loopback
30.0.0.120	/32	127.0.0.1	1	127.0.0.1	Host own IP address
30.0.0.0	/8	Direct	6	Int0	other hosts on LAN
30.255.255.255	/32	Direct	6	Int0	directed broadcast
255.255.255.255	/32	Direct	6	Int0	limited broadcast
224.0.0.0	/4	Direct	6	Int0	multicast
0.0.0.0	/0	30.0.0.7	6	Int0	default gateway

```
if( (DestIPAddress & AddressMask[i]) == DestinationNetwork[i])
     Forward to NextHop[i];
```


IP Datagram Forwarding/Example



Route Table at Router 1

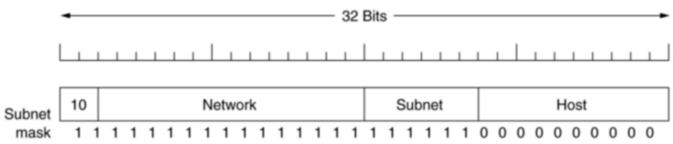
Network Destination	Netmask	Next Hop	Metric	Interface	Comments
30.0.0.0	/8	Direct	6	Int0	other hosts on LAN
40.0.0.0	/8	Direct	6	Int1	other hosts on LAN
128.2.0.0	/16	40.0.0.8	6	Int1	next hop
192.4.10.0	/24	40.0.0.8	6	Int1	next hop
0.0.0.0	/0	40.0.0.8	6	Int1	default gateway
....					other entries

```
if( (DestIPAddress & AddressMask[i]) == DestinationNetwork[i])
     Forward to NextHop[i];
```

Host **30.0.0.120** wants to send an IP packet to the host **128.2.0.1**.

(128.2.0.1) AND (255.0.0.0) = 128.0.0.0 ≠ 30.0.0.0
(128.2.0.1) AND (255.0.0.0) = 128.0.0.0 ≠ 40.0.0.0
(128.2.0.1) AND (255.255.0.0) = 128.2.0.0 = 128.2.0.0 **(Match, Longest)**
(128.2.0.1) AND (255.255.255.0) = 128.2.0.0 ≠ 192.4.10.0
(128.2.0.1) AND (0.0.0.0) = 0.0.0.0 = 0.0.0.0 **(Match)**

Subnets / Example



- For example, the class B network address 130.50.0.0/16 can be subnetted using **6 bits** for the Subnet ID into the following 2^6 = **64 subnets** (*see next*).
- To the outside world, it looks like one network with Network ID 130.50.X.Y (i.e., Subnet ID is part of Host ID).
- From the inside it is actually 64 networks with Network Addresses (130.50.0.0/22, 130.50.4.0/22, …, 130.50.252.0/22) (i.e., Subnet ID is part of Network ID).

Example Solution

130 . 50 . 0 . 0 / **16**

10000010 . 00110010 . / 00000000 . 00000000

10000010 . 00110010 . / 000000 / 00 . 00000000	130 . 50 . 0 . 0 / **22**
10000010 . 00110010 . / 000001 / 00 . 00000000	130 . 50 . 4 . 0 / **22**
10000010 . 00110010 . / 000010 / 00 . 00000000	130 . 50 . 8 . 0 / **22**
10000010 . 00110010 . / 000011 / 00 . 00000000	130 . 50 . 12 . 0 / **22**
10000010 . 00110010 . / 000100 / 00 . 00000000	130 . 50 . 16 . 0 / **22**
…	
10000010 . 00110010 . / 111110 / 00 . 00000000	130 . 50 . 248 . 0 / **22**
10000010 . 00110010 . / 111111 / 00 . 00000000	130 . 50 . 252 . 0 / **22**

Example 2 / Recursive

194 . 24 . 0 . 0 / **19**
194 . 24 . 000 / 00000 . 0

194 . 24 . 000 / 0 / 0000 . 0 — 194 . 24 . 0 . 0 / **20**
194 . 24 . 000 / 1 / 0000 . 0 — 194 . 24 . 16 . 0 / **20** ✓

194 . 24 . 0000 / 0 / 000 . 0 — 194 . 24 . 0 . 0 / **21** ✓
194 . 24 . 0000 / 1 / 000 . 0 — 194 . 24 . 8 . 0 / **21**

194 . 24 . 00001 / 0 / 00 . 0 — 194 . 24 . 8 . 0 / **22** ✓
194 . 24 . 00001 / 1 / 00 . 0 — 194 . 24 . 12 . 0 / **22** ✓

Address Aggregation / Summary

Observe the following possible IP address allocation for three UK universities:

University	Network Address	First IP Address	Last IP Address	Number of Addresses
Cambridge	194.24.0.0/21	194.24.0.1	194.24.7.254	2048 – 2
Edinburgh	194.24.8.0/22	194.24.8.1	194.24.11.254	1024 – 2
(Available)	194.24.12.0/22	194.24.12.1	194.24.15.254	1024 – 2
Oxford	194.24.16.0/20	194.24.16.1	194.24.31.254	4096 – 2

Routers outside the UK can aggregate all these entries into a single entry as follows:

194.24.0.0/19 **Forward to Next Hop to UK**

Subnetting / Homework

- Assume a medium-size business with four departments has acquired the IP address space **128.5.0.0/16**. Each one of its four departments has a separate physical LAN, and these LANs are connected together using routers. Show how you can divide the address space using subnet addressing, assuming:
  - Each department has **equal number** of computers.
  - Some departments have more computers than others.
- Show what type of information is stored at both: routers internal to the business and routers external to the business (e.g., the router that connects the business to its own ISP).

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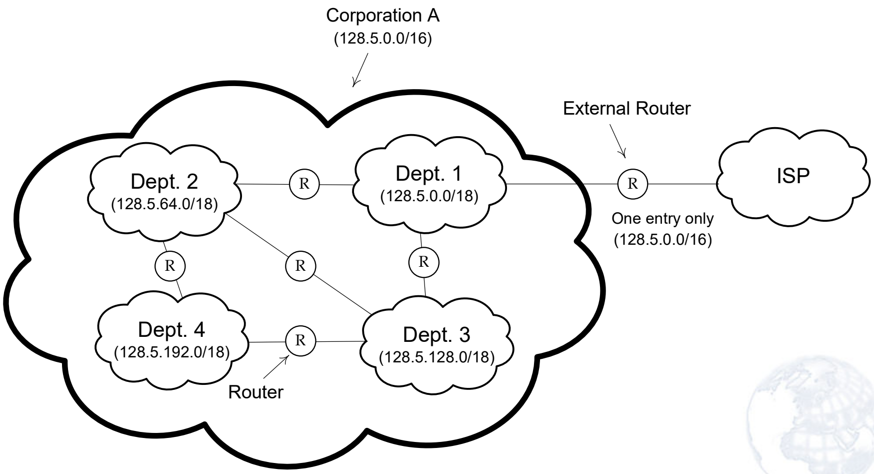
Homework (*Sol #1*)



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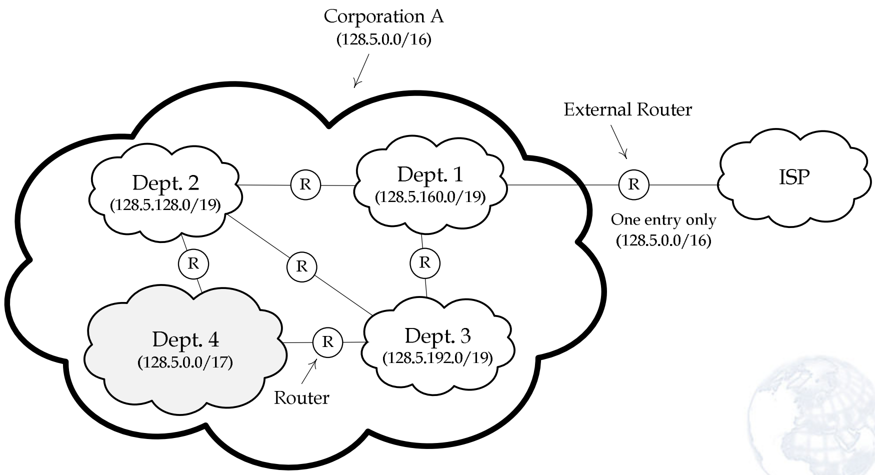
Homework (*Sol* #2)



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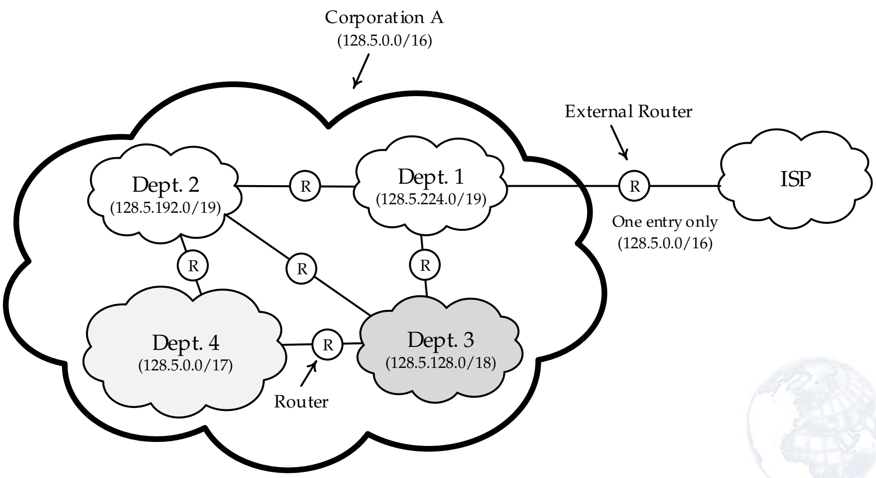
Homework (*Sol* #3)



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