École Pour l'Informatique et les Techniques Avancées – EPITA

BSc L1 – 27 April 2024

Course: Introduction to Computer Networks

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ÉCOLE D'INGÉNIEURS EN INFORMATIQUE

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Introduction to Computer Networks

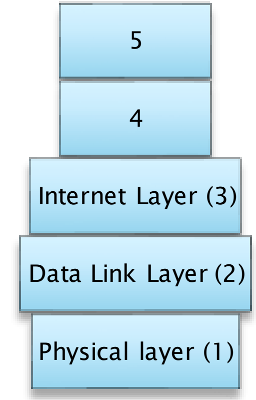
Course schedule (tentative)

Date & Time	No.	Topics	Duration (hours)
Fri 19/04/24 – 10:00–13:00	1	Primer, Network protocols, types, topology, architecture	3
Fri 26/04/24 – 10:00–13:00	2	Network models, TCP/IP model, Packet switching	3
Sat 27/04/24 – 10:00–13:00	3	Physical Layer (Function, Signals, Modulation, Multiplexing, Transmission media & Hardware, Optical networks)	3
Sat 27/04/24 – 14:00–17:00	4	Data Link Layer (Function, Framing, Protocols, Flow control, Access control, Error correction, Hardware)	3
Fri 03/05/24 – 14:30–17:30	**5**	**Network Layer (Function, IP addressing and subnets)**	**3**
Sat 04/05/24 – 10:00–13:00	6	Network Layer (Routing algorithms and protocols), Internet Control Message Protocol	3
Fri 17/05/24 – 14:00–17:00	7	Network Layer (IGP & EGP), Autonomous System, Border Gateway Protocol	3
Fri 18/05/24 – 14:00–17:00	8	Transport Layer (Function, Flow and congestion controls, Protocols)	3
Fri 24/05/24 – 10:00–13:00	9	Application Layer (Function, Protocols)	3

Lecture 5 Outline

- Network Layer (TCP/IP)
  - Functions
  - IP addressing (and schemes)
  - Subnetting, Subnet & Subnet Mask
  - Class exercise 8

Network Layer (Function)



- Layer-3 of TCP/IP model
  -> also known as Internet layer
- Primary function is **host-to-host (or source to destination) data transfer** using packets
- Provides:
  - Logical addressing and naming of hosts on the network (using Logical addresses)
  - Best path for data to travel from sender to receiver (using Routing protocols)
  - Error Handling and Packet Discard (using TTL expiration, Checksum, Routing errors)

IP address & their allocation

- IPv4: 4 bytes/octets (32 bits in total)
  - e.g., 163.1.125.98
  - In theory there are about 4 billion (2^32) available
- Controlled centrally by ICANN (The Internet Corporation for Assigned Names and Numbers)
  - A non-profit organization
  - Govern fairly strict rules on further delegation to avoid wastage
    - Have to demonstrate actual need for them!

Routing

- How does a device know where to send a packet?
  - Devices need to know what IP addresses are on directly attached networks
  - If the destination is on a local network, send it directly there
- If the destination address is not local
  - Most non-router devices just send everything to a single (local) router (default gateway)
  - Routers need to know which network corresponds to which IP address (range)

IP Address Scheme Categories

- Conventional (i.e., Classful) Addressing
  - Dividing line (b/w network & host bits) occurs only at octet boundaries
  - Class A, B, and C depending on how many octets for network ID and host ID

165.132.126.159 (Decimal)
10100101.10000100.01111110.10000011
(Dotted binary notation)

- Subnet (i.e., Classless) Addressing
  - **3 tier system: network ID (NID), subnet ID (SID), host ID (HID)** E.g.,
    - 24 (NID) + 8 (HID) -> Classful (Class C)
    - 24(NID) + 3(SID) + 5 (HID) -> Classless

Classful IP Address: Classes

- IP addresses are divided into 5 classes, each of which is designated with the alphabetic letters A to E
- Class D addresses are used for multicasting
- Class E addresses are reserved for testing and research purposes

Classful IP Address: Classes (Cont.)

- The 5 IP classes are split up based on the value in the 1st octet:

IP Address Class Assignments	
Class	**First Octet Value**
Class A	0 ~ 127
Class B	128 ~ 191
Class C	192 ~ 223
Class D	224 ~ 239
Class E	240 ~ 255

? Using above ranges, you can determine the class of an address from its 1st octet value

Classful IP Address: Classes (Cont.)

- E.g. an address having its first octet value:
  - 120 -> is a Class A address
  - 155 -> is a Class B address
  - 220 -> is a Class C address
- Governing rules:
  1. Leading bit(s) of the first octet is significant bit(s) which cannot be used to accomodate network addresses (i.e. each address starts with them)
     - Class A significant bit: 0
     - Class B significant bits: 10
     - Class C significant nits: 110
  2. Cannot be designated by all zeroes or all ones
     - Applies to both Network and Host parts

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Are You the Host or the Network?

- The 32 bits of the IP address are divided into Network & Host portions, with the octets assigned as a part of one or the other

Network & Host Representation By IP Address Class				
Class	*Octet1*	*Octet2*	*Octet3*	*Octet4*
Class A	Network	Host	Host	Host
Class B	Network	Network	Host	Host
Class C	Network	Network	Network	Host

ℹ Each Network is assigned a **network address** & every device or interface (such as a router port) on the network is assigned a **host address**

Class A IP Addresses

- The leading bit (1st Octet) which is always 0, including the remaining 7 bits are used to designate the Network as Class A
- There are 3 host octets:

  2^{24} or 16,777,216 hosts

- The formula goes as:

  2^n = Number of available/usable hosts

  - Note: The first address is always a network address and last address is a broadcast address i.e., $2^n - 2$
- You can use the same formula to determine the number of Networks in any address class
  - E.g. a Class A address uses 7 bits to designate the network, so: $2^7 = 128$ or there can be 128 Class A Networks
    - The significant bit is never counted

Class B IP Addresses

- The leading 2 bits (1st Octet) which are always 10, including the remaining 14 bits are used to designate the Network as Class B
  - This leaves 16 bits (two octets) to designate the Hosts
- So how many Class B Networks can there be?
  - Using our formula, (2^{14}), there can be 16,384 Class B Networks & each Network can have (2^{16}) Hosts, or 65,536 Hosts

Class C IP Addresses

- The leading 3 bits of all class C addresses are set to 110, leaving 21 bits for the Network address, which means there can be 2,097,152 (2^{21}) Class C Networks
- 256 (2^8) Hosts per Network

*-> For **no. Of Networks**:*
'Identify bits' are not counted

*-> For **no. of Networks or Hosts**, all zeros (broadcast) or all ones (default route) bits are not counted*

*-> For **no. usable Hosts**: Network, Default Gateway and Broadcast adresses are not counted*

In short!

Characteristics of the IP Address Classes

Class	Address Range	Identify Bits (binary value)	Bits in Network ID	Number of Networks	Bits in Host ID	Number of Hosts/ Network
A	0 ~ 127	1 (0)	7	126	24	16,777,214
B	128~191	2 (10)	14	16,382	16	65,534
C	192~223	3 (110)	21	2,097,150	8	254

Special Addresses

- A few addresses are set aside for specific purposes e.g., in Cisco 'realm'

Special IP Addresses			
Network Address	**Host Address**	**Description**	**Example**
0's	0's	Default Cisco Route	0.0.0.0
0's	Host Address	Local Network Hosts	0.0.0.115
1's	1's	Broadcast to Local Network	255.255.255.255
Network Address	1's	Broadcast to Network Address	192.21.12.255
127	Anything	Loopback Testing	127.0.0.1

ℹ For full list:
https://www.iana.org/assignments/iana-ipv4-special-registry/iana-ipv4-special-registry.xhtml

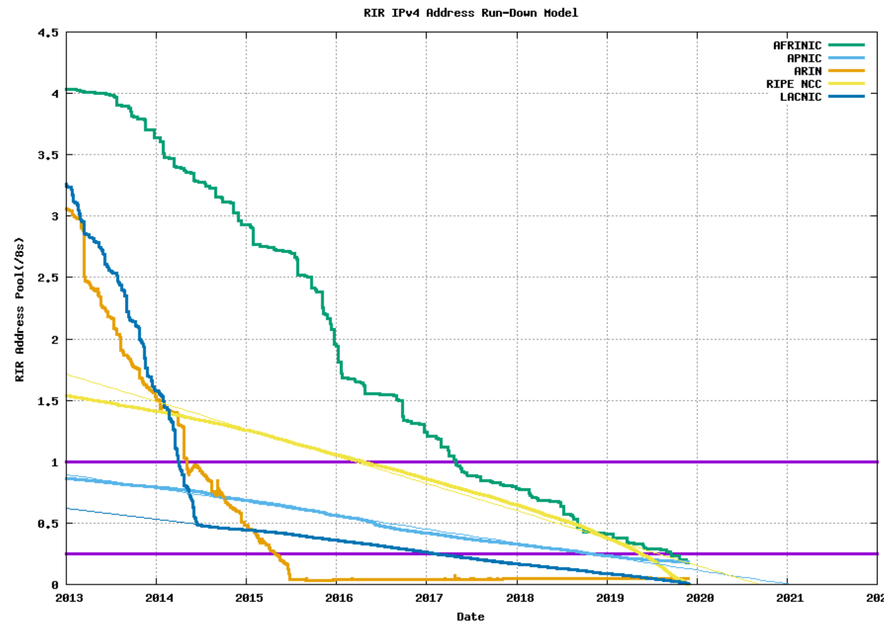
Special Addresses (Cont.)

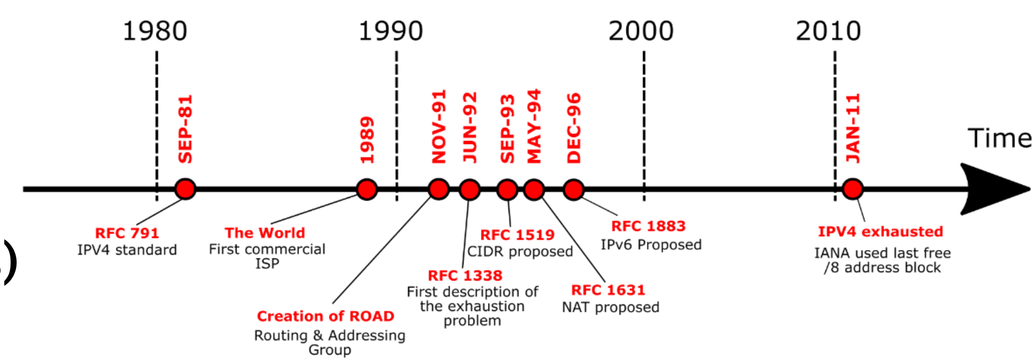
- **Within** each address class is a set of addresses that are set aside **for use in local networks,** sitting behind a firewall or NAT (Network Address Translation) device, or Networks not connected to the Internet
- A list of these addresses for each IP address class:

Special Local Network Addresses	
IP Class	**Address Range**
Class A	10.0.0.0 ~ 10.255.255.255
Class B	172.16.0.0 ~ 172.31.255.255
Class C	192.168.0.0 ~ 192.168.255.255

Limitations to Classful Addressing

- Limited IPv4 address space
  2^{32} = 4,294,967,296 addresses
- Class boundaries restricts efficient allocation of address space
- Lack of address class to support medium size company
  - -- Class B: 65534 hosts/network, *too big!*
  - -- Class C: 254 hosts/network, *too small!*





New direction:
IPv6 (128 bits or 16 bytes/octets)

Source: https://en.wikipedia.org/wiki/IPv4_address_exhaustion

Subnet Mask

- As we've seen, an IP address has 2 parts:
  - Network ID
  - Host ID
- Frequently, the Network & Host portions of the address need to be separately extracted
  - E.g. In classful IP scheme, if you know the address class, it's easy to separate the 2 portions.
- **To tackle IPv4 shortage / avoid wastage**:

  ℹ **Idea**: borrow additional bits from network or host part i.e. Network or Host (VLSM – Variable length subnet mask)

Subnet Mask (Cont.)

- Determines whether an IP address exists on the local network or whether it must be routed outside the local network
  - It is applied to a message's destination address to extract the network address
  - If the extracted network address matches the local network ID, the destination is located on the local network
- Following are the default subnet masks in **IP Address Classful scheme** for Class A, B and C addresses:

Default Subnet Masks	
Address Class	**Subnet Mask**
Class A	255.0.0.0
Class B	255.255.0.0
Class C	255.255.255.0

A Trial Separation (good to know)

- Using subnet mask to determine **Network ID** of the destination network:
  1. If a destination IP address is 206.175.162.21, we know that it is a Class C address & that its binary equivalent is:
     11001110.10101111.10100010.00010101
  2. We also know that the default standard Class C subnet mask is: 255.255.255.0 and that its binary equivalent is:
     11111111.11111111.11111111.00000000

A Trial Separation (Cont.)

3. When these two binary numbers (the IP address & the subnet mask) are combined using Boolean Algebra (AND operation), the result is the **Network ID** of the destination network:

206.175.162.21	11001110.10101111.10100010.00010101
and	
255.255.255.0	11111111.11111111.11111111.00000000
yields	
	11001110.10101111.10100010.00000000

ℹ If the result is the **IP address of the network** matches with one of the internal networks, then the packet belongs to the local network)

Subnetting, Subnet & Subnet Mask

- Subnetting is the process of dividing a network & its IP addresses into segments, each of which is called a subnetwork or subnet
  - The subnet mask is a 32-bit number that the router uses to cover up the network address, to show which bits are being used for identifying a subnet
- Subnetting, a subnet & a subnet mask are all different
  - In fact, the 1st creates the 2nd & is identified by the 3rd

Why Subnetting is important?

Limited IPv4 addresses	Subnetting helps in extending the existing address space (thereby reducing wastage)
Reduced size of routing tables	Smaller (divided) networks = smaller routing tables
Hide routing/interface flapping from outside routers	No private addresses + internal interface flapping (advertising alternate routes OR available and unavailable) exposed to 'outside routers'
Improve the available (shared) bandwidth	Cuts down on the amount of broadcast traffic generated over the entire network

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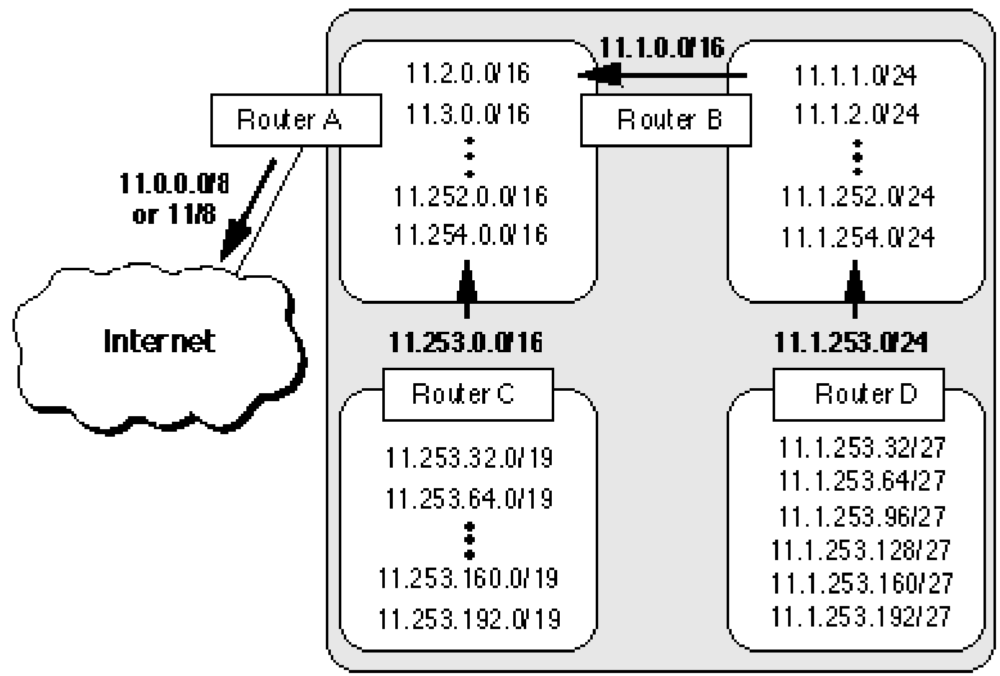
Subnetting (a single advertisement)

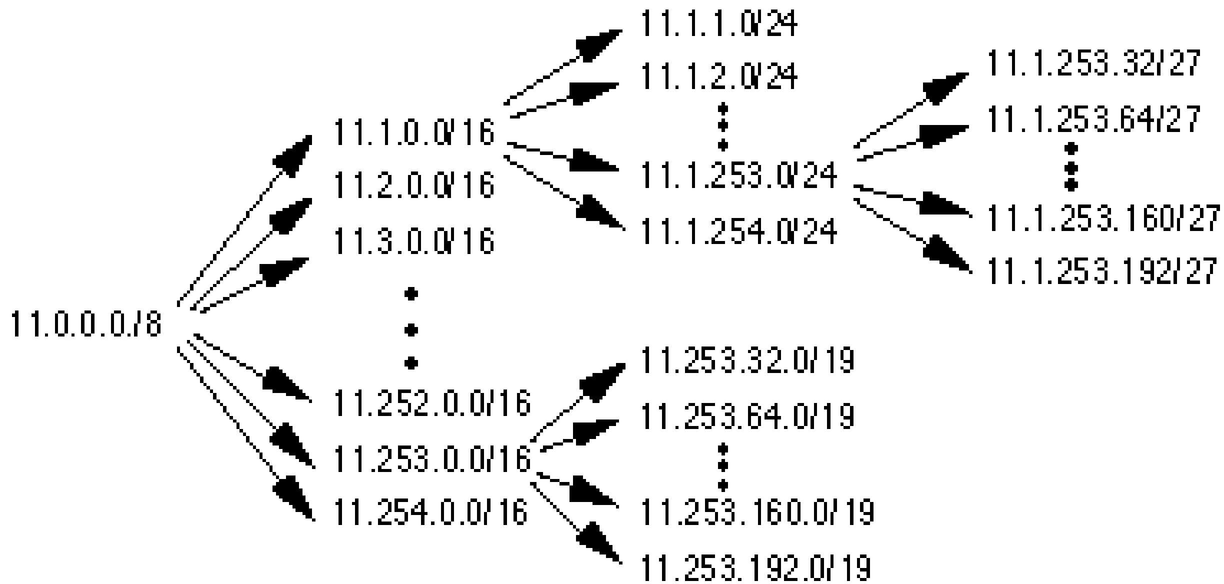
- A subnet summarizes all its lower level hierarchies into a single advertisement (or hides internal subnets from outside network)
- Allows the expansion of both Local Networks & the Internet in today’s world
  - A must-know for network administrators

A single advertisement to the outside world!



Subnet(s) (recursive division)

- Helps to reduce routing table size (Route Aggregation)
  - Can be further divided recursively while reducing the IP addresses wastage



VLSM and CIDR

- Variable Length Subnet Mask (VLSM):
  - Carrying bits from host portion (extended-network-prefix)
    - OR vice versa; depends on the requirements
  - Allow more efficient use of network addresses
    - Represented as e.g., **255.255.255.128**
- Classless Inter-Domain Routing (CIDR):
  - Gets translated into subnet mask
    - Represented as e.g., /**25**
    - Eliminates the class concept

Borrowing Bits to Grow a Subnet

- The key concept in subnetting is borrowing bits from the host portion of the network to create a subnetwork (or vice versa, based on the requirements)
- Rules govern this borrowing, ensures that some bits are left for a Host ID
  1. 2 bits remain available to use for the Host ID (allowing at least 3 Host addresses)
  2. Subnet bits cannot be all 1s or 0s at the same time

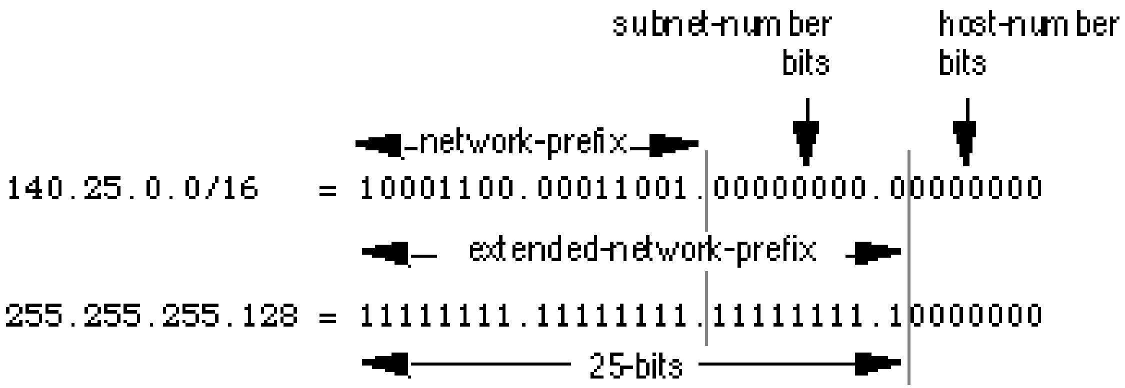
ℹ To split up a class C address into variable length subnets, **always start with the largest subnet first** and then work your way down e.g. /26 should be first, then /27s, /29's …

Subnetting (design example)

- An organization has been assigned with the network number **140.25.0.0/16** and it needs to create set of subnets that supports up to **60** hosts on each subnet <u>(with enough room for expansion)</u>

1: Defining the Subnet Mask (or Extended-Network-Prefix)

- $2^6 = 64$, not enough room for expansion
- **2^7 = 128 ->** *Network part: 25 bits; Host part: 7 bits*



Base Net: 10001100.00011001.00000000.00000000=**140.25.0.0/16**

2: OPTIONAL: Defining Subnet (SN) addresses

Took 9 bits from the host part -> 2^9 = 512 (total)

SN #0: 10001100.00011001.*00000000.0*0000000=**140.25.0.0/25**
SN #1: 10001100.00011001.*00000000.1*0000000=**140.25.0.128/25**
…
SN #256: 10001100.00011001.*11111111.1*0000000=140.25.255.128/25

3: Defining Hosts (+ broadcast) Addresses for Each Subnet

SN #0: 10001100.00011001.00000000.0*0000000*=140.25.0.0/25
Host #1: 10001100.00011001.00000000.0 *0000001* = 140.25.0.1/25
Host #2: 10001100.00011001.00000000.0 *0000010* = 140.25.0.2/25
…
Host #126: 10001100.00011001.00000000.0 *1111110* = 140.25.0.126/25

Default gateway

7 Host bits -> $2^6 + 2^5 + 2^4 + 2^3 + 2^2 + 2^1 + 2^0$ = **127 (Host range)**
Usable Hosts: 127-2=125

SN #0: Broadcast (all 1's in host part)
10001100.00011001.00000000.0 *1111111* = **140.25.0.127**

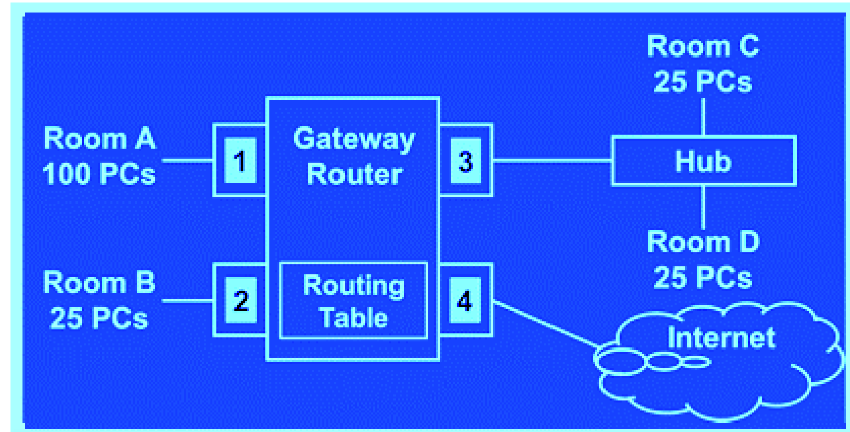
Subnet Design Considerations

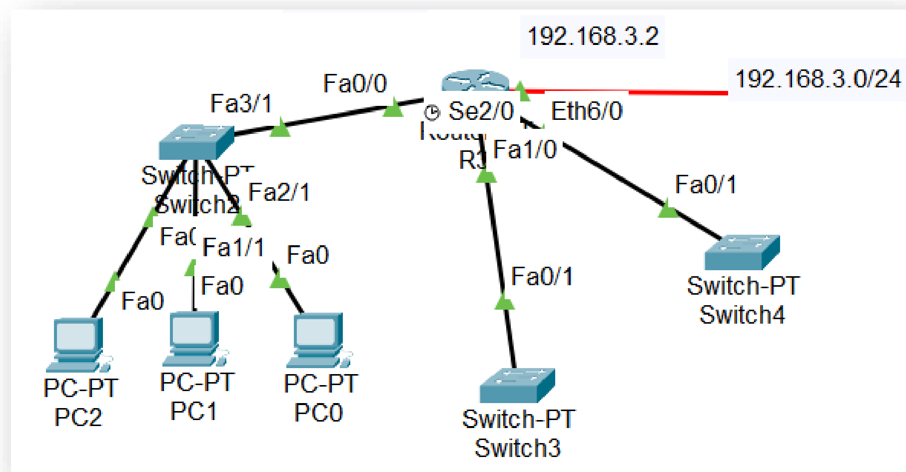
1. How many total subnets does the organization need today?
2. How many total subnets will the organization need in the future?
3. How many hosts are there on the organization's largest subnet today?
4. How many hosts will there be on the organization's largest subnet in the future?
5. …

Exercise 8: Practical work

- Using your last cisco packet tracer file:
  1. Subnet the given IP address: 165.132.9.0/24
     - Under the requirements as shown in the diagram
  2. Connect R3 to R2, using a serial cable, to extend and implement network topology (as shown in the diagram)

Save your cpt file with your 'First_Last name'





Deadline: See 'Teams' Assignment section

Subnet for Room A

- Room A (100 PCs): 100 IP addresses
- Network Destination: 1 IP address ← Lowest IP address in subnet
- Broadcast IP: 1 IP address ← Highest IP address in subnet
- Gateway Interface 1: 1 IP address ← Second highest IP address in subnet

103

→ IP Addresses Required = 103 addresses ≤ $128=2^7$

→ Subnet mask $11111111.11111111.11111111.1\underbrace{0000000}_{\text{7 zeros}}$ = 255.255.255.128

IP & Subnet for Room A

- IP address for Room A: 165.132.9.★

★

0	Network Destination
1-100	IP Addresses for 100 PCs
101-125	IP Addresses not used (25 reserved)
126	Gateway Interface 1 IP address
127	Broadcast IP Address

- We needed 103 ≤ 128 = 2^7 = Subnet Size

  Subnet mask 255.255.255.128 ← $(256-2^7) = 128$

- CIDR (Classless Inter-Domain Routing)
  - Network Destination / Subnet Mask 1's (32-7=25)
  - CIDR Network ID: 165.132.9.0/25

Subnet for Room B

- Room B (25 PCs): 25 IP addresses
- Network Destination: 1 IP address ← Lowest IP address in subnet
- Broadcast IP: 1 IP address ← Highest IP address in subnet
- Gateway Interface 2: 1 IP address ← Second highest IP address in subnet

28

→ IP Addresses Required = 28 addresses $\leq 32 = 2^5$

→ Subnet mask $11111111.11111111.11111111.111\underbrace{00000}_{\text{5 zeros}}$ = 255.255.255.224

IP & Subnet for Room B

- IP address for Room B: 165.132.9.★

★:

128	Network Destination
129~153	IP Addresses for 25 PCs
154~157	IP Addresses not used (4 reserved)
158	Gateway Interface 2 IP address
159	Broadcast IP Address

- We needed $28 \leq 32 = 2^5$ = Subnet Size

  Subnet mask 255.255.255.224 ← $(256-2^5) = 224$

> • Subnet Mask 1's (32-5=27)
> • CIDR Network ID: 165.132.9.128/27

Subnet for Room C & D

- Room C+D (50 PCs): 50 IP addresses
- Network Destination: 1 IP address ← Lowest IP address in subnet
- Broadcast IP: 1 IP address ← Highest IP address in subnet
- Gateway Interface 3: 1 IP address ← Second highest IP address in subnet

53

→ IP Addresses Required = 53 addresses ≤ 64 = 2^6

→ Subnet mask $11111111.11111111.11111111.11\underbrace{000000}_{\text{6 zeros}}$ = 255.255.255.192

165.132.9.160/26 will provide:
165.132.9.129 – 165.132.9.191

Above range conflicts with 165.132.9.128/27:
165.132.9.129 - 165.132.9.159 (/27)

What should be done to correct this?
-> Check Slide no. 34 info-box

IP & Subnet for Room C & D

- IP for Room C & D: 165.132.9.★

★

160	Network Destination
161-210	IP Addresses for 50 PCs
211-221	IP Addresses not used (11 reserved)
222	Gateway Interface 3 IP address
223	Broadcast IP Address

- We needed 53 ≤ 64 = 2^6 = Subnet Size

  Subnet mask 255.255.255.192 ← (256-2^6) = 192

  - We may need to assign IP address(es) for the Hub/Switch from the reserved IP addresses

Run-down: IP Routing Table

- Using the IP address from **Exercise 5**, following Routing Table will be maintained:

Routing Table Configuration of the Gateway/Router

Room	Destination (Network Destination)	Subnet Mask (Netmask)	Gateway	Interface (GW Port)	Metric
A	165.132.9.0	255.255.255.128	165.132.9.126	1	10
B	165.132.9.128	255.255.255.224	165.132.9.158	2	10
C, D	165.132.9.160	255.255.255.192	165.132.9.222	3	1
Internet	165.132.15.56	255.255.255.252	165.132.15.58	4	10
Default Route	0.0.0.0	0.0.0.0	165.132.15.58	4	10

Metric indicates the associated cost (efficiency) of the route ↗

- The last row has a Subnet Mask of 0.0.0.0 where all 32 bits of the Subnet Mask are 0s which makes it 'all pass' Subnet Mask
  - Therefore, the Internet row of the routing table can be combined into the last row of "Default Route"

Routing Table Configuration of the Gateway/Router

Room	Destination (Network Destination)	Subnet Mask (Netmask)	Gateway	Interface (GW Port)	Metric
A	165.132.9.0	255.255.255.128	165.132.9.126	1	10
B	165.132.9.128	255.255.255.224	165.132.9.158	2	10
C, D	165.132.9.160	255.255.255.192	165.132.9.222	3	1
Internet	0.0.0.0	0.0.0.0	165.132.15.58	4	10

"Default Route" row and "Internet" row are combined

- When an IP packet enters the Gateway/Router the routing table is used to determine where to send this packet out
- Upon receiving the IP packet,
  - **The 1st row is checked first**
  - Then going down, each row is sequentially checked in the routing table:

Room	Destination	Subnet Mask	Gateway	Interface	Metric
A	165.132.9.0	255.255.255.128	165.132.9.126	1	10
B	165.132.9.128	255.255.255.224	165.132.9.158	2	10
C, D	165.132.9.160	255.255.255.192	165.132.9.222	3	1
Internet	0.0.0.0	0.0.0.0	165.132.15.58	4	10

Verifying an IP Address

- IP addresses connectivity can be checked using PING (ICMP), Trace, Telnet, …
- It is important that you know that PING is used to verify IP address connections to the Network Layer & that Telnet is used to verify network IP address connections to the Application Layer

Verifying with Traceroute (tracert)

- The Traceroute (GNU/Linux) or Tracert (Windows) command is used to show the complete route from a source to a destination
  - It sends out probe packets one at a time to each router/hop/switch/… in the path between the source & the destination IP address entered
  - Displays the round-trip time for each packet sent to each upstream router

It is used to determine where a breakdown in a route may be occurring

Trace Command Response Codes	
Response	**Meaning**
*	Timed out
!H	Router received packet but did not forward it (usually due to an access list)
N	Network unreachable
P	Protocol unreachable
U	Port unreachable

Lecture 5 ends here

- Course Slides: Go to MS Teams:
  'Introduction to Computer Networks - Spring 2024 | BSc'
  -> Files section

- Send your questions by email:
  mohammad-salman.nadeem@epita.fr
  OR via direct message using MS Teams

- Thank You!