# Computer Networks - *Xarxes de Computadors*

## Outline

- Course Syllabus
- Unit 1: Introduction
- Unit 2. Network applications
- **Unit 3. IP Networks**
- Unit 4. TCP
- Unit 5. LANs

# Unit 3: IP Networks

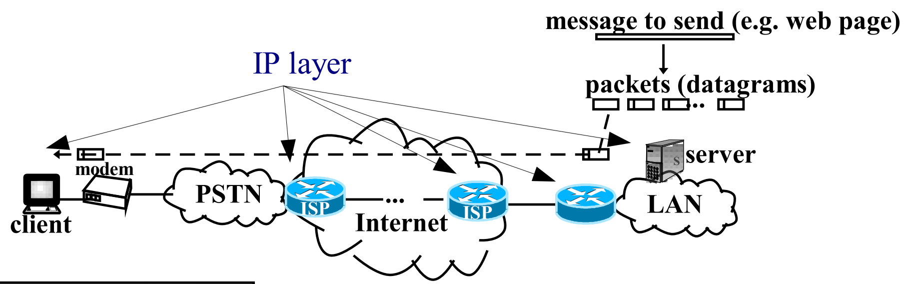
## Outline

- **IP layer service**
- IP addresses
- Subnetting
- Routing tables
- ARP protocol
- IP header
- ICMP protocol
- DHCP protocol
- NAT
- Routing algorithms
- Security in IP

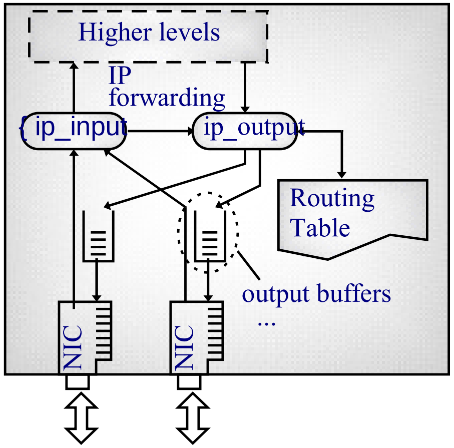
# Unit 3: IP Networks

## IP Layer Service

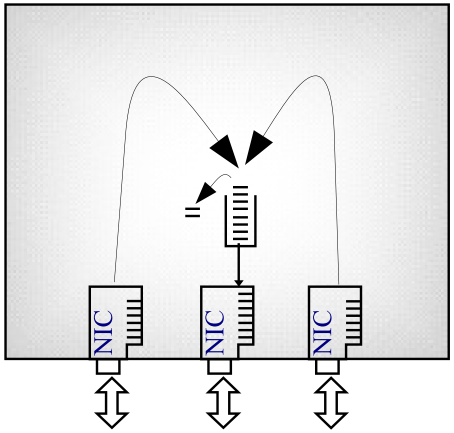
- Internet Protocol (IP) goal is routing datagrams.
- IP main design goal was interconnecting hosts attached to LANs/WANs networks of different technologies.
- IP characteristics are:
    - Connectionless
    - Stateless
    - Best effort




Commercial routers




Basic router architecture




Looses may occur due to buffer overflow

# Unit 3: IP Networks

## High Performance Routers

Source: Juniper

"There is a major upgrade going on in service providers upgrading their core networks," Chris Komatas, director of service provider marketing at Juniper, said.

"The next-generation core network is all about having the agility to support any service. T1600 is delivering No. 1 in scale, No. 1 in service control and No. 1 in efficiency. All the metrics that are important for a service provider."

The keys to the performance throughput on the Juniper T1600 are the 100Gbps-capable slots that can support all the major connectivity options that carriers may have. Among them is support for OC-768 (40 Gbps), OC-192 (10Gbps) and 10GbE (10 Gigabit Ethernet).

Juniper (www.juniper.net)

**Figure 1.** Cisco XR 12000 and 12000 series routing portfolio

**Table 1.** Product Specifications

| Product Specification | Cisco XR 12000 and 12000 Series 16-Slot Chassis | Cisco XR 12000 and 12000 Series 10-Slot Chassis | Cisco XR 12000 and 12000 Series 6-Slot Chassis | Cisco XR 12000 and 12000 Series 4-Slot Chassis |
|---|---|---|---|---|
| Slot capacity | 16 slots | 10 slots | 6 slots | 4 slots |
| Aggregate switching capacity | Cisco 12016: 80 Gbps<br>Cisco 12416: 320 Gbps<br>Cisco 12816: 1280 Gbps | Cisco 12010: 50 Gbps<br>Cisco 12410: 200 Gbps<br>Cisco12810: 800 Gbps | Cisco 12006: 30 Gbps<br>Cisco 12406: 120 Gbps | Cisco 12404: 80 Gbps |
| Full-duplex throughput per slot | Cisco 12016: 2.5 Gbps/slot<br>Cisco 12416: 10 Gbps/slot<br>Cisco 12816: 40 Gbps/slot | Cisco 12010: 2.5 Gbps/slot<br>Cisco 12410: 10 Gbps/slot<br>Cisco 12810: 40 Gbps/slot | Cisco 12006: 2.5 Gbps/slot<br>Cisco 12406: 10 Gbps/slot | Cisco 12404: 10 Gbps/slot |

cisco (www.cisco.com)

# Unit 3: IP Networks

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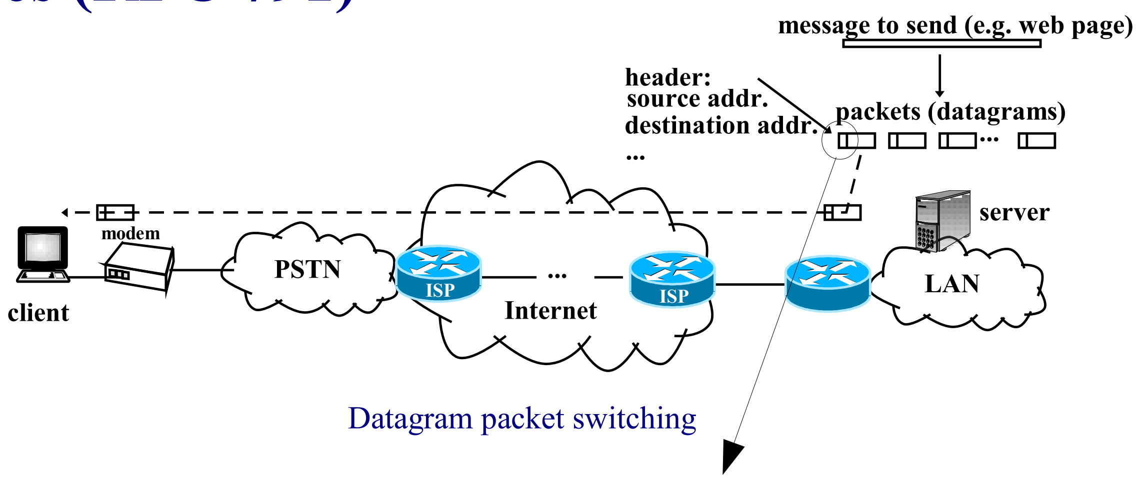
- Security in IP

# Unit 3: IP Networks

## IP Addresses (RFC 791)




Datagram packet switching

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

IP datagram header

# Unit 3: IP Networks

## IP Addresses

```
 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 bits
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          netid                  /                hostid          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- 32 bits (4 bytes).
- Dotted point notation: Four bytes in decimal, e.g. 147.83.24.28
- netid identifies the network.
- hostid identifies the host within the network.
- An IP address identifies an *interface*: an attachment point to the network.
- All IP addresses in Internet must be different. To achieve this goal, Internet Assigned Numbers Authority, IANA (http://www.iana.net) assign address blocs to Regional Internet Registries, RIR:
  - RIPE: Europe, http://www.ripe.net.
  - ARIN: USA, http://www.arin.net.
  - APNIC: ASIA http://www.apnic.net.
  - LACNIC: Latin America, http://www.lacnic.net.
- RIR assign addresses to ISPs, and ISPs to their customers.

# Unit 3: IP Networks

## IP Addresses - Classes

- The highest bits identify the class.
- The number of IP bits of netid/hostid varies in classes A/B/C.
- D Class is for multicast addresses (e.g. 224.0.0.2: "all routers")
- E Class are reserved addresses.

| Classe | netid (bytes) | hostid (bytes) | Codification | range |
|---|---|---|---|---|
| A | 1 | 3 | 0xxxx···x | 0.0.0.0 ∼ 127.255.255.255 |
| B | 2 | 2 | 10xxx···x | 128.0.0.0 ∼ 191.255.255.255 |
| C | 3 | 1 | 110xx···x | 192.0.0.0 ∼ 223.255.255.255 |
| D | - | - | 1110x···x | 224.0.0.0 ∼ 239.255.255.255 |
| E | - | - | 1111x···x | 240.0.0.0 ∼ 255.255.255.255 |

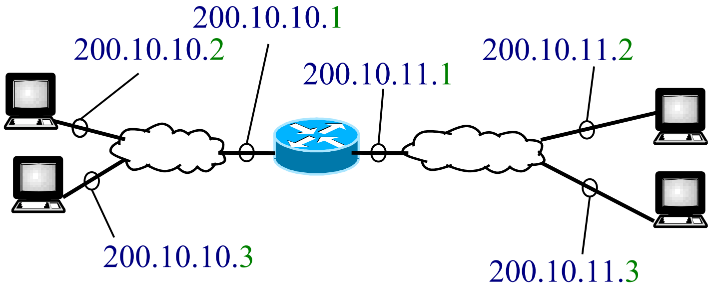
# Unit 3: IP Networks

## IP Addresses – Special Addresses

- Special addresses cannot be used for a physical interface.
- Each network has two special addresses: network and broadcast addresses.

| netid | hostid | Meaning |
|---|---|---|
| xxx | all ‘0’ | Identifies a network. It is used in routing tables. |
| xxx | all ‘1’ | Broadcast in the net. xxx. |
| all ‘0’ | all ’0’ | Identifies “this host” in “this net.”. Used as source address in configuration protocols, e.g. DHCP. |
| all ‘1’ | all ‘1’ | broadcast in “this net.”. Used as destination address in configuration protocols, e.g. DHCP. |
| 127 | xxx | host loopback: interprocess communication with TCP/IP. |

- Example:

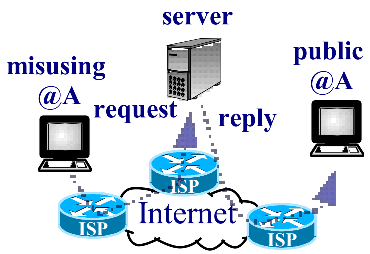


# Unit 3: IP Networks

## IP Addresses – Private Addresses (RFC 1918)

- Most commercial OSs include the TCP/IP stack.
- TCP/IP is used to network many kind of electronic devices:


- Addresses assigned to RIRs by IANA are called *public, global* or *registered*.
- What if we arbitrarily assign a registered address to a host?
  - It may be filtered by our ISP or cause trouble to the right host using that address.




- **Private addresses** has been reserved for devices not using public addresses. These addresses are not assigned to any RIR (are not unique). There are addresses in each class:
  - 1 class A network: 10.0.0.0
  - 16 class B networks: 172.16.0.0 ~ 172.31.0.0
  - 256 class C networks: 192.168.0.0 ~ 192.168.255.0

# Unit 3: IP Networks

## Outline

- IP layer service
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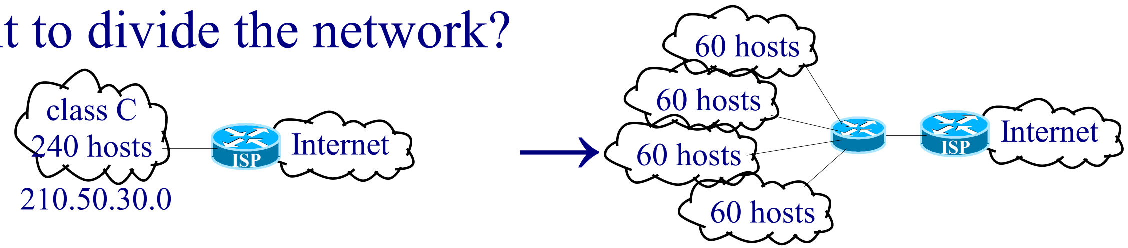
# Unit 3: IP Networks

## Subnetting (RFC 950)

- Initially the netid was given by the address class: A with $2^{24}$ addresses, B with $2^{16}$ addresses and C with $2^{8}$ addresses.
- What if we want to divide the network?




- Subnetting allows adding bits from the hostid to the netid (called subnetid bits).
- Example: For the ISP the network prefix is 24 bits. For the internal router the network prefix is 26 bits. The 2 extra bits allows 4 "subnetworks".
- A **mask** is used to identify the size of the netid+subnetid prefix.
- Mask notations:
  - dotted, as 255.255.255.192
  - giving the mask length (number of bits) as 210.50.30.0/26

# Unit 3: IP Networks

## IP Addresses – Subnetting Example

- We want to subnet the address 210.50.30.0/24 in 4 subnets


B = 210.50.30

| subnet | subnetid | IP net. addr. | range | broadcast | available |
|---|---|---|---|---|---|
| S1 | 00 | B.0/26 | B.0 $\sim$ B.63 | B.63 | $2^6 - 2 = 62$ |
| S2 | 01 | B.64/26 | B.64 $\sim$ B.127 | B.127 | $2^6 - 2 = 62$ |
| S3 | 10 | B.128/26 | B.128 $\sim$ B.191 | B.191 | $2^6 - 2 = 62$ |
| S4 | 11 | B.192/26 | B.192 $\sim$ B.255 | B.255 | $2^6 - 2 = 62$ |

# Unit 3: IP Networks

## IP Addresses – Variable Length Subnet Mask (VLSM)

- Subnetworks of different sizes.
- Example, subnetting a class C address:
  - We have 1 byte for subnetid + hostid.
  - subnetid is green, chosen subnets addresses are underlined.

0000 / 1000 ⟶ 1000 / 1100

1100 ⟶ 1100 / 1101 / 1110 / 1111

| subnet | subnetid | IP net. addr. | range | broadcast | available |
|---|---|---|---|---|---|
| S1 | 0 | B.0/25 | B.0 $\sim$ B.127 | B.127 | $2^7 - 2 = 126$ |
| S2 | 10 | B.128/26 | B.128 $\sim$ B.191 | B.191 | $2^6 - 2 = 62$ |
| S3 | 1100 | B.192/28 | B.192 $\sim$ B.207 | B.207 | $2^4 - 2 = 14$ |
| S4 | 1101 | B.208/28 | B.208 $\sim$ B.223 | B.223 | $2^4 - 2 = 14$ |
| S5 | 1110 | B.224/28 | B.224 $\sim$ B.239 | B.239 | $2^4 - 2 = 14$ |
| S6 | 1111 | B.240/28 | B.240 $\sim$ B.255 | B.255 | $2^4 - 2 = 14$ |

# Unit 3: IP Networks

## IP Addresses – Classless Inter-Domain Routing, CIDR (RFC 1519)

- Initially, Internet backbone routing tables did not use masks: netid was derived from the IP address class.
- When the number of networks in Internet started growing exponentially, routing tables size started exploding.
- In order to reduce routing tables size, CIDR proposed a "rational" geographical-based distribution of IP addresses to be able to "aggegate routes", and use masks instead of classes.
- Aggregation example:

200.1.10.0/24
200.1.11.0/24 ⟶ 200.1.10.0/23

- The term summarization is normally used when aggregation is done at a class boundary (e.g. a groups of subnets is summarized with their classful base address).

# Unit 3: IP Networks

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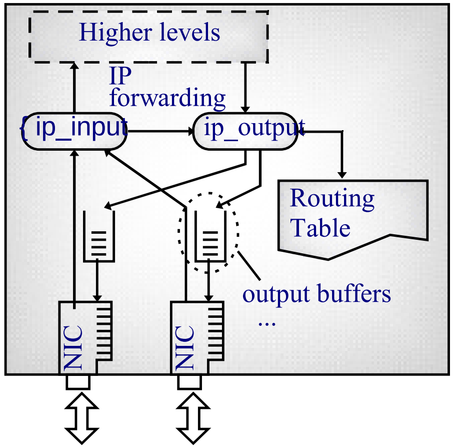
# Unit 3: IP Networks

## Routing Table

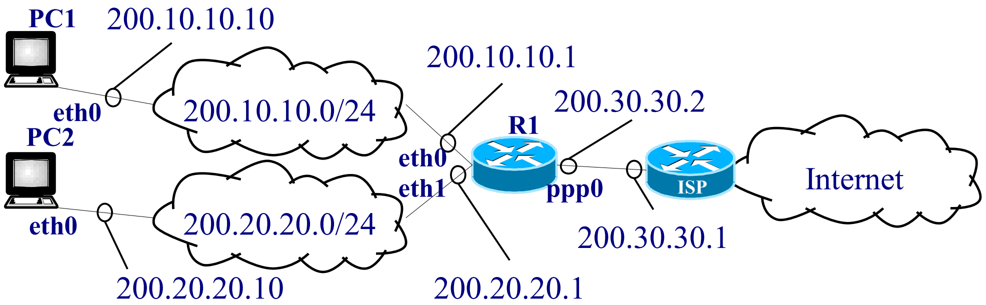
- ip_output() kernel function consults the routing table for each datagram.
- Routing can be:
  - Direct: The destination is directly connected to an interface.
  - Indirect: Otherwise. In this case, the datagram is sent to a router.
- Default route: Is an entry where to send all datagrams with a destination address to a network not present in the routing table. The default route address is 0.0.0.0/0.
- Hosts routing tables usually have two entries: The network where they are connected and a default route.




Basic router architecture

# Unit 3: IP Networks

## Routing Table – Unix Example




known destinations

how to reach the destinations

PC1 routing table:

| Destination | Genmask | Gateway | Iface |
|---|---|---|---|
| 200.10.10.0 | 255.255.255.0 | 0.0.0.0 | eth0 |
| 0.0.0.0 | 0.0.0.0 | 200.10.10.1 | eth0 |

PC2 routing table:

| Destination | Genmask | Gateway | Iface |
|---|---|---|---|
| 200.20.20.0 | 255.255.255.0 | 0.0.0.0 | eth0 |
| 0.0.0.0 | 0.0.0.0 | 200.20.20.1 | eth0 |

R1 routing table:

| Destination | Genmask | Gateway | Iface |
|---|---|---|---|
| 200.10.10.0 | 255.255.255.0 | 0.0.0.0 | eth0 |
| 200.20.20.0 | 255.255.255.0 | 0.0.0.0 | eth1 |
| 0.0.0.0 | 0.0.0.0 | 200.30.30.1 | ppp0 |

# Unit 3: IP Networks

## Routing Table – Tiscali ISP, CISCO 7200 Router

- Telnet to route-server.ip.tiscali.net (see http://www.bgp4.net server list)

```
+--------------------------------------------------------------------+
|          TISCALI International Network - Route Monitor             |
|                            (AS3257)                                |
|   This system is solely for internet operational purposes. Any     |
|   misuse is strictly prohibited. All connections to this router    |
|   are logged.                                                      |
|   This server provides a view on the TISCALI routing table that    |
|   is used in Frankfurt/Germany. If you are interested in other     |
|   regions of the backbone check out http://www.ip.tiscali.net/lg   |
|   Please report problems to noc@tiscali.net                        |
+--------------------------------------------------------------------+
route-server.ip.tiscali.net> show ip route
Codes: 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, 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

Gateway of last resort is 213.200.64.93 to network 0.0.0.0
B       85.27.76.0/22 [20/10] via 213.200.64.93, 4w2d
B       85.196.154.0/24 [20/10] via 213.200.64.93, 1d09h
B       85.158.216.0/21 [20/10] via 213.200.64.93, 2w6d
B       85.193.136.0/22 [20/10] via 213.200.64.93, 3d08h
B       85.121.48.0/21 [20/0] via 213.200.64.93, 1w4d
B       85.187.201.0/24 [20/10] via 213.200.64.93, 4d19h
B       85.114.0.0/20 [20/10] via 213.200.64.93, 1w5d
B       85.119.16.0/24 [20/10] via 213.200.64.93, 4w0d
B       85.119.16.0/21 [20/10] via 213.200.64.93, 4w0d
B       85.105.0.0/17 [20/10] via 213.200.64.93, 4w2d
B       85.93.52.0/24 [20/10] via 213.200.64.93, 4w0d
...
```

thousands of entries

Tiscali Network Map
http://www.tiscali.net

# Unit 3: IP Networks

## Routing Table – Datagram Delivery Algorithm

- 1. Check if the device itself is the destination:

```
if(Datagram Destination == address of any of the interfaces) {
    send the datagram to upper layers
}
```

- 2. Consult the routing table:

```
for each routing table entry ordered from longest to shortest mask
  (Longest Prefix Match) {
    if((Datagram Destination IP address & mask) == Destination
      table entry) {
        return (gateway, interface) ;
    }
```

- 3. Forward the datagram

```
if(it is a direct routing) {
    send the datagram to the Datagram Destination IP address
} else { /* it is an indirect routing */
    send the datagram to the gateway IP address
}
```

# Unit 3: IP Networks

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- IP layer service
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- **ARP protocol**
- IP header
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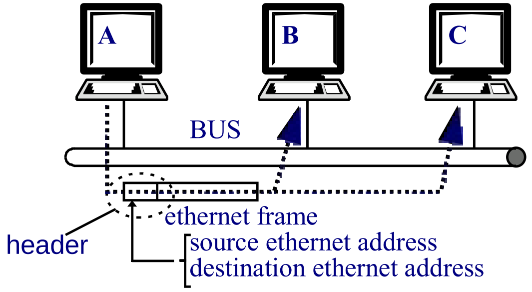
# Unit 3: IP Networks

## Address Resolution Protocol, ARP (RFC 826)

- To send the datagram, IP layer may have to pass a "physical address" to the NIC driver. Physical addresses are also called MAC or hardware addresses.
- ARP translate IP addresses to "physical addresses" (used by the physical network).
- If needed, IP calls ARP module to obtain the "physical addresses" before the NIC driver call.
- Ethernet example:



# Unit 3: IP Networks

## Address Resolution Protocol, messages

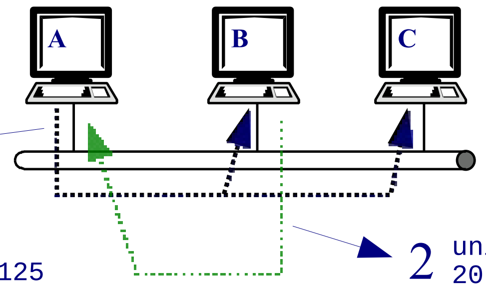
- When IP calls ARP:
  - If ARP table has the requested address, it is returned,
  - otherwise:
    - IP stores the datagram in a temporal buffer, and a resolution protocol is triggered.
    - IP initiates a timeout and starts forwarding the next datagram in the transmission queue.
    - If the timeout triggers before resolution, the datagram is removed.
    - If ARP returns the requested address, IP calls the driver with it.
- ARP resolution in an ethernet network (broadcast network):
  - A broadcast "ARP Request" message is sent indicating the IP address.
  - The station having the requested IP address sends a unicast "ARP Reply", and stores the requesting address in the ARP table.
  - Upon receiving the "ARP Reply", the requesting station return the IP call with it.
  - ARP entries have a timeout refreshed each time a match occurs.

# Unit 3: IP Networks

## Address Resolution Protocol, messages - Example

- ARP messages (tcpdump):

147.83.34.125 147.83.34.123




1 broadcast:
```
20:02:25.681331 arp who-has
 147.83.34.123 tell 147.83.34.125
```

2 unicast:
```
20:02:25.681490 arp reply 147.83.34.123
is-at 00:c0:49:d5:96:d8
```

- ARP tables:

```
A> /sbin/arp -n
Address                  HWtype  HWaddress           Flags Mask            Iface
147.83.34.123            ether   00:c0:49:d5:96:d8   C                     eth0
```

```
B> /sbin/arp -n
Address                  HWtype  HWaddress           Flags Mask            Iface
147.83.34.125            ether   00:14:F1:CC:59:00   C                     eth0
```

"Completed" flag

# Unit 3: IP Networks

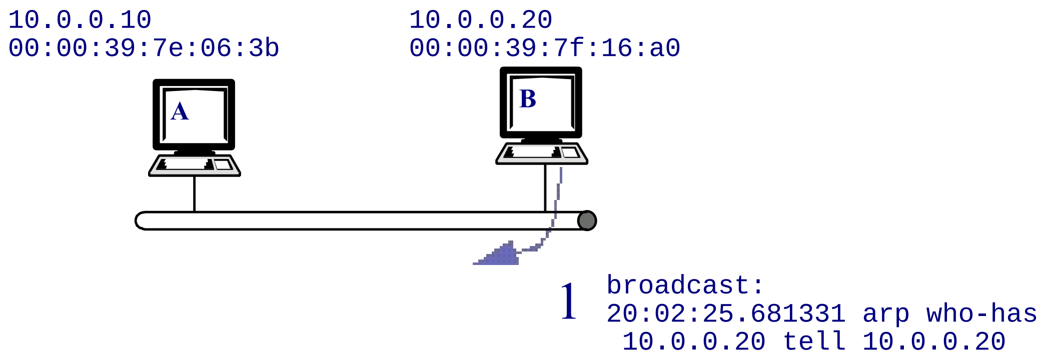
## Address Resolution Protocol – Message format (ethernet)

- ARP messages are encapsulated directly in a data-link frame.

```
 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 bits
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Hardware Type (16)            |  Protocol Type (16)           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Hard. Length(8)|Prot. Length(8)|  Opcode (16)                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       Sender Hardware                                         |
+       Address (48)            +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               | Sender Protocol Address (32)  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Sender Protocol Address (cont)|     Target Hardware           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+     Address (48)              +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       Target Protocol Address (32)                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

# Unit 3: IP Networks

## Address Resolution Protocol – Gratuitous ARP




- Goals:
  - Detect duplicated IP addresses.
  - Update MAC addresses in ARP tables after an IP or NIC change.

# Unit 3: IP Networks

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# Unit 3: IP Networks

## IP Header (RFC 791)

- Version: 4
- IP Header Length (IHL): Header size in 32 bit words.
- Type of Service: (ToS): *xxxdtrc0.*
- Total Length: Datagram size in bytes.
- Identification/Flags/Fragment Offset: used in fragmentation.
- Time to Live (TTL): if(--TTL==0) { discard ; }.
- Protocol: Encapsulated protocol (/etc/protocols in unix).
- Header Checksum: Header error detection.
- Source and Destination Addresses: End nodes addresses.
- Options: Rcord Route, Loose Source Routing, Strict Source Routing.

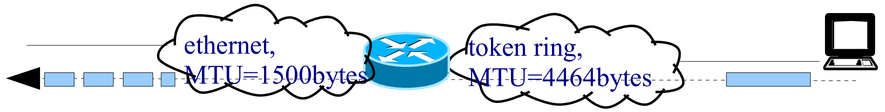
20 bytes

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

# Unit 3: IP Networks

## IP Fragmentation

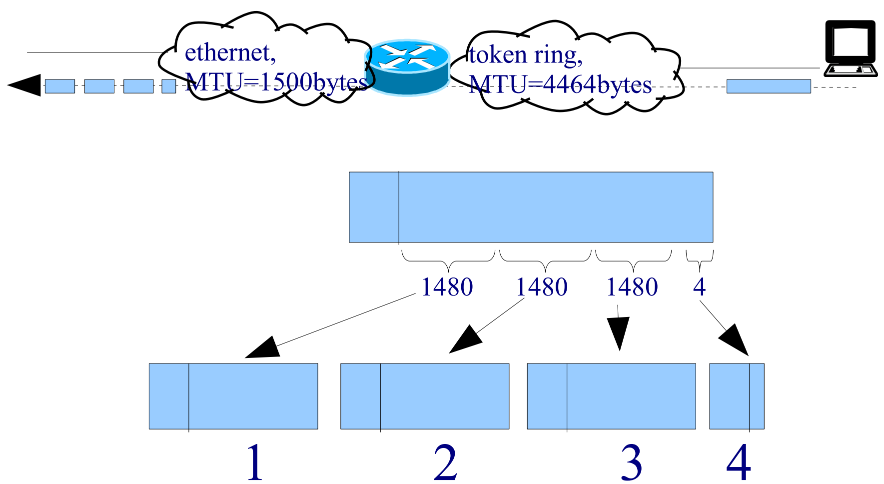
- Fragmentation may occur:
  - Router: Fragmentation may be needed when two networks with different *Maximum Transfer Unit* (MTU) are connected.
  - Host: Fragmentation may be needed using UDP. TCP segments are ≤ MTU.
- Datagrams are reconstructed at the destination.
- Fields:
  - Identification (16 bits): identify fragments from the same datagram.
  - Flags (3 bits):
    - D, don't fragment. Used in MTU path discovery
    - M, More fragments: Set to 0 only in the last fragment
  - Offset (13 bits): Position of the fragment first byte in the original datagram in 8 byte words (indexed at 0).



# Unit 3: IP Networks

## IP Fragmentation - Example

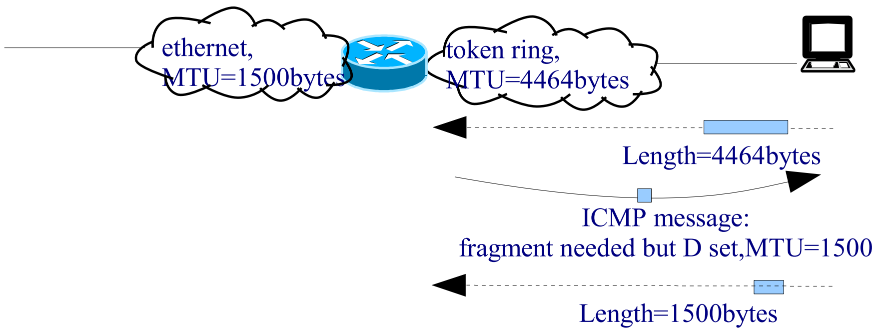
- Original datagram = 4464 bytes (4Mbps Token Ring): 20 header + 4444 payload.
- Fragment size = $\left\lfloor \frac{1500-20}{8} \right\rfloor = 185$ 8-byte-words (1480 bytes)
  - 1st fragment: offset = 0 , M = 1. 0~1479 payload bytes.
  - 2nd fragment: offset = 185, M = 1. 1480~2959 payload bytes.
  - 3rd fragment: offset = 370, M = 1 . 2960~4439 payload bytes.
  - 4th fragment: offset = 555, M = 0 . 4440~4443 payload bytes.



# Unit 3: IP Networks

## MTU Path Discovery

- Used in modern TCP implementations.
- TCP by default chooses the maximum segment size, to avoid headers overhead (segment efficiency = TCP payload / (TCP payload + Σ TCP,IP,Data-link,Physical headers)
- Goal: avoid fragmentation: The DF flag is set to one, segment size is reduced upon receiving ICMP error message “fragmentation needed but DF flag set”



# Unit 3: IP Networks

## Outline

- IP layer service
- IP addresses
- Subnetting
- Routing tables
- ARP protocol
- IP header
- **ICMP protocol**
- DHCP protocol
- NAT
- Routing algorithms
- Security in IP

# Unit 3: IP Networks

## Internet Control Message Protocol, ICMP (RFC 792)

- Used for attention and error messages.
- Can be generated by IP, TCP/UDP, and application layers.
- Are encapsulated into an IP datagram.
- Can be: (i) query, (ii) error.
- An ICMP error message cannot generate another ICMP error message (to avoid loops).

# Unit 3: IP Networks

## ICMP general format message (RFC 792)

```
 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 bits
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    contingut (variable)                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

Identifies the message                        Is computed using all the message
```

- Query type messages have an identifier field, for request-reply correspondence.
- Error messages have a field where the first 8 bytes of the datagram payload causing the error are copied. These bytes capture the TCP/UDP ports. E.g. Destination Unreachable Message:

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             unused                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Internet Header + 64 bits of Original Data Datagram      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

# Unit 3: IP Networks

## Common ICMP messages

| Type | Code | query/error | Name | Description |
|---|---|---|---|---|
| 0 | 0 | query | echo reply | Reply an echo request |
| 3 | 0 | error | network unreachable | Network not in the RT. |
| | 1 | error | host unreachable | ARP cannot solve the address. |
| | 2 | error | protocol unreachable | IP cannot deliver the payload |
| | 3 | error | port unreachable | TCP/UDP cannot deliver the payload |
| | 4 | error | fragmentation needed but DF set | MTU path discovery |
| 4 | 0 | error | source quench | Sent by a congested router. |
| 5 | 0 | error | redirect for network | When the router send a datagram by the same interface it was received. |
| 8 | 0 | query | echo request | Request for reply |
| 11 | 0 | error | TTL=0 during transit | Sent by a router when `--TTL=0` |

# Unit 3: IP Networks

## Outline

- IP layer service
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# Unit 3: IP Networks

## Dynamic Host Configuration Protocol, DHCP (RFC 2131)

- Improves and can interoperate with previous BOOTP protocol.
- Used for automatic network configuration:
  - Assign IP address and mask,
  - Default route,
  - Hostname,
  - DNS domain,
  - Configure DNS servers,
  - etc.
- IP address configuration can be:
  - Dynamic: During a leasing time.
  - Automatic: Unlimited leasing time.
  - Manual: IP addresses are assigned to specific MAC addresses.

# Unit 3: IP Networks

## DHCP – Protocol Messages (RFC 2131)

```
DHCPDISCOVER -  Client broadcast to locate available servers.

DHCPOFFER    -  Server to client in response to DHCPDISCOVER with
                offer of configuration parameters.

DHCPREQUEST  -  Client message to servers either (a) requesting
                offered parameters from one server and implicitly
                declining offers from all others, (b) confirming
                correctness of previously allocated address after,
                e.g., system reboot, or (c) extending the lease on a
                particular network address.

DHCPACK      -  Server to client with configuration parameters,
                including committed network address.

DHCPNAK      -  Server to client indicating client's notion of network
                address is incorrect (e.g., client has moved to new
                subnet) or client's lease as expired

DHCPDECLINE  -  Client to server indicating network address is already
                in use.

DHCPRELEASE  -  Client to server relinquishing network address and
                cancelling remaining lease.

DHCPINFORM   -  Client to server, asking only for local configuration
                parameters; client already has externally configured
                network address.
```

# Unit 3: IP Networks

## DHCP – Message Fields (RFC 2131)

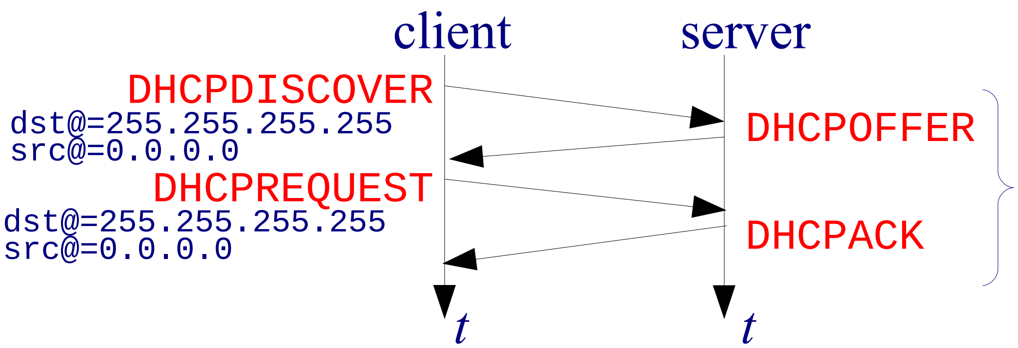
```
FIELD      OCTETS       DESCRIPTION
op            1  Message op code / message type. 1 = BOOTREQUEST, 2 = BOOTREPLY.
htype         1  Hardware address type.
hlen          1  Hardware address length.
hops          1  Client sets to zero, optionally used by relay agents
                 when booting via a relay agent.
xid           4  Transaction ID, a random number chosen by the
                 client, used by the client and server to associate
                 messages and responses between a client and a
                 server.
secs          2  Filled in by client, seconds elapsed since client
                 began address acquisition or renewal process.
flags         2  Flags.
ciaddr        4  Client IP address; only filled in if client is in
                 BOUND, RENEW or REBINDING state and can respond
                 to ARP requests.
yiaddr        4  'your' (client) IP address. Set by the server in
                 a DHCPOFFER message.
siaddr        4  IP address of next server to use in bootstrap;
                 returned in DHCPOFFER, DHCPACK by server.
giaddr        4  Relay agent IP address, used in booting via a
                 relay agent.
chaddr       16  Client hardware address.
sname        64  Optional server host name, null terminated string.
file        128  Boot file name, null terminated string; "generic"
                 name or null in DHCPDISCOVER, fully qualified
                 directory-path name in DHCPOFFER.
options     var  Optional parameters field.
```

```
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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     op (1)    |   htype (1)   |   hlen (1)    |   hops (1)    |
+---------------+---------------+---------------+---------------+
|                            xid (4)                            |
+-------------------------------+-------------------------------+
|           secs (2)            |           flags (2)           |
+-------------------------------+-------------------------------+
|                          ciaddr  (4)                          |
+---------------------------------------------------------------+
|                          yiaddr  (4)                          |
+---------------------------------------------------------------+
|                          siaddr  (4)                          |
+---------------------------------------------------------------+
|                          giaddr  (4)                          |
+---------------------------------------------------------------+
|                                                               |
|                          chaddr  (16)                         |
|                                                               |
|                                                               |
+---------------------------------------------------------------+
|                                                               |
|                          sname   (64)                         |
+---------------------------------------------------------------+
|                                                               |
|                          file    (128)                        |
+---------------------------------------------------------------+
|                                                               |
|                          options (variable)                   |
+---------------------------------------------------------------+
```

# Unit 3: IP Networks

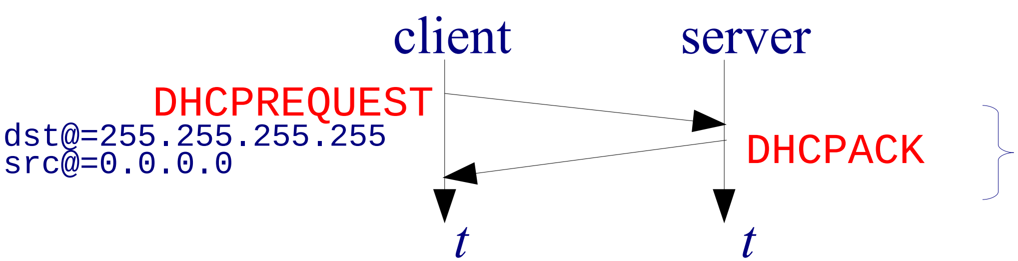
## DHCP – Client-server interaction (RFC 2131)

- UDP, server port = 67, client port = 68.




Can be unicast or broadcast, if requested by the client.

- The client can directly send `DHCPREQUEST`:
  - After rebooting if it remembers and wishes to reuse a previously allocated network address.
  - Extending the lease on a particular network address.




Can be unicast or broadcast, if requested by the client.

# DHCP – Example: tcpdump/dhcpdump capture

```
linux # tcpdump -lenx -s 1500 -i eth0 port bootps or port bootpc | dhcpdump
  TIME: 17:09:24.616312
    IP: 0.0.0.0.68 (00:30:1b:b4:6d:78) > 255.255.255.255.67 (ff:ff:ff:ff:ff:ff)
    OP: 1 (BOOTPREQUEST)
 HTYPE: 1 (Ethernet)
   XID: 181f0139
 FLAGS: 0
CIADDR: 0.0.0.0
YIADDR: 0.0.0.0
SIADDR: 0.0.0.0
GIADDR: 0.0.0.0
CHADDR: 00:30:1b:b4:6d:78:00:00:00:00:00:00:00:00:00:00
OPTION:  53 (  1) DHCP message type         3 (DHCPREQUEST)
OPTION:  57 (  2) Maximum DHCP message size 576
OPTION:  50 (  4) Request IP address        192.168.1.100
OPTION:  51 (  4) IP address leasetime      -1 ()
OPTION:  55 ( 21) Parameter Request List      1 (Subnet mask)
                                              3 (Routers)
                                              6 (DNS server)
                                             12 (Host name)
                                             15 (Domainname)
                                             23 (Default IP TTL)
                                             28 (Broadcast address)
                                             29 (Perform mask discovery)
                                             42 (NTP servers)
                                              9 (LPR server)
                                            119 (Domain Search)
                                            ...
---------------------------------------------------------------------------
  TIME: 17:09:24.619312
    IP: 192.168.1.1.67 (00:18:39:5d:74:9d) > 192.168.1.100.68 (00:30:1b:b4:6d:78)
    OP: 2 (BOOTPREPLY)
 HTYPE: 1 (Ethernet)
   XID: 181f0139
 FLAGS: 0
CIADDR: 0.0.0.0
YIADDR: 192.168.1.100
SIADDR: 192.168.1.1
GIADDR: 0.0.0.0
CHADDR: 00:30:1b:b4:6d:78:00:00:00:00:00:00:00:00:00:00
OPTION:  53 (  1) DHCP message type         5 (DHCPACK)
OPTION:  54 (  4) Server identifier         192.168.1.1
OPTION:  51 (  4) IP address leasetime      86400 (24h)
OPTION:   1 (  4) Subnet mask               255.255.255.0
OPTION:   3 (  4) Routers                   192.168.1.1
OPTION:   6 (  4) DNS server                192.168.0.1
OPTION:  15 (  3) Domainname                lan
```

# Unit 3: IP Networks

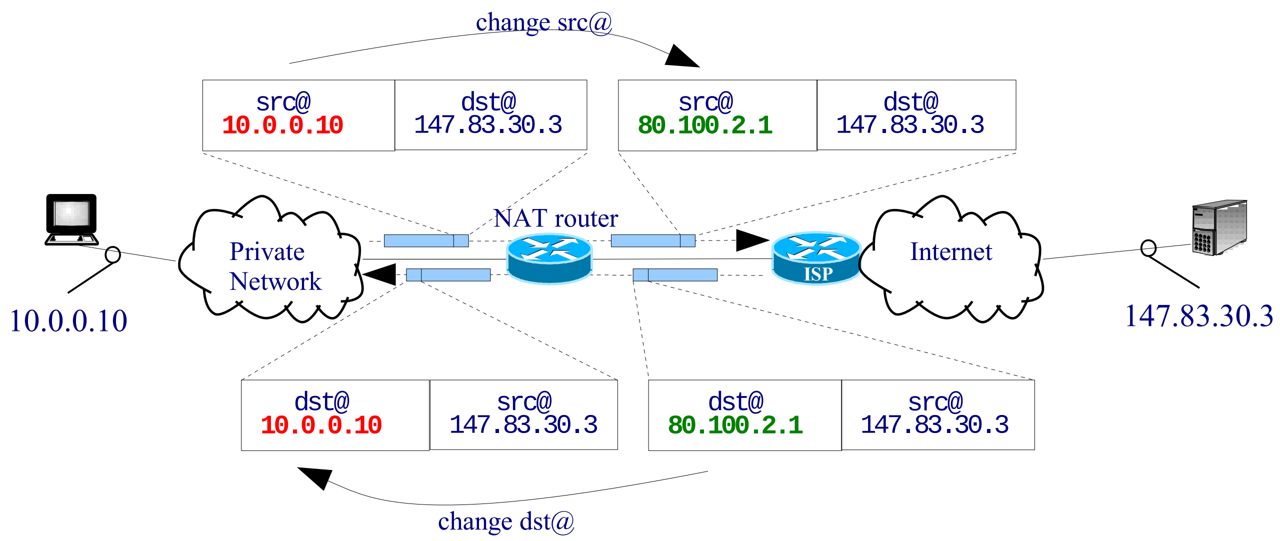
## Outline

- IP layer service
- IP addresses
- Subnetting
- Routing tables
- ARP protocol
- IP header
- ICMP protocol
- DHCP protocol
- **NAT**
- Routing algorithms
- Security in IP

# Unit 3: IP Networks

## Network Address Translation, NAT (RFCs 1631, 2663 3022)

- Typical scenario: Private addresses (internal addresses) are translated to public addresses (external addresses).
- A NAT table is used for address mapping.
- Advantages:
  - Save public addresses.
  - Security.
  - Administration, e.g. changing ISP does not imply changing private network addressing.



# Unit 3: IP Networks

## NAT – Types of translations

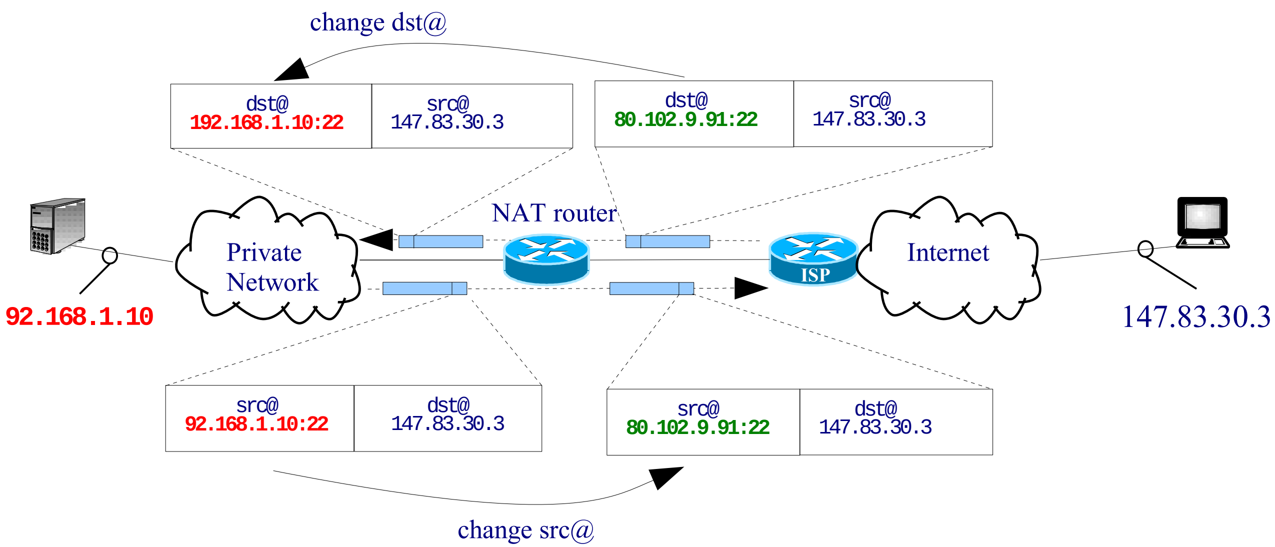
- NOTE: NAT is a technique, not a protocol. Implementations and terminology may change from one manufacturer to another.
- Basic NAT:
  - A different external address is used for each internal address → a different public IP address is needed for each hosts accessing Internet.
  - Each NAT table entry has the tuple: (internal address, external address).
  - Each host requires one NAT table entry.
- Port and Address Translation, PAT:
  - The same external address can be used for each internal address → a unique public IP address can be used for all hosts accessing Internet.
  - Each NAT table entry has the tuple: (int. address/port, ext. address/port)
  - Each connection requires one NAT table entry.
- The NAT table entries can be:
  - Static: Manually added.
  - Dynamic:
    - Entries are automatically added when an internal connection is initiated.
    - External addresses are chosen from a pool.
    - Table entries have a timeout.

# Unit 3: IP Networks

## DNAT

- What if we want external connections to internal servers? (DNAT in linux-iptables terminology).
- The address translation is exactly the same as NAT, but, the connection is initiated from an external client.
- Typically, some static configuration is needed to configure the server IP/port.

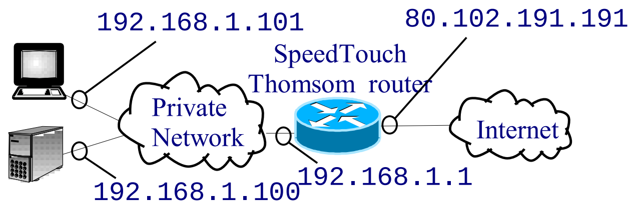
```
Static entry in the NAT router:
Inside-address:Port  Outside-address:Port
192.168.1.10:22      80.102.9.91:22
```



# Unit 3: IP Networks

## NAT – ADSL commercial router example

- NAT outgoing packets to 80.102.191.191
- DNAT incoming packets, port 22 (ssh) to 192.168.1.100




```
       linux # telnet 192.168.1.1
       Trying 192.168.0.1...
       Connected to 192.168.1.1.
       =>nat
       [nat]=>list
       Indx Prot Inside-address:Port  Outside-address:Port  Foreign-address:Port Flgs  Expir  State  Control
DNAT     2    6   192.168.1.100:22     80.102.191.191:22           0.0.0.0:0      instance
         6    6   192.168.1.101:1420   80.102.191.191:10079   83.60.122.22:45730   1   14m48      1
        11    6   192.168.1.101:1337   80.102.191.191:10060  85.56.136.231:16000   1   14m30      1
SNAT    12    6   192.168.1.101:1402   80.102.191.191:10064   82.159.8.187:1755    1     14s      5
        ...
```

# Unit 3: IP Networks

## Outline

- IP layer service
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- DHCP protocol
- NAT
- **Routing algorithms**
- Security in IP

# Unit 3: IP Networks

## Routing algorithms

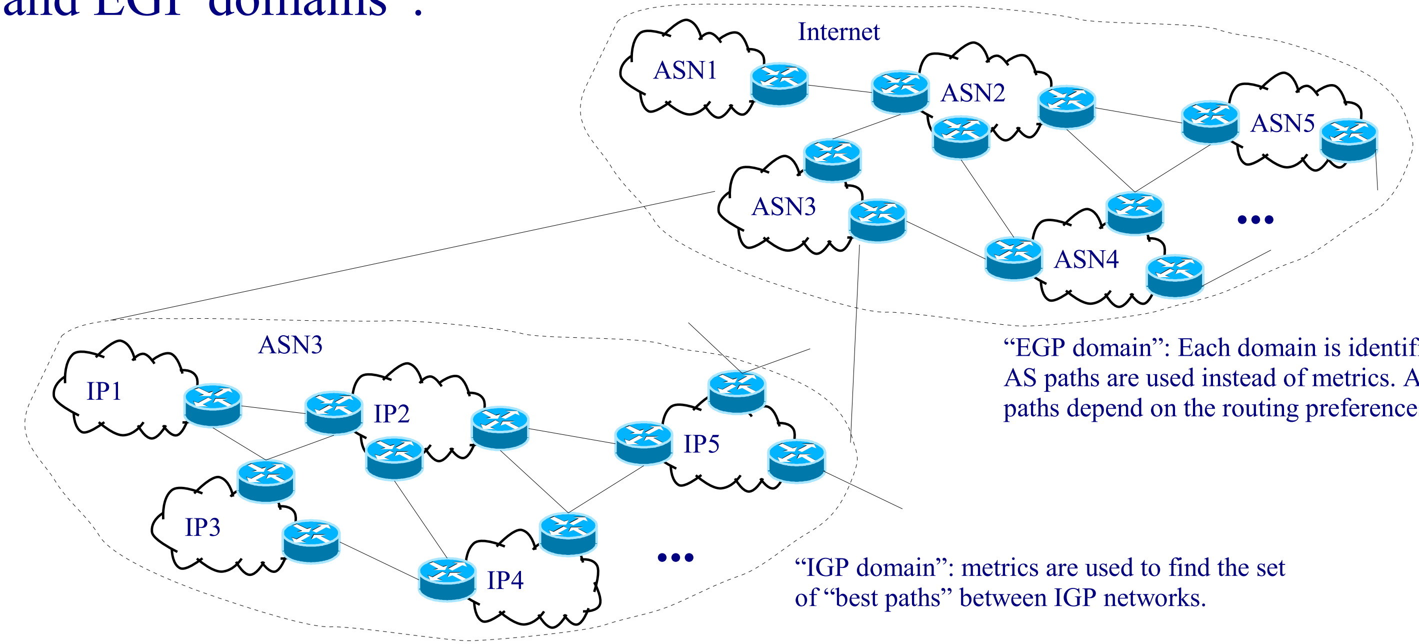
- Objective: add entries to routing tables. Can be:
  - Static: Manual, scripts, DHCP.
  - Dynamic: Automatically update table entries, e.g. when a topology change occurs.

- Internet is organized in Autonomous Systems (AS). In terms of ASs, routing algorithms are classified as:
  - Interior Gateway Protocols (IGPs): Inside the same AS. Examples:
    - RFC standards: RIP, OSPF.
    - Proprietary: CISCO IGRP.
  - Exterior Gateway Protocols (EGPs): Between different ASs. Currently BGPv4.

# Unit 3: IP Networks

## Routing algorithms - Autonomous Systems (AS)

- AS definition (RFC 1930): "An AS is a connected group of one or more IP prefixes run by one or more network operators which has a SINGLE and CLEARLY DEFINED routing policy".
- Each AS is identified by a 16 bits AS Number (ASN) assigned by IANA.
- ASs facilitate Internet routing by introducing a two-level hierarchy: "IGP and EGP domains".




"EGP domain": Each domain is identified by a ASN. AS paths are used instead of metrics. Advertised AS paths depend on the routing preferences between ASs.

"IGP domain": metrics are used to find the set of "best paths" between IGP networks.

# Unit 3: IP Networks

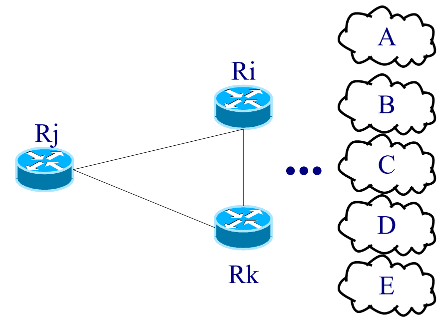
## Routing Information Protocol, RIP (RFC 2453)

- The metric (distance) to a destination is the number of hops (i.e. transmissions) to reach the destination: 1 if the destination is attached to a directly connected network, 2 if 1 additional router is needed ...
- Routers send RIP updates every 30 seconds to the neighbors.
- RIP updates use UDP, src./dst. well-known port = 520, broadcast dst. IP addr.
- RIP updates include destinations and metrics tuples.
- A neighbor is considered down if no RIP messages are seen during 180 seconds.
- Infinite metric is 16.
- Two versions of RIP: Version 2 allows variable masks ans uses the multicast dst. address 244.0.0.9 (all RIPv2 routers).
- The routing algorithm is known as “distance-vector” or “Bellman-Ford algorithm”.

# Unit 3: IP Networks

## RIP – Routing Table (RT) Update Example

- Example: When Ri receives an update message from Rj:
  - Increase the message metrics.
  - Add new destinations.
  - Change entries with other routers with larger metrics.
  - Update metrics using Rj's gateway.




| D | G | M |
|---|---|---|
| A | Rk | 4 |
| B | Rj | 3 |
| C | Rk | 5 |
| D | Rj | 2 |

Ri's RT

➡

| D | M |
|---|---|
| A | 1 |
| B | 4 |
| C | 5 |
| D | 1 |
| E | 3 |

Ri receives Rj's update message

➡

| D | M |
|---|---|
| A | 2 |
| B | 5 |
| C | 6 |
| D | 2 |
| E | 4 |

Rj's metrics increased

➡

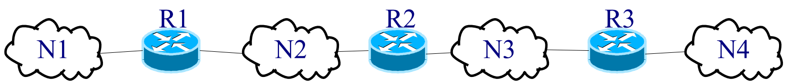
| D | G | M |
|---|---|---|
| A | Rj | 2 |
| B | Rj | 5 |
| C | Rk | 5 |
| D | Rj | 2 |
| E | Rj | 4 |

Ri's RT updated

# Unit 3: IP Networks

## RIP – Count to Infinity

- Depending on the route update message order, convergence problems may arise:




| D | G | M |
|---|---|---|
| N1 | * | 1 |
| N2 | * | 1 |
| N3 | R2 | 2 |
| N4 | R2 | 3 |

R1's RT

| D | G | M |
|---|---|---|
| N1 | R1 | 2 |
| N2 | * | 1 |
| N3 | * | 1 |
| N4 | R3 | 2 |

R2's RT

| D | G | M |
|---|---|---|
| N1 | R2 | 3 |
| N2 | R2 | 2 |
| N3 | * | 1 |
| N4 | * | 1 |

R3's RT

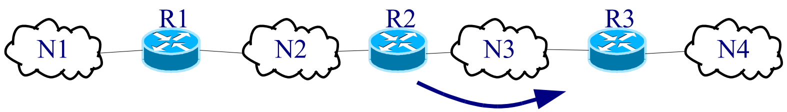
- Evolution of D=N4 entry when R3 fails:

| | G | M | R3 fails | G | M | R1 upd | G | M | R2 upd | G | M | R1 upd | G | M | | G | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1: | R2 | 3 | → | R2 | 3 | → | R2 | 3 | → | R2 | **5** | → | R2 | 5 | ... | R2 | **16** |
| R2: | R3 | 2 | → | R3 | **16** | → | R1 | **4** | → | R1 | 4 | → | R1 | **6** | ... | R1 | **16** |

# Unit 3: IP Networks

## RIP – Count to Infinity Solutions

- Split horizon: When the router sends the update, removes the entries having a gateway in the interface where the update is sent:




| D | G | M |
|---|---|---|
| N1 | R1 | 2 |
| N2 | * | 1 |
| N3 | * | 1 |
| N4 | R3 | 2 |

R2's RT

| D | M |
|---|---|
| N1 | 2 |
| N2 | 1 |

update sent by R2

- Split horizon with Poisoned Reverse: Consists of adding the entries having a gateway with M=16.
- Triggered updates: Consists of sending the update before the 30 seconds timer expires when a metric change in the routing table.
- Hold down timer (CISCO): When a route becomes unreachable (metric = 16), the entry is placed in *holddown* during 280 seconds. During this time, the entry is not updated.

# Unit 3: IP Networks

## Open Shortest Path First, OSPF (RFC 2328)

- IETF standard for high performance IGP routing protocol.
- *Link State* protocol: Routers monitor neighbor routers and networks and send this information to all OSPF routers (*Link State Advertisements*, LSA).
- LSA are encapsulated into IP datagrams with multicast destination address 224.0.0.5, and routed using *flooding*.
- LSA are only sent when changes in the neighborhood occur, or when a LSA Request is received.
- Neighbor routers are monitored using a *hello protocol*.
- OSPF routers maintain a LS database with the information received with LSA. The Shortest Path First algorithm (Dijkstra algorithm) is used to optimal build routing table entries.
- The metric is computed taking into account link bitrates, delays etc.
- The infinite metric is the maximum metric value.
- There is no convergence (count to infinity) problems.

# Unit 3: IP Networks

## Outline

- IP layer service
- IP addresses
- Subnetting
- Routing tables
- ARP protocol
- IP header
- ICMP protocol
- DHCP protocol
- NAT
- Routng algorithms
- **Security in IP**

# Unit 3: IP Networks

## Security in IP

- Goals:
  - Confidentiality: Who can access.
  - Integrity: Who can modify the data.
  - Availability: Access guarantee.
- Vulnerabilities:
  - Technological: Protocols (e.g. ftp and telnet send messages in “clear text”) and networking devices (routers...)
  - Configuration: Servers, passwords, ...
  - Missing security policies: Secure servers, encryption, firewalls, ...

# Unit 3: IP Networks

## Security in IP – Attacks

- Reconnaissance: Previous to an attack.
  - Available IP addresses.
  - Available servers and ports.
  - Types of OSs, versions, devices...
  - Eavesdropping
- Access: Unauthorized access to an account or service.
- Denial of Service: Disables or corrupts networks, systems, or services.
- Viruses, worms , trojan horses...: Malicious software that replicate itself.

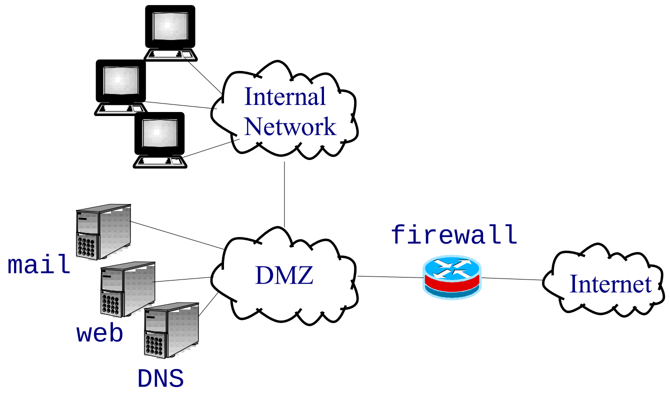
## Security in IP – Basic Solutions

- Firewalls.
- Virtual Private Networks (VPN).

# Unit 3: IP Networks

## Security in IP – Firewalls

- Firewall: System or group of systems that enforces an access control policy to a network.
- There are many firewall types: From simple packet filtering based on IP/TCP/UDP header rules, to state-full connection tracking and application-based filtering, defense against network attacks, ...

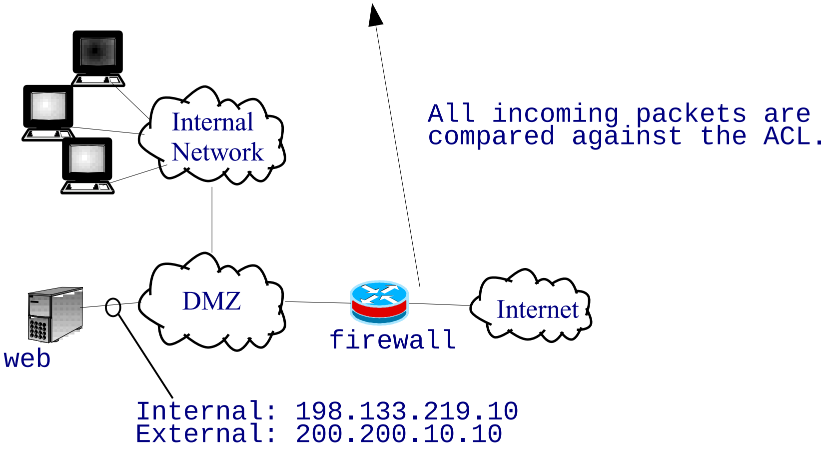


# Unit 3: IP Networks

## Security in IP – Basic Firewall Configuration

- NAT
- Access Control List, ACL

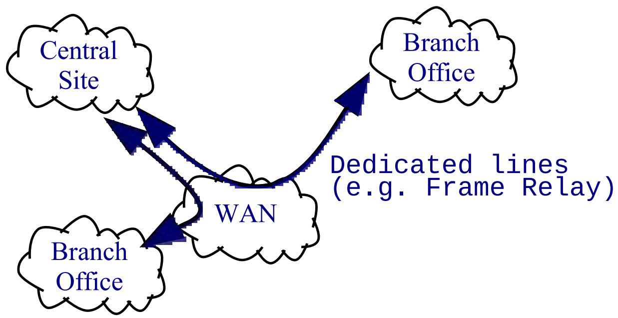
| Protocol | IP-src | IP-dst | Port-src | Port-dst | Action |
|---|---|---|---|---|---|
| TCP | *any* | 200.200.10.10/32 | *any* | 80 | *accept* |
| TCP | *any* | *any* | $< 1024$ | $\geq 1024$ | *accept* |
| ICMP | *any* | *any* | – | – | *accept* |
| IP | *any* | *any* | – | – | *deny* |

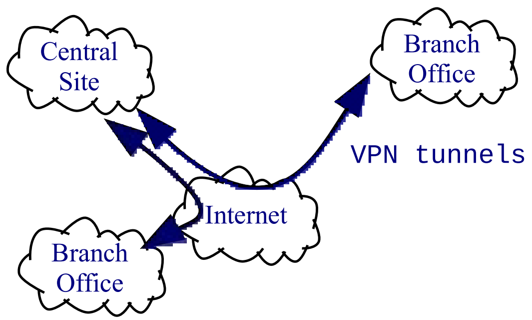


# Unit 3: IP Networks

## Security in IP – Virtual Private Network, VPN

- Provides connectivity for remote users over a public infrastructure, as they would have over a private network.



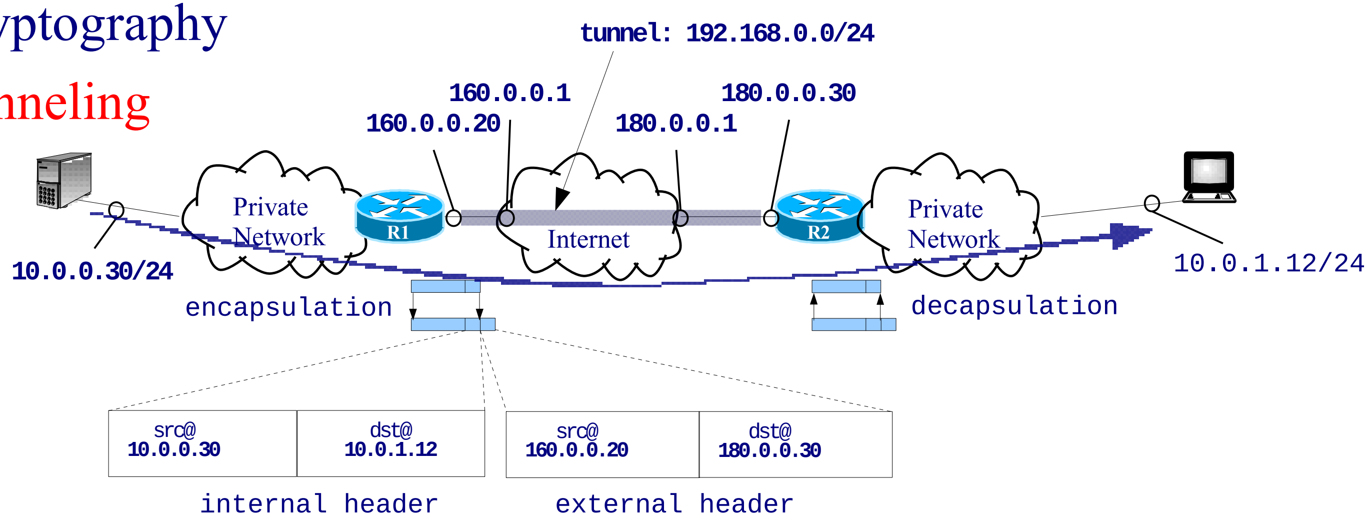

Conventional Private Network
- More cost.
- Less flexible.
- WAN management.

VPN
- Less cost.
- More flexible.
- Simple management.
- Internet availability.

# Unit 3: IP Networks

## Security in IP – VPN Security

- Authentication
- Cryptography
- Tunneling




```
Example: creating a tunnel in linux:
R1# ip tunnel add tun0 mode gre remote  180.0.0.30 local 160.0.0.20 ttl 255
```

| Destination | Gateway | Genmask | Iface |
|---|---|---|---|
| 10.0.0.0 | 0.0.0.0 | 255.255.255.0 | eth0 |
| 160.0.0.1 | 0.0.0.0 | 255.255.255.255 | ppp0 |
| 0.0.0.0 | 160.0.0.1 | 0.0.0.0 | ppp0 |
| 192.168.0.0 | 0.0.0.0 | 255.255.255.0 | tunl0 |
| 10.0.1.0 | 192.168.0.2 | 255.255.255.0 | tunl0 |

R1 Routing Table

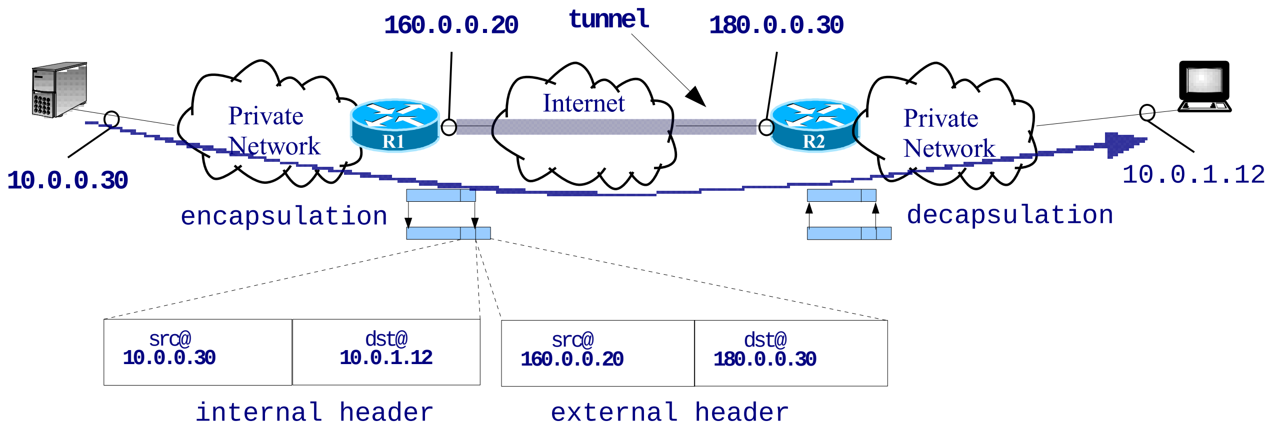
| Destination | Gateway | Genmask | Iface |
|---|---|---|---|
| 10.0.1.0 | 0.0.0.0 | 255.255.255.0 | eth0 |
| 180.0.0.1 | 0.0.0.0 | 255.255.255.255 | ppp0 |
| 0.0.0.0 | 180.0.0.1 | 0.0.0.0 | ppp0 |
| 192.168.0.0 | 0.0.0.0 | 255.255.255.0 | tunl0 |
| 10.0.0.0 | 192.168.0.1 | 255.255.255.0 | tunl0 |

R2 Routing Table

# Unit 3: IP Networks

## Security in IP – VPN Tunneling Problems

- Fragmentation inside the tunnel will use the external header, thus, the exit router of the tunnel may reassemble fragmented datagrams.
- ICMP messages sent inside the tunnel are addressed to the tunnel entry.
- MTU path discovery may fail.
- Solution: the router entry maintains a "tunnel state", e.g. the tunnel MTU, and generate ICMP messages that would be generated inside the tunnel. Furthermore, the tunnel entry router typically fragment the datagrams, if needed, before encapsulation, to avoid the exit router having to reassemble fragmented datagrams.



# Unit 3: IP Networks

## Security in IP – VPN Tunneling

- IP over IP (RFC 2003): Basic encap.
- Generic Routing Encapsulation, GRE (RFC 1701): There is an additional GRE header: different protocol encap (not only IP).
- Point-to-Point Tunneling Protocol (RFC 2637): Add the ppp functionalities.
- IPsec (RFC 2401): Standards to introduce authentication and encryption and tunneling to IP layer.