Outline

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

These slides are based on the set of slides provided by Llorenç Cerdà for this course. They include some modifications and some new slides.

Unit 2: IP Networks

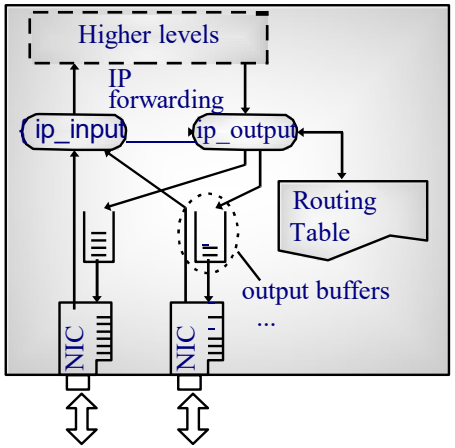
Outline

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

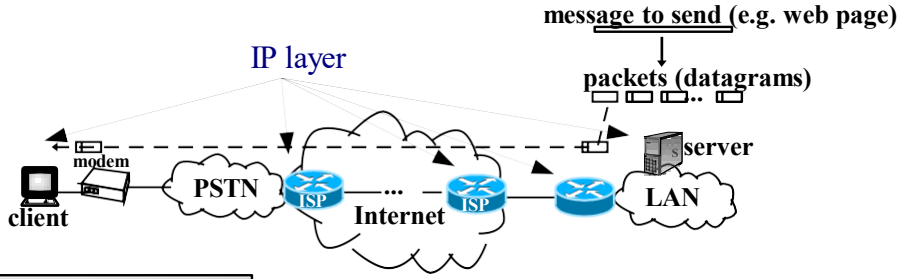
IP Layer Service

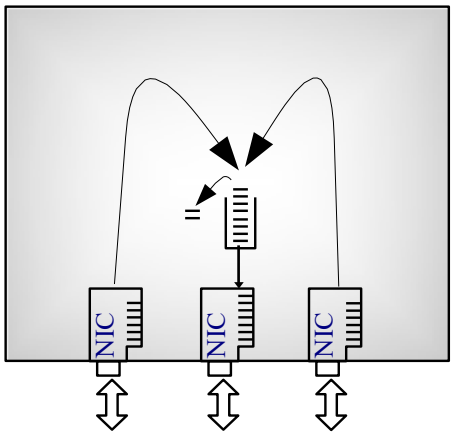
- Internet Protocol (IP) goal is routing datagrams.
- IP main design goal was interconnecting hosts attached to LANs/WANs networks of different technologies.
- IP characteristics:
  - Connectionless
  - Stateless
  - Best effort

Commercial routers



Basic router architecture





Looses may occur due to buffer overflow

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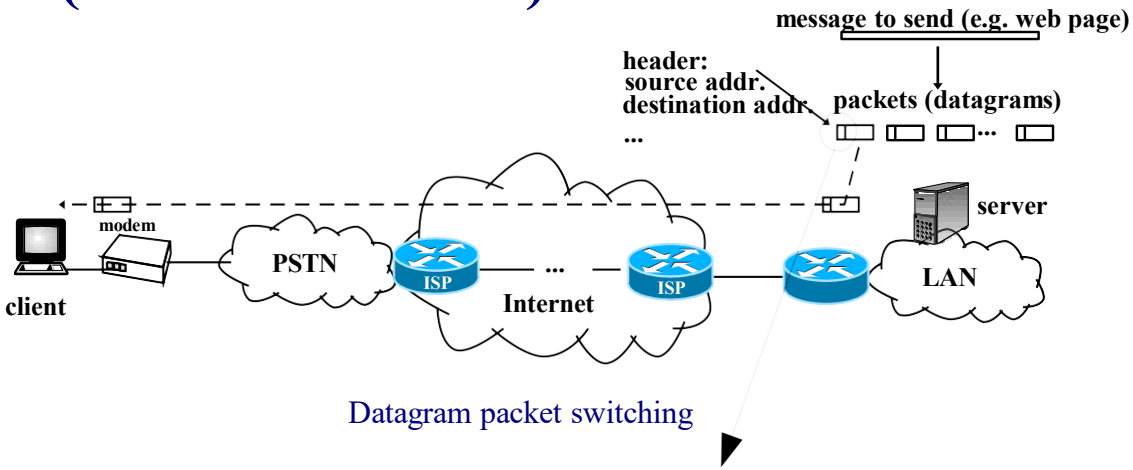
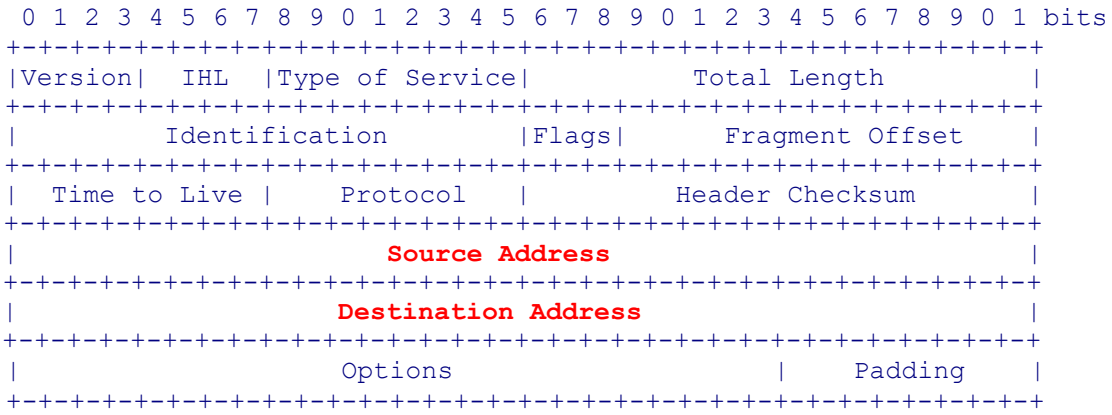
IP Addresses (RFC 791 Y1981)

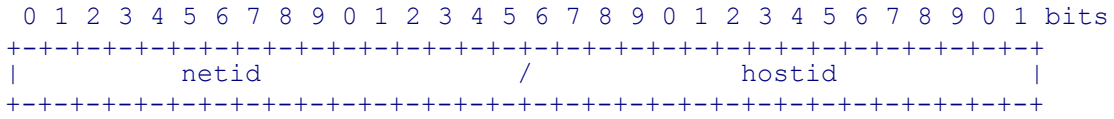


Datagram packet switching



IP datagram header

IP Addresses



- 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.
  - AFRINIC: Africa, http://www.afrinic.net.

  RIR assign addresses to ISPs, and ISPs to their customers.

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

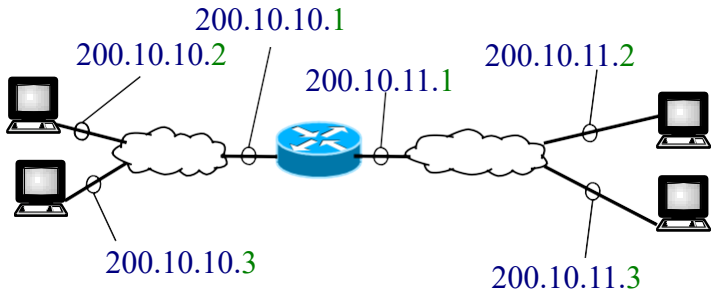
2^7 (128) class A networks with 2^{24} addresses
2^{14} (16.384) class B networks with 2^{16} addresses
2^{21} (2.097.152) class C networks with 2^8 addresses
2^{28} class D (multicast) addresses
2^{28} class E (reserved) addresses

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.

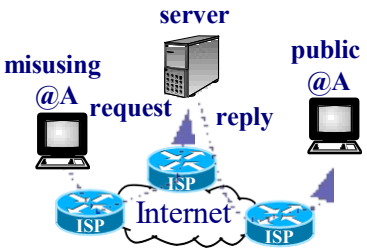
- Example:



IP Addresses – Private Addresses (RFC 1918 Y1996)

- 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 2: IP Networks

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- **Subnetting**
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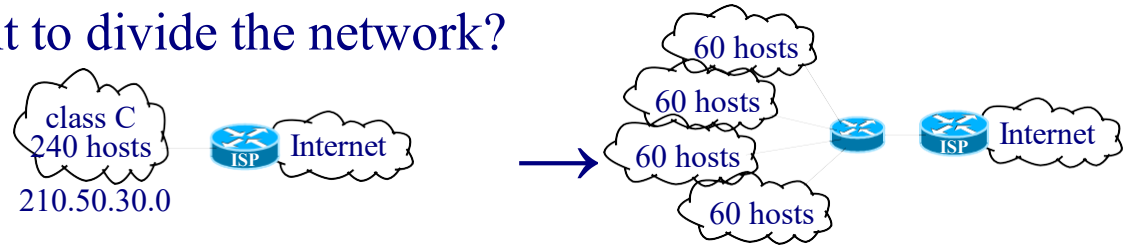
Subnetting (RFC 950 Y1985)

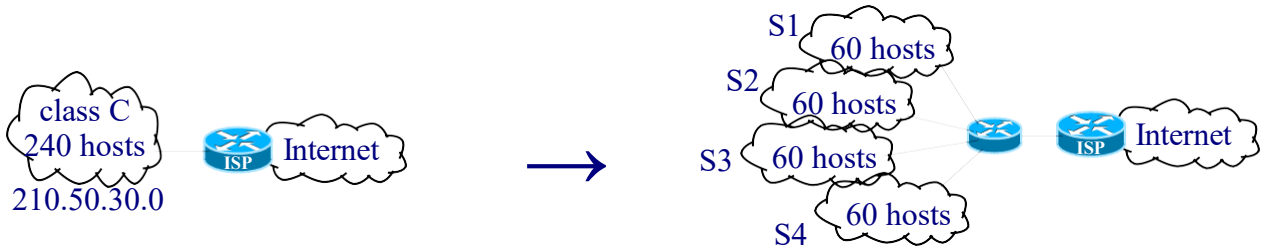
- Initially the netid was given by the address class: A with 2^{24} addresses, B with 2^{16} addresses and C with 2^{8} addresses.
- What if we want to divide the network?



- 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

IP Addresses – Subnetting Example

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

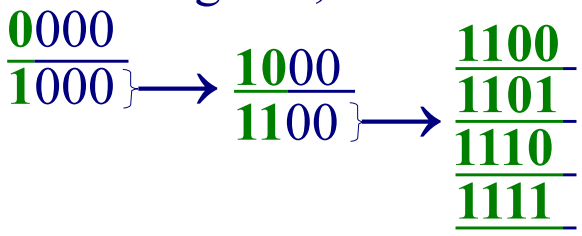


B = 210.50.30

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

IP Addresses – Variable Length Subnet Mask (VLSM)

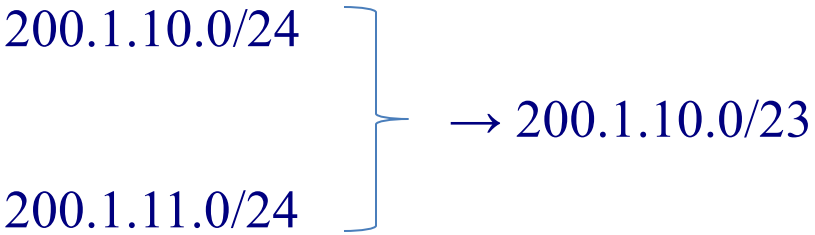
- Subnetworks of different sizes.
- Example, subnetting a class C address:
  - We have 1 byte for subnetid + hostid.
  - subnetid is green, chosen subnets addresses are underlined.



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

Classless Inter-Domain Routing, CIDR (RFC 1519 Y1993)

- Initially, Internet backbone routing tables did not use masks: netid was derived from the IP address class (default /8, /16, /24).
- 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 "aggregate routes", and use masks instead of classes.
- Aggregation example:



- 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).

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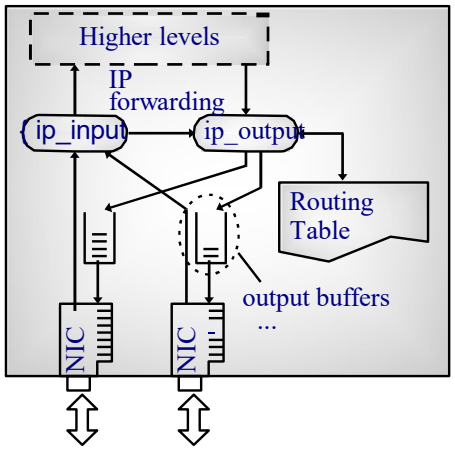
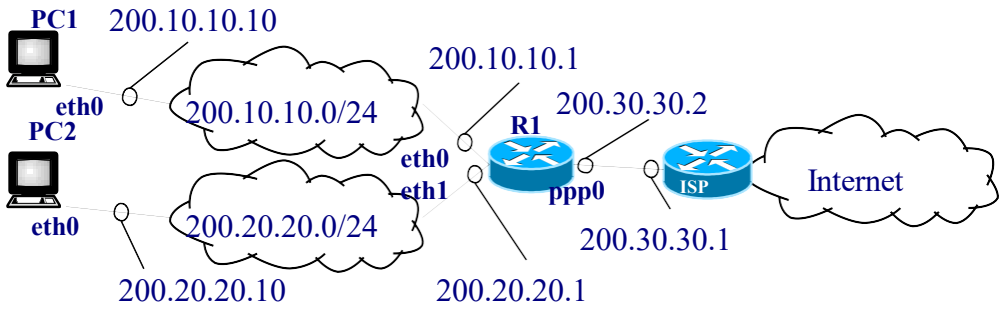
Routing Table

- 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 to and a default route.



Basic router architecture

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
200.30.30.0	255.255.255.0	0.0.0.0	ppp0
0.0.0.0	0.0.0.0	200.30.30.1	ppp0

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
}
```

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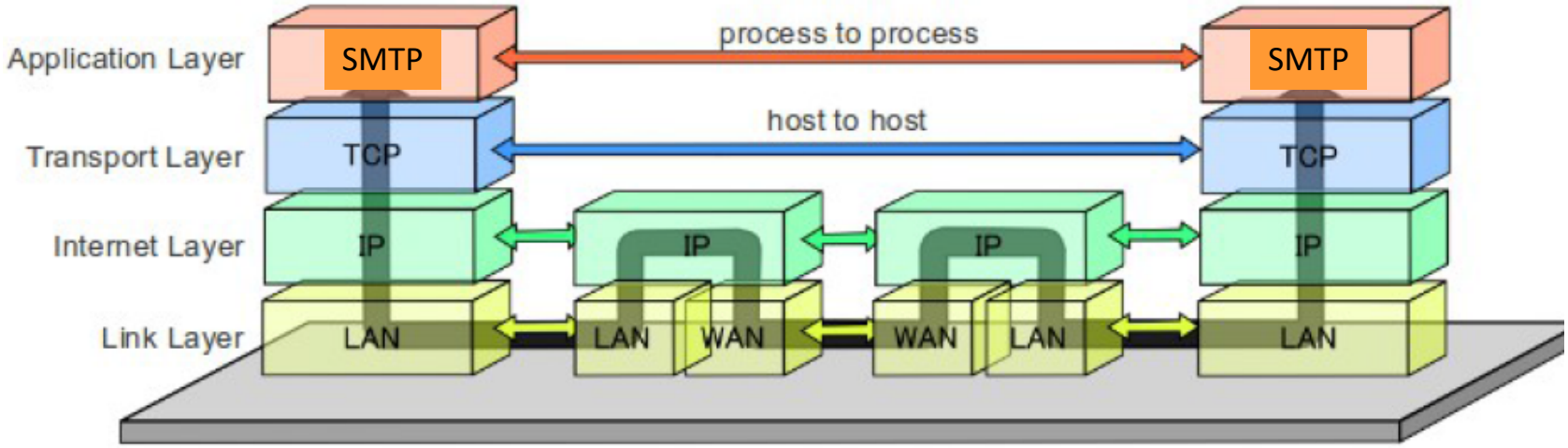
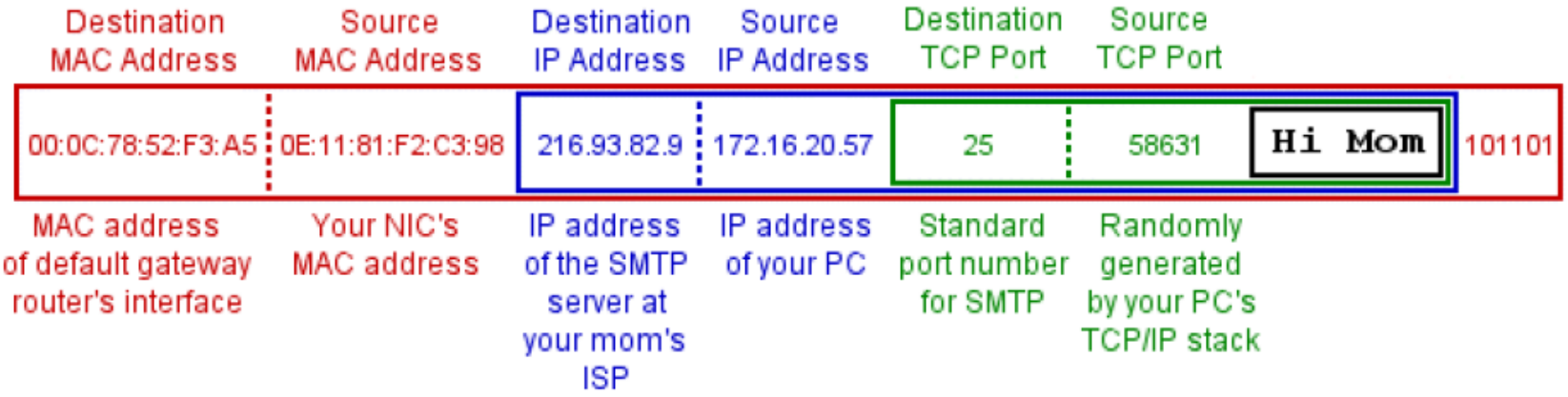
Data Flow of the Internet Protocol Suite



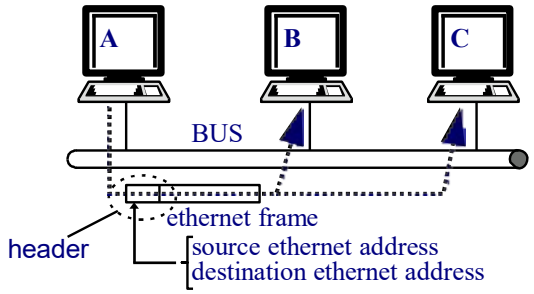
Outgoing E-mail Frame



Address Resolution Protocol, ARP (RFC 826 Y1982)

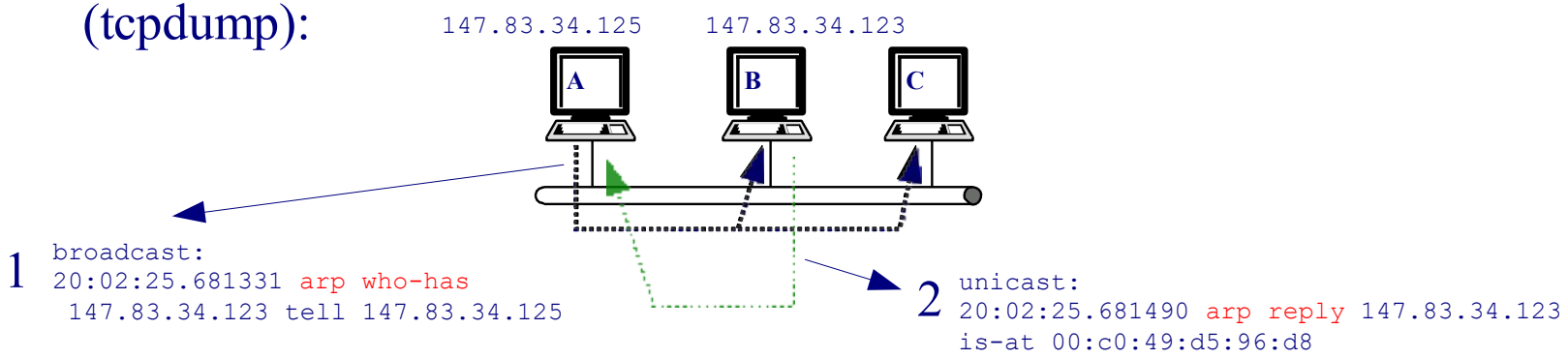
- To send the datagram, IP layer may have to pass a "physical address" to the NIC driver. Physical addresses are also called MAC or hardware addresses.
- ARP translate IP addresses to "physical addresses" (used by the physical network).
- If needed, IP calls ARP module to obtain the "physical addresses"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

- Ethernet example:



Address Resolution Protocol, messages - Example

- ARP messages (tcpdump):



- 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
```

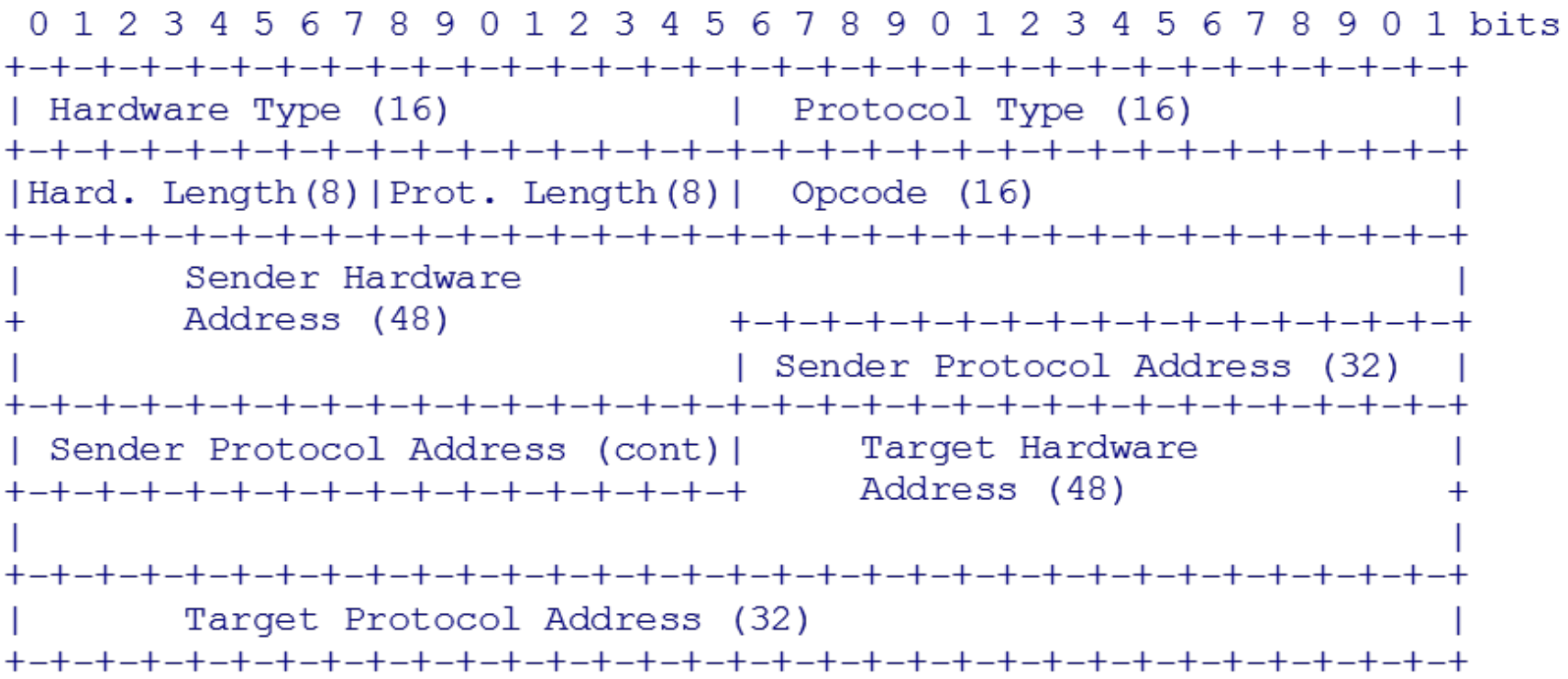
"Completed" flag

Address Resolution Protocol

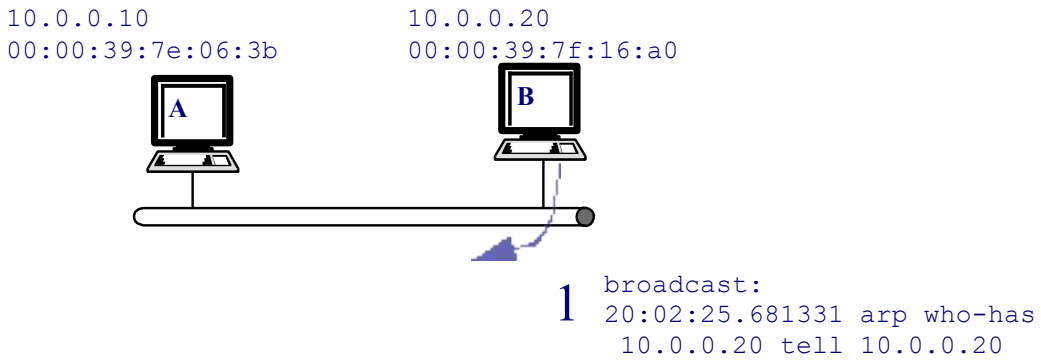
- ARP resolution in an ethernet network (broadcast network):
  - A broadcast "ARP Request" message is sent indicating the IP address.
  - The station having the requested IP address sends a unicast "ARP Reply", and stores the requesting address in the ARP table.
  - Upon receiving the "ARP Reply", the requesting station return the IP call with it.
  - ARP entries have a timeout refreshed each time a match occurs.

Address Resolution Protocol – Message format (ethernet)

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



Address Resolution Protocol – Gratuitous ARP



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

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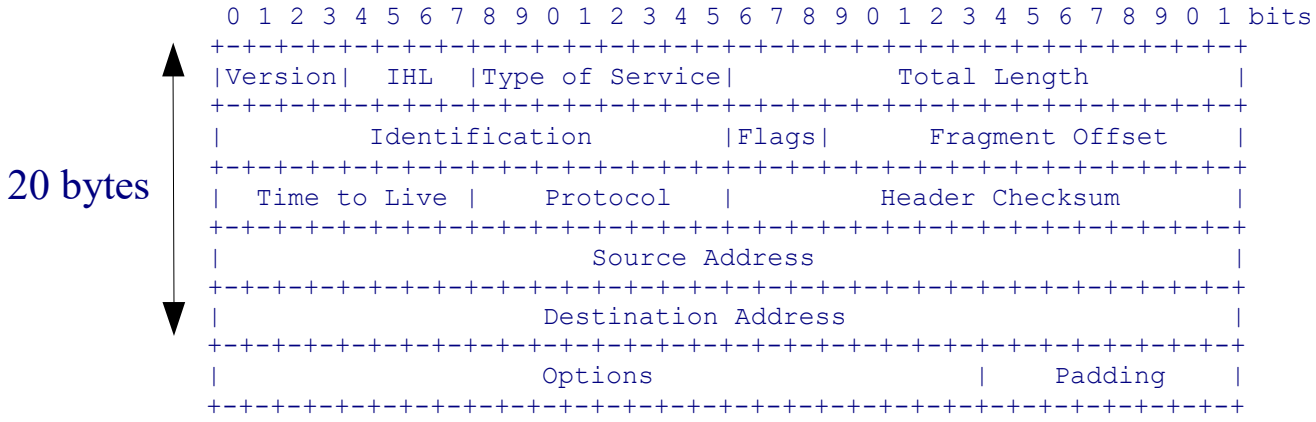
IP Header (RFC 791 Y1981 updated by 1349 Y1992, 2474 Y1998, 6864 Y2013)

- 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 node addresses.
- Options: Record Route, Loose Source Routing, Strict Source Routing.



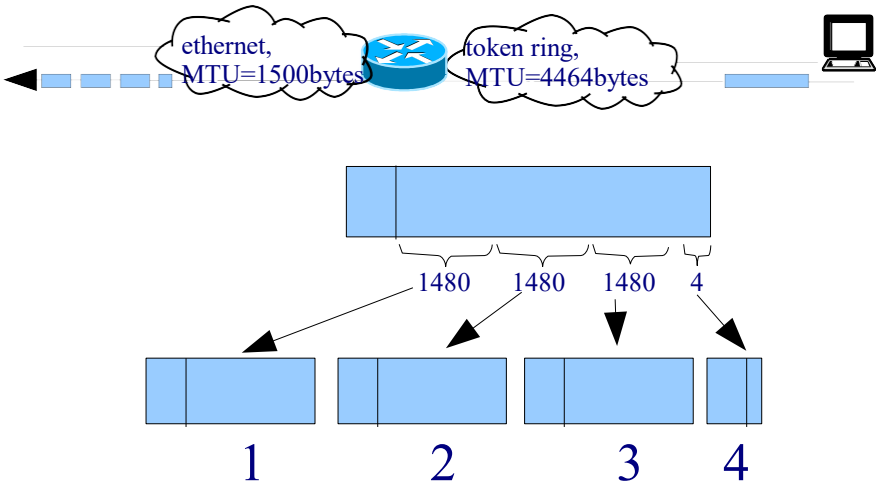
IP Fragmentation

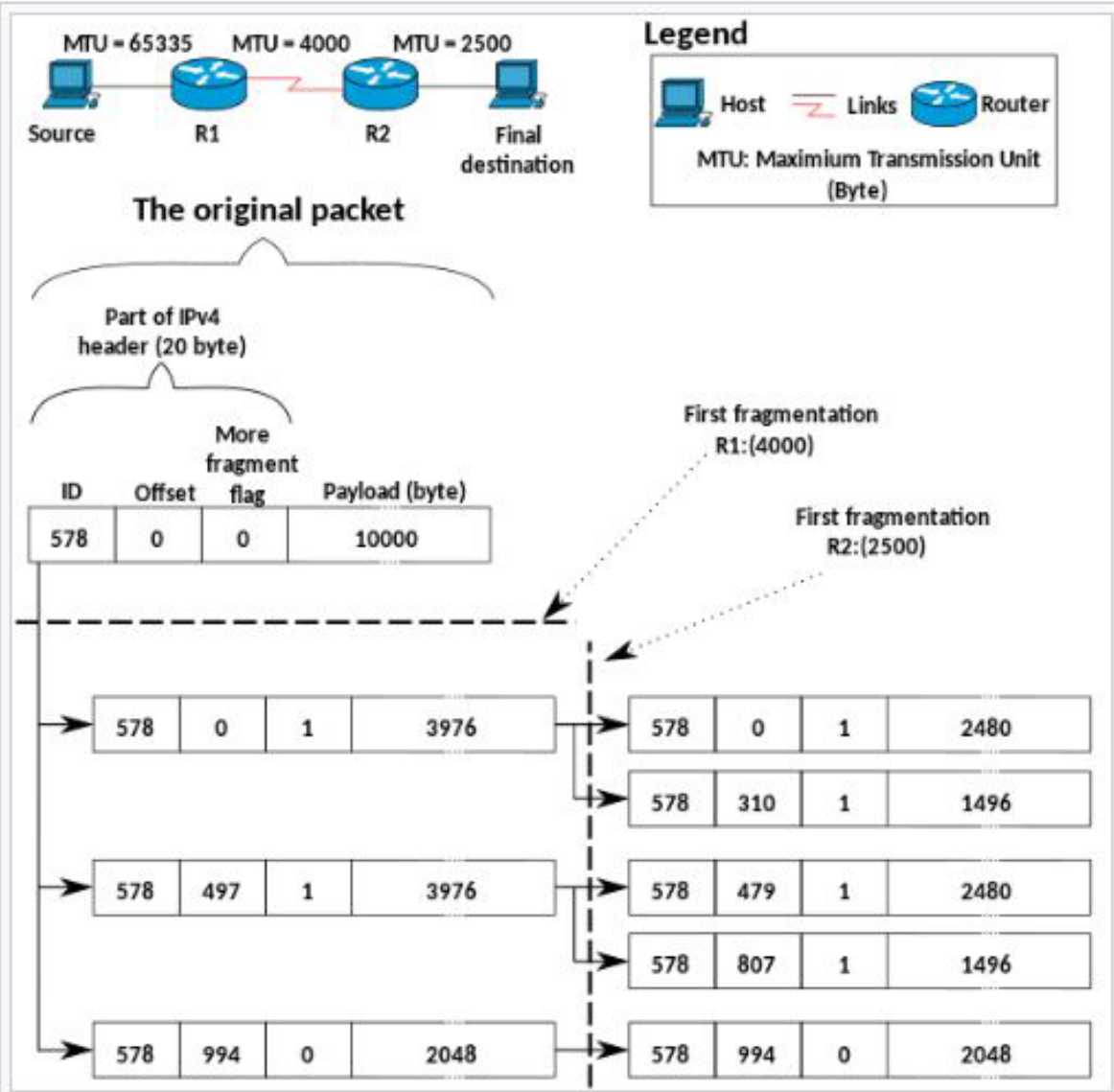
- Fragmentation may occur:
  - Router: Fragmentation may be needed when two networks with different *Maximum Transfer Unit* (MTU) are connected.
  - Host: Fragmentation may be needed using UDP. TCP segments are ≤ MTU.
- Datagrams are reconstructed at the destination.
- Fields:
  - Identification (16 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).

MTU examples:
Ethernet: 1500
WiFi: 2312
Token Ring 4M: 4464
FDDI: 4352
PPP: 250
X.25: 576

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.





An example of IPv4 multiple fragmentation. The fragmentation takes place on two levels: in the first one the maximum transmission unit is 4000 bytes, and in the second it is 2500 bytes.

Source: Wikepedia

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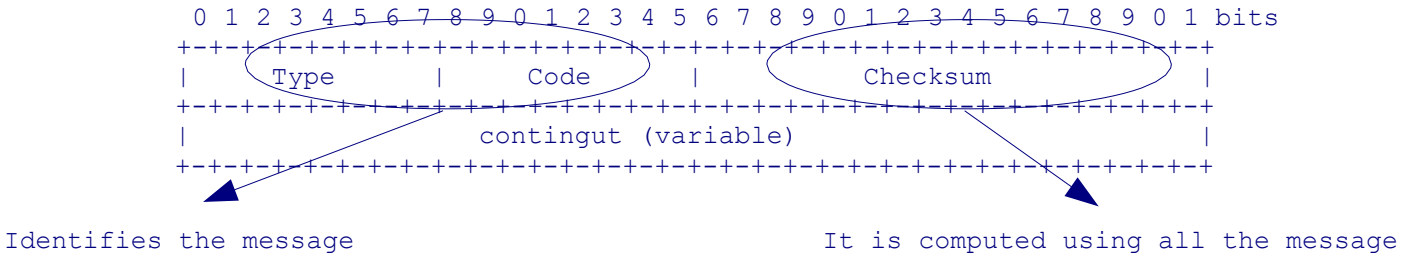
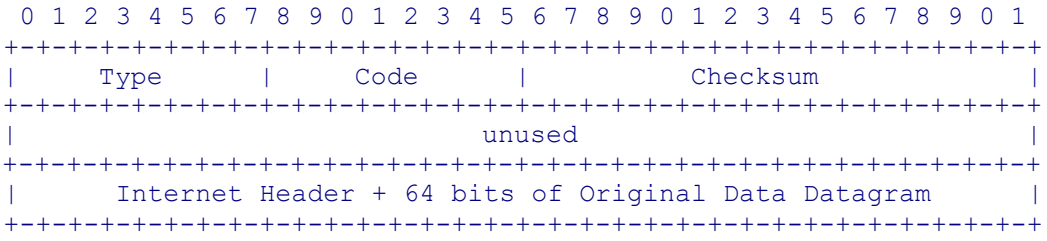
Internet Control Message Protocol, ICMP (RFC 792 Y1981)

- Used for attention and error messages.
- Can be generated by IP, TCP/UDP, and application layers. ICMP
- Messages are encapsulated into an IP datagram (protocol = 1)
- Messages can be: (i) query, (ii) error.
- An ICMP error message cannot generate another ICMP error message (to avoid loops).

ICMP general format message (RFC 792 Y1981)



- 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:

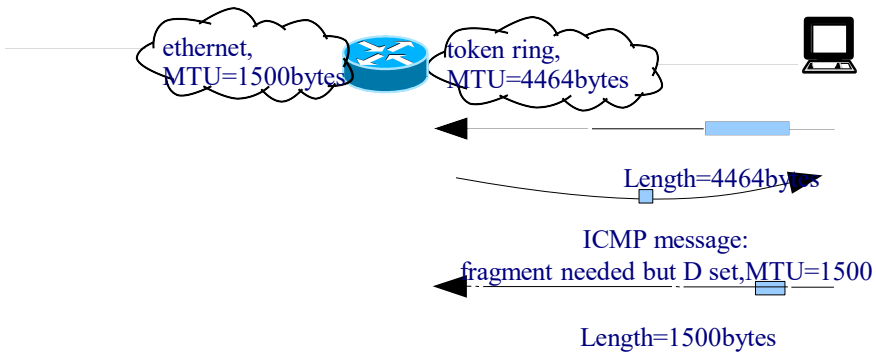


Common ICMP messages

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`

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 2: IP Networks

Outline

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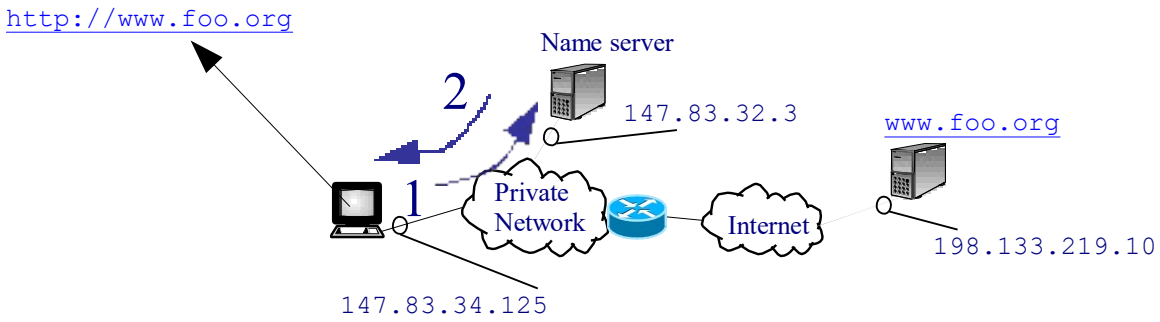
- DNS
- DHCP protocol
- NAT
- Routing algorithms
- Security in IP

Domain Name System DNS (RFC 1034, 1035 Y1987)

- Allows users to use names instead of IP addresses: e.g. rogent.ac.upc.edu instead of 147.83.31.7, www.upc.edu instead of 147.83.194.21, etc.
- Names consists of a node-name and a domain-mane: rogent.ac.upc.edu, www.upc.edu
- DNS consists of a worldwide distributed data base.
- DNS data base entries are referred to as *Resource Records* (RR).
- The information associated with a name is composed of 1 or more RRs.
- Names are case insensitive (e.g. www.upc.edu and WWW.UPC.EDU are equivalent).

DNS - Protocol

- Client-server paradigm
- UDP/TCP. For short messages it uses UDP.
- Well-known port: 53



1 18:36:00.322370 IP (proto: UDP) 147.83.34.125.1333 > 147.83.32.3.53: 53040+ A? www.foo.org. (31)

2 18:36:00.323080 IP (proto: UDP) 147.83.32.3.53 > 147.83.34.125.1333: 53040 1/2/2 www.foo.org. A 198.133.219.10 (115)

Unit 2: IP Networks

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Dynamic Host Configuration Protocol, DHCP (RFC 2131 Y1997)

- Improves and can interoperate with previous BOOTP protocol.
- Used for automatic network configuration:
  - Assign IP address and mask
  - Default route
  - Configure DNS servers
  - Hostname
  - DNS domain

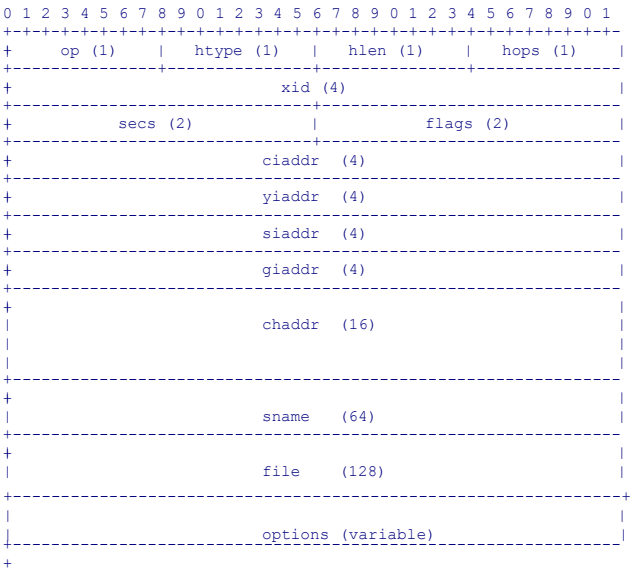
- IP address configuration can be:
  - Dynamic: During a leasing time.
  - Automatic: Unlimited leasing time.
  - Manual: IP addresses are assigned to specific MAC addresses.

DHCP – Protocol Messages (RFC 2131 Y1997)

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.

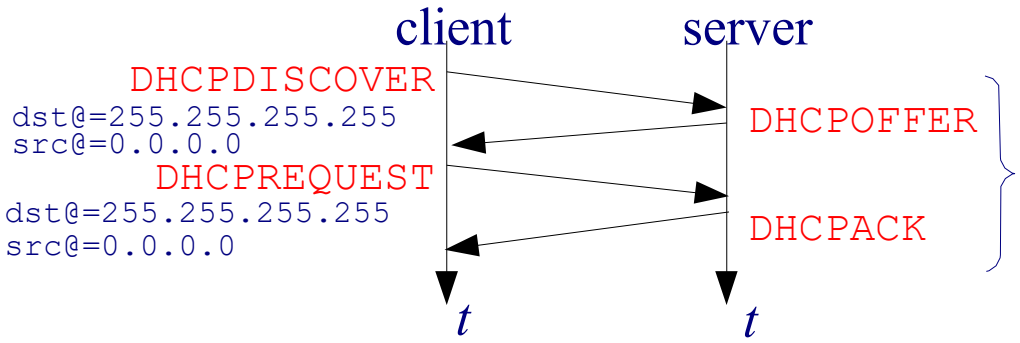
DHCP – Message Fields (RFC 2131)

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.



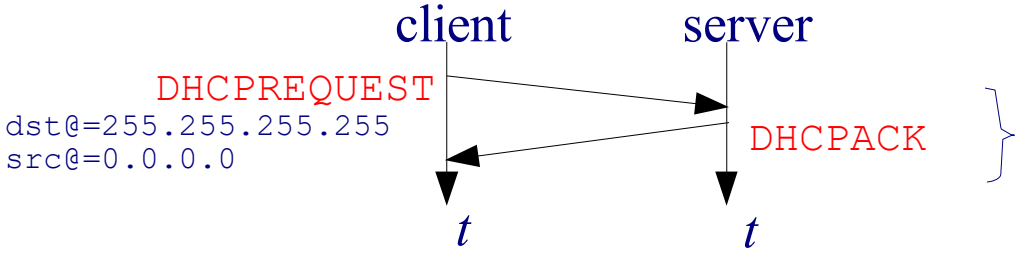
DHCP – Client-server interaction (RFC 2131)

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



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

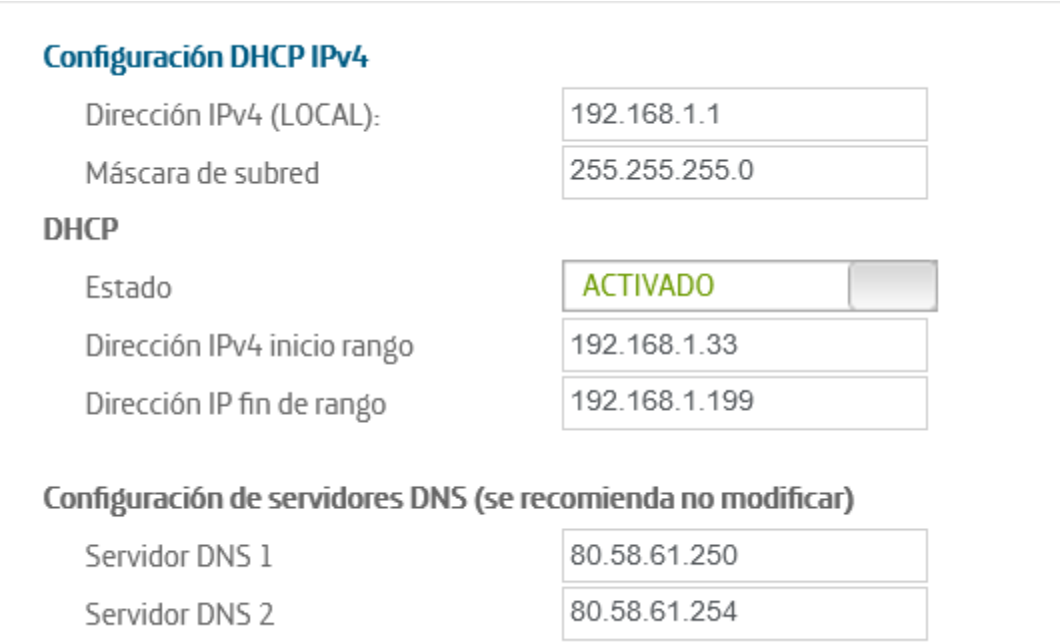
- The client can directly send `DHCPREQUEST`:
  - After rebooting if it remembers and wishes to reuse a previously allocated network address.
  - Extending the lease on a particular network address.

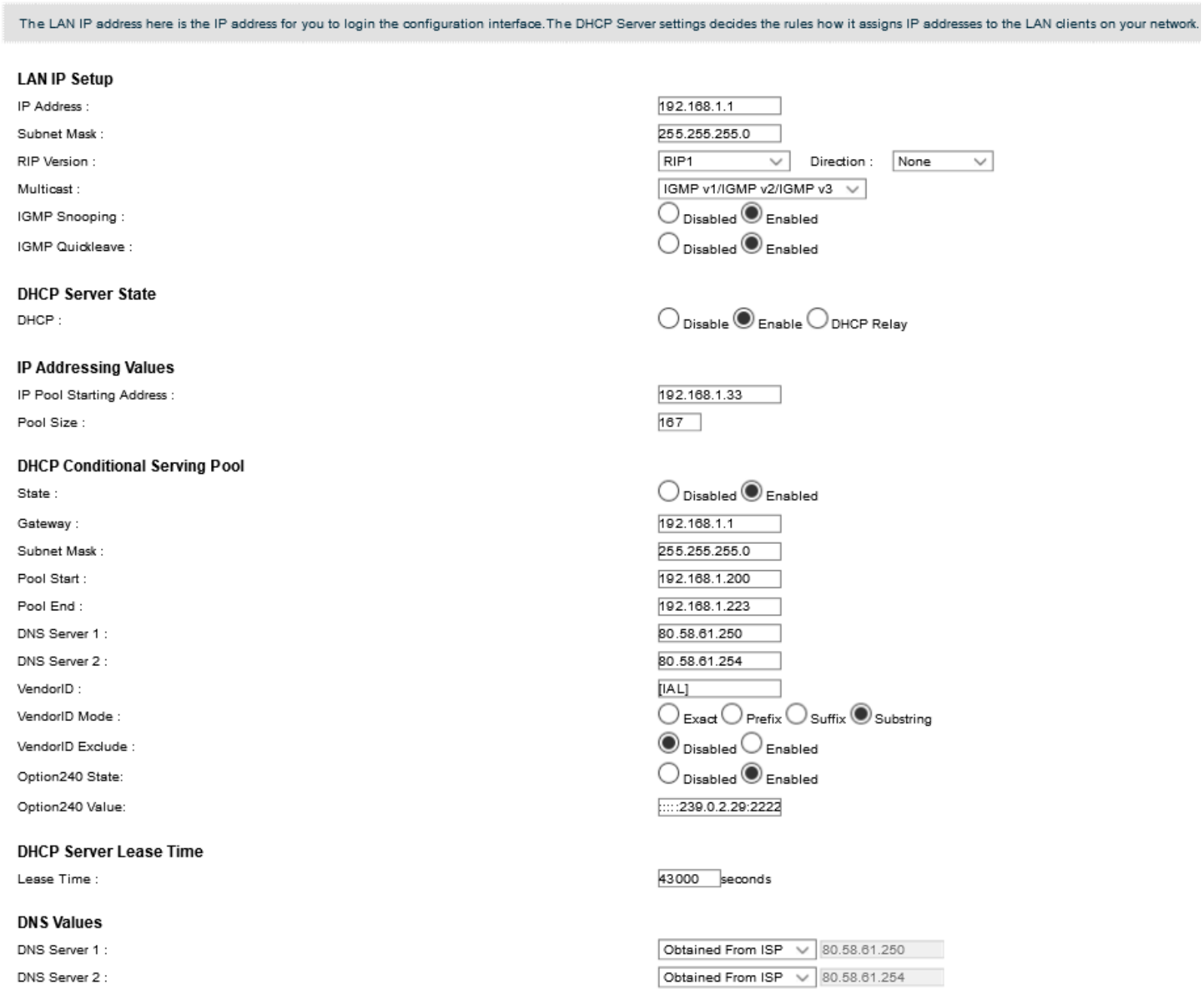


Can be unicast or broadcast, if requested by the client.

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
```


Configuración DHCP IPv4
Dirección IPv4 (LOCAL):
192.168.1.1
Máscara de subred
255.255.255.0
DHCP
Estado
ACTIVADO
Dirección IPv4 inicio rango
192.168.1.33
Dirección IP fin de rango
192.168.1.199
Configuración de servidores DNS (se recomienda no modificar)
Servidor DNS 1
80.58.61.250
Servidor DNS 2
80.58.61.254


The LAN IP address here is the IP address for you to login the configuration interface.The DHCP Server settings decides the rules how it assigns IP addresses to the LAN clients on your network.
LAN IP Setup
IP Address :
192.168.1.1
Subnet Mask :
255.255.255.0
RIP Version :
RIP1
Direction :
None
Multicast :
IGMP v1/IGMP v2/IGMP v3
IGMP Snooping :
Disabled
Enabled
IGMP Quickleave :
Disabled
Enabled
DHCP Server State
DHCP :
Disable
Enable
DHCP Relay
IP Addressing Values
IP Pool Starting Address :
192.168.1.33
Pool Size :
167
DHCP Conditional Serving Pool
State :
Disabled
Enabled
Gateway :
192.168.1.1
Subnet Mask :
255.255.255.0
Pool Start :
192.168.1.200
Pool End :
192.168.1.223
DNS Server 1 :
80.58.61.250
DNS Server 2 :
80.58.61.254
VendorID :
[IAL]
VendorID Mode :
Exact
Prefix
Suffix
Substring
VendorID Exclude :
Disabled
Enabled
Option240 State:
Disabled
Enabled
Option240 Value:
::::239.0.2.29:2222
DHCP Server Lease Time
Lease Time :
43000
seconds
DNS Values
DNS Server 1 :
Obtained From ISP
80.58.61.250
DNS Server 2 :
Obtained From ISP
80.58.61.254

Detalles de la conexión de red:

Propiedad	Valor
Sufijo DNS específico para...	Home
Descripción	D-Link DWA-171 AC600 MU-MIMO Wi-Fi USE
Dirección física	C4-E9-0A-07-21-3A
Habilitado para DHCP	Sí
Dirección IPv4	192.168.1.69
Máscara de subred IPv4	255.255.255.0
Concesión obtenida	jueves, 04 de marzo de 2021 11:47:34
La concesión expira	viernes, 05 de marzo de 2021 23:38:33
Puerta de enlace predeter...	192.168.1.1
Servidor DHCP IPv4	192.168.1.1
Servidores DNS IPv4	80.58.61.250
	80.58.61.254
Servidor WINS IPv4	192.168.1.1
Habilitado para NetBios a t...	Sí
Vínculo: dirección IPv6 local	fe80::a023:3477:5ab2:81b9%12
Puerta de enlace predeter...	
Servidor DNS IPv6	

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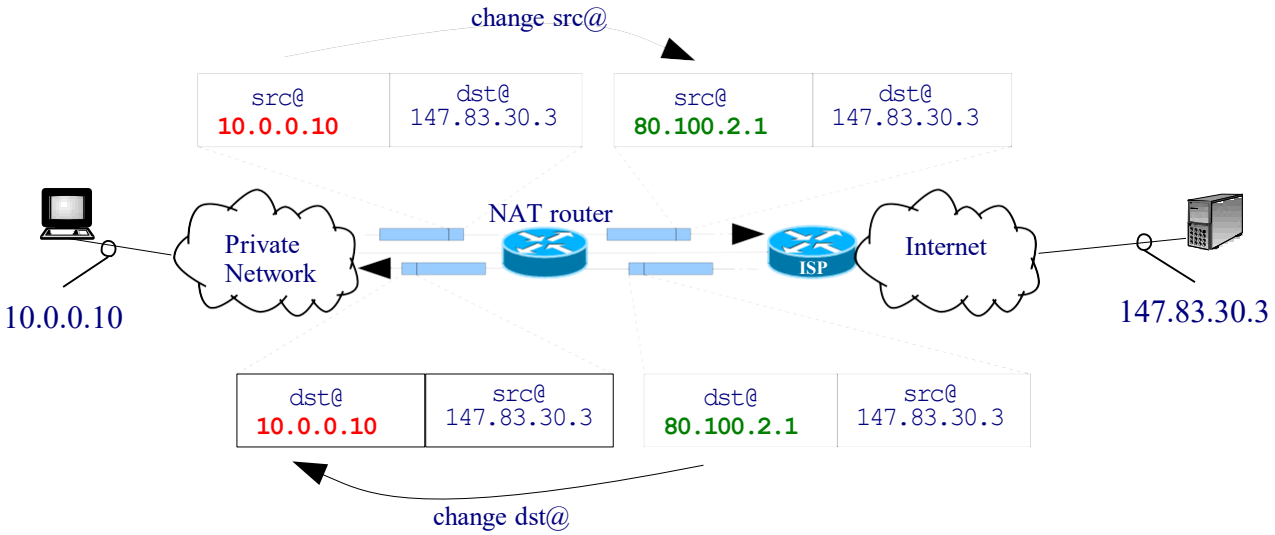
Network Address Translation, NAT (RFCs 1631, 2663 3022)

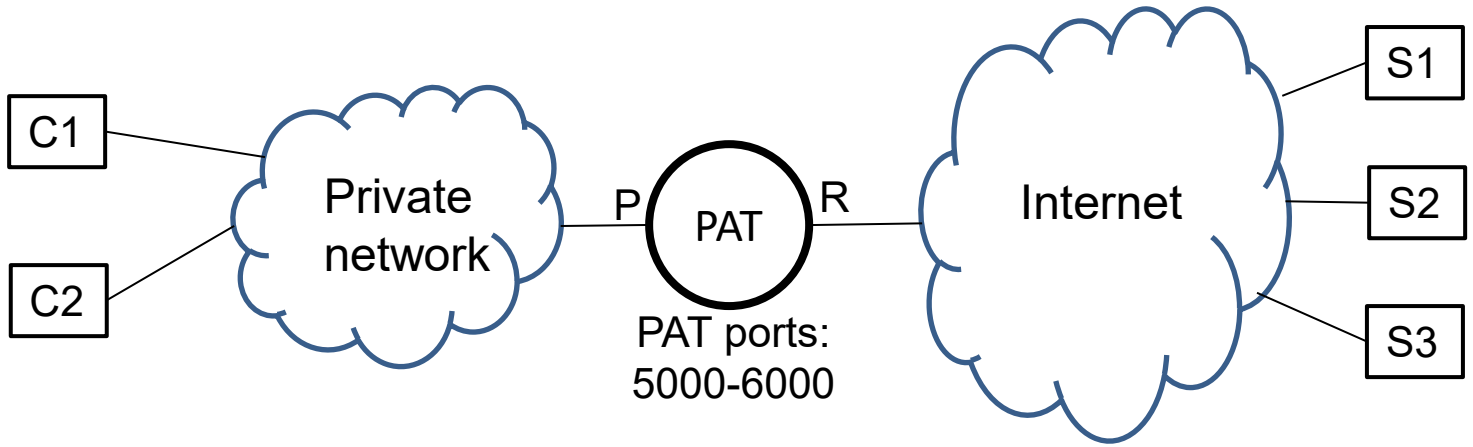
- Typical scenario: Private addresses (internal addresses) are translated to public addresses (external addresses).
- A NAT table is used for address mapping.
- Advantages:
  - Save public addresses.
  - Security.
  - Administration, e.g. changing ISP does not imply changing private network addressing.



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 (PNAT, NAPT):
  - 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.

Port and Address Translation (PAT)



C1, C2, P are private IP addresses R, S1, S3, S3 are public IP addresses

connection			
src		dst	
C1	P1	S1	80
S1	80	C1	P1
C1	P2	S1	53
S1	53	C1	P2

Inside		Outside		Foreign/remote	
C1	P1	R	5000	S1	80
C1	P2	R	5001	S1	53

connection			
src		dst	
R	5000	S1	80
S1	80	R	5000
R	5001	S1	53
S1	53	R	5001

C2	P1	S1	80
S1	80	C2	P1

C2	P1	R	5002	S1	80

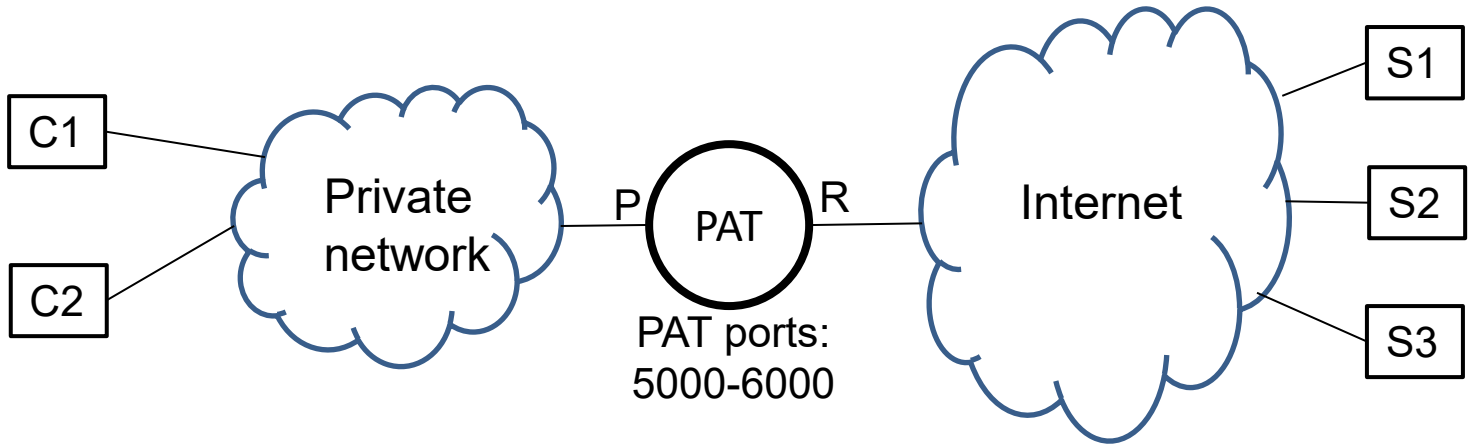
R	5002	S1	80
S1	80	R	5002

C2	P2	S2	80
S2	80	C2	P2

C2	P2	R	5003	S2	80

R	5003	S2	80
S2	80	R	5003

Port and Address Translation (PAT)



C1, C2, P are private IP addresses R, S1, S3, S3 are public IP addresses

connection src		dst	
C1	P1	S1	80
S1	80	C1	P1
C1	P2	S1	53
S1	53	C1	P2

Inside		Outside		Foreign/remote	
C1	P1	R	5000	S1	80
C1	P2	R	5001	S1	53

connection src		dst	
R	5000	S1	80
S1	80	R	5000
R	5001	S1	53
S1	53	R	5001

C2# ping S2

C2	S2
S2	C2

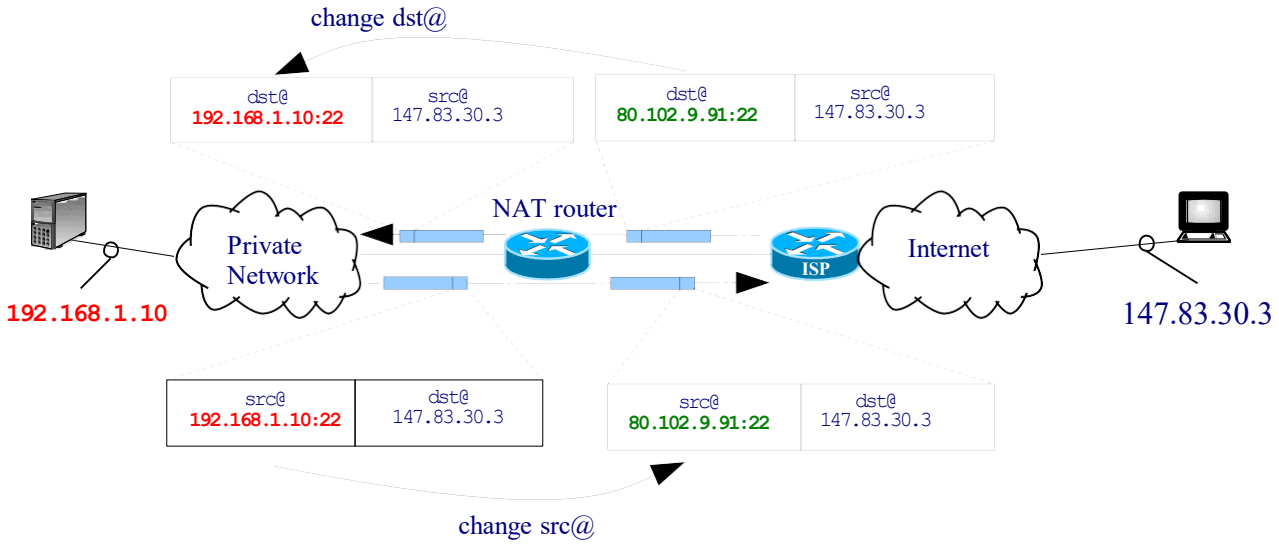
C2	id_{ICMP}	R	id_{PAT}	S2	id_{PAT}

R	S2
S2	R

DNAT (Destination NAT)

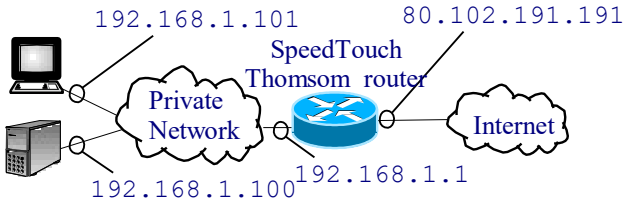
- What if we want external connections to internal servers? (DNAT in linux-iptables terminology).
- The address translation is exactly the same as NAT, but, the connection is initiated from an external client.
- Typically, some static configuration is needed to configure the server IP/port.

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



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
  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
 12    6   192.168.1.101:1402   80.102.191.191:10064    82.159.8.187:1755    1     14s      5
 ...
```

DNAT

SNAT

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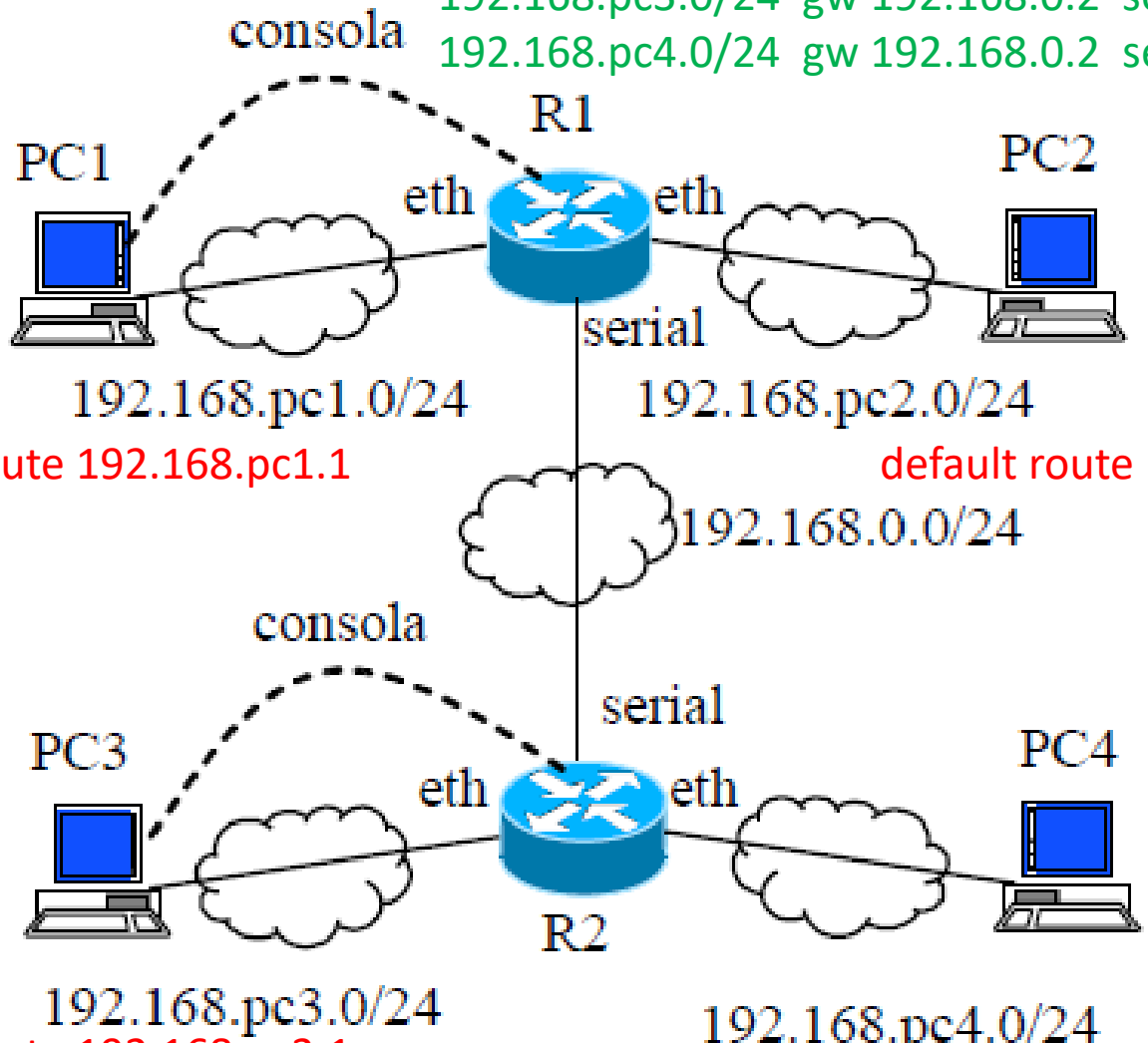
192.168.pc3.0/24 gw 192.168.0.2 serial0
192.168.pc4.0/24 gw 192.168.0.2 serial0



default route 192.168.pc1.1

default route 192.168.pc2.1

default route 192.168.pc3.1

default route 192.168.pc4.1

192.168.pc1.0/24 gw 192.168.0.1 serial0
192.168.pc2.0/24 gw 192.168.0.1 serial0

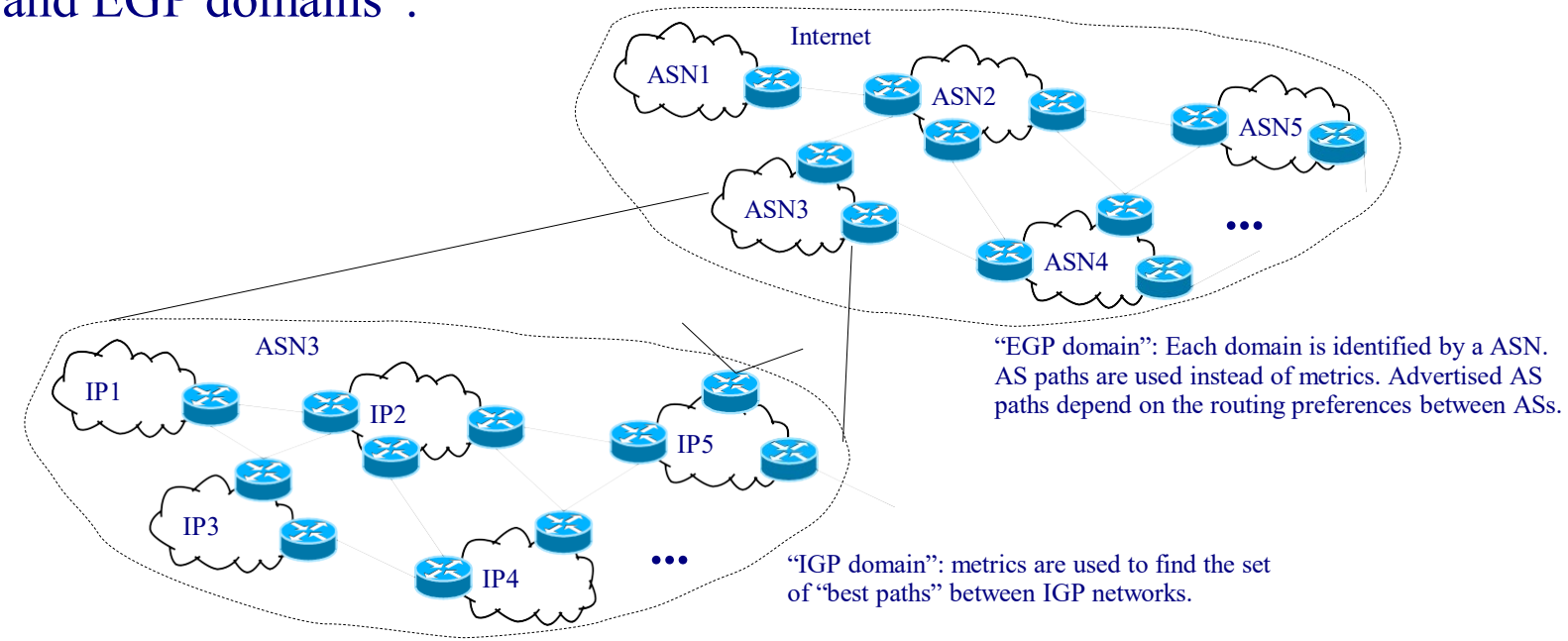
Routing algorithms

- Objective: add entries to routing tables:
  - 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.

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".

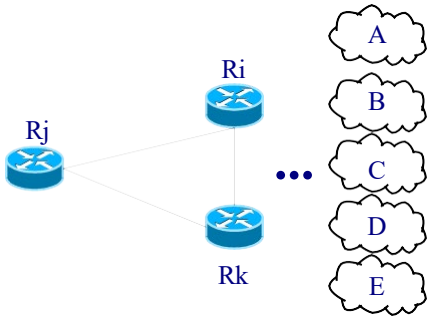


Routing Information Protocol, RIP (RFC 2453 RIPv2 Y1998)

- 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, well-known port = 520, to broadcast IP address.
- 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.
- RIP Version 2 allows variable masks and uses the multicast destination address 244.0.0.9 (all RIPv2 routers).
- The routing algorithm is known as “distance-vector” or “Bellman-Ford algorithm”.

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

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

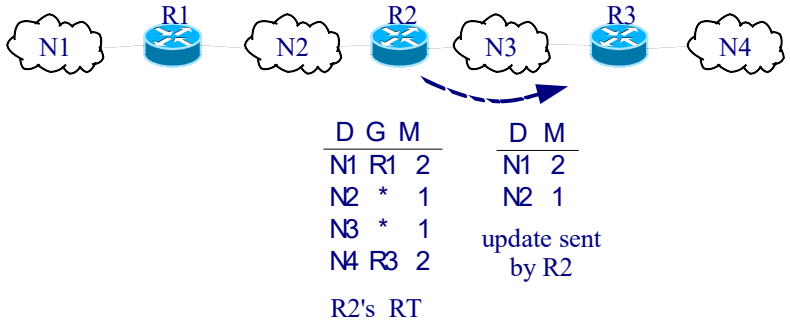
R3's RT

- Example: 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**

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:



- Split horizon with Poisoned Reverse: Consists of adding the entries having a gateway with metric 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.

Open Shortest Path First, OSPF (RFC 2328, OSPF v2 Y1998)

- 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 2: IP Networks

Outline

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

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, ...

Security in IP – Attacks

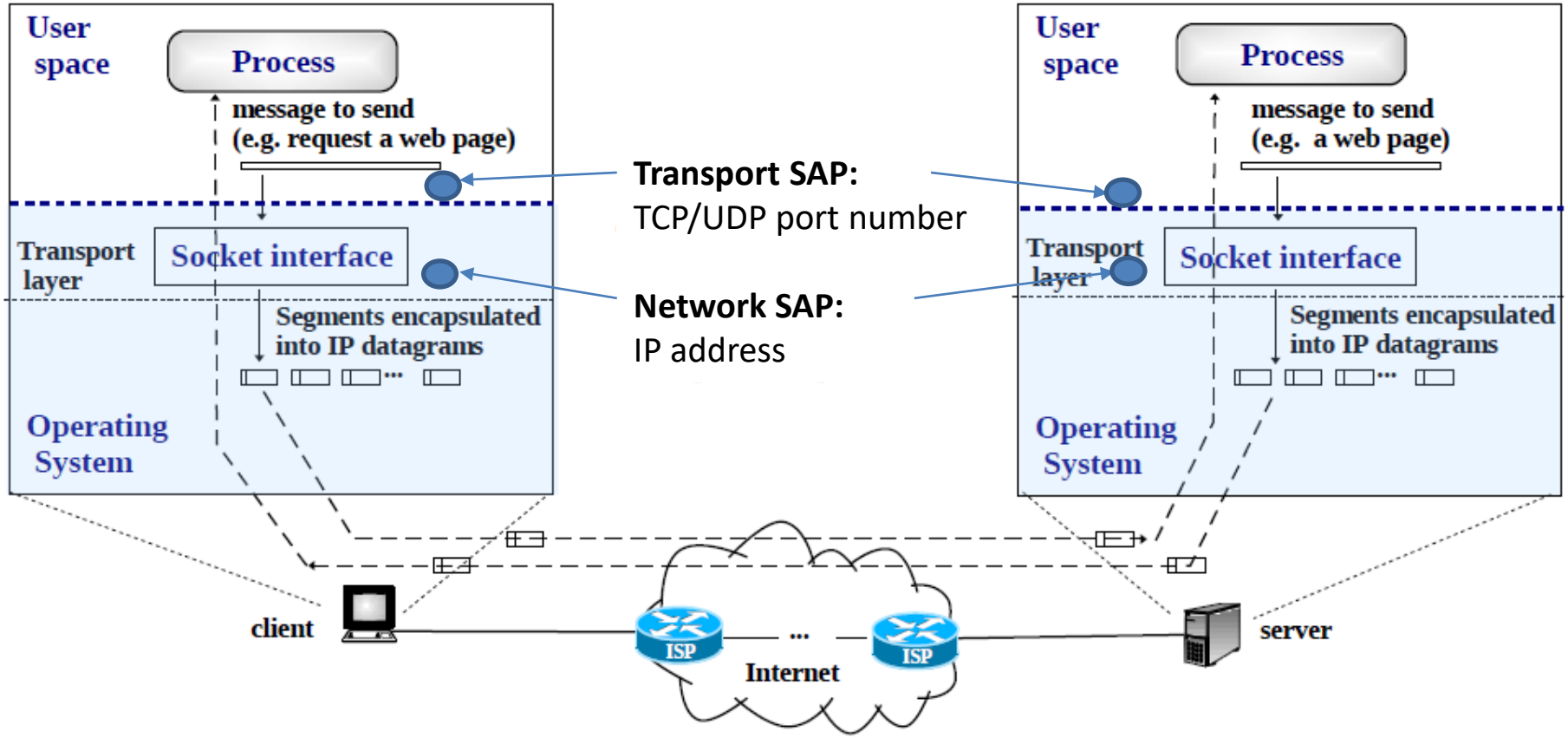
- Detection: Previous to an attack.
  - Available IP addresses.
  - Available servers and ports.
  - Types of OSs, versions, devices...
  - Eavesdropping
- Access: Unauthorized access to an account or service.
- Denial of Service: Disables or corrupts networks, systems, or services.
- Viruses, worms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

Security in IP – Basic Solutions

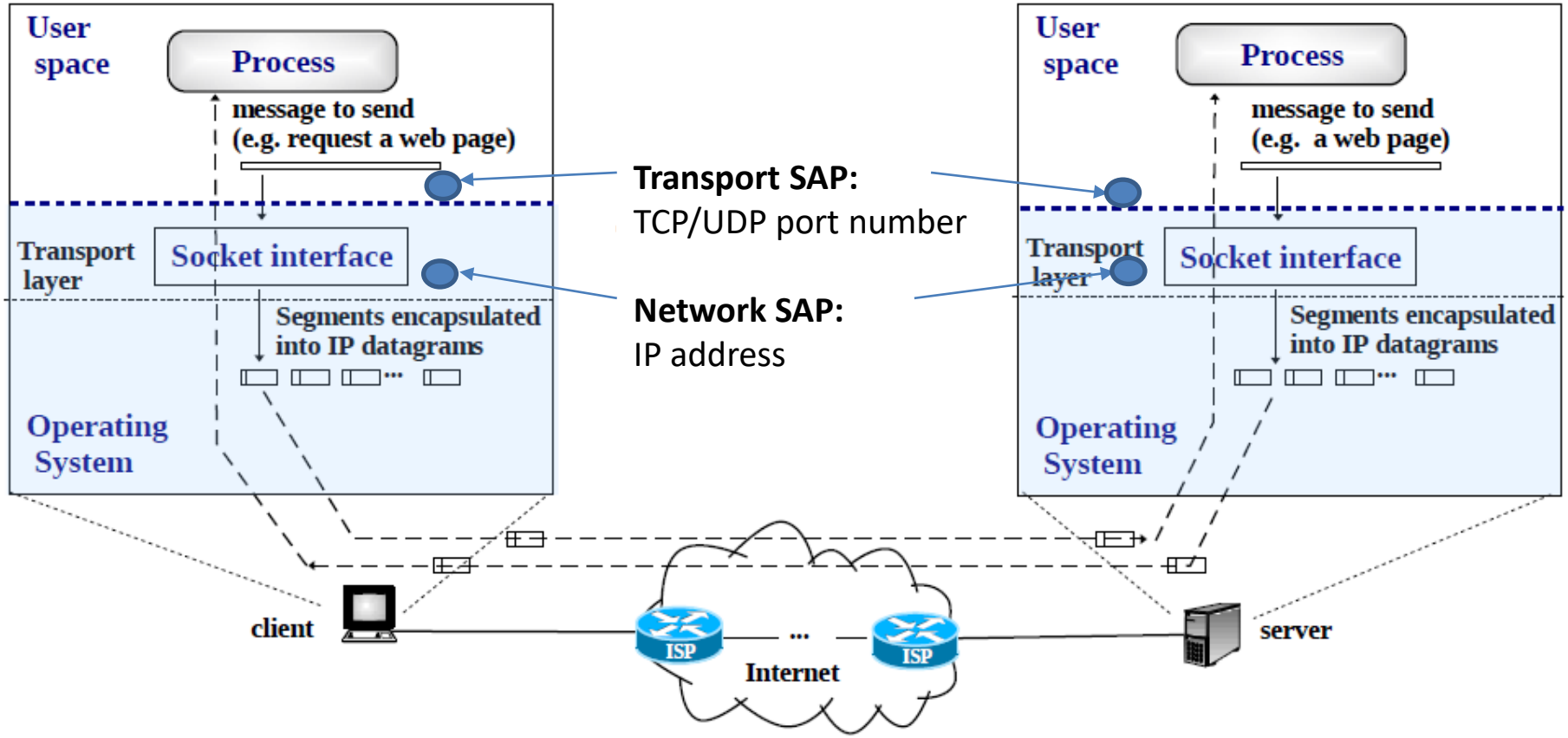
- Firewalls.
- Virtual Private Networks (VPN).

An end-to-end connection is univocally defined by:

source IP address (source device),
destination IP address (destination device),
source port number (application at source device),
destination port number (application at destination device) and
the protocol used in the communication



An end-to-end connection is univocally defined by:	**Header**
source IP address (source device),	IP
destination IP address (destination device),	IP
source port number (application at source device),	TCP/UDP
destination port number (application at destination device) and	TCP/UDP
the protocol used in the communication	IP



Example

Connection between an email client and an email server:

IP of the client device
Transport Protocol: TCP
Port number assigned to the email client by the client device

IP of the email server
Standard port number for email (SMTP): 25

The set of five fields identify a connection (flow)

Example

Client to Server

Connection between an email client and an email server:

IP of the client device	Source IP header
Transport Protocol: TCP	Source IP header
Port number assigned to the email client by the email client	Source TCP header
IP of the email server	Destination IP header
Standard port number for email (SMTP): 25	Destination TCP header

The set of five fields identify a connection (flow)

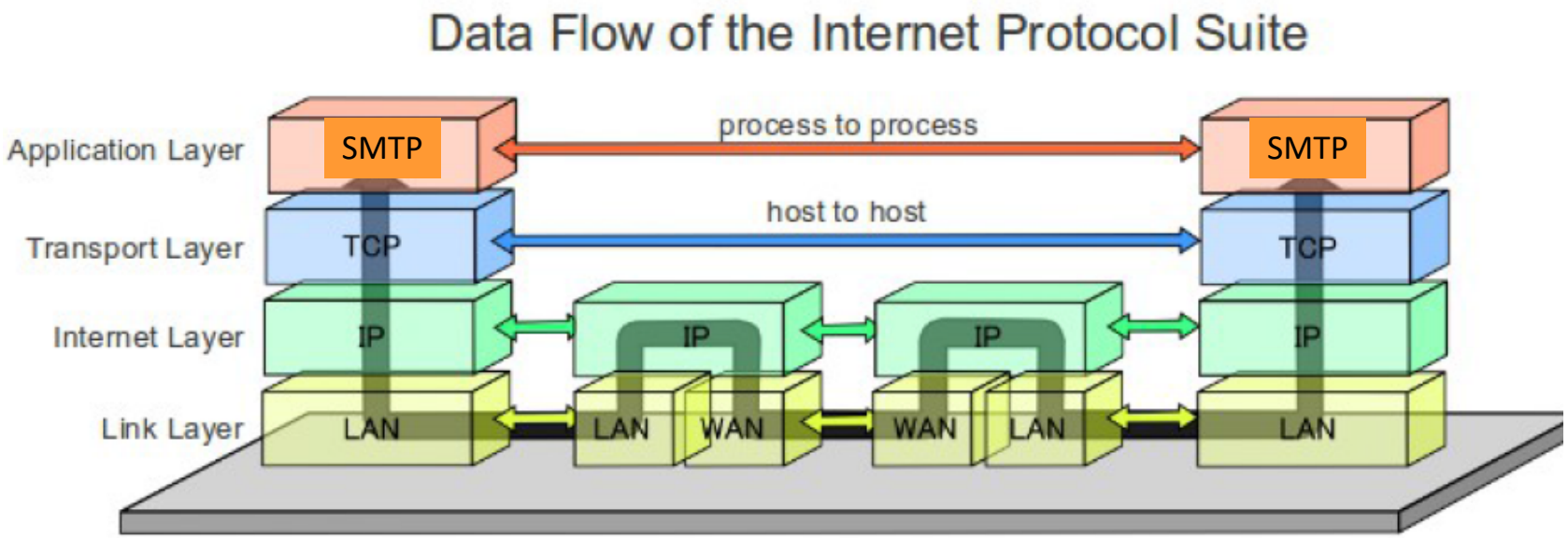
Example

Server to Client

Connection between an email client and an email server:

IP of the client device	Destination IP header
Transport Protocol: TCP	Destination IP header
Port number assigned by the email client	Destination TCP header
IP of the email server	Source IP header
Standard port number for email (SMTP): 25	Source TCP header

The set of five fields identify a connection (flow)

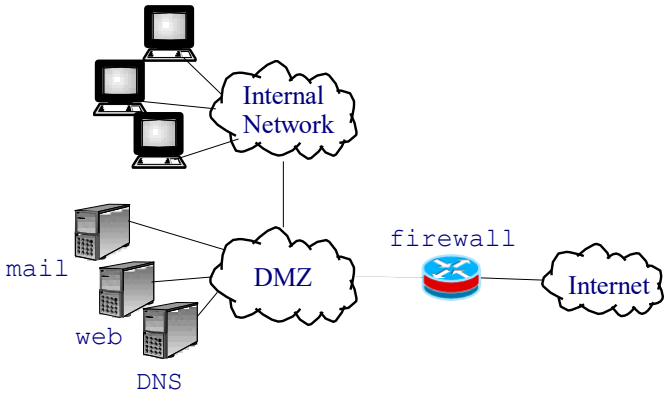


Outgoing E-mail Frame

Destination MAC Address	Source MAC Address	Destination IP Address	Source IP Address	Destination TCP Port	Source TCP Port		
00:0C:78:52:F3:A5	0E:11:81:F2:C3:98	216.93.82.9	172.16.20.57	25	58631	Hi Mom	101101
MAC address of default gateway router's interface	Your NIC's MAC address	IP address of the SMTP server at your mom's ISP	IP address of your PC	Standard port number for SMTP	Randomly generated by your PC's TCP/IP stack		

Security in IP – Firewalls

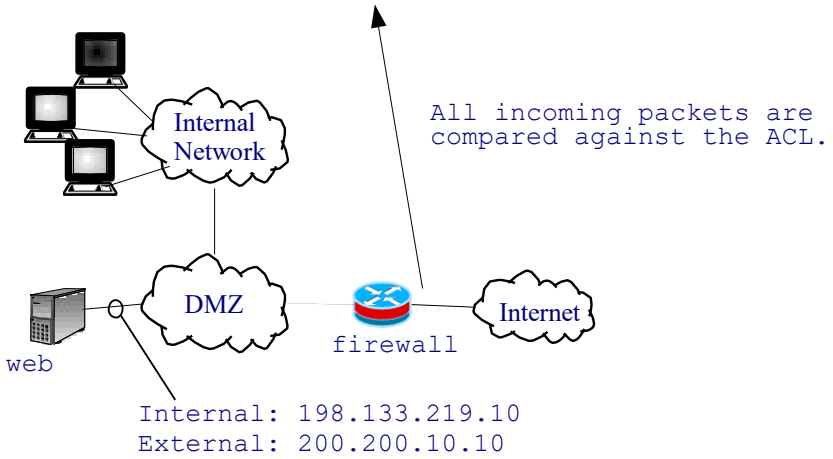
- Firewall: System or group of systems that enforces an access control policy to a network.
- There are many firewall types: From simple packet filtering based on IP/TCP/UDP header rules, to state-full connection tracking and application-based filtering, defense against network attacks, ...



Security in IP – Basic Firewall Configuration

- Access Control List, ACL

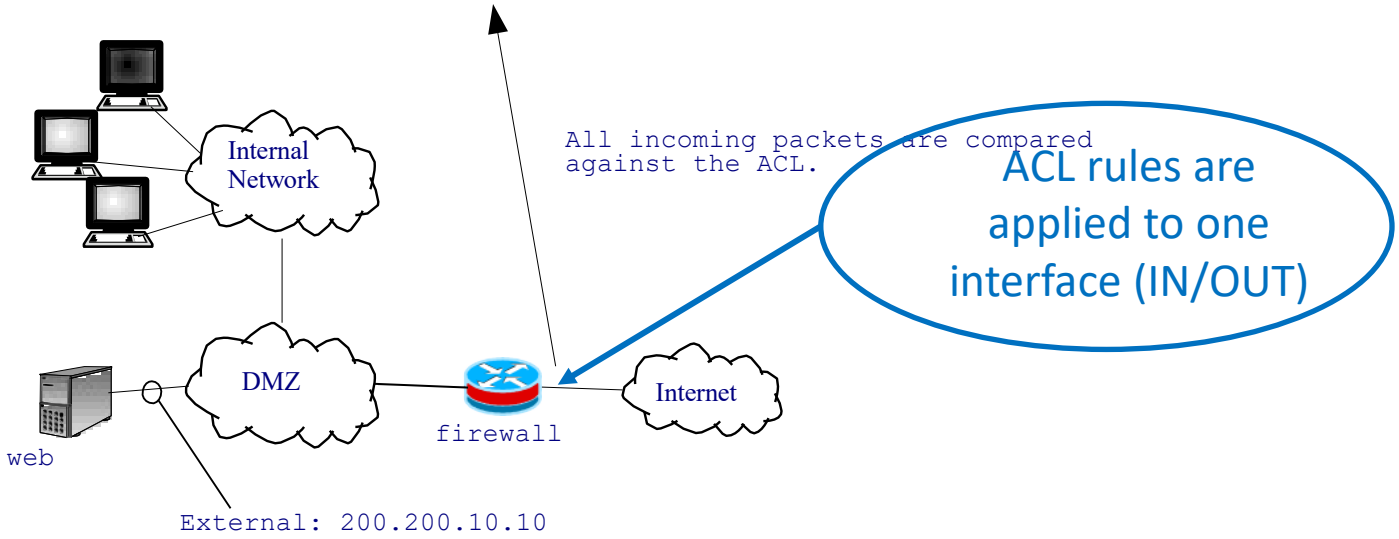
Protocol	IP-src	IP-dst	Port-src	Port-dst	Action
TCP	*any*	200.200.10.10/32	*any*	80	*accept*
TCP	*any*	*any*	< 1024	≥ 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*



Security in IP/TCP/UDP – Basic Firewall Configuration

- Access Control List, ACL

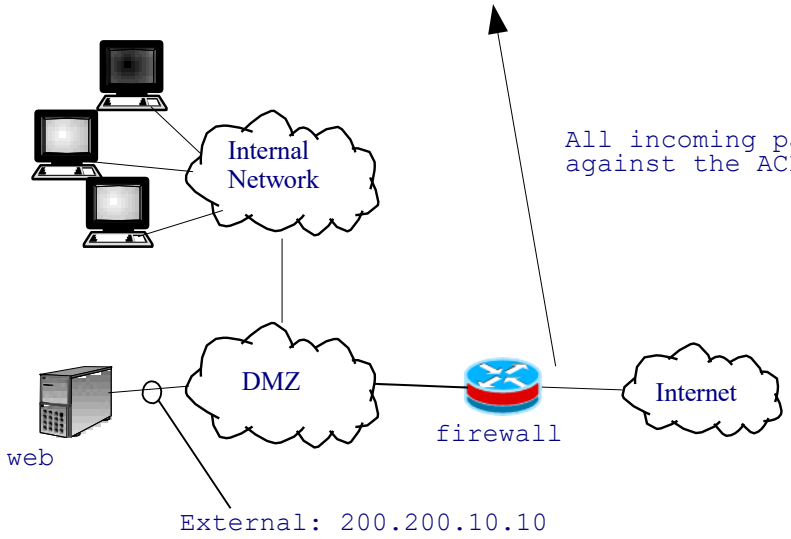
Protocol	IP-src	IP-dst	Port-src	Port-dst	Action
TCP	*any*	200.200.10.10/32	*any*	80	*accept*
TCP	*any*	*any*	< 1024	≥ 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*

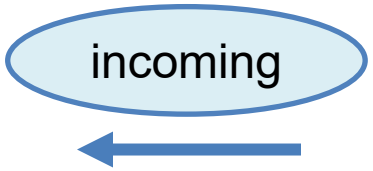


Security in IP/TCP/UDP – Basic Firewall Configuration

- 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	≥ 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*





FROM

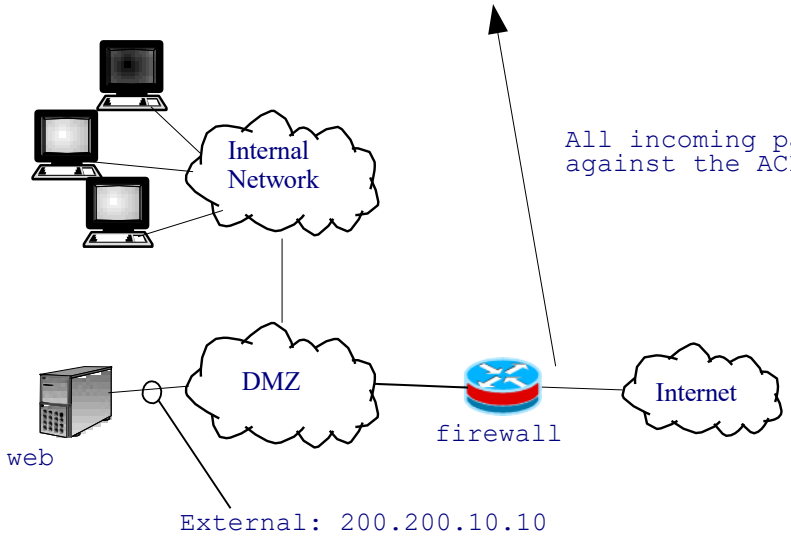
TO

ONLY the Web server accepts connections from an external web client

Security in IP/TCP/UDP – 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	≥ 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*



incoming

FROM

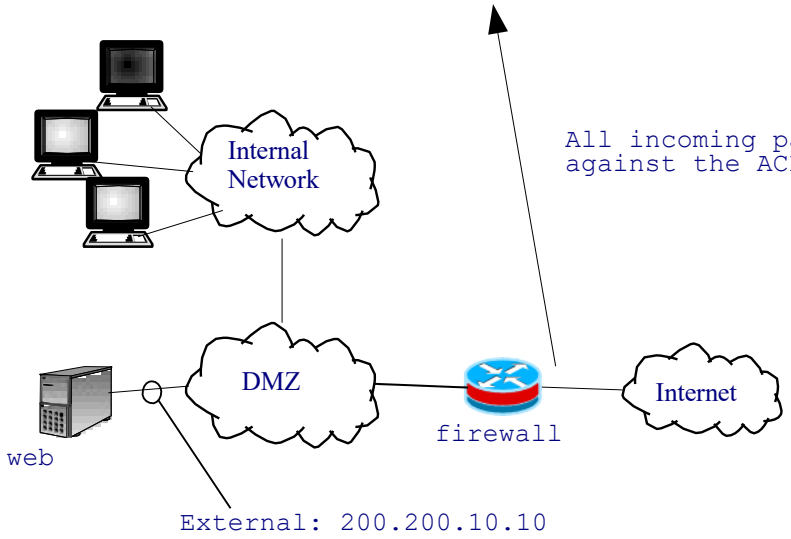
TO

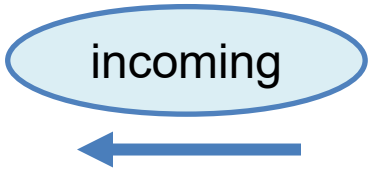
ANY internal client accepts connections from any external server

Security in IP/TCP/UDP – 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	< 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*



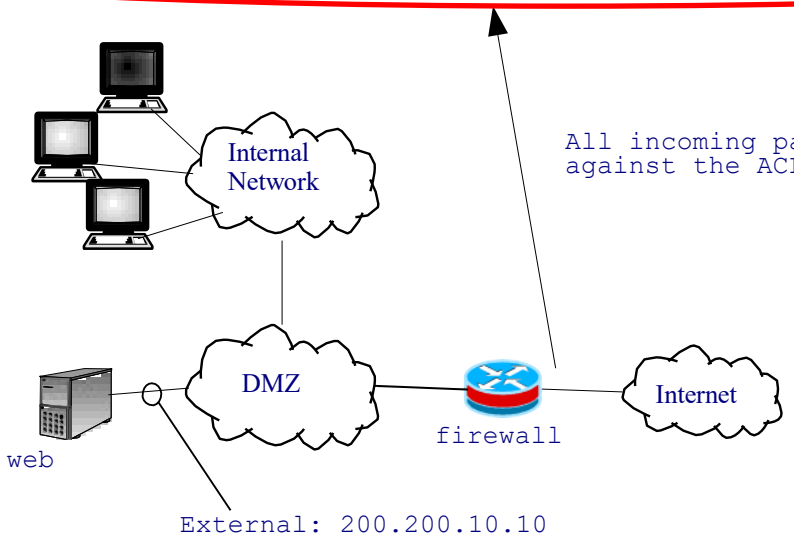


ANY incoming ICMP datagram going to ANY internal device is allowed

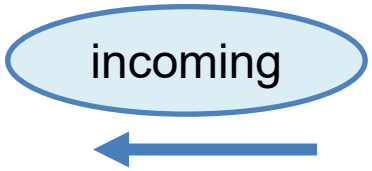
Security in IP/TCP/UDP – Basic Firewall Configuration

- 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	≥ 1024	*accept*
ICMP	*any*	*any*	–	–	*accept*
IP	*any*	*any*	–	–	*deny*



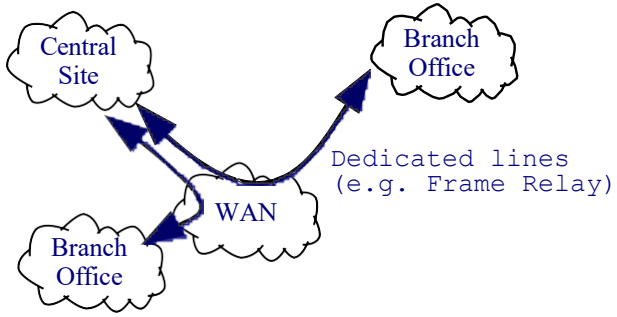
All incoming packets are compared against the ACL.



ANY other flows than the previous ones are NOT allowed to enter

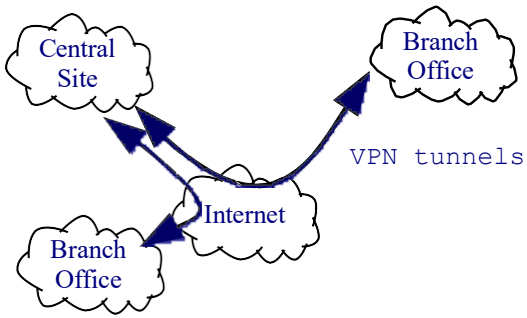
Security in IP – Virtual Private Network, VPN

- 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.

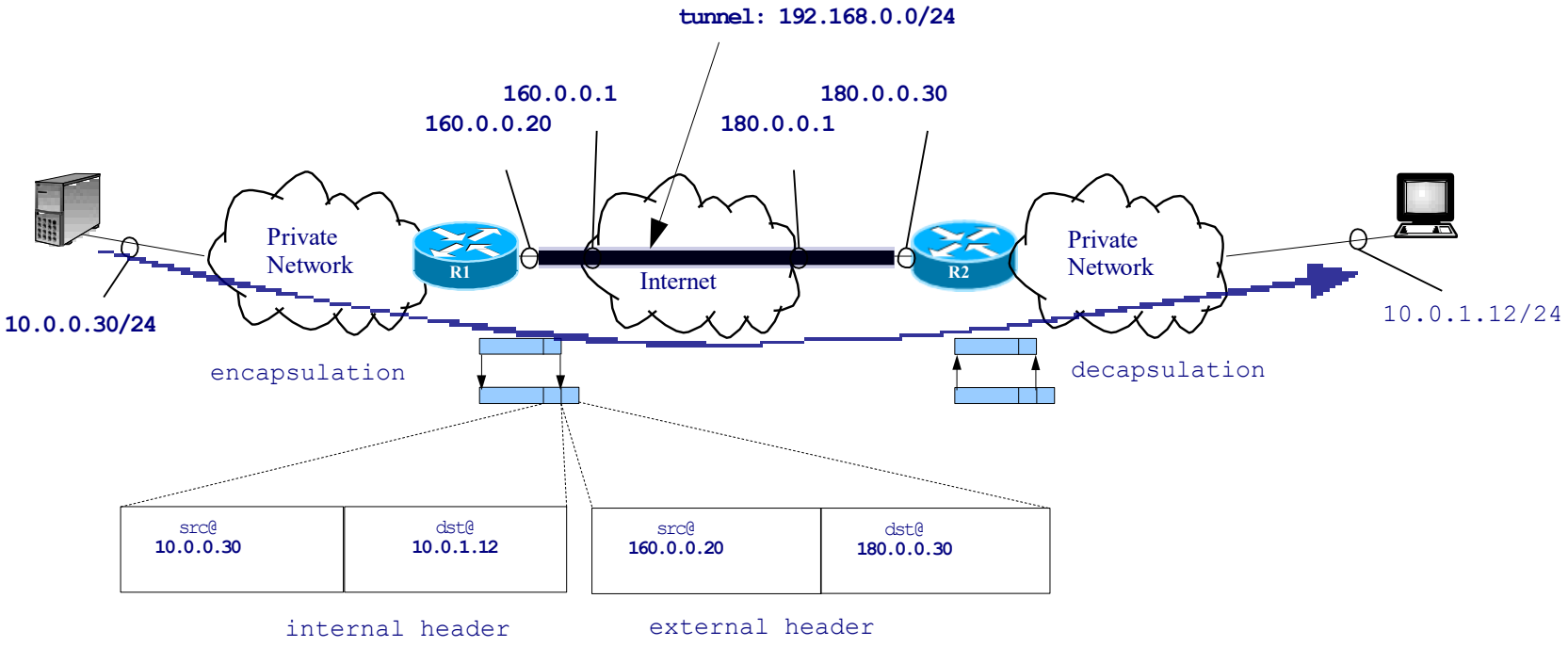


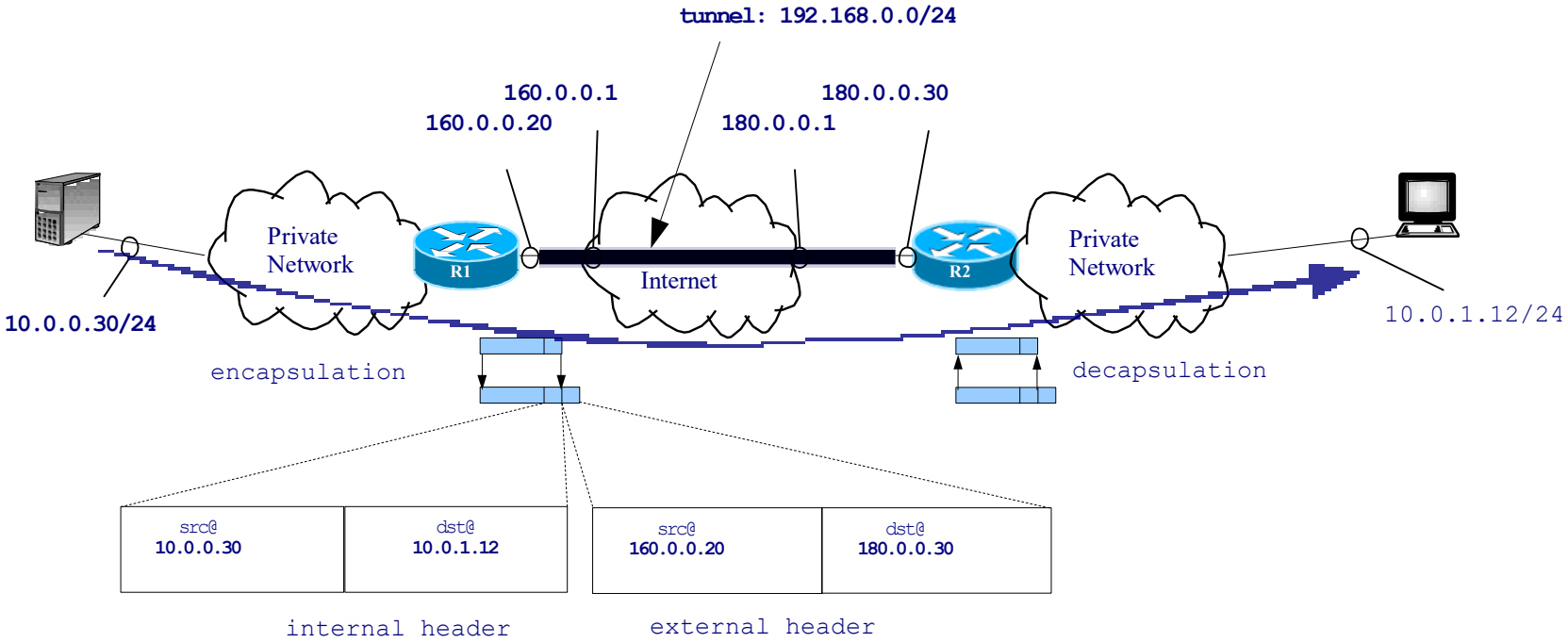
Virtual Private Network (VPN)

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

Security in IP – VPN Security

- Authentication
- Cryptography
- Tunneling





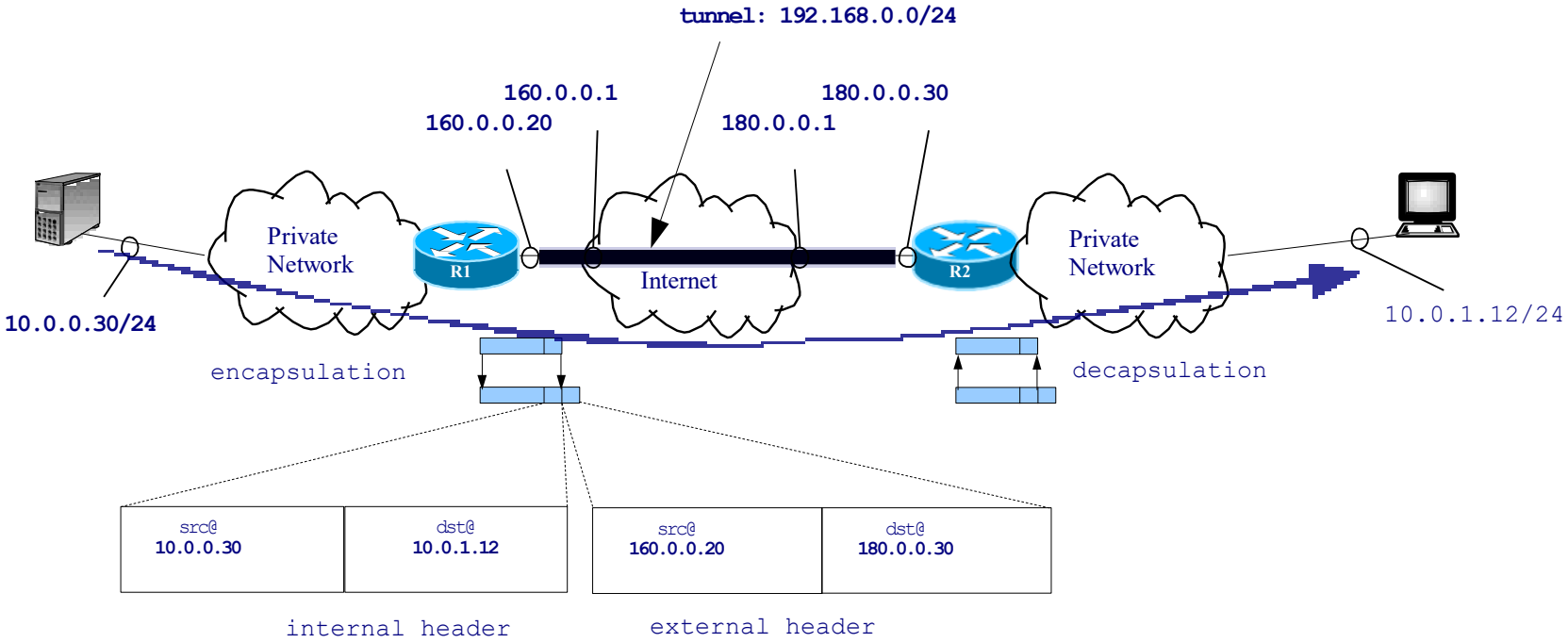
Routing tables before the tunnel configuration

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

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

R2 Routing Table




```
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
```

Tunnel configuration

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

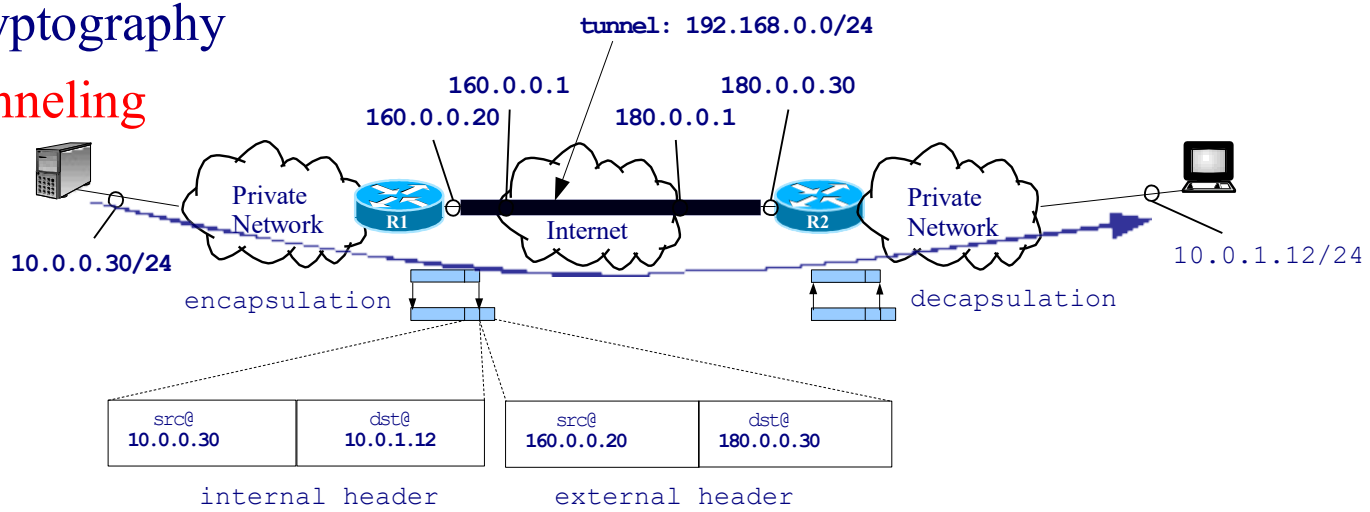
Destination	Gateway	Genmask	Iface
10.0.1.0	0.0.0.0	255.255.255.0	eth0
180.0.0.1	0.0.0.0	255.255.255.255	ppp0
0.0.0.0	180.0.0.1	0.0.0.0	ppp0
192.168.0.0	0.0.0.0	255.255.255.0	tunl0
10.0.0.0	192.168.0.1	255.255.255.0	tunl0

R2 Routing Table

Virtual interface for the tunnel
Static route to remote network

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

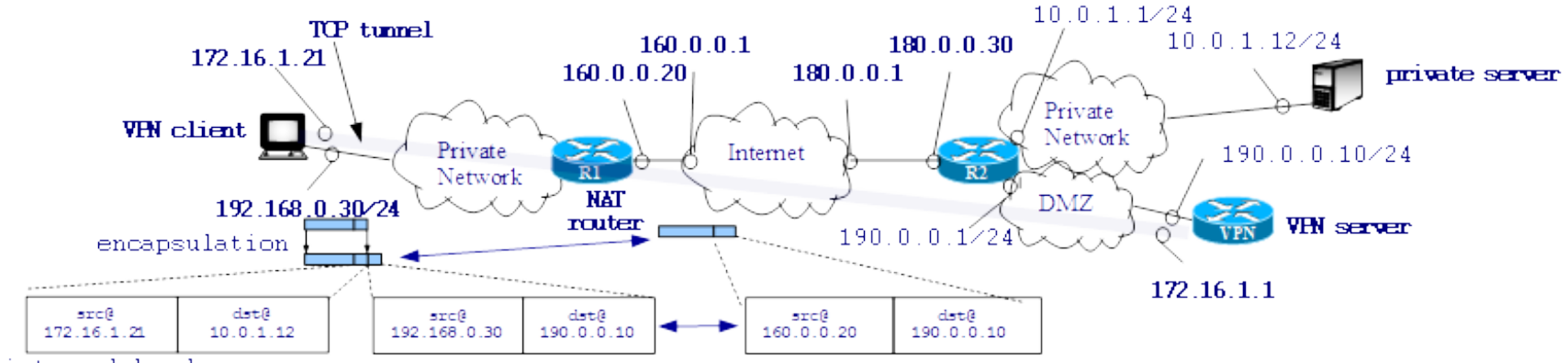
R1 Routing Table

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

- **TCP/UDP tunnels:**
  Typically used in VPNs to be able to cross NAT routers

Example: openvpn client



Client routing table

Destination	Gateway	Genmask	Iface
192.168.0.0	0.0.0.0	255.255.255.0	eth0
0.0.0.0	192.168.0.1	0.0.0.0	eth0
172.16.1.1	0.0.0.0	255.255.255.255	tun0
10.0.1.0	172.16.1.1	255.255.255.0	tun0

Network reachable through the tunnel

Private server routing table

Destination	Gateway	Genmask	Iface
10.0.1.0	0.0.0.0	255.255.255.0	eth0
0.0.0.0	10.0.1.1	0.0.0.0	eth0

VPN server routing table

Destination	Gateway	Genmask	Iface
190.0.0.0	0.0.0.0	255.255.255.0	eth0
172.16.1.21	0.0.0.0	255.255.255.255	tun0
172.16.1.23	0.0.0.0	255.255.255.255	tun3
...			
0.0.0.0	190.0.0.1	0.0.0.0	eth0

Other VPN clients

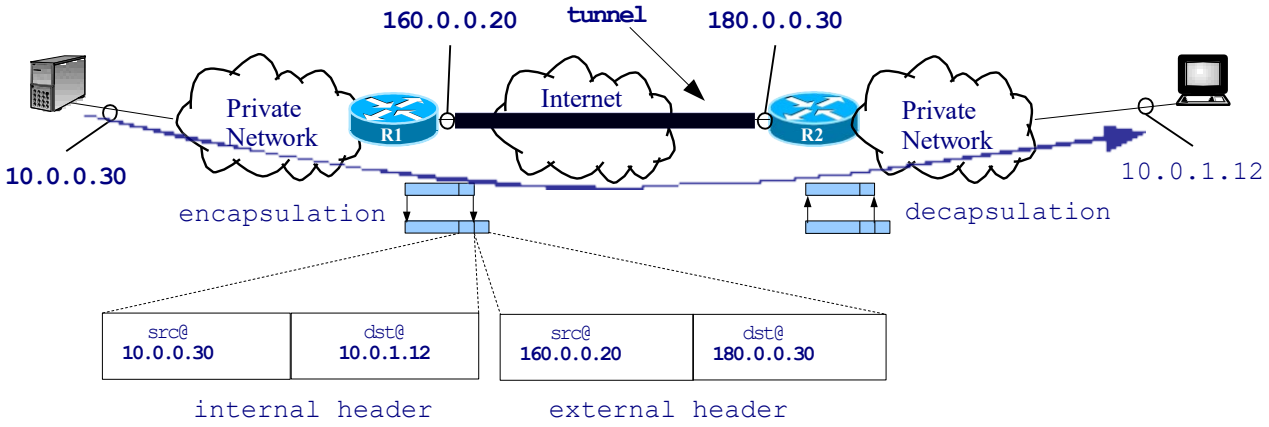
R2 routing table

Destination	Gateway	Genmask	Iface
10.0.1.0	0.0.0.0	255.255.255.0	eth0
190.0.0.0	0.0.0.0	255.255.255.0	eth1
172.16.1.0	190.0.0.10	255.255.255.0	eth1
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

VPN network

Security in IP – VPN Tunneling Issues

- Fragmentation inside the tunnel will use the external header, thus, the exit router of the tunnel should reassemble fragmented datagrams.
- ICMP messages sent inside the tunnel are addressed to the tunnel entry.
- MTU path discovery may fail (may not detect small MTU in the tunnel).
- 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 fragments the datagrams before encapsulation, if needed, to avoid the exit router having to reassemble fragmented datagrams.



Security in IP – VPN Tunneling

- IP over IP (RFC 2003): Basic encapsulation.
- Generic Routing Encapsulation, GRE (RFC 1701):
  There is an additional GRE header: different protocol encapsulation (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.

IP Networks

Outline

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