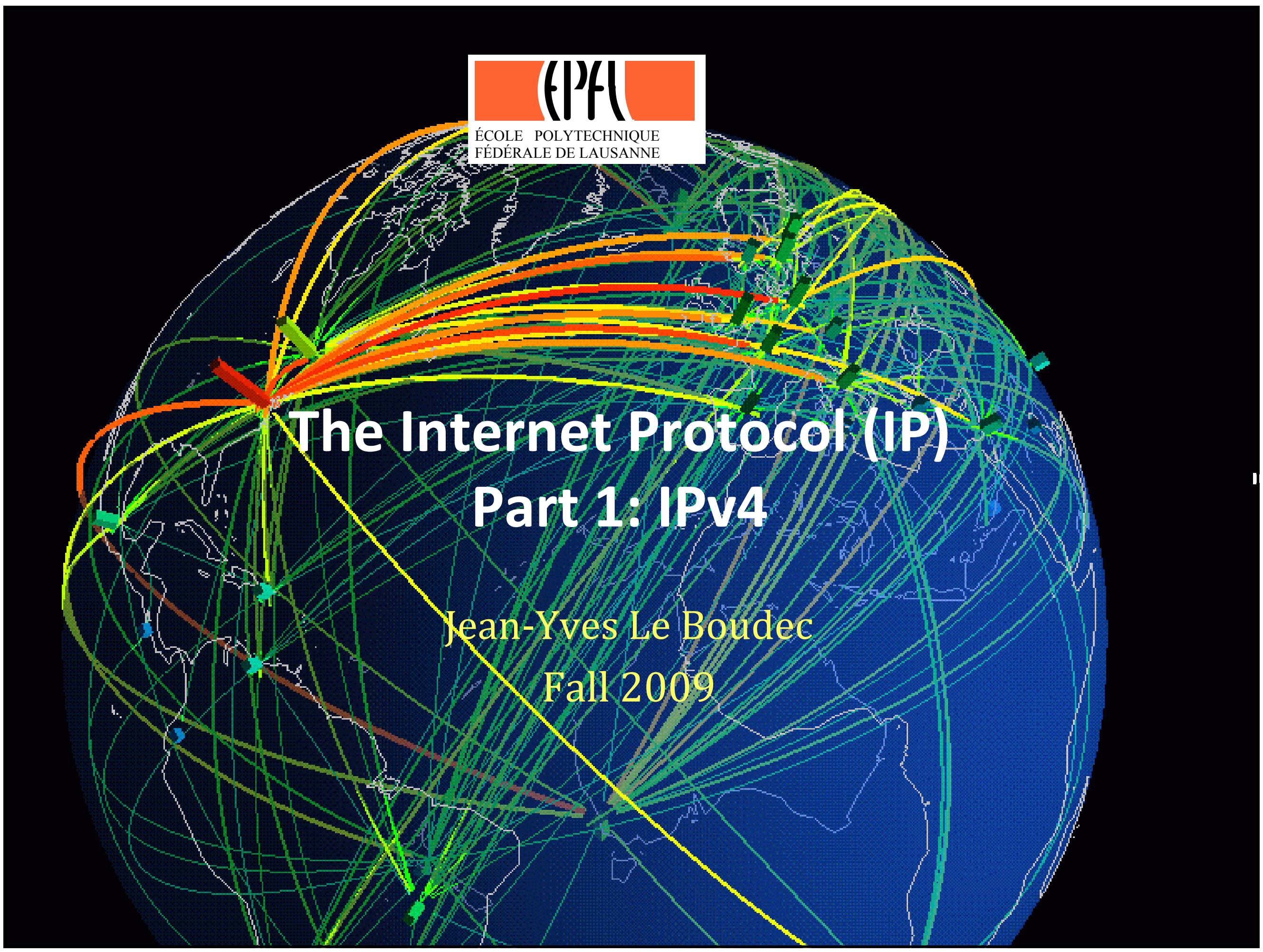

The Internet Protocol (IP)
Part 1: IPv4

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- 2. Addressing
- 3. Packet Delivery and Forwarding
- 4. IP header
- 5. ICMP
- 6. Fragmentation
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1. Why a network layer?

- We would like to interconnect all devices in the world. We have seen that we can solve the interconnection problem with bridges and the MAC layer. However this is not sufficient as it does not *scale* to large networks.

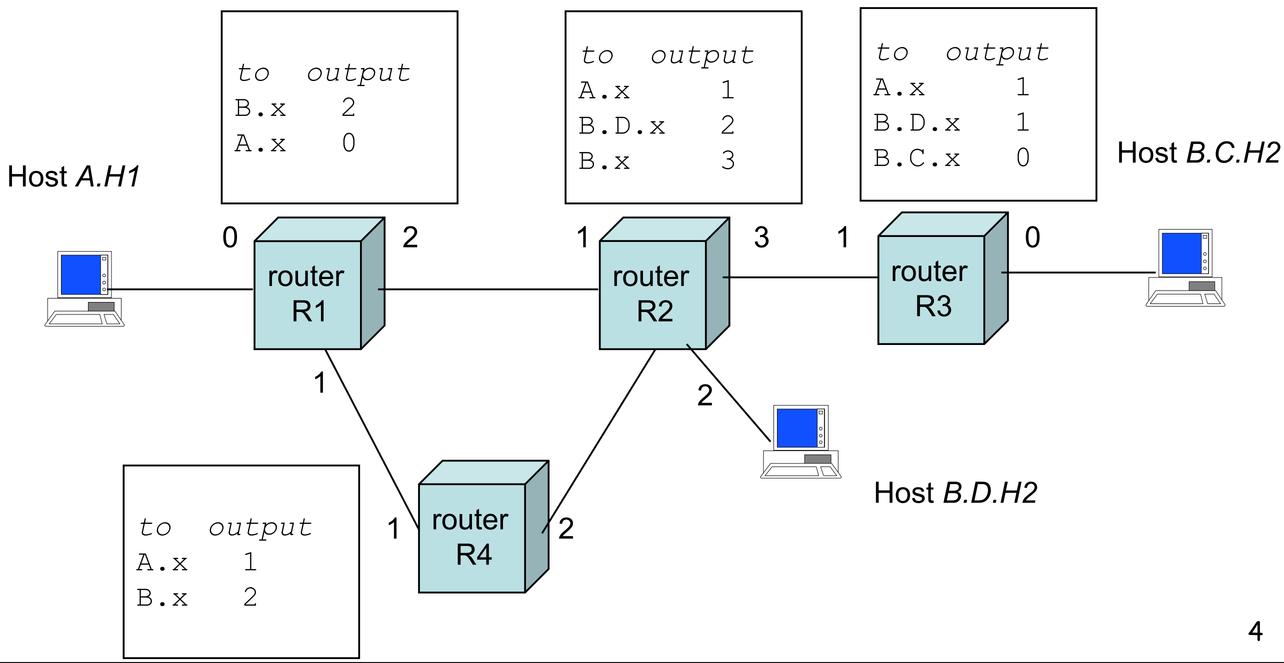
  solution

  Q. Why ?

- Solution: connectionless network layer (eg. Internet Protocol, IP):
  - every host receives a network layer address (IP address)
  - intermediate systems forward packets based on destination address

Connectionless Network Layer

- **Connectionless** network layer = no connection
- every packet contains destination address
- intermediate systems (= routers) forward based on **longest prefix match**



IP Principles

Homogeneous addressing

- an IP address is unique across the whole network (= the world in general)
- IP address is the address of an interface
- communication between IP hosts requires knowledge of IP addresses

Routers between subnetworks only:

- a subnetwork = a collection of systems with a common prefix
- inside a subnetwork: hosts communicate directly without routers
- between subnetworks: one or several routers are used

- Host either sends a packet to the destination using its LAN, or it passes it to the router for forwarding

- Terminology:
  - host = end system; router = intermediate system
  - subnetwork = one collection of hosts that can communicate directly without routers

2. IP addresses

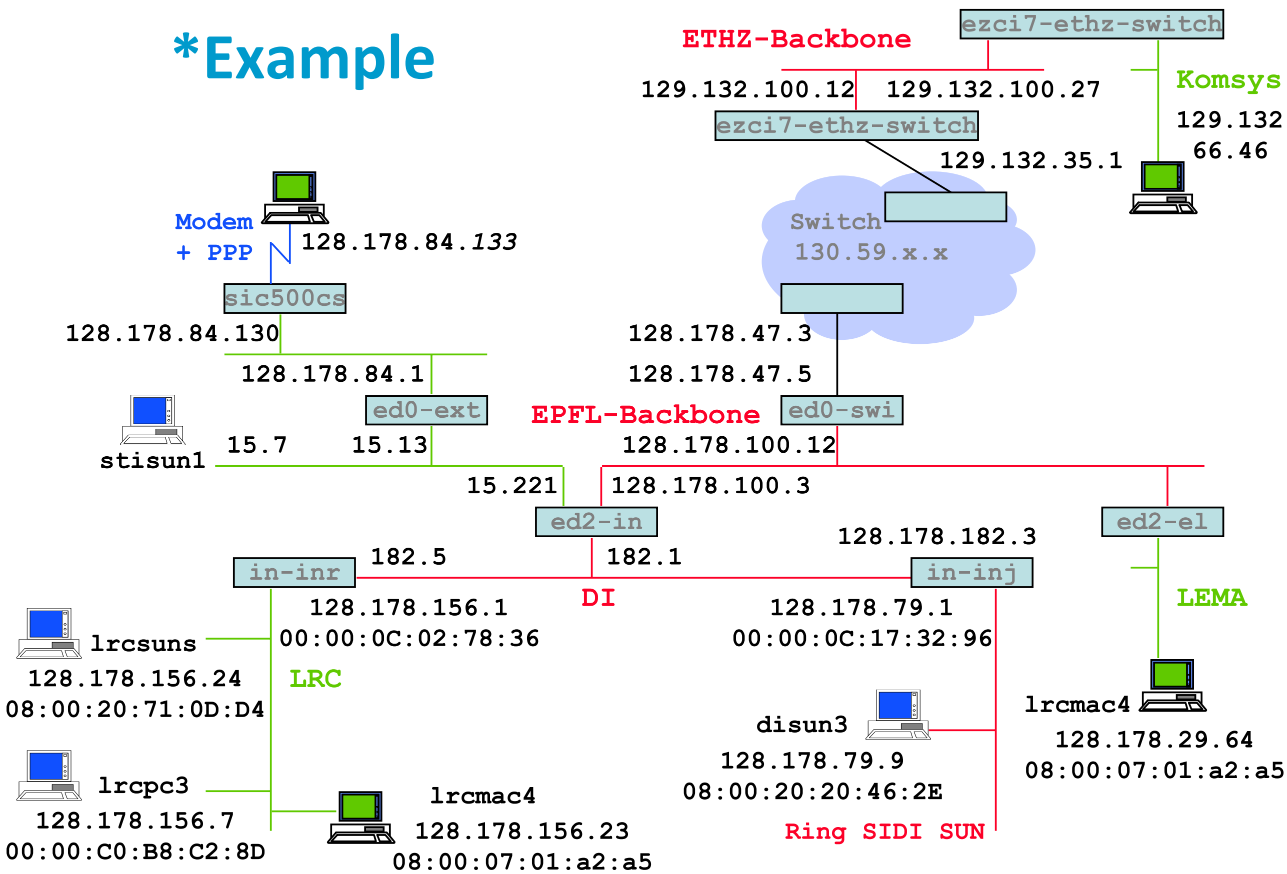
IP address

- Unique addresses in the world, decentralized allocation
- The current format is IPv4; next format will be IPv6; we will see IPv6 at the end of the lecture. By default, “IP address” = “IPv4 address”
- An IP address is 32 bits, noted in dotted decimal notation: **`192.78.32.2`**

Host and Prefix Part

- An IP address has a prefix and a host part:
  - **`prefix:host`**
- Prefix identifies a subnetwork
- The subnet prefix can be any length; frequent case is 24 bits but not always
- In order to know its prefix, a host needs to know how many bits constitute it
  - usually by means of a “subnet mask” (see later)

*Example


ETHZ-Backbone
ezci7-ethz-switch
129.132.100.12
129.132.100.27
Komsys
ezci7-ethz-switch
129.132
66.46
129.132.35.1
Modem
+ PPP
128.178.84.133
Switch
130.59.x.x
sic500cs
128.178.84.130
128.178.47.3
128.178.84.1
128.178.47.5
ed0-ext
EPFL-Backbone
ed0-swi
stisun1
15.7
15.13
128.178.100.12
15.221
128.178.100.3
ed2-in
ed2-el
128.178.182.3
in-inr
182.5
182.1
in-inj
DI
LEMA
128.178.156.1
00:00:0C:02:78:36
128.178.79.1
00:00:0C:17:32:96
lrcsuns
128.178.156.24
08:00:20:71:0D:D4
LRC
lrcmac4
disun3
128.178.29.64
08:00:07:01:a2:a5
128.178.79.9
08:00:20:20:46:2E
lrcpc3
128.178.156.7
00:00:C0:B8:C2:8D
lrcmac4
128.178.156.23
08:00:07:01:a2:a5
Ring SIDI SUN

Binary, Decimal and Hexadecimal

- Given an integer B “the basis”: any integer can be represented in “base B” by means of an alphabet of B symbols
- Usual cases are
  - decimal: 234
  - binary: b1110 1010
  - hexadecimal: xEA

- Mapping binary <-> hexa is simple: one hexa digit is 4 binary digits
  - xE = b1110 xA = b1010 xEA= b1110 1010

- Mapping binary <-> decimal is best done by a calculator
  - b1110 1010 = 128 + 64 + 32 + 8 + 2 = 234

- Special Cases to remember
  - xF = b1111 = 15
  - xFF = b1111 1111 = 255

Representation of IP Addresses

- **dotted decimal**: group bits in bytes, write the decimal representation of the number
  - example 1: `128.191.151.1`
  - example 2: `129.192.152.2`
- **hexadecimal**: hexadecimal representation -- fixed size string
  - example 1: `x80 BF 97 01`
  - example 2: `x`
- **binary**: string of 32 bits (2 symbols: 0, 1)
  - example 1: `b0100 0000 1011 1111 1001 0111 0000 0001`
  - example 2: `b`

solution

An IP address Prefix is written using one of two Notations: masks / prefixes

- Using a mask: address + mask :
  - example : 128.178.156.13 mask 255.255.255.0
    - the mask is the dotted decimal representation of the string made of : 1 in the prefix, 0 elsewhere
    - bit wise address & mask gives the prefix
    - here: prefix is 128.178.156.0
  - example 2: 129.132.119.77 mask 255.255.255.192
    - Q1: what is the prefix ?
    - Q2: how many host ids can be allocated ?

  solution

  - Typically used in host configuration

Prefix Notation

- prefix – notation: 128.178.156.1/24
  - the 24 first bits of the binary representation of the string, interpreted as dotted decimal
  - here: the prefix is 128.178.156.0
  - bits in excess are ignored
    - 128.178.156.1/24 is the same as 128.178.156.22/24 and 128.178.156/24
  - typically used in routing tables to identify routing prefixes
- example 2:
  - Q1: write 129.132.119.77 mask 255.255.255.192 in prefix notation
  - Q2: are these prefixes different ?
    - 201.10.0.00/28, 201.10.0.16/28, 201.10.0.32/28, 201.10.0.48/28
    - how many IP addresses can be allocated to each of the distinct prefixes ?

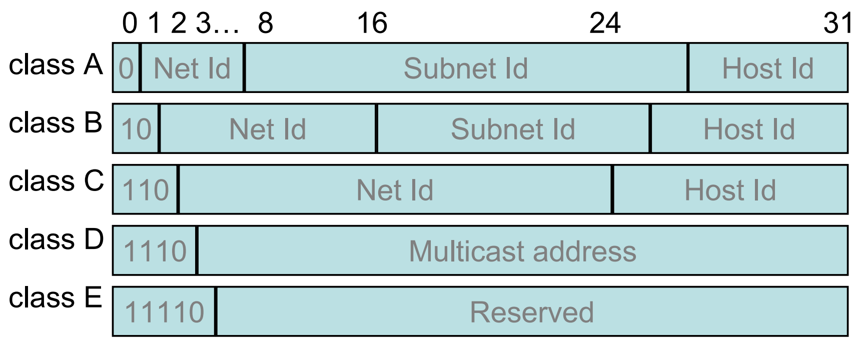
solution

*IP Address Hierarchies

- The prefix of an IP address can itself be structured into subprefix in order to support aggregation
  - For example: 128.178.x.y represents an EPFL host
    128.178.156 / 24 represents the LRC subnet at EPFL
    128.178 / 16 represents EPFL
  - Used between routers by routing algorithms
  - This way of doing is called classless and was first introduced in inter domain routing under the name of CIDR (classless interdomain routing)

- IP address classes
  - IP addresses are sorted into classes
  - This is an obsolete classification – no longer used
    - At the origin, the prefix of an IP address was defined in a very rigid way. For class A addresses, the prefix was 8 bits. For class B, 16 bits. For class C, 24 bits. The interest of that scheme was that by simply analyzing the address you could find out what the prefix was.
    - It was soon recognized that this form was too rigid. Then subnets were added. It was no longer possible to recognize from the address alone where the subnet prefix ends and where the host identifier starts. For example, the host part at EPFL is 8 bits; it is 6 bits at ETHZ. Therefore, an additional information, called the subnet mask, is necessary.
    - Class C addresses were meant to be allocated one per network. Today, they are allocated in contiguous blocks.

*IP address classes



Examples: 128.178.x.x = EPFL host; 129.132.x.x = ETHZ host
9.x.x.x = IBM host 18.x.x.x = MIT host

Class	*Range*
A	0.0.0.0 to 127.255.255.255
B	128.0.0.0 to 191.255.255.255
C	192.0.0.0 to 223.255.255.255
D	224.0.0.0 to 239.255.255.255
E	240.0.0.0 to 247.255.255.255

- Class B addresses are close to exhausted; new addresses are taken from class C, allocated as continuous blocks

*Address allocation

- World Coverage
  - Europe and the Middle East (RIPE NCC)
  - Africa (ARIN & RIPE NCC)
  - North America (ARIN)
  - Latin America including the Caribbean (ARIN)
  - Asia-Pacific (APNIC)
- Current allocations of Class C
  - `193-195/8, 212-213/8, 217/8` for RIPE
  - `199-201/8, 204-209/8, 216/8` for ARIN
  - `202-203/8, 210-211/8, 218/8` for APNIC
- Simplifies routing
  - short prefix aggregates many subnetworks
  - routing decision is taken based on the short prefix

*Address delegation

- Europe
  - 62/8, 80/8, 193-195/8, ... solution
  - ISP-1
    - 62.125/16
    - customer 1: banana foods
      - 62.125.44.128/25
    - customer 2: sovkom
      - 62.125.44.50/24
  - ISP-2
    - 195.44/14
    - customer 1:
      - 195.46.216/21
    - customer 2:
      - 195.46.224/21

Q. Assume sovkom moves from ISP-1 to ISP-2; comment on the impact.

Special case IP addresses

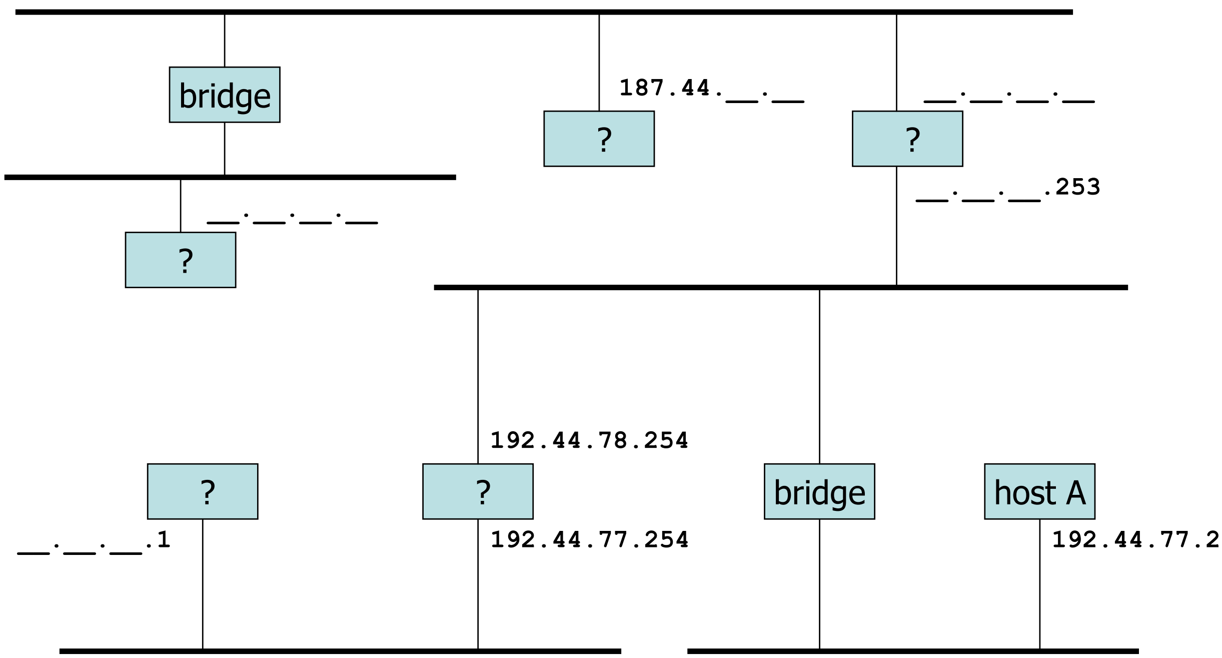
```
1. 0.0.0.0                  this host, on this network
2. 0.hostId                 specified host on this net
                               (initialization phase)
3. 255.255.255.255          limited broadcast
                                (not forwarded by routers)
4.  subnetId.all 1's             broadcast on this subnet
5.  subnetId.all 0's             BSD used it for broadcast
                                       on this subnet
   (obsolate)
6.  127.x.x.x                    loopback

7. 10/8                     reserved networks for
  172.16/12                  internal use (Intranets)
   192.168/16
```

- 1,2: source IP@ only; 3,4,5: destination IP@ only

Test Your Understanding (1)

solution



Q: Can host A have this address? (masks are all 255.255.255)

Test your Understanding (2)

- Q1: An Ethernet segment became too crowded; we split it into 2 segments, interconnected by a router. Do we need to change some IP host addresses?
- Q2: same with a bridge.
- Q3: compare the two

solutions

3. IP packet forwarding

The IP packet forwarding algorithm is the core of the TCP/IP architecture. It defines what a system should do with a packet it has to send or forward. The rule is simple :

- Rule for sending packets (hosts, routers)
  - if the destination IP address has the same prefix as one of my interfaces, send directly to that interface
  - otherwise send to a router as given by the IP routing table

It uses the IP routing table; the table can be checked with a command such as “netstat” with Unix or “Route” with Windows.

In reality, there are exceptions to the rule. The complete algorithm is in the next slide; the cases should be tested in that order (it is a nested **if then else** statement).

IP packet forwarding algorithm

destAddr = destination address /* unicast! */

if /*case 1*/: a **host route** exists for destAddr

    for every entry in routing table
      if (destinationAddr = destAddr)
      then send to nextHop IPaddr; leave

else if /*case 2*/: destAddr is on a **directly connected network** (= on-link):

    for every physical interface IP address A and subnet mask SM
      if(A & SM = destAddr & SM)
      then send directly to destAddr; leave

else if /*case 3 */ there is a **matching entry in routing table**

find the **longest prefix match** for destAddr

    send to nextHop IP addr given by matching entry; leave
    /* this includes as special case the default route, if it exists */

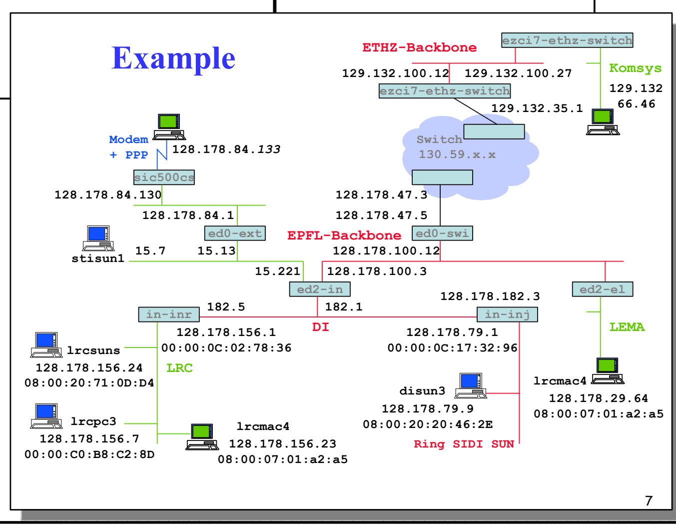
else /* error*/

send ICMP error message "destination unreachable" to source

*Example

- Q1: Fill in the table if an IP packet has to be sent from **lrcsuns**

final destination	next hop	case number
128.178.79.9 128.178.156.7 127.0.0.1 128.178.84.133 129.132.1.45		



- Q2: Fill in the table if an IP packet has to be sent from ed2-in

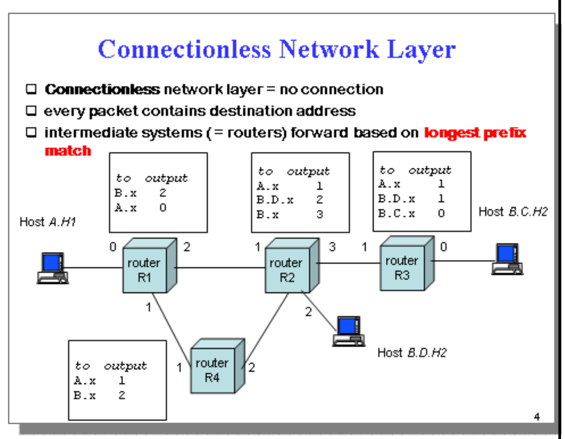
solutions

Routing Tables

- Hosts and routers have routing tables, but only routers have significant routing tables

- Routing tables at routers are maintained manually or, more usually, by *routing protocols*

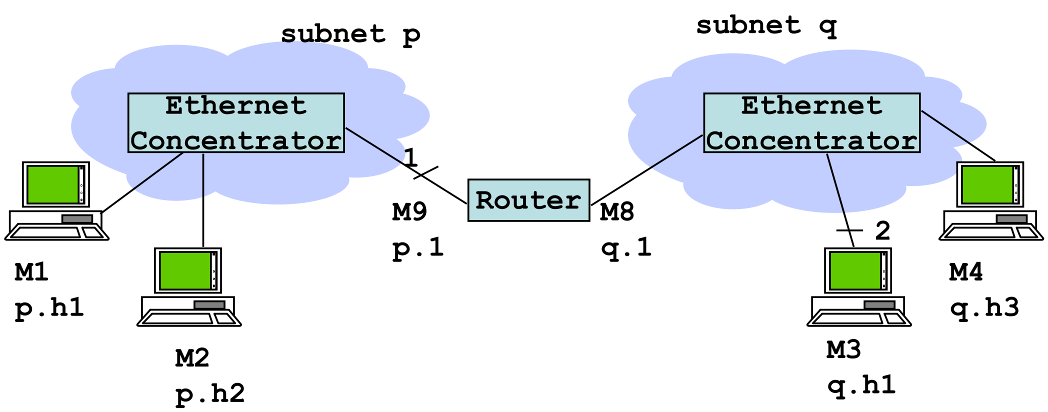
- Do not confuse
  - Packet forwarding:
    determine which outgoing interface to use
    real time
  - Routing
    compute the values in the routing table
    background job



Test Your Understanding (3)

- **Q1.** What are the MAC and IP addresses at points 1 and 2 for packets sent by M1 to M3 ? At 2 for packets sent by M4 to M3 ?(Mx = mac address)

solution



Direct Packet Forwarding: ARP

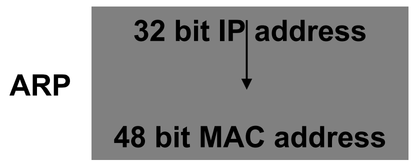
- Sending to host on the same subnet = direct packet forwarding
  - does not use a router
- Requires the knowledge of the MAC address on a LAN

  (called “physical” address)

  There are four types of solutions for that; all exist in some form or another.

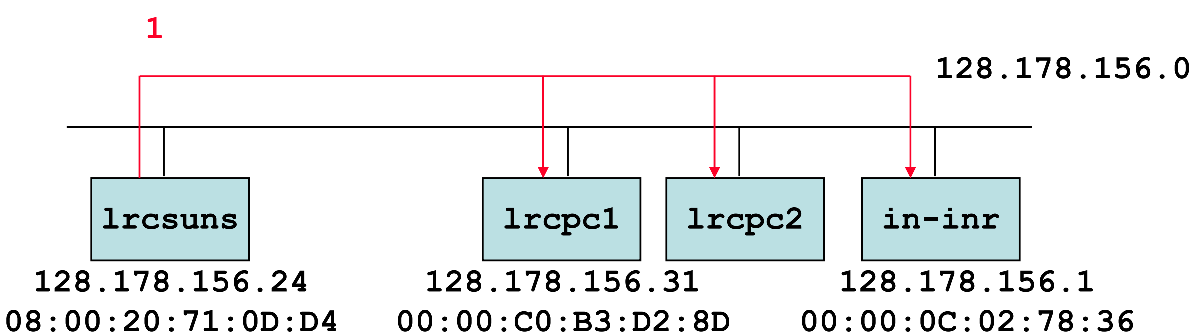
  1. write arp table manually: can always be implemented manually on Unix or Windows NT using the arp command
  2. Derive MAC address algorithmically from IP address. This requires that the MAC address fits in the IP address; it is used with IPv6 but not with the current version of IP.
  3. Write the mappings MAC <-> IP in a server (used in special cases like ATM or frame relay).
  4. Use a discovery protocol by broadcast. This is done on all LANs (Ethernet, WiFi).

  - on LANs: uses the Address Resolution Protocol



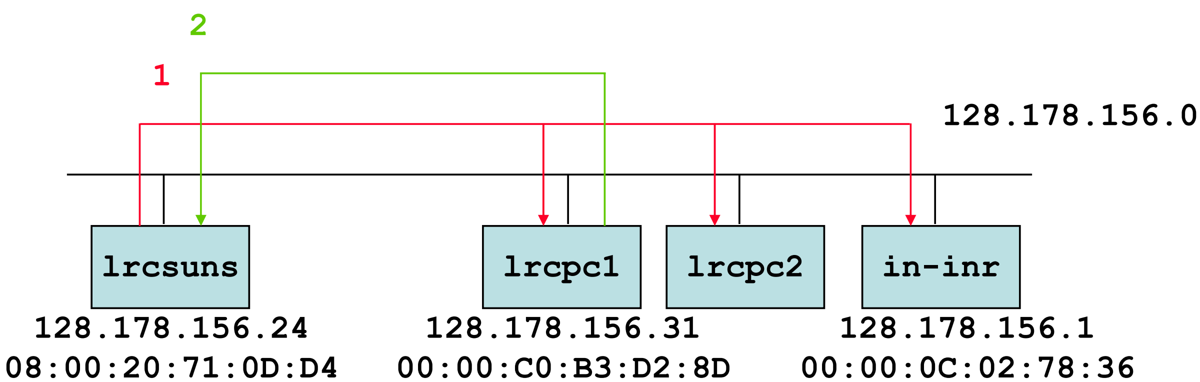
ARP Protocol

- 1: `lrcsuns` has a packet to send to `128.178.156.31 (lrcpc1)`



- this address is on the same subnet
- `lrcsuns` sends an ARP request to all systems on the subnet (broadcast)
- target IP address = `128.178.156.31`
- ARP request is received by all IP hosts on the local network
- is not forwarded by routers

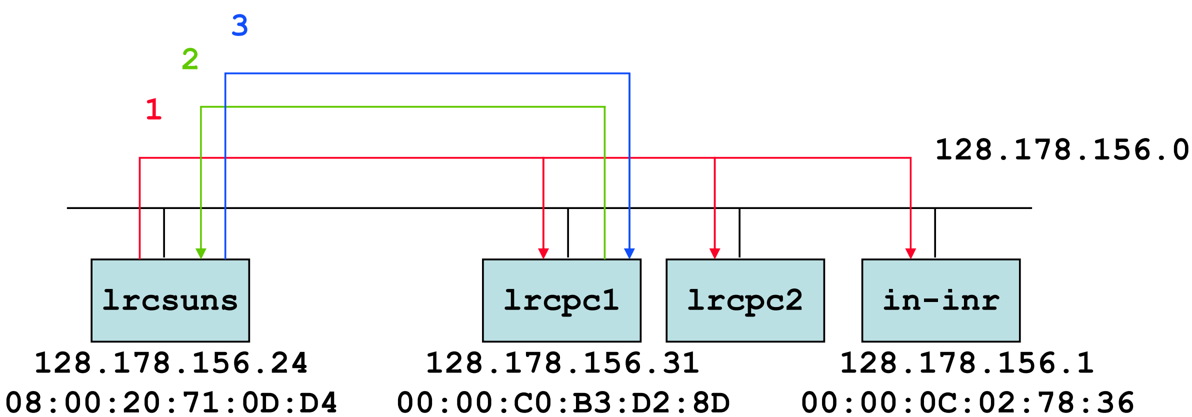
ARP Protocol



2: `lrcpc1` has recognized its IP address

- sends an ARP reply packet to the requesting host
- with its IP and MAC addresses

ARP Protocol



3: `lrcsuns` reads ARP reply, stores in a cache and sends IP packet to `lrcpc1`

Systems learn from ARP-REQUESTs. At the end of flow 1, all systems have learnt the mapping IP <-> MAC addr for the source of the ARP REQUEST, namely, they have updated the following entry in their ARP table:

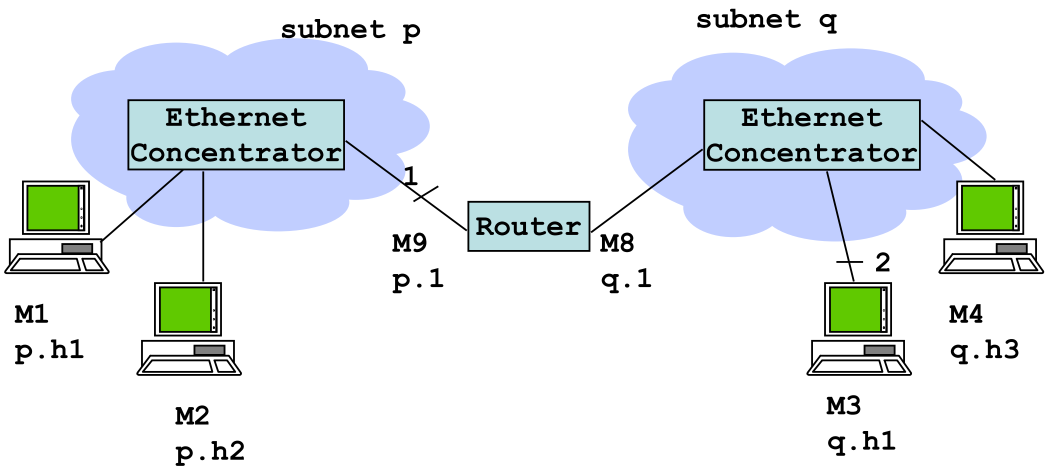
IP addr: 128.178.156.24
MAC addr: 08:00:20:71:0D:D4.

As a result, lrcpc1 will not send an ARP-REQUEST to communicate back with lrcsuns. Gratuitous ARP consists in sending an ARP-REQUEST to self's address. This is used at bootstrap to test the presence of a duplicate IP address. It is also used to force ARP cache entries to be changed after an address change (because systems learn from the ARP-REQUEST). As flow 2 shows, the ARP-REPLY is not broadcast, but sent directly to the system that issued the request. The "arp" command on Unix can be used to see or modify the ARP table.

Test Your Understanding (3, cont'd)

- Q2: What must the router do when it receives a packet from M2 to M3 for the first time?

solution



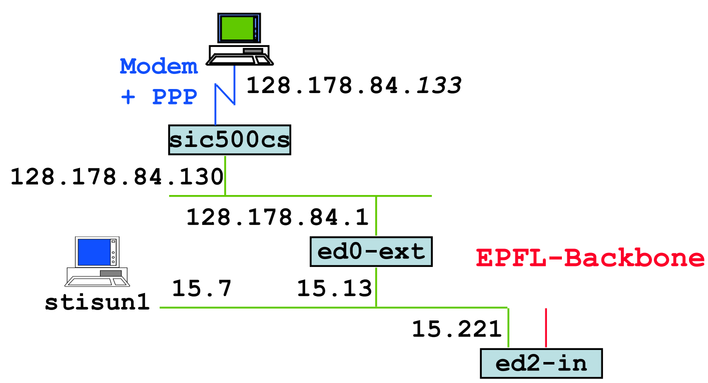
*Look inside an ARP packet

```
Ethernet II
    Destination: ff:ff:ff:ff:ff:ff (ff:ff:ff:ff:ff:ff)
    Source: 00:03:93:a3:83:3a (Apple_a3:83:3a)
    Type: ARP (0x0806)
    Trailer: 000000000000000000000000000000000...
Address Resolution Protocol (request)
    Hardware type: Ethernet (0x0001)
    Protocol type: IP (0x0800)
    Hardware size: 6
    Protocol size: 4
    Opcode: request (0x0001)
    Sender MAC address: 00:03:93:a3:83:3a (Apple_a3:83:3a)
    Sender IP address: 129.88.38.135 (129.88.38.135)
    Target MAC address: 00:00:00:00:00:00 (00:00:00_00:00:00)
    Target IP address: 129.88.38.254 (129.88.38.254)
```

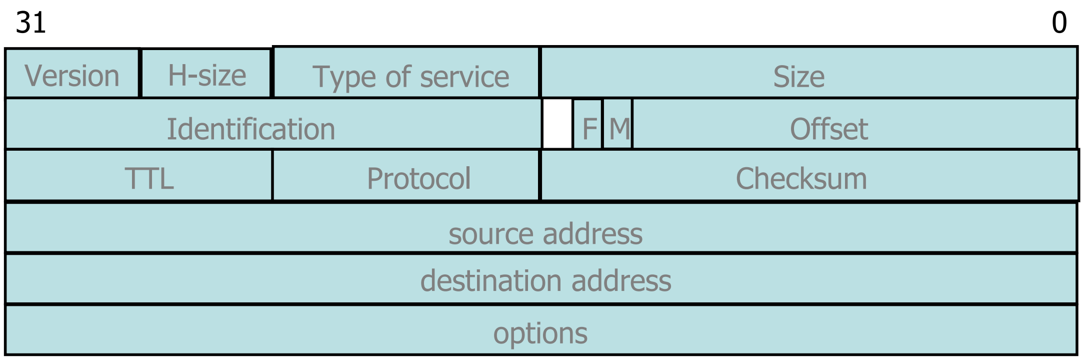
Proxy ARP

- Proxy ARP = a host answers ARP requests on behalf of others
  - example: `sic500cs` for PPP connected computers
  - Allows to *cheat*: connect to different physical networks that have same subnet prefix
  - Price to pay: ad-hoc configuration + single point of failure
- Q1: how must sics500cs routing table be configured ?
- Q2: explain what happens when ed2-in has a packet to send to 128.178.84.133

  solution



*4. IP header



- Transmitted "big-endian" - bit 31 first
  - Version is always 4 (IPv6 uses a different packet format)
  - Header size
    - options - variable size
    - in 32 bit words

*IP header

- Type of service
  - Previously used to encode priority;
  - now used by DiffServ (Differentiated Services)
  - 1 byte codepoint determining QoS class
    - Expedited Forwarding (EF) - minimize delay and jitter
    - Assured Forwarding (AF) - four classes and three drop-precedences (12 codepoints)
  - Used only in corporate networks
- Packet size
  - in bytes including header
  - $\leq$ 64 Kbytes; limited in practice by link-level MTU (Maximum Transmission Unit)
  - every subnet should forward packets of 576 = 512 + 64 bytes
- Id
  - unique identifier for re-assembling
- Flags
  - M : more ; set in fragments
  - F : prohibits fragmentation
- Offset
  - position of a fragment in multiples of 8 bytes
- TTL (Time-to-live)
  - in seconds
  - now: number of hops
  - router : --, if 0, drop (send ICMP packet to source)
- Protocol
  - identifier of protocol (1 - ICMP, 6 - TCP, 17 - UDP)
- Checksum
  - only on the header

*IP Checksum

- The IP checksum is a simple example of error detecting code. It works as follows. Consider a sequence of bytes and group them by 16-bit words. If the sequence has an odd number of bytes, add an extra 0 byte at the end. Obtain the 16 bits words W_0 to W_j. Consider the number $x = 2^{16j} W_j + 2^{16(j-1)} W_{j-1} + \ldots + 2^{16} W_1 + W_0$

  The checksum is $y = (2^{16}-1) - z$ with

  $$z = x \bmod (2^{16}-1)$$

  The computation of y is algorithmically simple. Note that $2^{16} = 1 \bmod (2^{16}-1)$ and thus

  $$z = W_j + W_{j-1} + \ldots + W_1 + W_0 \bmod (2^{16}-1)$$

  The algorithm is:

  compute $z = W_j + W_{j-1} + \ldots + W_1 + W_0$
  group the result by blocks of 16 bits; obtain $x' = 2^{16j'} W'_{j'} + 2^{16(j'-1)} W'_{j'-1} + \ldots + 2^{16} W'_1 + W'_0$
  start again with x' instead of x
  until z is a 16 bit word

- Comments:
  - Addition modulo $(2^{16}-1)$ is called « one's complement addition »
  - The method is the same as the « proof by 9 » used by scholars before calculators existed, with 9 replaced by $2^{16}-1$;

    ex: 2345678 mod 9 = 2+3+4+5+6+7+8 mod 9 = 35 mod 9 = 3+5 mod 9 = 8
  - See RFC 1624 for how to do the computations in practice with 32 bit arithmetic.

*Examples of IP Checksums

all numbers are written in hexa

data: 0103 0012 W_1=0103 W_0= 0012

z =

checksum y =

data: 0100 F203 F4F5 F6F7

z = 0100 + F203 + F4F5 + F6F7 =

checksum y =

solution

source: http://www.netfor2.com/checksum.html

*Verifying a Checksum

- Destination receives W_j … W_0 y
  If there is no error we should have: $W_j + \ldots + W_0 + y = 0 \bmod (2^{16} - 1)$
  Destination computes the one's complement sum of the block including checksum and verifies if the result is 0 mod $(2^{16} - 1)$
- Examples:

received block 0103 0012 FEEA
verification: 0103 + 0012 + FEEA = FFFF √

received block 0100 F203 F4F5 F6F7 210E
verification: 0100 + F203 + F4F5 + F6F7 + 210E = 2 FFFD
2 + FFFD = FFFF √

*IP header Options

- Options
  - strict source routing
    - all routers
  - loose source routing
    - some routers
  - record route
  - timestamp route
  - router alert
    - used by IGMP or RSVP for processing a packet

Look inside an IP packet

```
Ethernet II
    Destination: 00:03:93:a3:83:3a (Apple_a3:83:3a)
    Source: 00:10:83:35:34:04 (HEWLETT-_35:34:04)
    Type: IP (0x0800)
Internet Protocol, Src Addr: 129.88.38.94 (129.88.38.94), Dst Addr:
   129.88.38.241 (129.88.38.241)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
    Total Length: 1500
    Identification: 0x624d
    Flags: 0x04
    Fragment offset: 0
    Time to live: 64
    Protocol: TCP (0x06)
    Header checksum: 0x82cf (correct)
    Source: 129.88.38.94 (129.88.38.94)
    Destination: 129.88.38.241 (129.88.38.241)
```

5. ICMP: Internet Control Message Protocol

- used by router or host to send error or control messages to other hosts or routers
- error or control messages relate to layer 3 only
- carried in IP datagrams (protocol type = 1)

- ICMP message types
  - echo request (reply) -> used by ping
  - destination unreachable
  - time exceeded (TTL = 0) -> used for traceroute responses
  - address mask request/reply
  - source quench
  - redirect - router discovery
  - timestamps
  - ICMP messages never sent in response to
    - ICMP error message - datagram sent or multicast or broadcast IP or layer 2 address - fragment other than first

*ICMP Redirect

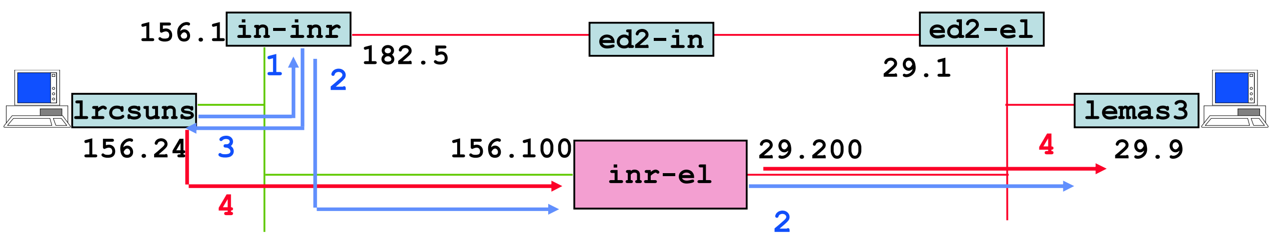
- Sent by router R1 to source host A when R1 receives a packet from A with destination = B, and R1 finds that the next hop is R2, A is on-link with R2 (thus A should not have sent to R1, but directly to R2)
  - R1 sends ICMP redirect to A saying next hop for destination B is R2
  - A updates its routing table with a host route

ICMP Redirect Format

```
/                                                               /
|                  IP datagram header  (prot = ICMP)            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=5       |      code      |            checksum         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|              Router IP address that should be preferred       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|        IP header plus 8 bytes of original datagram data       |
/                                                               /
```

- General routing principle of the TCP/IP architecture:
  - host have minimal routing information
    - learn host routes from ICMP redirects
  - routers have extensive knowledge of routes

*ICMP Redirect Example



	dest IP addr	srce IP addr	prot	data part
1:	128.178.29.9	128.178.156.24	udp	xxxxxxx
2:	128.178.29.9	128.178.156.24	udp	xxxxxxx
3:	128.178.156.24	128.178.156.1	icmp	type=redir code=host cksum
				128.178.156.100
				xxxxxxx (28 bytes of 1)
4:	128.178.29.9	128.178.156.24	udp	....

ICMP Redirect Example (cont'd)

After 4

```
lrcsuns:/export/home1/leboudec$ netstat -nr
Routing Table:
  Destination           Gateway              Flags  Ref   Use   Interface
-------------------- -------------------- ----- ----- ------ ---------
127.0.0.1            127.0.0.1             UH        0  11239  lo0
128.178.29.9         128.178.156.100       UGHD      0     19
128.178.156.0        128.178.156.24        U         3  38896  le0
224.0.0.0            128.178.156.24        U         3      0  le0
default              128.178.156.1         UG        0  85883
```

*6. MTU

Link-layer networks have different maximum frame length

- MTU (maximum transmission unit) = maximum frame size usable for an IP packet
- value of short MTU ? of long MTU ?

solution

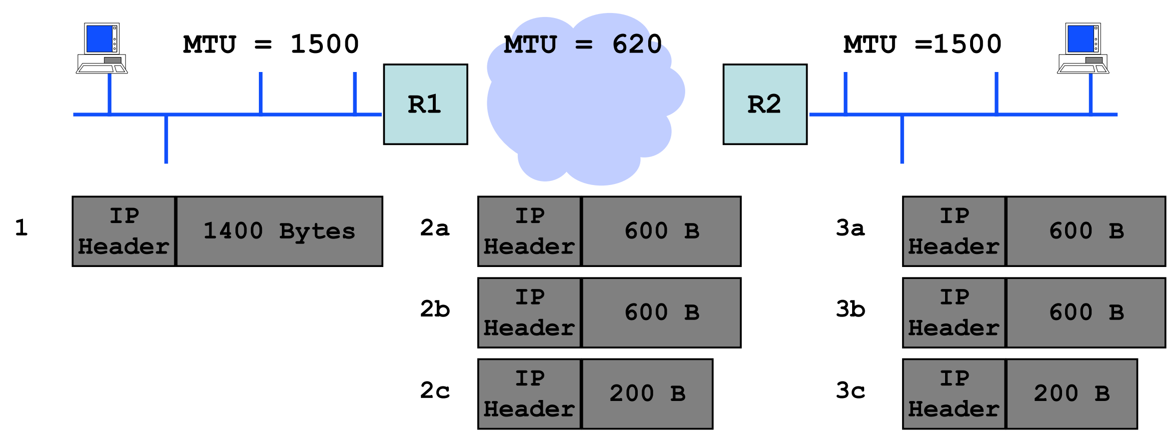
Link-layer Network	MTU
Ethernet, WiFi	1500
802.3 with LLC/SNAP	1492
Token Ring 4 Mb/s	4464
16 Mb/s	17914
FDDI	4352
X.25	576
Frame Relay	1600
ATM with AAL5	9180
Hyperchannel	65535
PPP	296 to 1500

```
lrcsuns:/export/home1/leboudec$ ifconfig -a
lo0: flags=849<UP,LOOPBACK,RUNNING,MULTICAST> mtu 8232
        inet 127.0.0.1 netmask ff000000
le0: flags=863<UP,BROADCAST,NOTRAILERS,RUNNING,MULTICAST> mtu 1500
        inet 128.178.156.24 netmask ffffff00 broadcast
128.178.156.255
        ether 8:0:20:71:d:d4
```

IP Fragmentation

IP hosts or routers may have IP datagrams larger than MTU

- Fragmentation is performed when IP datagram too large
- re-assembly is only at destination, never at intermediate points
- fragmentation is in principle avoided with TCP



IP Fragmentation (2)

- IP datagram is *fragmented* if
  MTU of interface < datagram total length
- all fragments are self-contained IP packets
- fragmentation controlled by fields: Identification, Flag and Fragment Offset
- IP *datagram* = original ; IP *packet* = fragments or complete datagram

	1	2a	2b	2c
Length	1420	620	620	220
Identification	567	567	567	567
More Fragment flag	0	1	1	0
Offset	0	0	75	150
8 * Offset	0	0	600	1200

Fragment data size (here 600) is always a multiple of 8
Identification given by source

*Fragmentation Algorithm

- Repeated fragmentations may occur
- `Don't fragment` flag prevents fragmentation
- Fragmentation Algorithm:

```
procedure sendIPp(P0):

if P0.totalLength > MTU then
   data1Length = (MTU-P0.HLEN rounded to multiple of 8)
   data1= first data1Length bytes of P0 data part
   data2= remainder of P0 data part
   header1 = P0.header with
                More bit set
                totalLength = P0.HLEN + data1Length
   P1= new (IPPacket; header1; data1)
   send P1 on data link layer
   header2 = P0.header with
                totalLength = P0.totalLength - data1Length
                fragmentOffset += data1Length/8
   P2= new(IPPacket; header2; data2)
   sendIPp(P2)
else
   send P0 on data link layer
```

```
IP packets are sorted in fragment lists
        one fragment list per (Identification, source IP @)
        sorted by increasing Fragment Offset
Fragments F1 and F2 are contiguous iff
        F1.moreBit = 1
        F1.fragmentOffset + F1.dataLength/8 = F2.fragmentOffset
Fragment List F0…Fn is complete iff
        F0.fragmentOffset = 0
        Fi and Fi+1 are contiguous for i=0…(n-1)
        Fn.moreBit = 0
```

```
IP packet arrival (P0) /* and packet is not a complete datagram */ ->
  if (P0.(identification, source address)) is new
   then if (new(fragmentList, P0.(identification, source address), fl))
           then insert P0 in fl
                start reassemblyTimer(fl)
   else
        fl = fragmentList(P0.(identification, source address))
        insert(fl,P0)
        if fl is complete
           then deliver IP datagram
           else start reassemblyTimer(fl)

reassemblyTimer(fl) expires ->
  send ICMP error message to source
  delete(fl)
```

Comments: new(fragment list) may fail if there is no buffer left; in that case the datagram is lost
insert may fail; if insert fails, then the fragment is discarded

*Issues with Fragmentation

- Fragmentation requires re-assembly; issues are
  - deadlocks
  - identification wrapping problem
  - unit of loss is smaller than unit of re-transmission: can worsen congestion

    Q. explain why

    solution

- Solution = avoid fragmentation
  - Path MTU = minimum MTU for all links of one path
  - Discovery of path MTU
    - heuristics: local -> 1500; other : 576 (subnetsarelocal variable)

  Path MTU discovery avoids fragmentation

Path MTU Discovery

- Method for Path MTU (PMTU) discovery
  - 1. host sets Don’t Fragment bit on all datagrams and estimate PMTU to local MTU
  - 2. routers send an ICMP message: “destination unreachable/ fragmentation needed”
  - 3. host reduces PMTU estimate to next smallest value
  - 4. after timeout, host increases PMTU estimate
  - route changes may cause 2

TCP, UDP and Fragmentation

- The UDP service interface accepts a datagram up to 64 KB
  - UDP datagram passed to the IP service interface as one SDU
  - is fragmented at the source if resulting IP datagram is too large
- The TCP service interface is stream oriented
  - packetization is done by TCP
  - several calls to the TCP service interface may be grouped into one TCP segment (many small pieces)
  - or: one call may cause several segments to be created (one large piece)
  - TCP always creates a segment that fits in one IP packet: no fragmentation at source
  - fragmentation may occur in a router, if IPv4 is used, and if PMTU discovery is not implemented

Q. If all sources use PMTU discovery, in which cases has a router to fragment a packet ?

solution

7. Terminology

- **Architecture** IP router
  - a system that forwards packets based on IP addresses
  - performs packet forwarding + control method
- **Implementation**:
  - any UNIX machine can be configured as IP router
  - normally, dedicated box with specialized hardware called router

What is a “Multiprotocol Router” ?

- Multiprotocol router
  - a system that forwards packets based on layer 3 addresses for various protocol architectures (ex: IP, Appletalk)
  - CISCO, IBM, etc…
  - most multiprotocol routers perform both bridging and routing
    - architecture: bridge + router
    - implementation: one CISCO
  - IP router boxes also perform other functions: port filtering, DHCP relay, …
- **Q.** In a pure IP world (if all machines run TCP/IP) do we need multiprotocol routers ?
  A. Yes if both IPv4 and IPv6 are used.

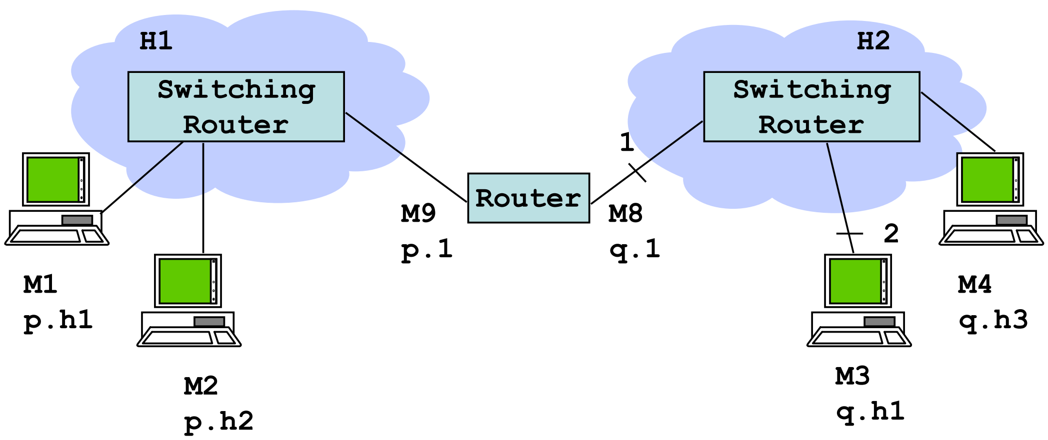
solution

* Example of Combined Functions in One Product

- Put a bridge + Ethernet concentrator + router in the same box
- The resulting product is called "switching router"
  - Avoids ARP broadcasts

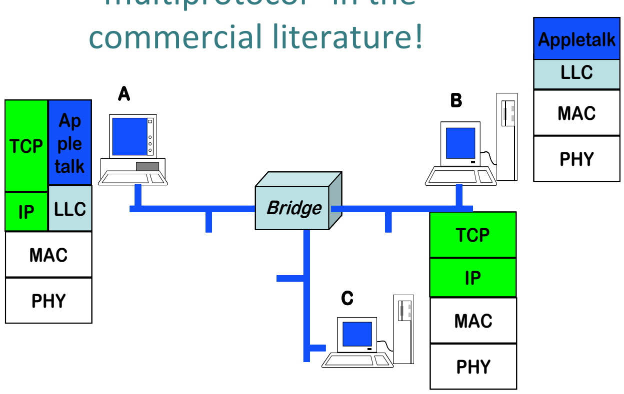
The words switches and routers are normally used in many different ways. For us, a switch is an intermediate system for connection oriented network layers such as ATM or Frame Relay. For the commercial literature, it usually means a fast packet forwarder, usually implemented in hardware. In reality, routers can be implemented exactly in the same way and with the same performance as "switches". The main difference is for multiprotocol routers that need to understand not just one network layer, but many. In such cases, only software implementations are available. In contrast, IP only routers are emerging with a performance similar to that of switches.

The "switching router" concept is an example of product, which is new as a product, but from an architecture viewpoint is nothing new. Since the router is in the same box as the Ethernet concentrator, it can know (by software) the MAC address of directly attached systems. Thus, the ARP broadcasts are avoided.



Why are Bridges called "Multiprotocol" ?

- Some network protocols (ex: Appletalk, IPX, IPv6) are not compatible with IPv4
  - routers must be multiprotocol
  - but bridges work independently of which network layer protocol is used -- they are called "multiprotocol" in the commercial literature!



B (an old Macintosh file server) runs only Appletalk. Only applications using the Appletalk protocols can be used (MacOS file sharing, printing). TCP/IP applications such as the web cannot be used on B.

C (a modern PC) runs only TCP/IP. All TCP/IP applications can be used, but not native MacOS file sharing.

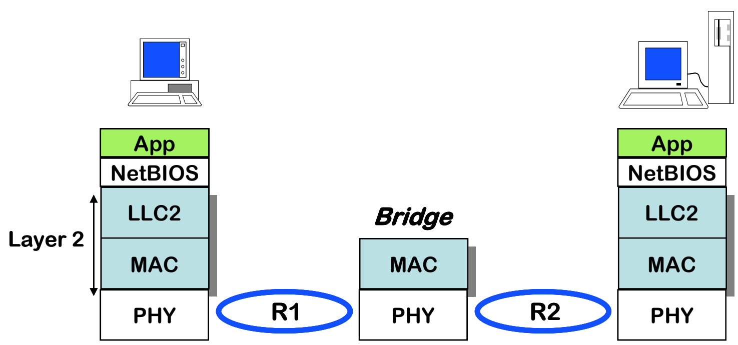
A (a windows server) runs both in parallel. It can talk to both C and B.

A bridge can be used to interconnect A, B and C; there is nothing special to do. If a router is used instead, it must run in parallel Appletalk and IP.

The protocol stacks shown are all implemented in software. They use the standard Ethernet adapters.

What is a “Non Routable Protocol” ?

- NetBIOS was originally developed to work only in one bridged LAN
  - uses LLC-2, similar to TCP but located in layer 2 (also called NETBEUI)
  - in that form, it is not “routable”: can only be bridged
    NetBIOS is an interface for distributed applications that is commonly used with IBM and Microsoft systems. Only MAC addresses are used. In addition, NetBIOS offers a naming service. This version of NetBIOS works only in a bridged environment.



- NetBIOS today is offered as a TCP/IP application
  - uses the NBT reserved port
  - Windows machines at EPFL use TCP/IP only

*Virtual LANs and Subnets

- IP requires machines to be organized by subnets
  -- This is a problem when machines (and people) move
- One solution is provided by layer 2: virtual LANs
  - What is does : define LANs independent from location
  - How: associate (by configuration rules) hosts with virtual LAN labels.

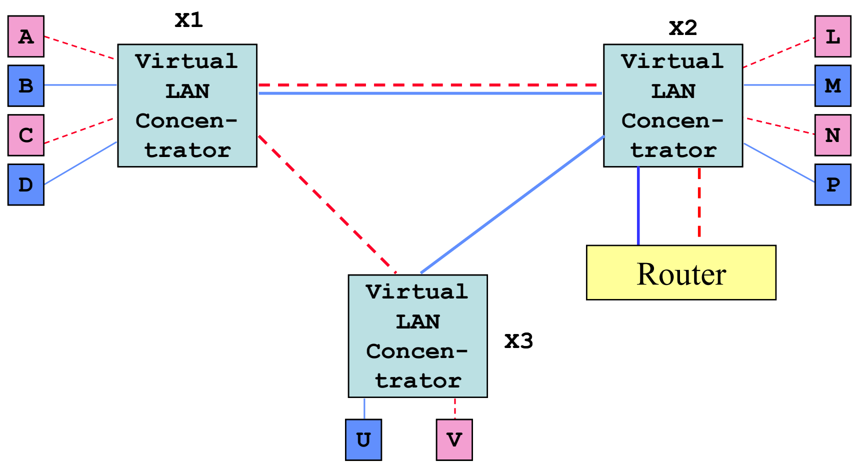
    The picture shows two virtual LANs: (ACLNV) and (BDMPU). The concentrators perform bridging between the different collision domains of the *same* virtual LAN.

    Between two virtual LANs, a router must be used. The figure shows one router that belongs to both VLANs

    Between X1 and X2, the two virtual LANs use the same physical link. This is made possible by adding a label to the Ethernet packet header, that identifies the virtual LAN.

  - **Q.** How many spanning trees are there in this network ?
    solution

- **Q.** Can you think of another solution to the same problem ?
  solution


X1
X2
A
B
C
D
Virtual LAN Concen- trator
L
M
N
P
Virtual LAN Concen- trator
Router
Virtual LAN Concen- trator
X3
U
V

Facts to Remember

- IP is a connectionless network layer
- IPv4 addresses are 32 bit numbers
- One IP address per interface
- Routers scale well because they can aggregate routes
- Hosts on the Internet exchange packets with IP addresses

Solutions

1. Why a network layer?

- We would like to interconnect all devices in the world. We have seen that we can solve the interconnection problem with bridges and the MAC layer. However this is not sufficient as it does *scale* to large networks.

  Q. Why ?
  A.

  1. Bridges use a tree. This is not efficient in a large network, as the tree concentrates all traffic.
  2. Bridges use forwarding tables that are not structured. A bridge must lookup the entire table for *every* packet. The table size and lookup time would be prohibitive.

- Solution: connectionless network layer (eg. Internet Protocol, IP):
  - every host receives a network layer address (IP address)
  - intermediate systems forward packets based on destination address

back

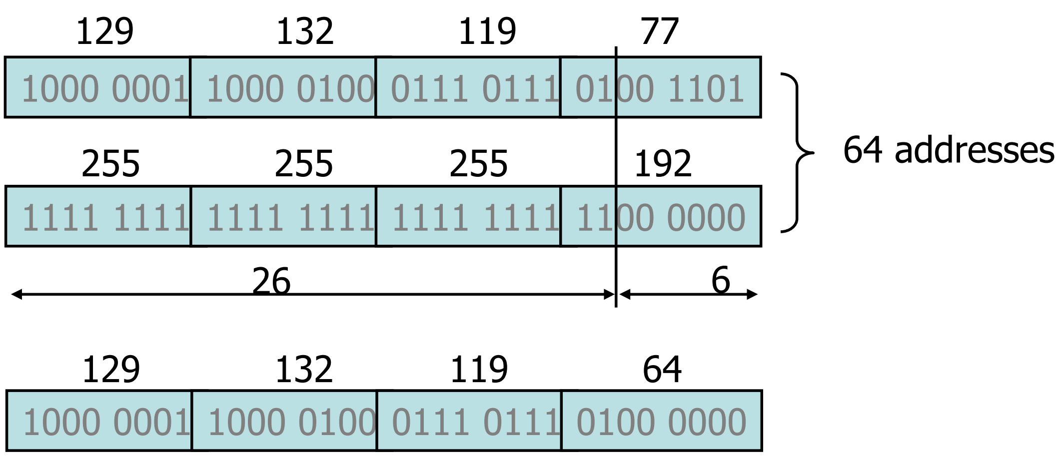
Representation of IP Addresses

- **dotted decimal**: group bits in bytes, write the decimal representation of the number
  - example 1: 128.191.151.1
  - example 2: 129.192.152.2
- **hexadecimal**: hexadecimal representation -- fixed size string
  - example 1: x80 BF 97 01
  - example 2: x81 C0 98 02
- **binary**: string of 32 bits (2 symbols: 0, 1)
  - example 1: b0100 0000 1011 1111 1001 0111 0000 0001
  - example 2: b0100 0001 1100 0000 1001 1000 0000 0010

back

A Subnet Prefix is written using one of two Notations: masks / prefixes

- example 2: 129.132.119.77 mask 255.255.255.192
  - Q1: what is the prefix ? A: 129.132.119.64



back

  - Q2: how many host ids can be allocated ? A: 64 (minus the reserved addresses: 62)

Prefix Notation

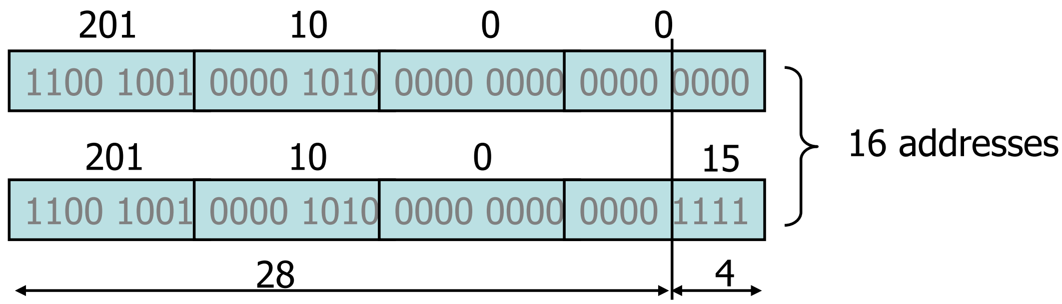
example 2:

- Q1: write 129.132.119.77 mask 255.255.255.192 in prefix notation
  A: 129.132.119.77/26 or 129.132.119.64/26
- Q2: are these prefixes different ?
  - 201.10.0.00/28, 201.10.0.16/28, 201.10.0.32/28, 201.10.0.48/28

  A: they differ in bits that are not the last 4 ones, thus they are all different prefixes

  - how many IP addresses can be allocated to each of the distinct subnets ?

  A: 14 (16 minus 2 reserved)



back

Address delegation

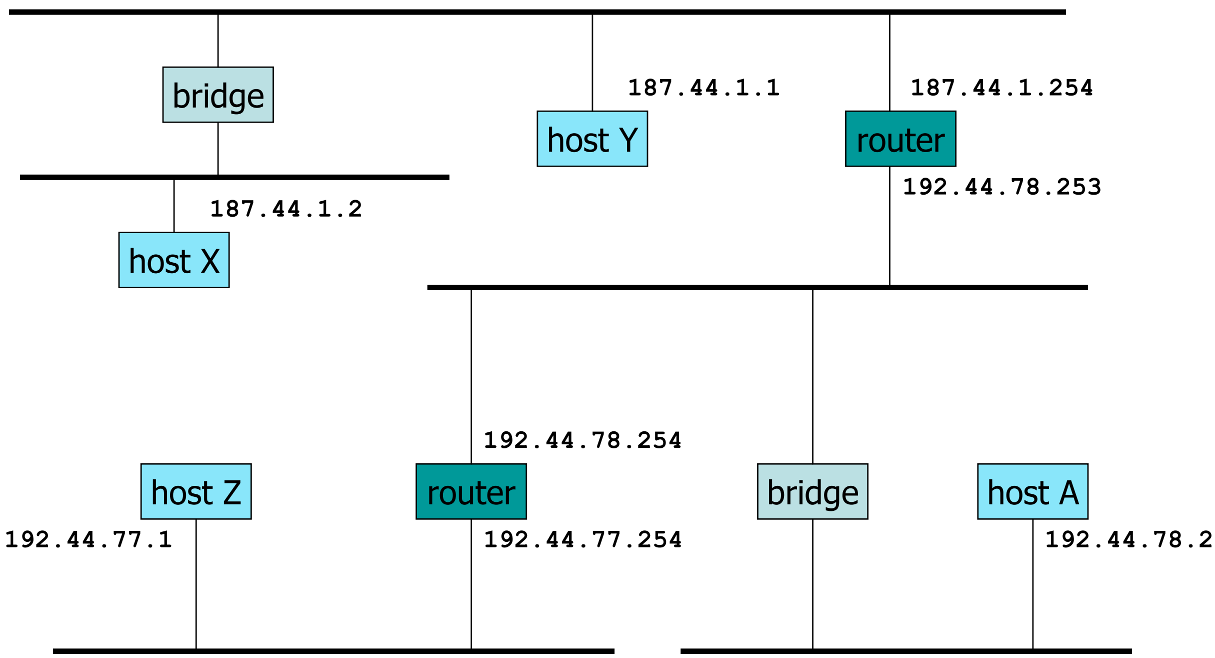
- Europe
  - 62/8, 80/8, 193-195/8, ...
  - ISP-1
    - 62.125/16
    - customer 1: banana foods
      - 62.125.44.128/25
    - customer 2: sovkom
      - 62.125.44.50/24
  - ISP-2
    - 195.44/14
    - customer 1:
      - 195.46.216/21
    - customer 2:
      - 195.46.224/21

back

Q. Assume sovkom moves from ISP-1 to ISP-2; comment on the impact.
A. If sovkom keeps the same IP addresses, the set of addresses of ISP-2 is no longer continguous. It cannot be represented by one single entry in routing tables. Routing tables in the internet need to represent ISP-2 by two entries: 195.44/14 and 62.125.44.50/24

Test Your Understanding (1)

back



- A: No, host A is on subnetwork **192.44.78**

Test your Understanding (2)

- Q1: An Ethernet segment became too crowded; we split it into 2 segments, interconnected by a router. Do we need to change some IP host addresses ?

  A: yes in general. Two different subnets cannot have the same prefix
- Q2: same with a bridge
  A: no, bridging is transparent.
- Q3: compare the two
  A: bridging is plug and play but the network performance is more difficult to guarantee (broadcasts + spanning tree)

back

back

Example

- Q: Fill in the table if an IP packet has to be sent from `lrcsuns`

final destination	next hop	case number
128.178.79.9	128.178.156.1	3
128.178.156.7	128.178.156.7	2
127.0.0.1	loopback	2
128.178.84.133	128.178.156.1	3
129.132.1.45	128.178.156.1	3

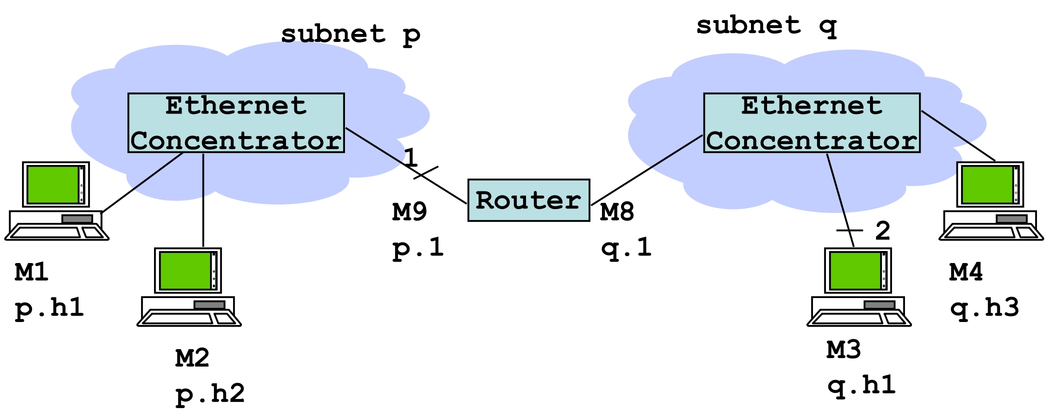
- Q:

final destination	next hop	case number
128.178.79.9	128.178.182.3	3
128.178.156.7	128.178.182.5	3
127.0.0.1	loopback	2
128.178.84.133	128.178.15.13	3
129.132.1.45	128.178.100.12	3

Test Your Understanding (3)

back

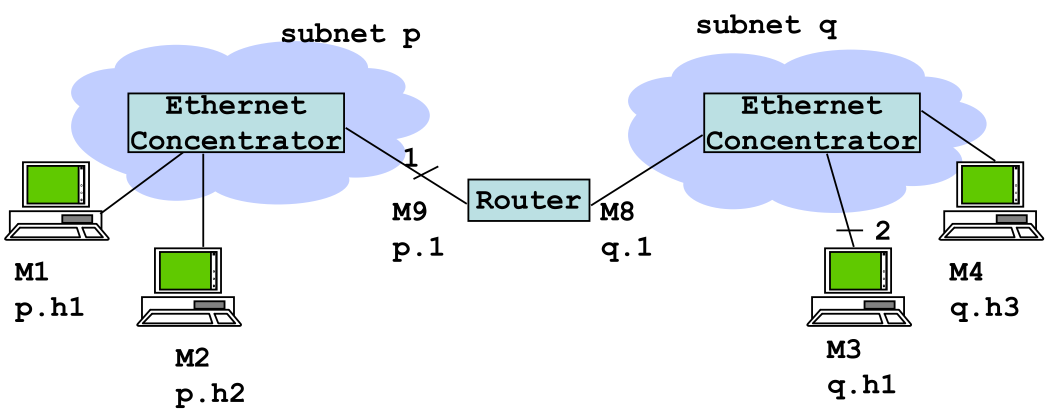
- Q1: What are the MAC and IP addresses at points 1 and 2 for packets sent by M1 to M3 ? At 2 for packets sent by M4 to M3 ?(Mx = mac address)
  A: at 1: srce IP@=p.h1, dest IP@=q.h1, MACsrce=M1, MACdest=M9
  at 2: srce IP@=p.h1, dest IP@=q.h1, MACsrce=M8, MACdest=M3
  at 2: srce IP@=q.h3, dest IP@=q.h1, MACsrce=M4, MACdest=M3



Test Your Understanding (3)

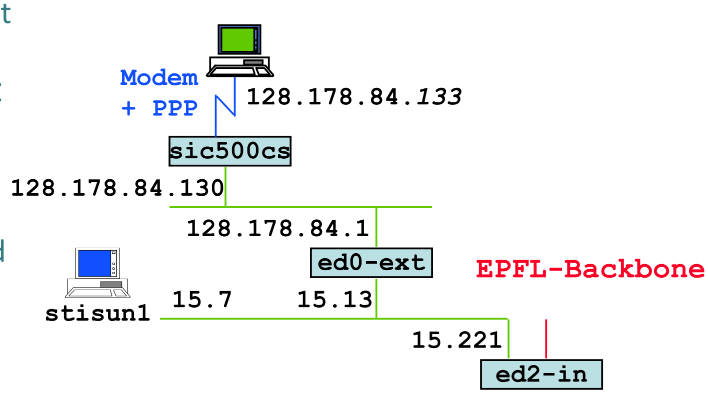
- Q2: What must the router do when it receives a packet from M2 to M3 for the first time?
  A: send an ARP request broadcast on LAN q

back



Proxy ARP

- Q1: how must sics500cs routing table be configured ?
  - A: one host route per host such as 128.178.84.133
- Q2: explain what happens when ed2-in has a packet to send to 128.178.84.133
  - packet sent to ed0-ext
  - ARP sent by ed0-ext for target address = 128.178.84.133
  - sics500cs responds with MAC addr = sic500cs's MAC addr
  - packet sent ed0-ext to sic500cs
  - sic500cs reads host route and forwards to 128.178.84.133 (case 1 of IP forwarding algorithm)



back

Examples of IP Checksums

all numbers are written in hexa

data: 0103 0012 W_1=0103 W_0= 0012

z = 0103 + 0012 = 01 15

checksum y = FFFF – z = FEEA

data: 0100 F203 F4F5 F6F7

z = 0100 + F203 + F4F5 + F6F7 = 0002 DEEF

z = 0002 + DEEF = DEF1

checksum y = FFFF - DEF1= 210E

back

source: http://www.netfor2.com/checksum.html

MTU

- value of short MTU ?
  - reduces queue lengths and delays
  - on lossy links (radio) reduces proba of packet error
- of long MTU ?
  - reduces per packet processing

back

Issues with Fragmentation

back

- Fragmentation requires re-assembly; issues are
  - deadlocks
  - identification wrapping problem
  - unit of loss is smaller than unit of re-transmission: can worsen congestion

    Q. explain why
    A. when a network is congested, packets get lost. Assume every datagram is fragmented in 10, and a single loss causes retransmission. The losses of a *n* packets (belonging to different datagrams) causes 10*n* retransmissions, which increases the offered traffic and makes congestion worse.

- Solution = avoid fragmentation
  - Path MTU = minimum MTU for all links of one path
  - Discovery of path MTU
    - heuristics: local -> 1500; other : 576 (subnetsarelocal variable)

  Path MTU discovery avoids fragmentation

Fragmentation (sol)

- The UDP service interface accepts a datagram up to 64 KB
  - UDP datagram passed to the IP service interface as one SDU
  - is fragmented at the source if resulting IP datagram is too large
- The TCP service interface is stream oriented
  - packetization is done by TCP
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  - or: one call may cause several segments to be created (one large piece)
  - TCP always creates a segment that fits in one IP packet: no fragmentation at source
  - fragmentation may occur in a router, if IPv4 is used, and if PMTU discovery is not implemented

Q. If all sources use PMTU discovery, in which cases has a router to fragment a packet ?
A. 1. UDP packets sent by sources that have a larger local MTU than the path MTU
2. TCP packets where PMTU estimation failed (due to path changes)
back

What is a "Multiprotocol Router" ?

- Multiprotocol router
  - a system that forwards packets based on layer 3 addresses for various protocol architectures (ex: IP, Appletalk)
  - CISCO, IBM, etc…
  - most multiprotocol routers perform both bridging and routing
    - architecture: bridge + router
    - implementation: one CISCO
  - IP router boxes also perform other functions: port filtering, DHCP relay, …
- **Q.** In a pure IP world (if all machines run TCP/IP) do we need multiprotocol routers ?
  A. Yes if both IPv4 and IPv6 are used.

back

Virtual LANs and Subnets

- IP requires machines to be organized by subnets
  -- This is a problem when machines (and people) move
- One solution is provided by layer 2: virtual LANs
  - What is does : define LANs independent from location
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    The picture shows two virtual LANs: (ACLNV) and (BDMPU). The concentrators perform bridging between the different collision domains of the *same* virtual LAN.

    Between two virtual LANs, a router must be used. The figure shows one router that belongs to both VLANs

    Between X1 and X2, the two virtual LANs use the same physical link. This is made possible by adding a label to the Ethernet packet header, that identifies the virtual LAN.

  - **Q.** How many spanning trees are there in this network ?
    A. 2 (one per virtual LAN)

back

Virtual LANs and Subnets

- **Q.** Can you think of another solution to the same problem ?
  A. DHCP

back