Reti

(già "Reti di Calcolatori")

Livello Rete
Indizzamento IP (v4) e inoltro dei pacchetti

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http://disi.unitn.it/locigno/teaching-duties/reti

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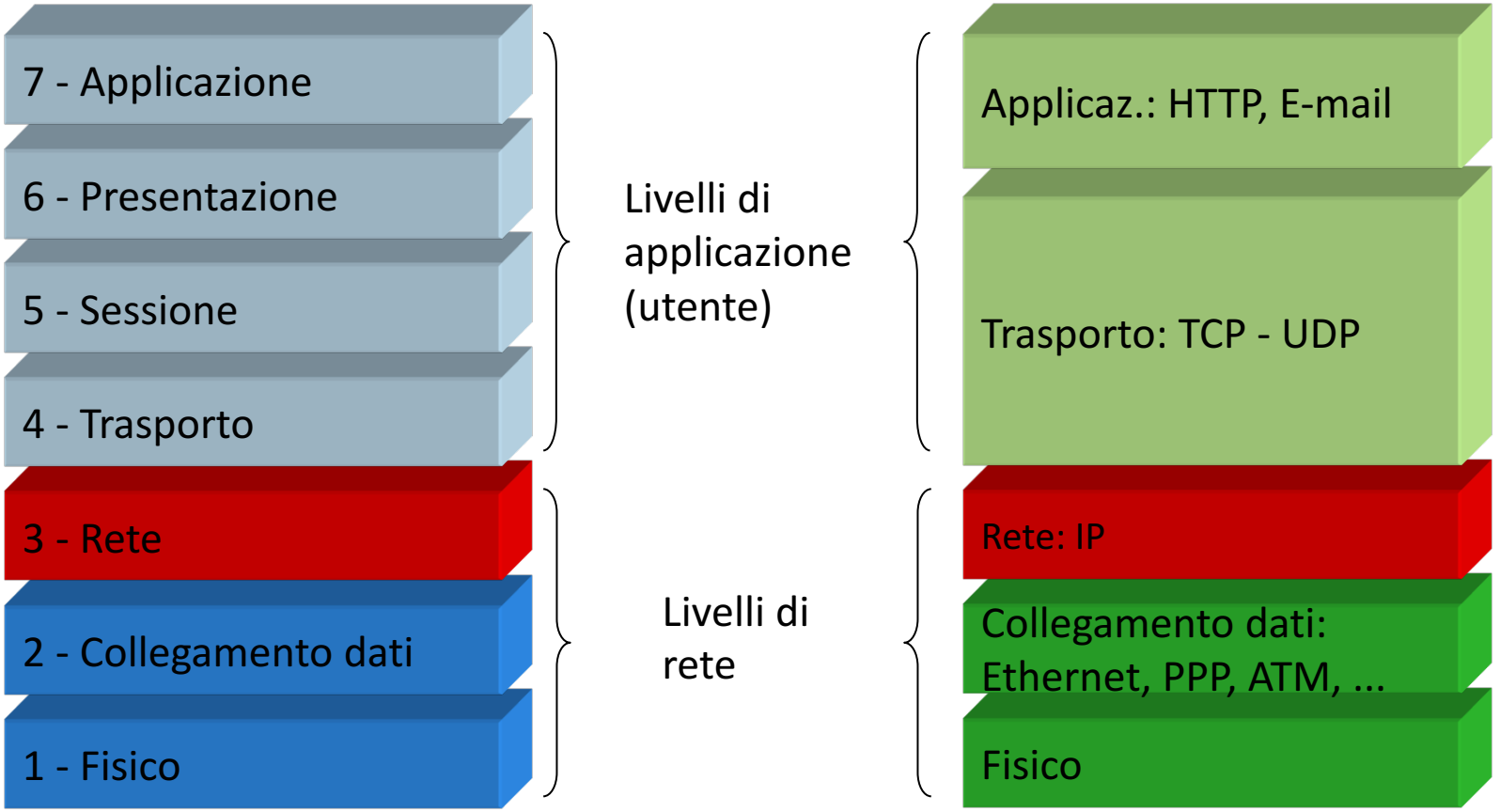
    - *Behrouz A. Forouzan, Sophia Chung Fegan, "TCP/IP Protocol Suite," McGraw-Hill*, January 2005
- La traduzione, se presente, è in generale opera (e responsabilità) del docente

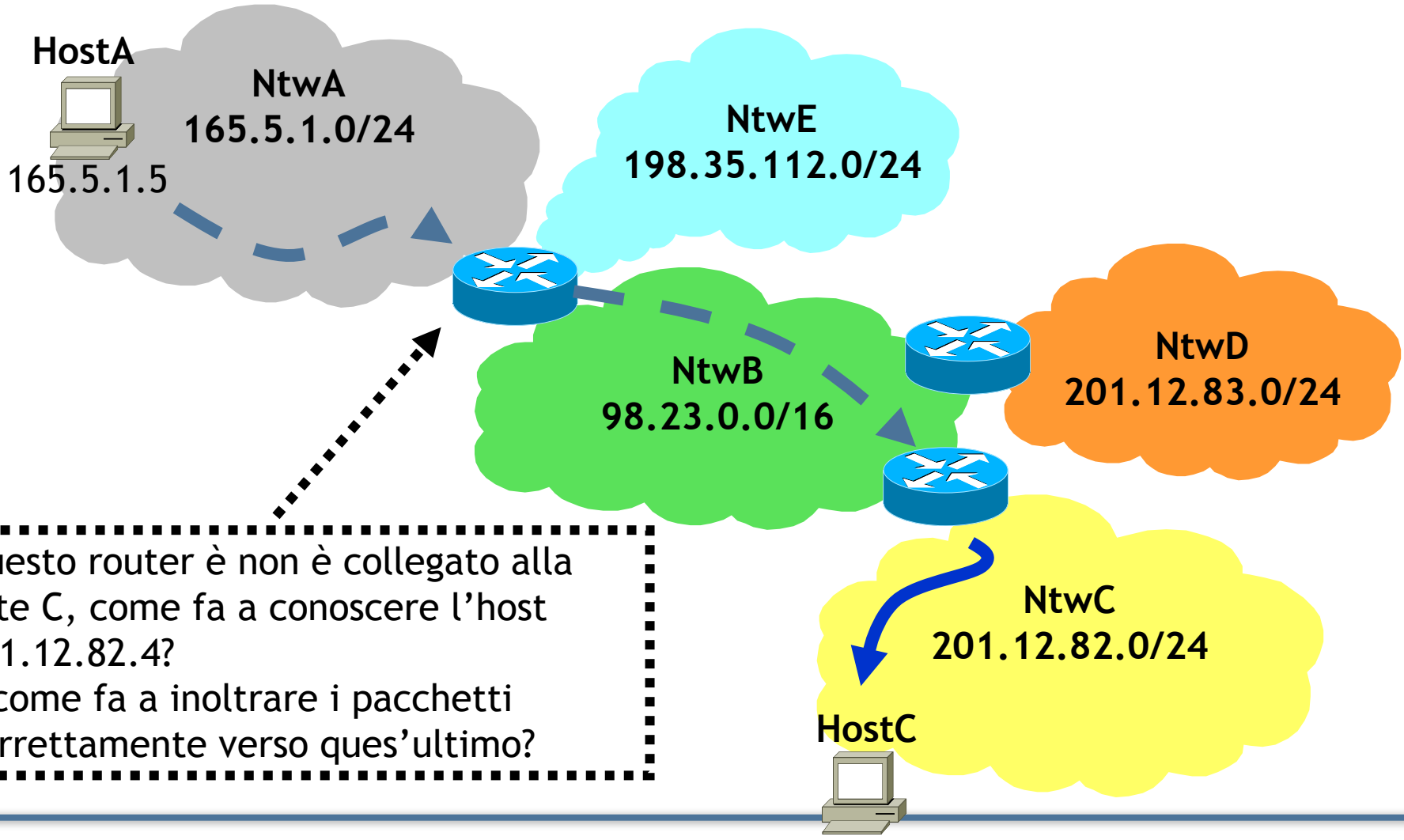
Contenuto e temi

- **Spazio di indirizzamento**
- **Indirizzi IP e loro uso**
- **Consegna dei pacchetti**
- Configurazione dei PC e delle reti
- Instradamento e Routing

Livello Rete



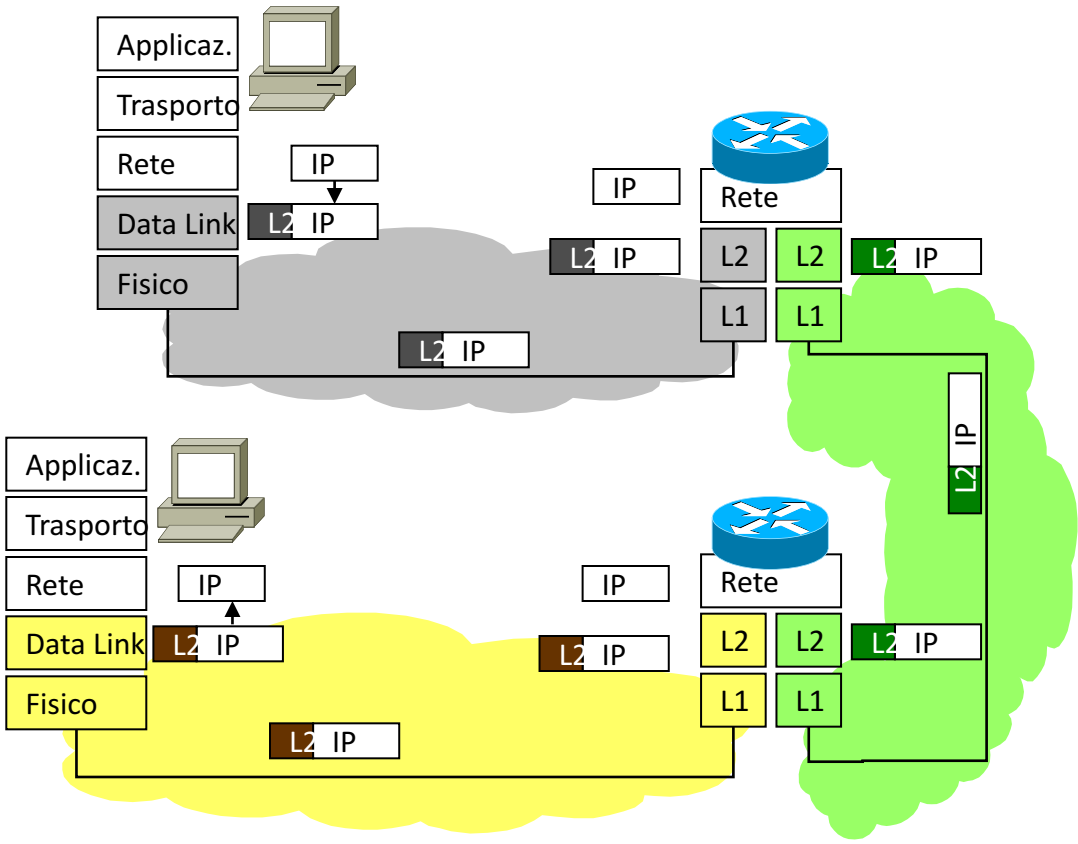
Consegna Diretta e Indiretta



Questo router è non è collegato alla rete C, come fa a conoscere l'host 201.12.82.4?
E come fa a inoltrare i pacchetti correttamente verso ques'ultimo?

Prospettiva globale

- Trasporto dei pacchetti da sorgente a ricevitore. I pacchetti contengono un segmento di livello trasporto
- I pacchetti sono incapsulati in trame L2
- Al ricevitore i segmenti sono estratti dai pacchetti e consegnati al livello trasporto
- **I protocolli di rete sono in tutti gli host e router**
- Un router deve esaminare l'intestazione di tutti i pacchetti che lo attraversano

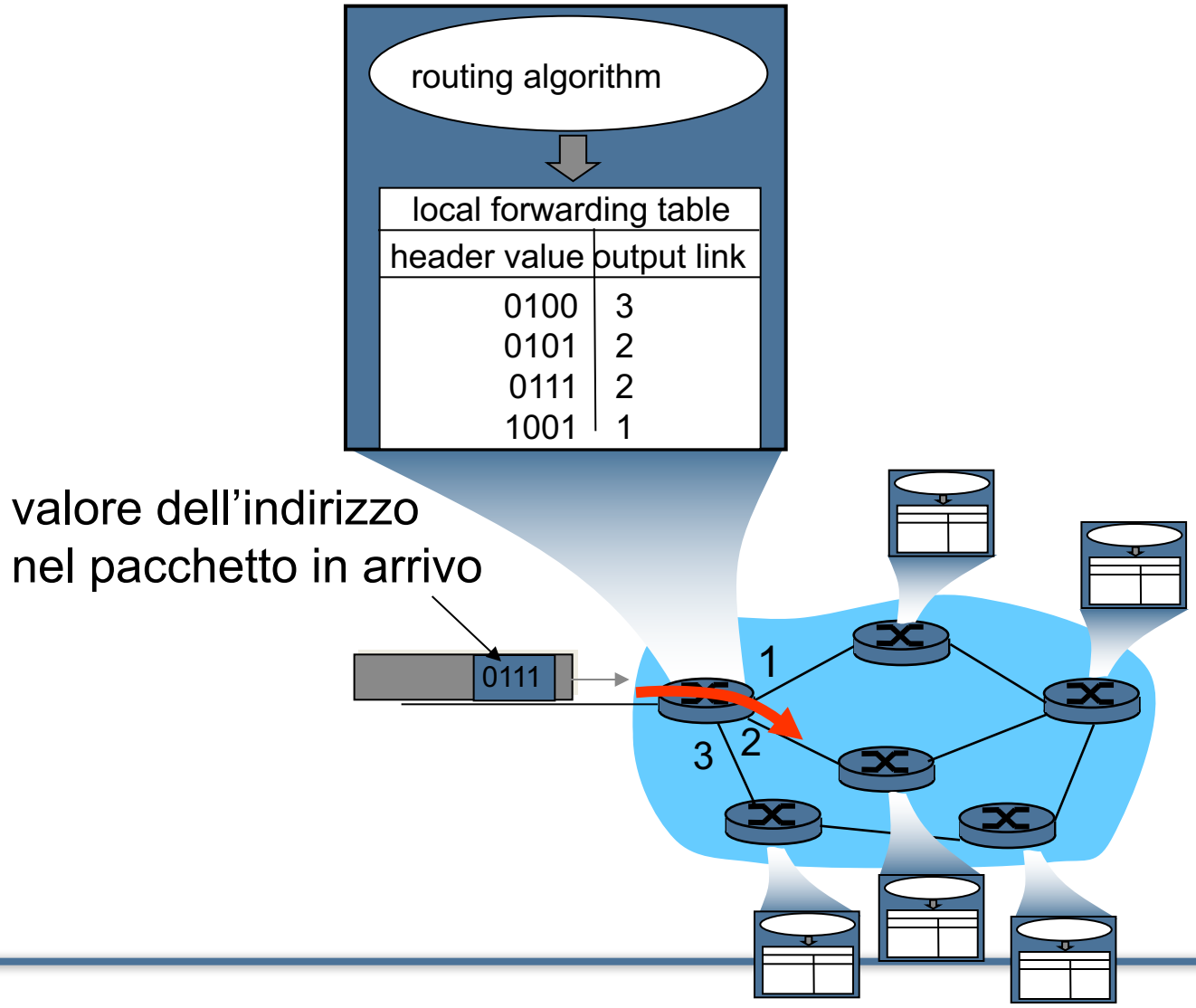


Funzioni fondamentali del livello rete

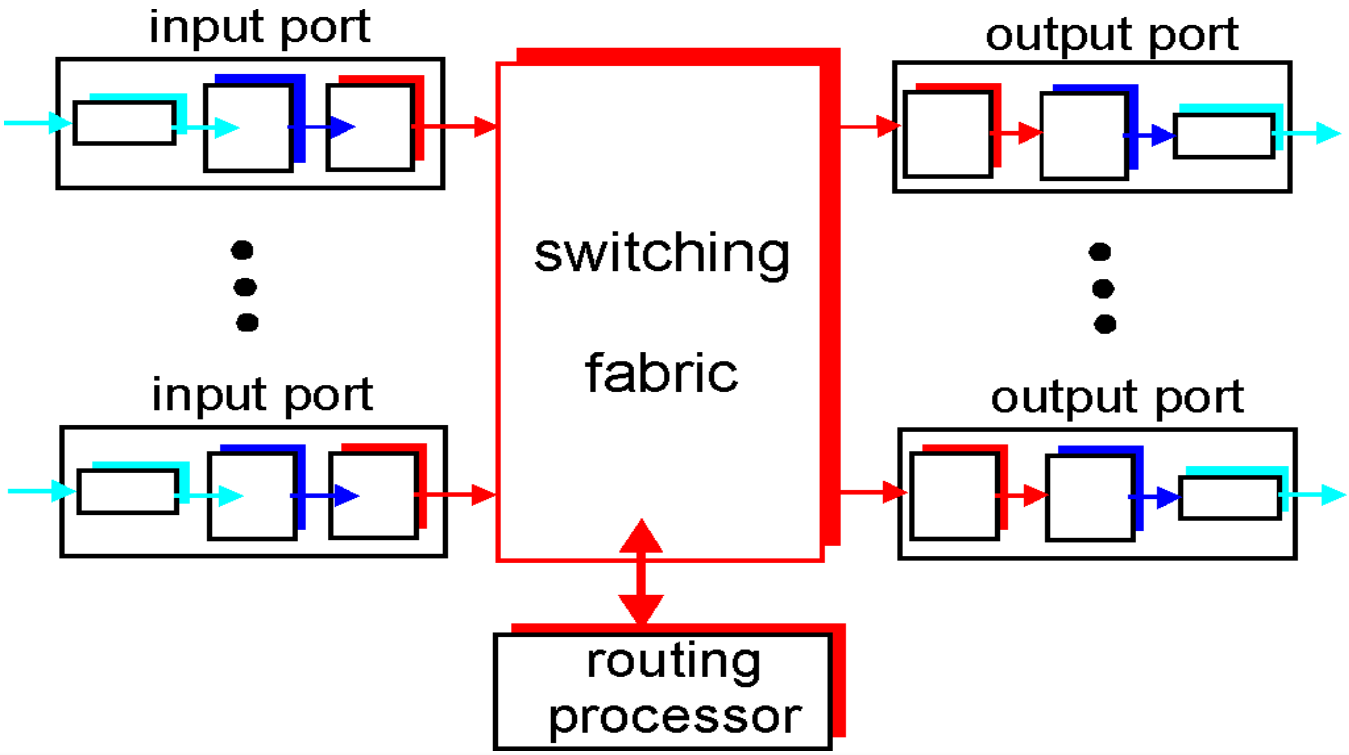
- **Instradamento (Routing)**
  - Trovare il percorso dalla sorgente alla destinazione

  ➔ Algoritmi di Routing
    - Simile a pianificare un viaggio: devo determinare le strade da fare e gli incroci in cui cambiare la mia strada
- **Inoltro (Forwarding)**
  - Funzione che esegue il trasporto dei pacchetti dagli ingressi alle uscite dei router ... dato che il percorso è già noto
    - Simile a prendere l'uscita giusta di una rotonda, sapendo che devo andare in una specifica direzione
- Entrambe richiedono uno spazio di indirizzamento appropriato ... e i relativi indirizzi

Relazione tra routing e forwarding



- due funzioni fondamentali:
  - eseguire i protocolli e algoritmi di instradamento (RIP, OSPF, BGP)
  - inoltrare i datagrammi (pacchetti) dagli ingressi alle uscite



IL PROTOCOLLO IP
(VERSIONE 4)

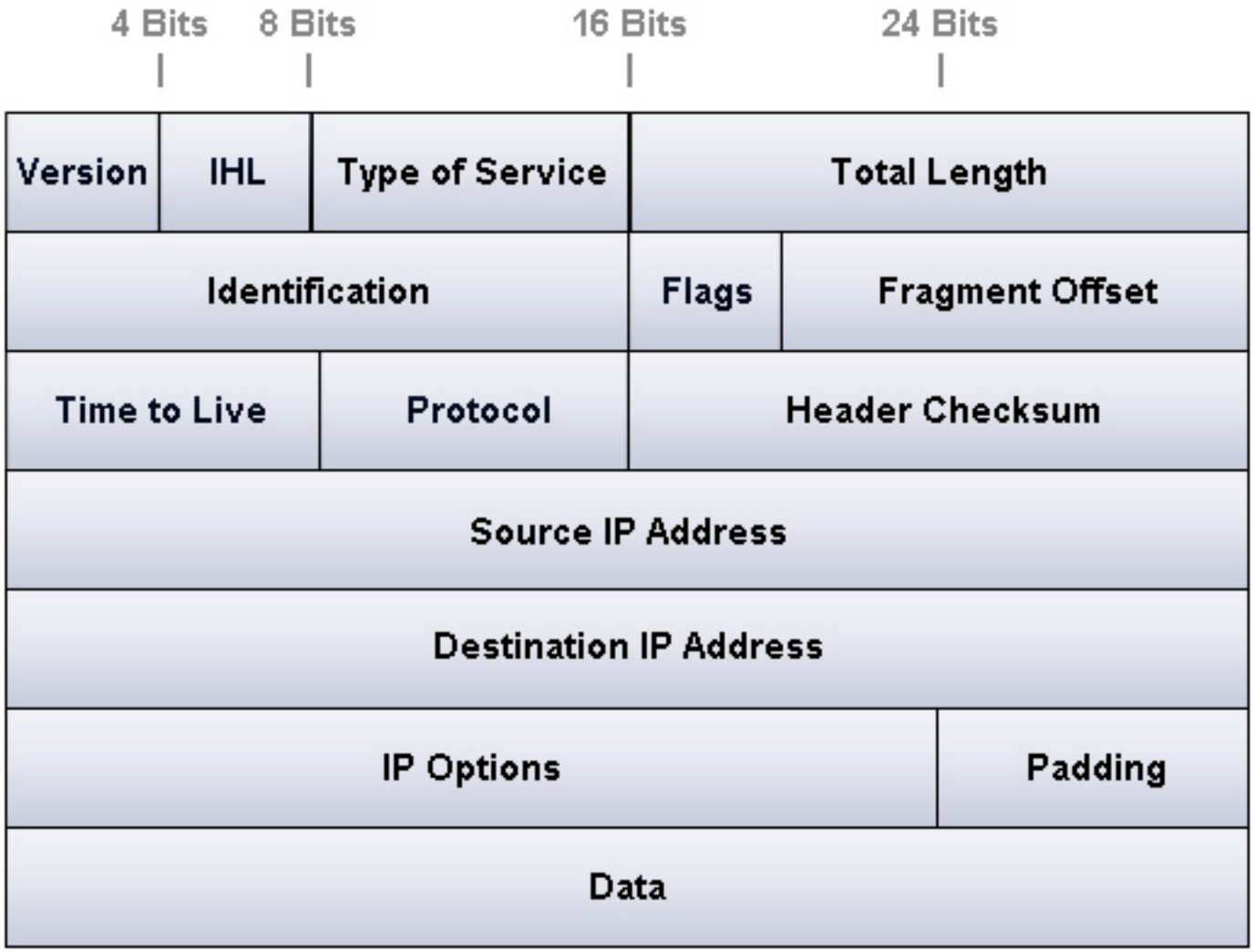
Il Datagramma IP

- TCP/IP usa il termine “IP datagram” per identificare un pacchetto di livello rete
- Ciascun datagramma è composto da una **intestazione** (header)
  - da 20 a 60 bytes che contengono le informazioni essenziali per l’instradamento e la consegna
- seguita dai **dati trasportati** (payload)
  - La dimensione dei payload non è fissa
  - La dimensione effettiva è determinata dall’applicazione e/o dal protocollo di trasporto
  - C’e` una dimensione massima di 64kB (65536)

Formato del Datagramma IP

- L'header contiene informazioni utili per l'instradamento del datagramma:
  - L'indirizzo della sorgente (chi ha inviato per primo il datagramma)
  - L'indirizzo della destinazione (chi riceverà il datagramma se tutto va bene)
  - Il tipo di protocollo che ha generato i dati
  - ...
- Gli indirizzi sono di tipo IP (ovvio)
- Gli indirizzi MAC sono "esterni" al datagramma
- I campi sono di dimensione fissa per efficienza di manipolazione

The IP Datagram Header Format



The IP Datagram Header Format

- **VERS:** Each datagram begins with a 4-bit protocol version number
- **H.LEN**: 4-bit header specifies the number of 32-bit quantities in the header
  - If no options are present, the value is 5
- Type of Service (**ToS**)
  - 8-bit field that carries a class of service for the datagram
    - potentially used for DiffServ and ECN (Explicit Congestion Notification)
    - seldom used in practice
- **TOTAL LENGTH**: 16-bit integer that specifies the total number of bytes including both the header and the data

- IDENTIFICATION
  - 16-bit number (usually sequential) assigned to the datagram
    - used to gather all fragments for reassembly to the datagram
- FLAGS
  - 3-bit field with individual bits specifying whether the datagram is a fragment
    - If so, then whether the fragment corresponds to the last piece of the original datagram
- FRAGMENT OFFSET
  - 13-bit field that specifies where in the original datagram the data in this fragment belongs
  - the value of the field is multiplied by 8 to obtain an offset

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- **TIME TO LIVE (TTL)**
  - 8-bit integer initialized by the original sender
  - it is decremented **by each router** that processes the datagram
  - if the value **reaches zero (0) the datagram is discarded** and an error message is sent back to the source
- PROTOCOL
  - 8-bit field that specifies the type of the payload, i.e., the protocol above (e.g., 6 for TCP, 17 for UDP)
- HEADER CHECKSUM
  - 16-bit ones-complement checksum of header fields
- SOURCE IP ADDRESS
  - 32-bit Internet address of the original sender

- DESTINATION IP ADDRESS
  - The 32-bit Internet address of the ultimate destination
- IP OPTIONS
  - Optional header fields used to control routing and datagram processing
  - Most datagrams do not contain any options
- PADDING
  - If options do not end on a 32-bit boundary
    - zero bits of padding are added to make the header a multiple of 32 bits

FRAMMENTAZIONE DEI PACCHETTI IP

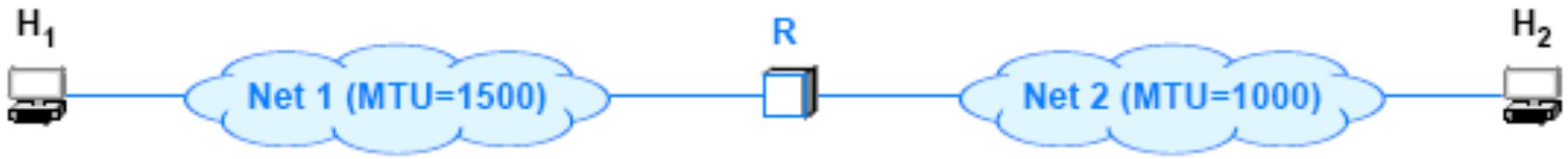
L'USO DELLA FRAMMENTAZIONE È "DEPRECATO".
MOLTI ROUTER SEMPLICEMENTE NON LA IMPLEMENTANO E SCARTANO IL PACCHETTO.

MTU and Datagram Fragmentation

- Each hardware technology specifies the maximum amount of data that a frame can carry
  - The limit is known as a Maximum Transmission Unit (MTU)
- Network hardware is not designed to accept or transfer frames that carry more data than the MTU allows
  - A datagram must be smaller or equal to the network MTU
    - or it cannot be encapsulated for transmission
- In an internet that contains heterogeneous networks, MTU restrictions create a problem
- A router can connect networks with different MTU values
  - a datagram that a router receives over one network can be too large to send over another network

MTUs for some networks

Protocol	*MTU*
Hyperchannel	65,535
Token Ring (16 Mbps)	17,914
Token Ring (4 Mbps)	4,464
FDDI	4,352
Ethernet	1,500
X.25	576
PPP	variabile



- Example: a router interconnects two networks with MTU values of 1500 and 1000
  - Host H_1 attaches to a network with an MTU of 1500
    - and can send a datagram that is up to 1500 octets
  - Host H_2 attaches to a network that has an MTU of 1000
    - which means that it cannot send/receive a datagram larger than 1000 octets
  - If host H_1 sends a 1500-octet datagram to host H_2
    - router R will not be able to encapsulate it for transmission across network 2

MTU and Datagram Fragmentation

- When a datagram is larger than the MTU of the network over which it must be sent
  - the router divides the datagram into smaller pieces called fragments
  - and sends each fragment independently
- A fragment has the same format as other datagrams
  - a bit in the FLAGS field of the header indicates whether a datagram is a fragment or a complete datagram
- Other fields in the header are assigned information for the ultimate destination to reassemble fragments
  - to reproduce the original datagram
- The FRAGMENT OFFSET specifies where in the original datagram the fragment belongs

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- A router uses the network MTU and the header size to calculate
  - the maximum amount of data that can be sent in each fragment
  - and the number of fragments that will be needed
- The router creates the fragments
  - It uses fields from the original header to create a fragment header
  - It copies the appropriate data from the original datagram into the fragment
  - Transmits the result

Flags field

D: Do not fragment
M: More fragments

Reassembling a Datagram

- Example: packets sent from H1 to H2
  - if host H1 sends a 1500-octet datagram to host H2, router R1 will divide the datagram into two fragments, which it will forward to R2
  - Router R2 does not reassemble the fragments
    - Instead R uses the destination address in a fragment to forward the fragment as usual
  - The ultimate destination host, H2, collects the fragments and reassembles them to produce the original datagram

Reassembling a Datagram

- Requiring the ultimate destination to reassemble fragments has two advantages:
  - It reduces the amount of state information in routers
    - When forwarding a datagram, a router does not need to know whether the datagram is a fragment
  - It allows routes to change dynamically
    - If an intermediate router were to reassemble fragments, all fragments would need to reach the router
- By postponing reassembly until the ultimate destination
  - IP is free to pass some fragments from a datagram along different routes than other fragments

The Consequence of Fragment Loss

- A datagram cannot be reassembled until all fragments arrive
- The receiver must save (buffer) the fragments
  - In case missing fragments are only delayed
  - A receiver cannot hold fragments an arbitrarily long time
- IP specifies a maximum time to hold fragments
- When the first fragment arrives from a given datagram
  - the receiver starts a reassembly timer
- If all fragments of a datagram arrive before the timer expires
  - the receiver cancels the timer and reassembles the datagram
- Otherwise the receiver discards the fragments

GLI INDIRIZZI DI INTERNET: IPV4

Gli indirizzi di Internet

- Lo spazio di indirizzamento è un componente critico
- Tutti gli host e i router devono usare uno schema di indirizzamento **uniforme**
- Gli indirizzi Unicast, che identificano una specifica interfaccia devono essere **unici**
- Esistono due spazi di indirizzamento specificati per Internet
  - **IPv4**: quello attualmente in uso con indirizzi a 32 bit
  - IPv6: il sistema di indirizzamento che avrebbe dovuto sostituire IPv4, ma che continua a non farlo
    - indirizzi a 128 bit
    - funzioni “avanzate”
    - esistono molte “isole” IPv6 e ormai tutti i router dei maggiori vendor lo supportano

- IP addresses are supplied by protocol software

- Each network interface is assigned a unique 32-bit number
  - The interface IP address or Internet address
- When sending a packet across the Internet, sender's protocol software must specify
  - its own 32-bit IP address (the source address)
  - and the address of the intended recipient (the destination address)
- Routers only use the destination address for forwrding and routing

Dotted Decimal Notation

- Instead of writing 32 bits, a notation more convenient for humans to understand is used, known as dotted decimal notation
  - express each 8-bit section of a 32-bit number as a decimal value
  - use periods to separate the sections
- Dotted decimal treats each octet (byte) as an unsigned binary integer
  - the smallest value, 0
    - occurs when all bits of an octet are zero (0)
  - the largest value, 255
    - occurs when all bits of an octet are one (1)
  - dotted decimal addresses range

    0.0.0.0 through 255.255.255.255

Dotted Decimal Notation: examples

32-bit Binary Number	Equivalent Dotted Decimal
10000001 00110100 00000110 00000000	129.52.6.0
11000000 00000101 00110000 00000011	192.5.48.3
00001010 00000010 00000000 00100101	10.2.0.37
10000000 00001010 00000010 00000011	128.10.2.3
10000000 10000000 11111111 00000000	128.128.255.0

The IP Address Hierarchy

- IP address is divided into two parts:
- A prefix ➔ identifies the physical network to which the host is attached (also known ad NetID)
  - Each network in the Internet is assigned a unique network number
- A suffix ➔ identifies a specific interface on the network (also known ad HostID)
  - Each NIC on a given network is assigned a unique suffix
- IP address scheme guarantees two properties:
  - Each computer is assigned a unique address
  - Network numbers (prefix) must be coordinated globally
  - Suffixes are assigned locally without global coordination

INDIRIZZAMENTO CON CLASSI (OBSOLETO)

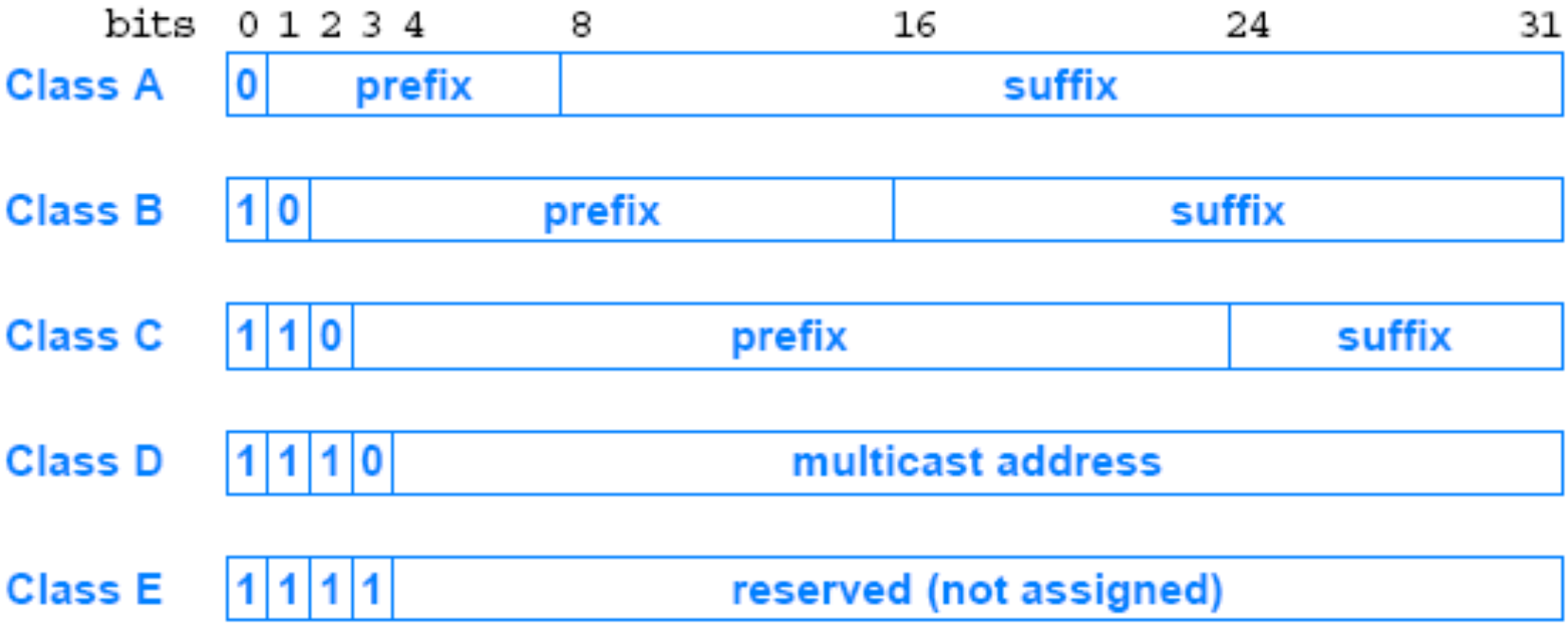
Schema di organizzazione degli indirizzi usato fino alla metà degli anni ‘90 e basato su una divisione statica tra NetID e HostID

È uso ancora oggi riferire l’organizzazione degli indirizzi ad un concetto (e terminologia) di classe

Original Classes of IP Addresses

- Internet contains a few large physical networks and many small networks
  - the designers chose an addressing scheme to accommodate a combination of large and small networks
- The original classful IP addressing divided the IP address space into 3 primary classes
  - each class has a different size prefix and suffix
- The first four bits of an IP address determined the class to which the address belonged
  - It specifies how the remainder of the address was divided into prefix and suffix

Original Classes of IP Addresses



Division of the Address Space

- The classful scheme divided the address space into unequal sizes
- The designers chose an unequal division to accommodate a variety of scenarios
  - For example, although it is limited to 128 networks, class A contains half of all addresses
    - The motivation was to allow major ISPs to each deploy a large network that connected millions of computers
    - But A classes were assigned to small networks all in the US ...
  - Similarly, the motivation for class C was to allow an organization to have a few computers connected on a LAN

Division of the Address Space

Address Class	Bits In Prefix	Maximum Number of Networks	Bits In Suffix	Maximum Number Of Hosts Per Network
A	7	128	24	16777216
B	14	16384	16	65536
C	21	2097152	8	256

Authority for Addresses

- Internet Corporation for Assigned Names and Numbers (ICANN) authority has been established
  - to handle address assignment and adjudicate disputes
- ICANN does not assign individual prefixes
  - Instead, ICANN authorizes a set of registrars to do so
- Registrars make blocks of addresses available to ISPs
  - ISPs provide addresses to subscribers
- To obtain a prefix
  - a corporation usually contacts an ISP

INDIRIZZAMENTO SENZA CLASSI E CIDR

Schema in uso attuale con divisione dinamica tra NetID e HostID

CIDR (Classless Inter-Domain Routing) consente l'instradamento globale senza usare la nozione di classe

Subnets and Classless Addressing

- As the Internet grew the original classful addressing scheme became a limitation
- Everyone demanded a class A or class B address
  - So they would have enough addresses for future growth
    - but many addresses in class A and B were unused
- Two mechanisms, closely related, were designed to overcome the limitation
  - Subnet addressing
  - Classless addressing
- Instead of having three distinct address classes, allow the division between prefix/suffix on an arbitrary bit boundary

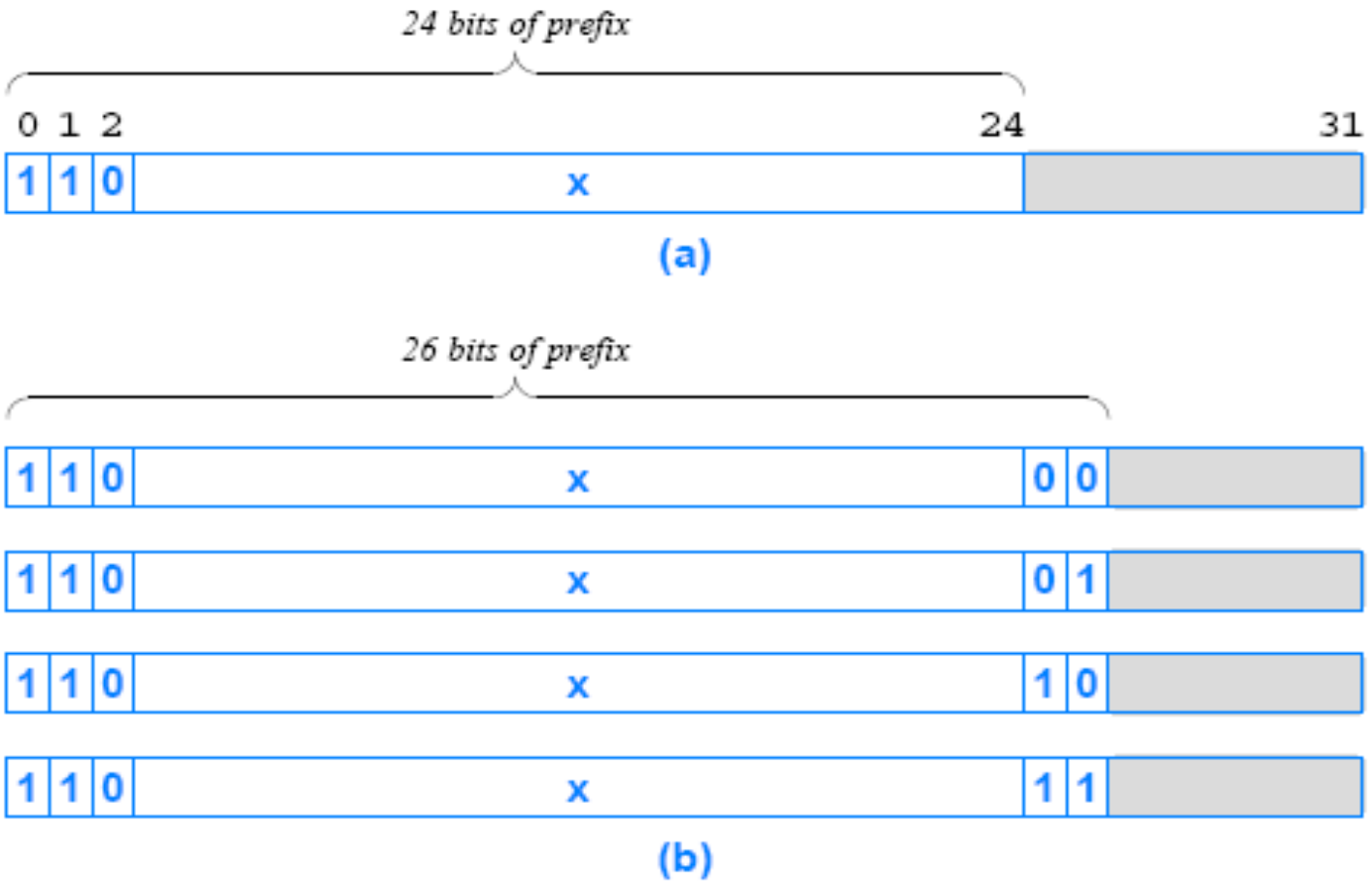
Classless Addressing: Motivation

- Consider an ISP that hands out prefixes. Suppose a customer of the ISP requests a prefix for a network that contains 55 hosts
  - classful addressing requires a complete class C prefix
  - only 6 bits of suffix are needed to represent all possible host values
    - means 190 of the 254 possible suffixes would never be assigned
  - most of the class C address space is wasted
- For the above example
  - classless addressing allows the ISP to assign
    - a prefix that is 26 bits long
    - a suffix that is 6 bits long

Classless Addressing: Example

- Assume an ISP owns a class C prefix
  - Classful addressing assigns the entire prefix to one organization
- With classless addressing
  - the ISP can divide the prefix into several longer prefixes
- For instance, the ISP can divide a class C prefix into 4 longer prefixes
  - each one can accommodate a network of up to 62 hosts
    - all 0s and all 1s are reserved
- The original class C address has 8 bits of suffix
  - and each of the classless addresses has 6 bits of suffix
- Thus, instead of wasting addresses
  - ISP can assign each of the 4 classless prefixes to a subscriber

Classless Addressing: Example



Address (subnet) Masks

- How can an IP address be divided at an arbitrary boundary?
- The classless and subnet addressing schemes require hosts and routers to store an additional piece of information:
  - a value that specifies the exact boundary between prefix and suffix
- To mark the boundary, IP uses a 32-bit value
  - known as an address mask, also called a subnet mask
- Why store the boundary size as a bit mask?
  - A mask makes processing efficient
- Hosts and routers need to compare the network prefix portion of the address to a value in their forwarding tables
  - The bit-mask representation makes the comparison efficient

Address Masks

- Suppose a router is given
  - a destination address, D
  - a network prefix represented as a 32-bit value, N
  - a 32-bit address mask, M
- Assume the top bits of N contain a network prefix, and the remaining bits have been set to zero
- To test whether the destination lies on the specified network, the router tests the condition:

$$N == (D \,\&\, M)$$

- The router
  - uses the mask with a “logical and (&)” operation to set the host bits of address D to zero (0)
  - and then compares the result with the network prefix N

Address Masks: Example

- Consider the following 32-bit network prefix:

  10000000 00001010 00000000 00000000 → 128.10.0.0

- Consider a 32-bit mask:

  11111111 11111111 00000000 00000000 → 255.255.0.0

- Consider a 32-bit destination address, which has a

  10000000 00001010 00000010 00000011 → 128.10.2.3

- A logical & between the destination address and the address mask extracts the high-order 16-bits

  10000000 00001010 00000000 00000000 → 128.10.0.0

CIDR Notation

- Classless Inter-Domain Routing (CIDR)
- Consider a mask defining a subnet with 2^6 nodes
  - It has 26 bits of 1s followed by 6 bits of 0s
  - In dotted decimal, the mask is: 255.255.255.192
- The general form of CIDR notation is: ddd.ddd.ddd.ddd/m
  - ddd is the decimal value for an octet of the address
  - m is the number of one bits in the mask
- Thus, one might write the following: 192.5.48.69/26
  - which specifies a mask of 26 bits

A CIDR Example

- Assume an ISP has the following block 128.211.0.0/16
- Suppose the ISP has 2 customers
  - one customer needs 12 IP addresses and the other needs 9
- The ISP can assign
  - customer1 CIDR: 128.211.0.16/28
  - customer2 CIDR: 128.211.0.32/28
  - both customers have the same mask size (28 bits), the prefixes differ

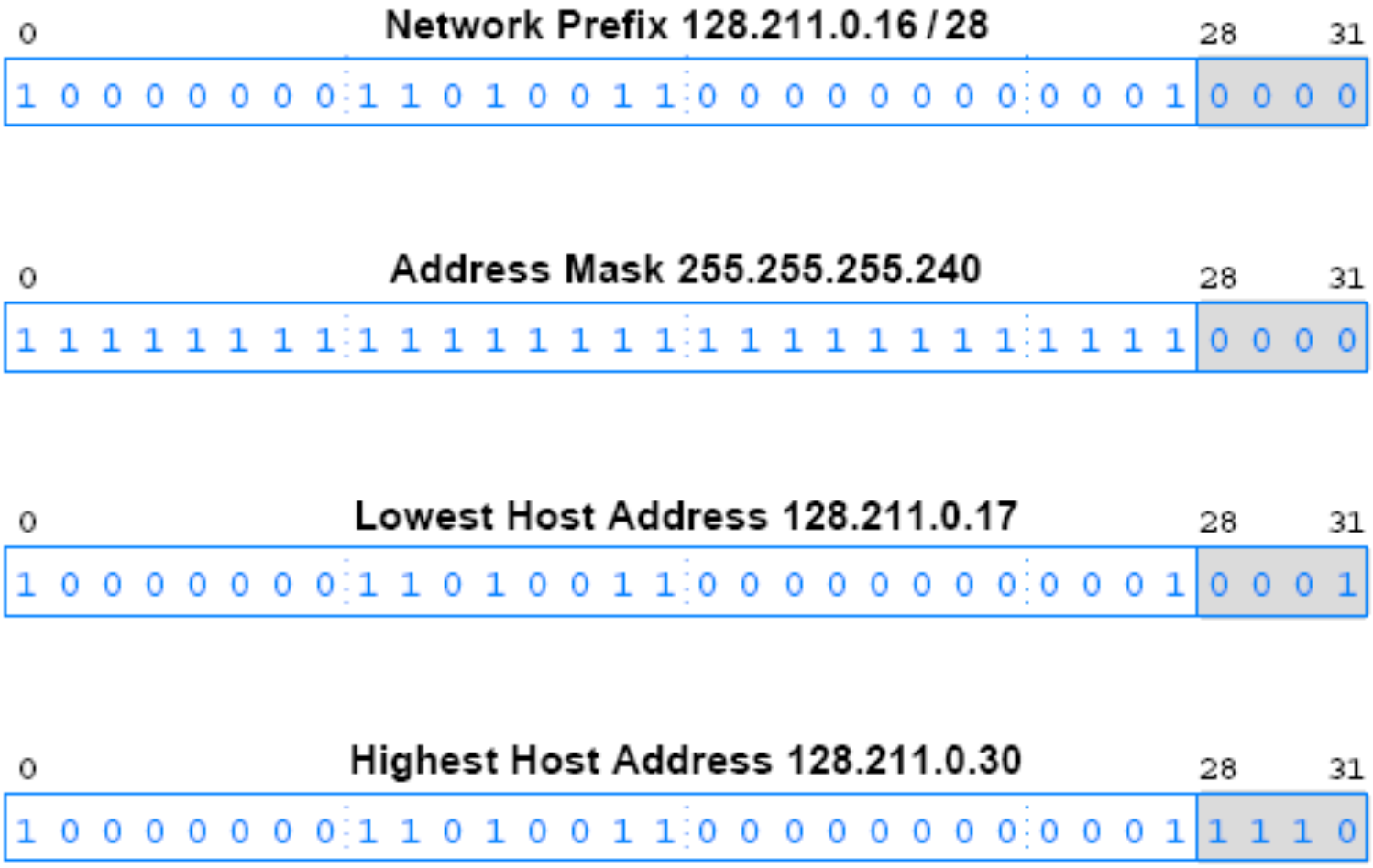
A CIDR Example (cont'd)

- The binary value assigned to customer1 is:
  - 10000000 11010011 00000000 00010000
- The binary value assigned to customer2 is:
  - 10000000 11010011 00000000 00100000
- There is no ambiguity
  - Each customer has a unique prefix
  - More important, the ISP retains most of the original address block
    - it can then allocate to other customers

CIDR Host Addresses

- Once an ISP assigns a customer a CIDR prefix
  - the customer can assign host addresses for its network users
- Suppose an organization is assigned 128.211.0.16/28
  - the organization will have 4-bits to use as a host address field
- Disadvantage of classless addressing
  - Because the host suffix can start on an arbitrary boundary, values are not easy to read in dotted decimal

CIDR Host Addresses



INDIRIZZI PRIVATI, SPECIALI E INDIRIZZI DEI ROUTER

Non tutti gli indirizzi IP sono utilizzabili, alcuni indirizzi hanno significato solo interno al computer e altri consentono di fare il bootstrap delle macchine prima che abbiano un indirizzo IP con cui comunicare.
I Router sono macchine con più indirizzi IP ... anche se non sempre con più interfacce fisiche di comunicazione.

Indirizzi pubblici e privati

- Non tutti gli indirizzi IP Unicast validi sono uguali
- Alcuni indirizzi sono stati definiti “privati” e non sono instradabili in Internet
  - Possono essere usati per costruire Intra-net private
- Un host con indirizzo IP privato ha bisogno di una apparato attivo che traduca opportunamente i suoi pacchetti per accedere a Internet
- NAT: Network Address Translator
  - Mappa la 5-tupla che identifica un flusso su un’altra 5-tupla con indirizzo pubblico, lavora a livello L3/L4
- Proxy
  - Gateway di L7, che interconnette a livello di singola applicazione

Indirizzi Privati

- 10.0.0.0 – 10.255.255.255
- 172.16.0.0 – 172.31.255.255
- 192.168.0.0 – 192.168.255.255

- Un indirizzo privato può essere riutilizzato in molti posti diversi
- All'interno di una stessa rete devono essere unici e possono essere "routati" fino a un "border router" che invece impedisce di andare verso Internet
- Normalmente sono assegnati tramite DHCP e non sono assegnati staticamente a un host
- Non c'è una reale differenza tra i tre gruppi di indirizzi, ma in genere i router "domestici" usano 192.168.x.y/24

Special IP Addresses

- IP defines a set of special address forms that are reserved
  - That is, special addresses are never assigned to hosts
- Examples:
  - Network Address
  - Directed Broadcast Address
  - Limited Broadcast Address
  - This Computer Address
  - Loopback Address
  - Multicast addresses

Network Address

- It is convenient to have an address that can be used to denote the prefix assigned to a given network
- IP reserves host address zero
  - and uses it to denote a network
- Thus, the address 128.211.0.16/28 denotes a network
  - because the bits beyond the 28 are zero
  - 10000000 11010011 00000000 00010000
- A network address should never appear as the destination address in a packet

Directed Broadcast Address

- To simplify broadcasting (send to all)
  - IP defines a directed broadcast address for each physical network
- When a packet is sent to a network's directed broadcast
  - a single copy of the packet travels across the Internet
    - until it reaches the specified network
  - the packet is then delivered to all hosts on the network
- The directed broadcast address for a network is formed by adding a suffix that consists of all 1 bits to the network prefix
  - 10000000 11010011 00000000 00011111

Limited Broadcast Address

- Limited broadcast refers to a broadcast on a directly-connected network:
  - informally, we say that the broadcast is limited to a “single LAN” meaning that it will never be forwarded by a router, even if the “LAN” can be a huge Campus LAN with hundreds of computers
- Limited broadcast is used during system startup
  - by a computer that does not yet know the network number
- IP reserves the address consisting of 32-bits of 1s
  - 11111111 11111111 11111111 11111111
- Thus, IP will broadcast any packet sent to the all-1s address across the local network

This Computer Address

- A computer needs to know its IP address
  - before it can send or receive Internet packets
- TCP/IP contains protocols a computer can use to obtain its IP address automatically when the computer boots
  - … but the startup protocols also use an IP to communicate
- When using such startup protocols
  - a computer cannot supply a correct IP source address
  - To handle such cases IP reserves the address that consists of all 0s to mean this computer
  - 00000000 00000000 00000000 00000000

Loopback Address

- Loopback address used to test network applications
  - e.g., for preliminary debugging after a network application has been created
- A programmer must have two application programs that are intended to communicate across a network
- Instead of executing each program on a separate computer
  - the programmer runs both programs on a single computer
  - and instructs them to use a loopback address when communicating
- When one application sends data to another
  - data travels down the protocol stack to the IP software
  - then forwards it back up through the protocol stack to the second program

Loopback Address (cont'd)

- IP reserves the network prefix 127/8 for use with loopback
- The host address used with 127 is irrelevant
  - all host addresses are treated the same
  - programmers often use host number 1
  - so it makes 127.0.0.1 the most popular loopback address
- During loopback testing no packets ever leave a computer
  - the IP software forwards packets from one application to another
- The loopback address never appears in a packet traveling across a network

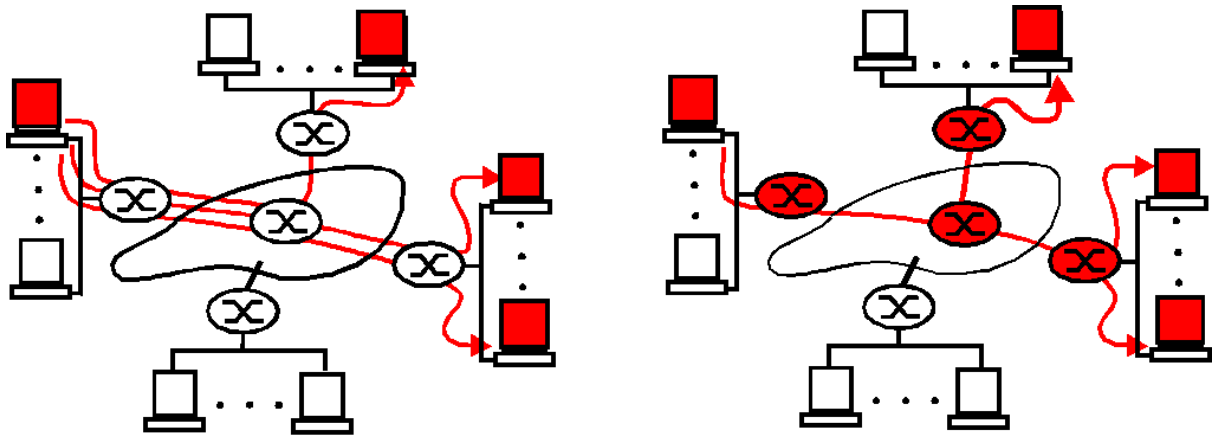
Summary of Special IP Addresses

Prefix	Suffix	Type Of Address	Purpose
all-0s	all-0s	this computer	used during bootstrap
network	all-0s	network	identifies a network
network	all-1s	directed broadcast	broadcast on specified net
all-1s	all-1s	limited broadcast	broadcast on local net
127 / 8	any	loopback	testing

Indirizzo Multicast

- Internet ammette l'invio di pacchetti a "molti"
- I router si preoccupano (complesso, non lo vediamo in questo corso) di capire il punto ottimo dove duplicare l'informazione
- Un pacchetto multicast è inviato a un indirizzo di "gruppo"
- In IPv4: Class D, iniziano per 1110
- 224.0.0.0 – 239.255.255.255
- Esistono gruppi multicast "well known"
- 224.0.0.1: All Hosts on this Subnet
- 224.0.0.2: All Routers on this Subnet
- Gli altri possono essere usati per applicazioni proprietarie o nuove
- Purtroppo non tutti gli ISP permettono traffico multicast se non per la gestione dei protocolli di routing stessi

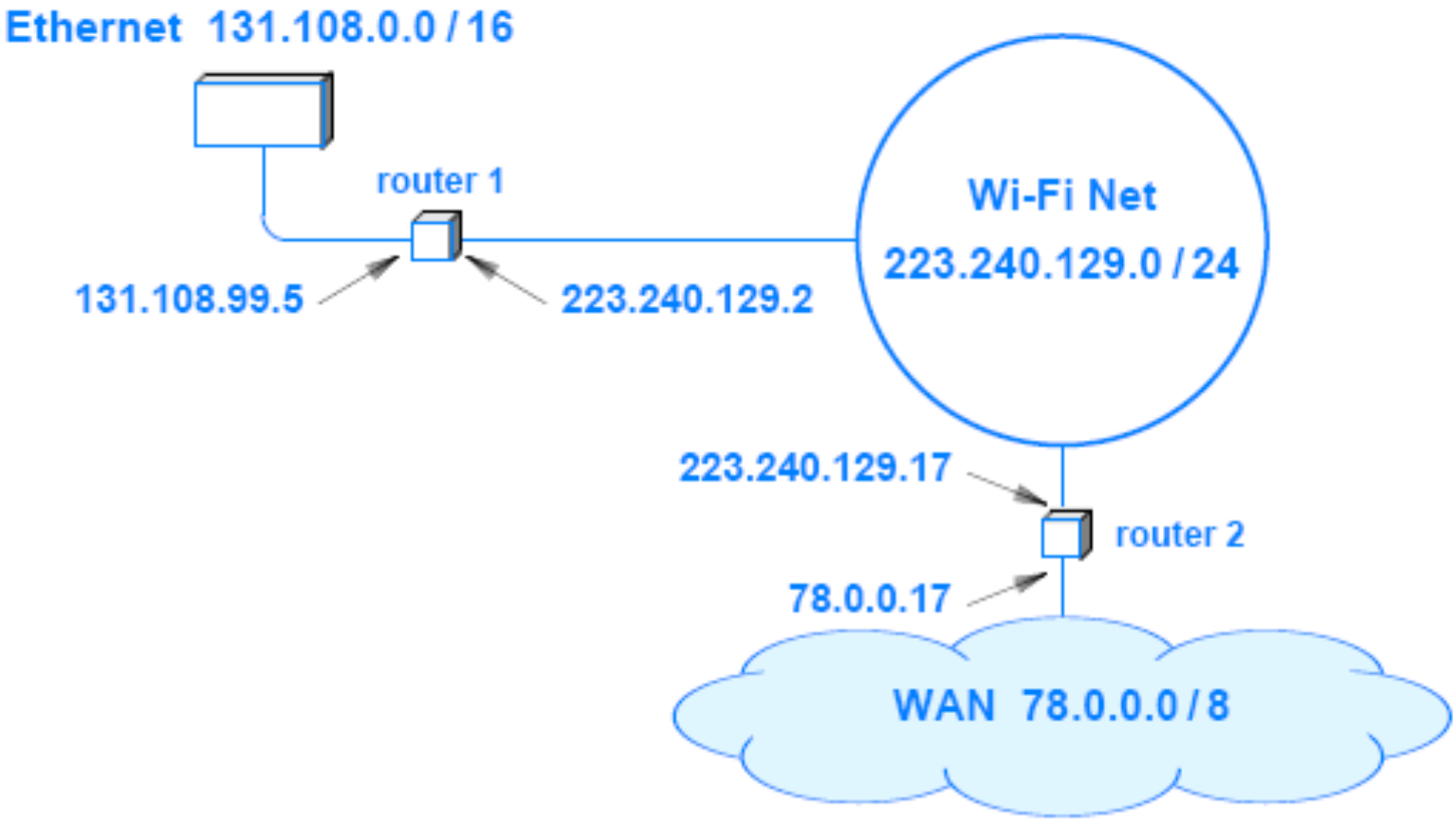
- Multicast: delivery of same packet to a group of receivers with the minimum overhead
- Multiple unicast vs. multicast
  - Host based vs. network based



Routers and IP Addresses

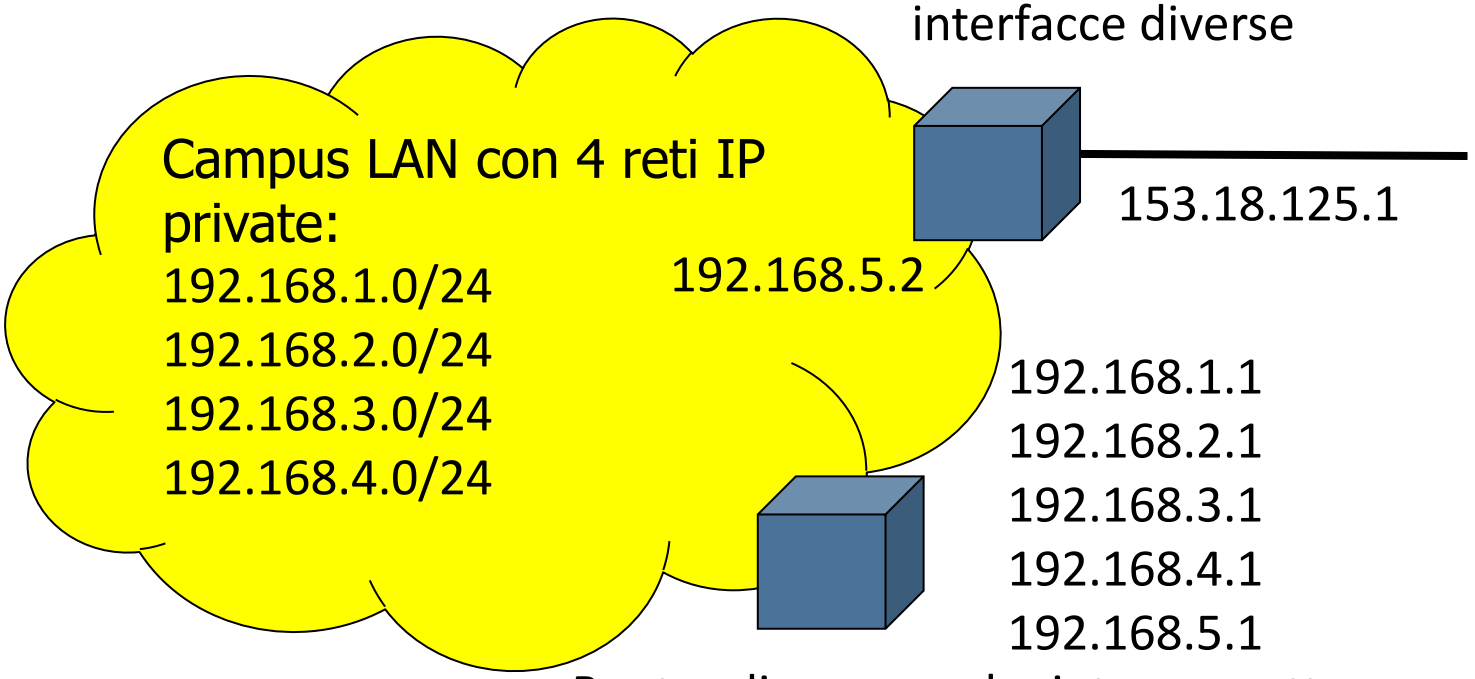
- Each router is assigned two or more IP addresses
  - one address for each logical network to which the router attaches
- To understand why, recall two facts:
  - A router connects multiple IP networks (by definition)
  - Each IP address contains a prefix that specifies a logical network
- A single IP address does not suffice for a router
  - because each router connects to multiple networks
  - and each network has a unique prefix
- The IP scheme can be explained by a principle:
  - An IP address does not identify a specific computer
  - each address identifies in interface, i.e., a logical connection between a computer and a network
  - A computer with multiple network connections (e.g., a router) must be assigned one IP address for each connection

An Example


Ethernet 131.108.0.0 / 16
router 1
131.108.99.5
223.240.129.2
Wi-Fi Net
223.240.129.0 / 24
223.240.129.17
router 2
78.0.0.17
WAN 78.0.0.0 / 8

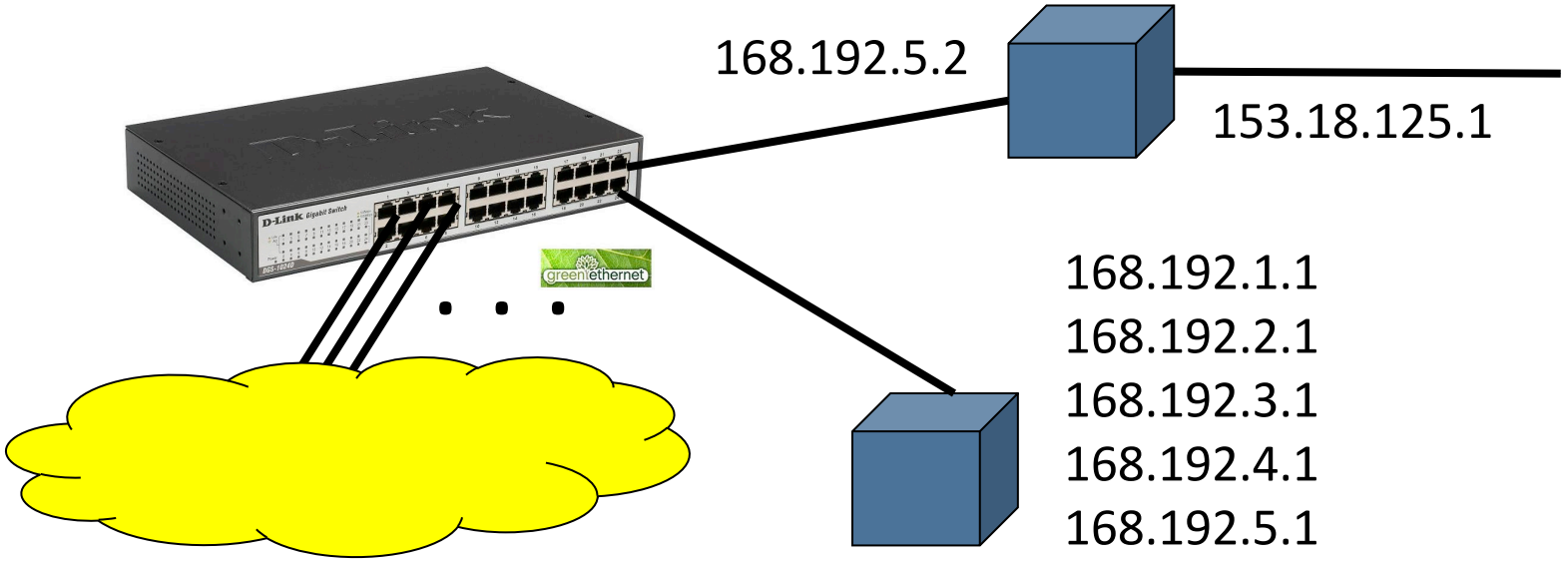
Un altro esempio

Router, NAT Firewall per accesso a Internet 2 indirizzi IP su due interfacce diverse



Router di campus che interconnette le 4 reti ed inoltra al Router NAT di collegamento verso Internet: 5 indirizzi IP tutti sulla stessa interfaccia fisica della campus LAN

Collegamento a livello ethernet



Router di campus che interconnette
le 4 reti ed inoltra al Router NAT di
collegamento verso Internet: 5 indirizzi IP
tutti sulla stessa interfaccia fisica della campus LAN