

# Chapter 6

## Link Layer and LANs

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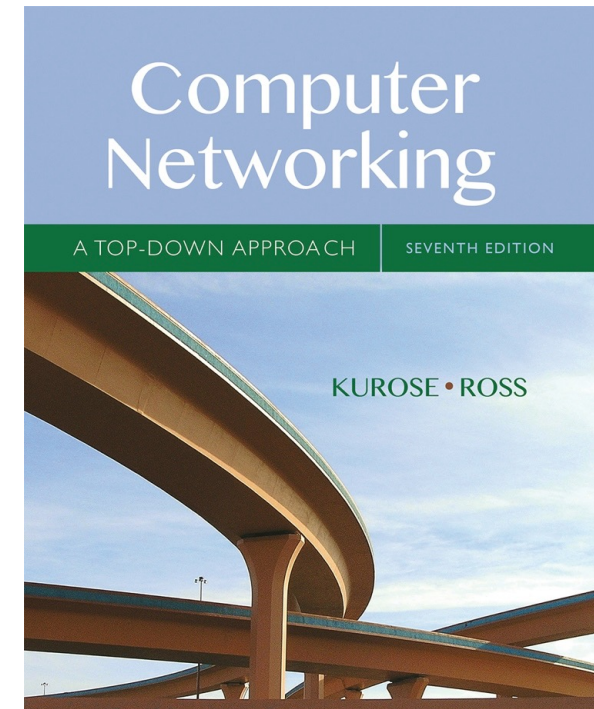
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**Computer  
Networking: A Top  
Down Approach**  
6<sup>th</sup> and 7<sup>th</sup> edition  
Jim Kurose, Keith Ross  
Addison-Wesley  
March 2012, 2017.

# Chapter 6: Link layer and LANs

our goals:

- ❖ understand principles behind link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
  - local area networks: Ethernet, VLANs
- ❖ instantiation, implementation of various link layer technologies

# Link layer, LANs: outline

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6.1 introduction, services

6.2 error detection,  
correction

6.3 multiple access protocols

6.4 LANs

- addressing, ARP
- Ethernet
- switches
- VLANs

6.5 link virtualization: MPLS

6.6 data center networking

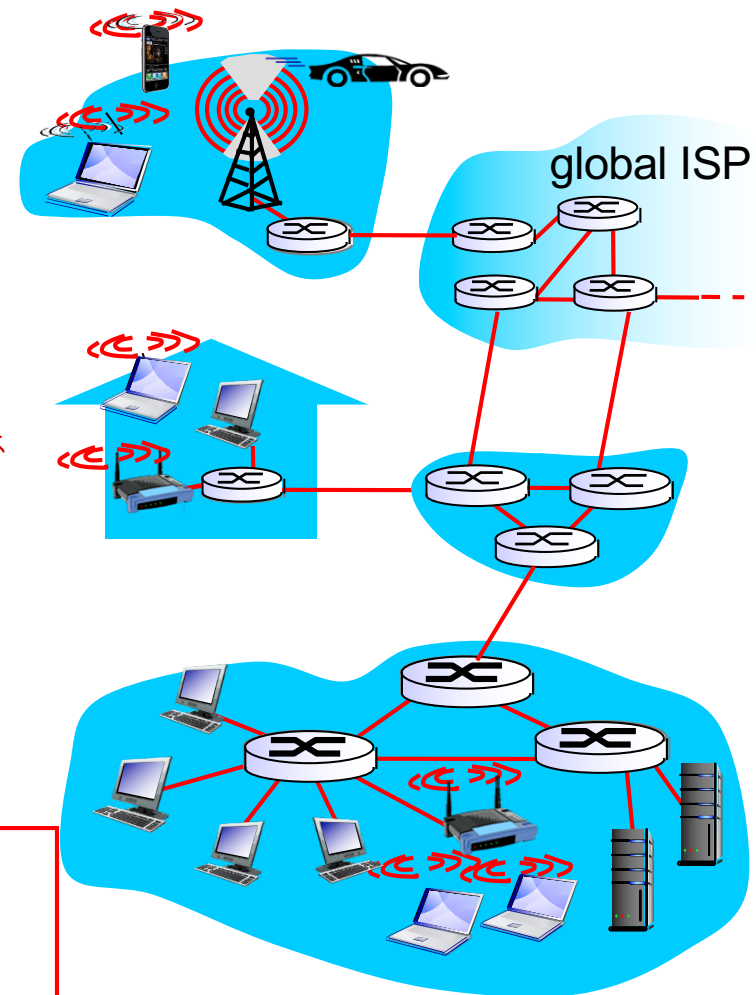
6.7 a day in the life of a web  
request

# Link layer: introduction

## terminology:

- ❖ hosts and routers: **nodes**
- ❖ communication channels that connect adjacent nodes along communication path: **links**
  - wired links
  - wireless links
  - LANs
- ❖ layer-2 packet: **frame**, encapsulates datagram

**data-link layer** has responsibility of transferring datagram from one node to **physically adjacent** node over a link



# Link layer: context

- ❖ datagram transferred by different link protocols over different links:
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- ❖ each link protocol provides different services
  - e.g., may or may not provide reliable data transfer (rdt) over each link

transmission  
level ←

## transportation analogy:

- ❖ trip from Princeton to Lausanne
  - car: Princeton to JFK
  - plane: JFK to Geneva
  - train: Geneva to Lausanne
- ❖ tourist = datagram
- ❖ transport segment = communication link
- ❖ transportation mode = link layer protocol
- ❖ travel agent = routing algorithm

# Link layer services

## ❖ framing, link access:

- encapsulate datagram into frame, adding header, trailer
- obtain channel access if shared medium
- “MAC” addresses used in frame headers to identify source, destination
  - different from IP address!

## ❖ reliable delivery between adjacent nodes

- seldom used on low bit-error link (fiber, some twisted pair)
- wireless links: high error ratios
  - Q: why both link-level and end-end reliability?

# Link layer services (more)

## ❖ flow control:

→ control  
de  
fluxo

- pacing between adjacent sending and receiving nodes

## ❖ error detection:

→ control  
de  
erros

- errors caused by signal attenuation, noise.
- receiver detects presence of errors:
  - signals sender for retransmission or drops frame (rdt vs. no rdt)

## ❖ error correction:

- receiver identifies **and corrects** bit error(s) without resorting to retransmission

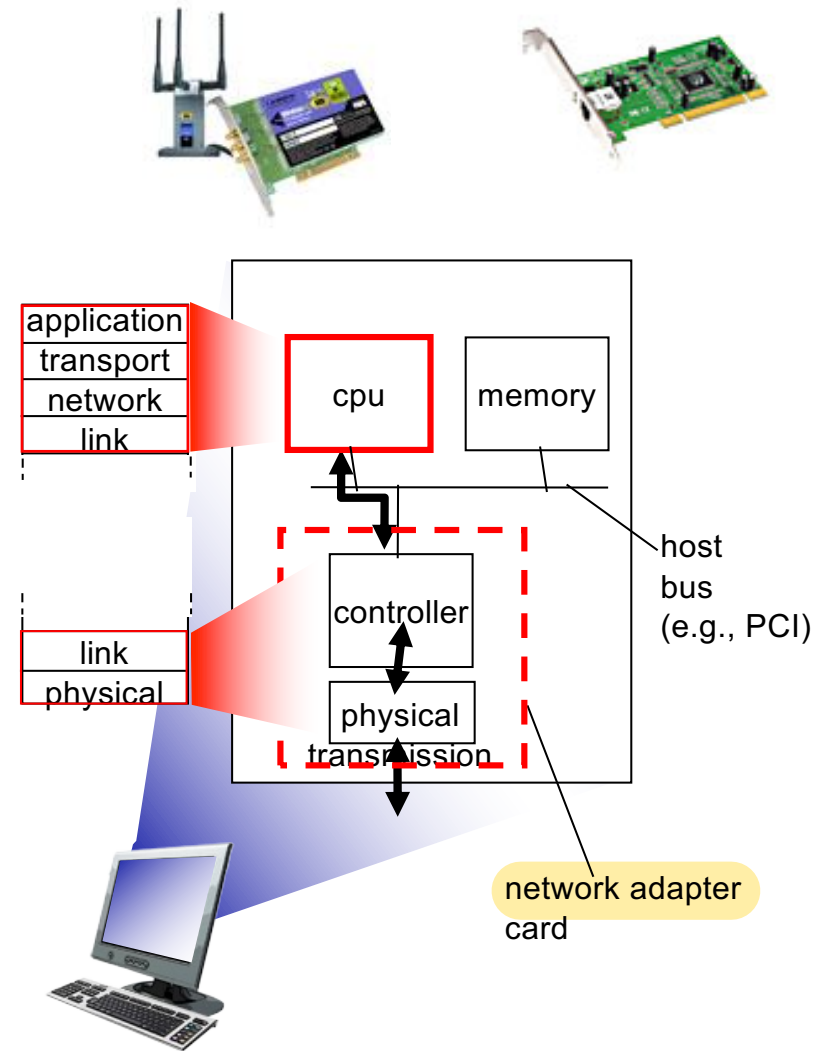
## ❖ half-duplex and full-duplex

- with half duplex, nodes at both ends of link can transmit, but not at same time

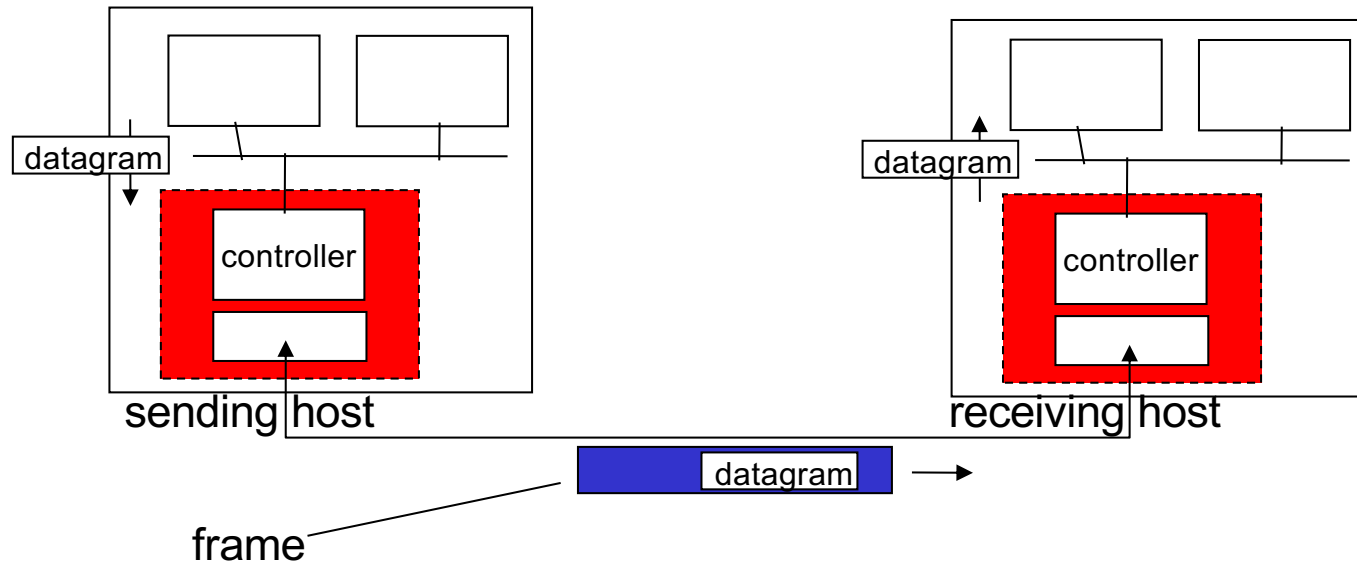


# Where is the link layer implemented?

- ❖ in each and every host
- ❖ link layer implemented in “adaptor” (aka **network interface card** NIC) or on a chip
  - Ethernet card, 802.11 card; Ethernet chipset
  - implements link, physical layer
- ❖ attaches into host's system buses
- ❖ combination of hardware, software, firmware



# Adaptors communicating



## ❖ sending side:

- encapsulates datagram in frame
- adds (**eventually**) error checking bits, reliability (rdt), flow control, etc.

## ❖ receiving side

- if in use, looks for errors, rdt, flow control, etc.
- extracts datagram, passes to upper layer at receiving side

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- switches
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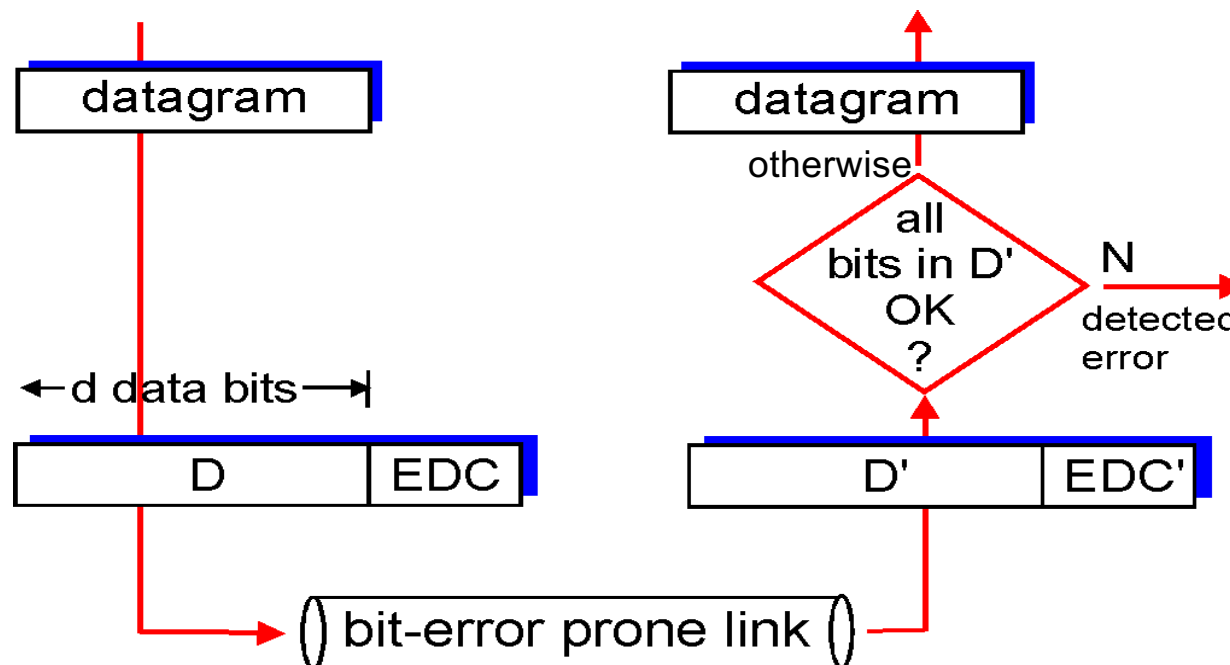
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# Error detection

EDC= Error Detection and Correction bits (redundancy)

D = Data protected by error checking, may include header fields

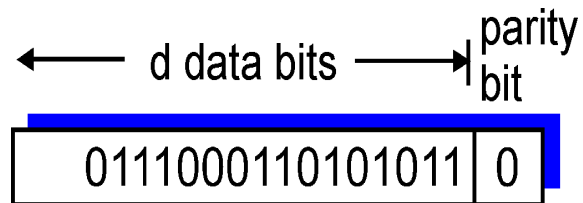
- Error detection not 100% reliable!
  - protocol may miss some errors, but rarely
  - larger EDC field yields better detection and correction



# Parity checking

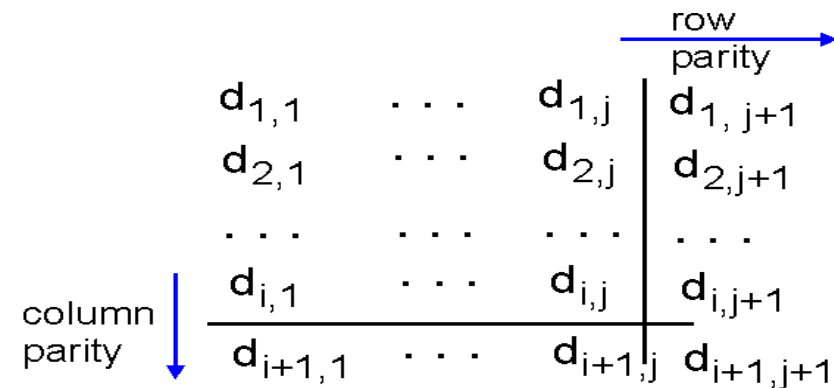
## single bit parity:

- ❖ detect single bit errors



## two-dimensional bit parity:

- ❖ detect and correct single bit errors



1	0	1	0	1	1
1	1	1	1	0	0
0	1	1	1	0	1
0	0	1	0	1	0

*no errors*

1	0	1	0	1	1
1	0	1	1	0	0
0	1	1	1	0	1
0	0	1	0	1	0

parity  
error

*correctable  
single bit error*

# Internet checksum (review)

**goal:** detect “errors” (e.g., flipped bits) in transmitted packet (note: used at transport layer only)

## sender:

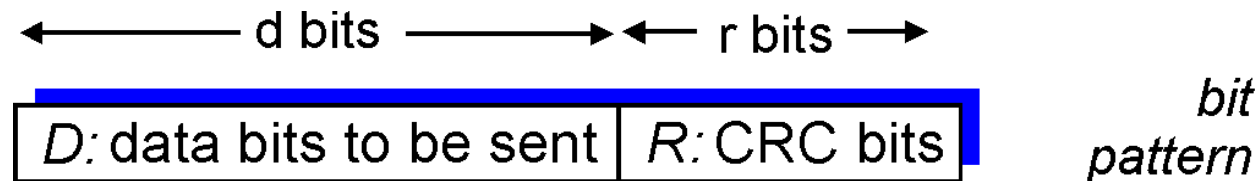
- ❖ treat segment contents as sequence of 16-bit integers
- ❖ checksum: addition (1's complement sum) of segment contents
- ❖ sender puts checksum value into UDP checksum field

## receiver:

- ❖ compute checksum of received segment
- ❖ check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. But maybe errors nonetheless?

# Cyclic redundancy check

- ❖ more powerful error-detection coding
- ❖ view data bits, **D**, as a binary number
- ❖ choose  $r+1$  bit pattern (generator), **G**
- ❖ goal: choose  $r$  CRC bits, **R**, such that
  - $\langle D, R \rangle$  exactly divisible by  $G$  (modulo 2)
  - receiver knows  $G$ , divides  $\langle D, R \rangle$  by  $G$ . If non-zero remainder: error detected!
  - can detect all burst errors less than  $r+1$  bits
- ❖ widely used in practice (Ethernet, 802.11 WiFi, ATM)



$$D * 2^r \text{ XOR } R$$

*mathematical formula*

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**want:**

$$D \cdot 2^r \text{ XOR } R = nG$$

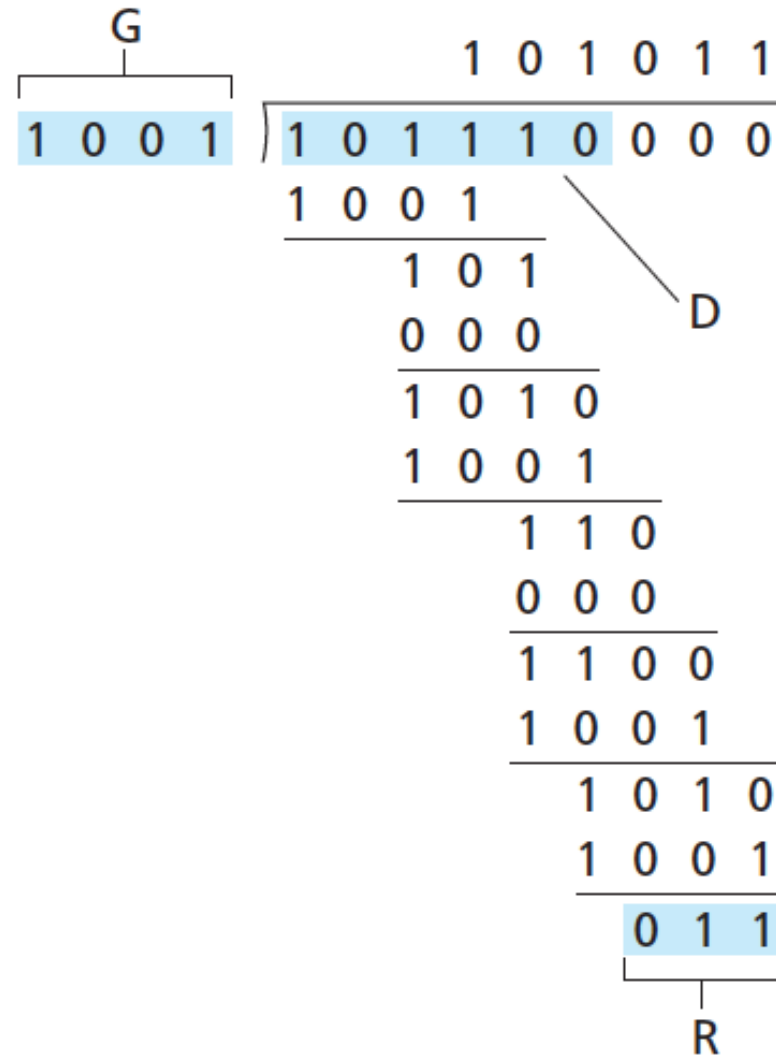
equivalently:

$$D \cdot 2^r = nG \text{ XOR } R$$

equivalently:

if we divide  $D \cdot 2^r$  by  $G$ , want remainder  $R$  to satisfy:

$$R = \text{remainder}\left[\frac{D \cdot 2^r}{G}\right]$$





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# Multiple access links, protocols

two types of “links”:

## ❖ point-to-point

- (PPP for dial-up access; HDLC for point-to-point or point-to-multipoint)
- point-to-point link between Ethernet switch, host

## ❖ broadcast (shared wire or medium)

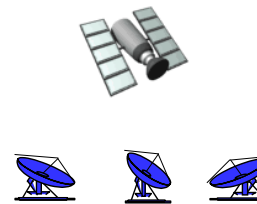
- old-fashioned Ethernet
- upstream HFC (Hybrid Fiber Coax)
- 802.11 wireless LAN



shared wire (e.g.,  
cabled Ethernet)



shared RF  
(e.g., 802.11 WiFi)



shared RF  
(satellite)



humans at a  
cocktail party  
(shared air, acoustical)

# Multiple access protocols

- ❖ single shared broadcast channel
- ❖ two or more simultaneous transmissions by nodes: interference
  - **collision** if node receives two or more signals at the same time

## multiple access protocol

- ❖ distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- ❖ communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

# An ideal multiple access protocol

**given:** broadcast channel of rate  $R$  bps

**desiderata:** (seria desejável...)

1. when one node wants to transmit, it can send at rate  $R$ .
2. when  $M$  nodes want to transmit, each can send at average rate  $R/M$
3. fully decentralized:
  - no special node to coordinate transmissions
  - no synchronization of clocks, slots
4. simple

# MAC protocols: taxonomy

three broad classes:

- ❖ **channel partitioning**

- divide channel into smaller “pieces” (time slots, frequency,...)
- allocate piece to node for exclusive use

- ❖ **random access**

- channel not divided, allow collisions
- “recover” from collisions

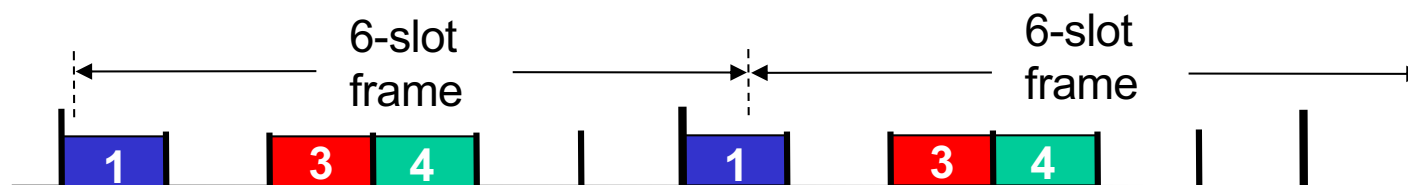
- ❖ **“taking turns”**

- nodes take turns, but nodes with more to send can take longer turns

# Channel partitioning MAC protocols: TDMA

## TDMA: time division multiple access

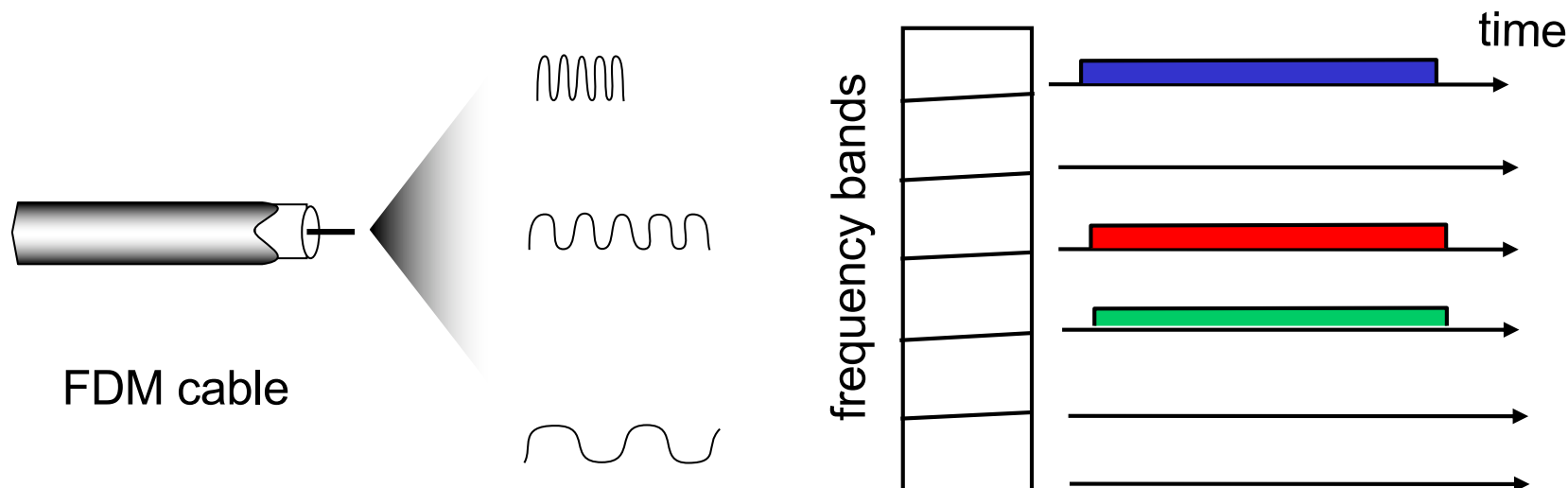
- ❖ channel capacity is divided in time frames, and then time frames in time slots
- ❖ access to channel in "rounds"
- ❖ each station gets fixed length slot (length = pkt transmission time) in each round (each transmitting at  $R/N$ )
- ❖ unused slots go idle
- ❖ example: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle
- ❖ Pros: no collisions, fair. Cons: time wait, may waste capacity



# Channel partitioning MAC protocols: FDMA

## FDMA: frequency division multiple access

- ❖ channel spectrum divided into frequency bands
- ❖ each station assigned fixed frequency band
- ❖ unused transmission time in frequency bands goes idle
- ❖ example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle



# Random access protocols

- ❖ when node has packet to send
  - transmit at full channel data rate  $R$ .
  - no a priori coordination among nodes
- ❖ two or more transmitting nodes → “collision”
- ❖ **random access MAC protocol** specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)
- ❖ examples of random access MAC protocols:
  - ALOHA; slotted ALOHA (not covered in SCR)
  - CSMA, CSMA/CD, CSMA/CA



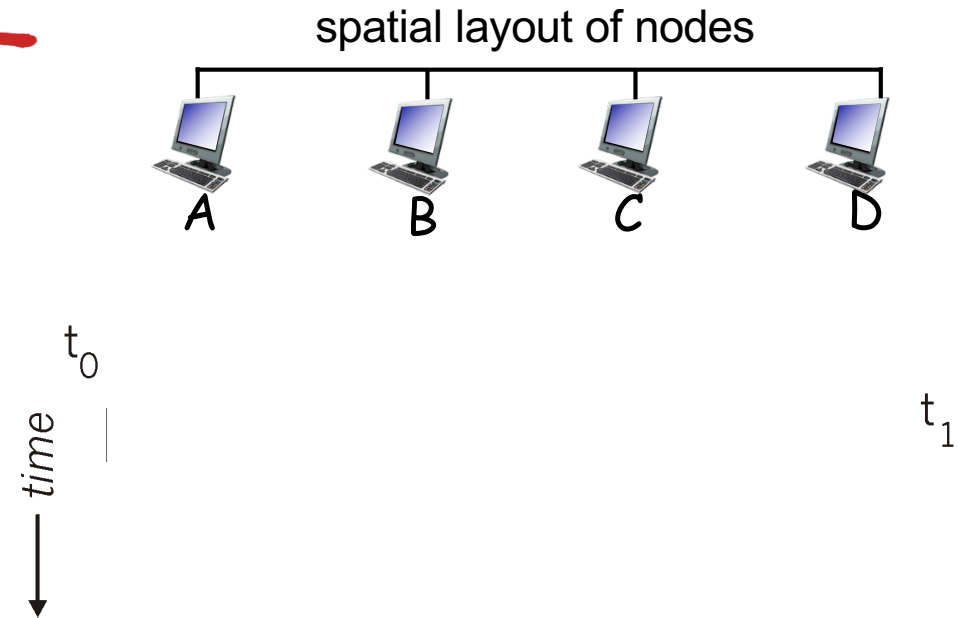
# CSMA (carrier sense multiple access)

**CSMA:** listen before transmit:

- ❖ if channel sensed idle: transmit entire frame
- ❖ if channel sensed busy, defer transmission
  
- ❖ human analogy: don't interrupt others!

# CSMA collisions

- ❖ collisions can still occur: propagation delay means two nodes may not hear each other's transmission
- ❖ collision: entire packet transmission time wasted
  - distance & propagation delay play role in determining collision probability



# CSMA/CD (collision detection)

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**CSMA/CD:** carrier sensing, deferral as in CSMA

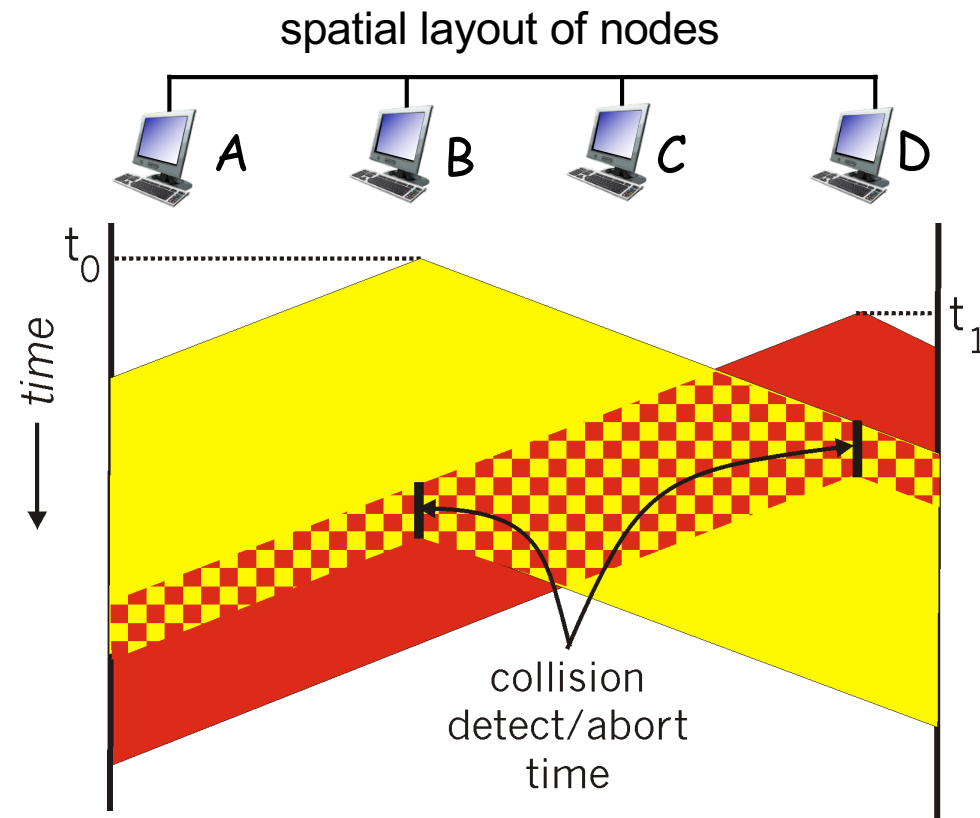
- collisions detected within short time
- colliding transmissions aborted, reducing channel wastage

❖ collision detection:

- easy in wired LANs: measure signal strengths, compare transmitted, received signals
- difficult in wireless LANs: received signal strength overwhelmed by local transmission strength

❖ human analogy: the polite conversationalist

# CSMA/CD (collision detection)



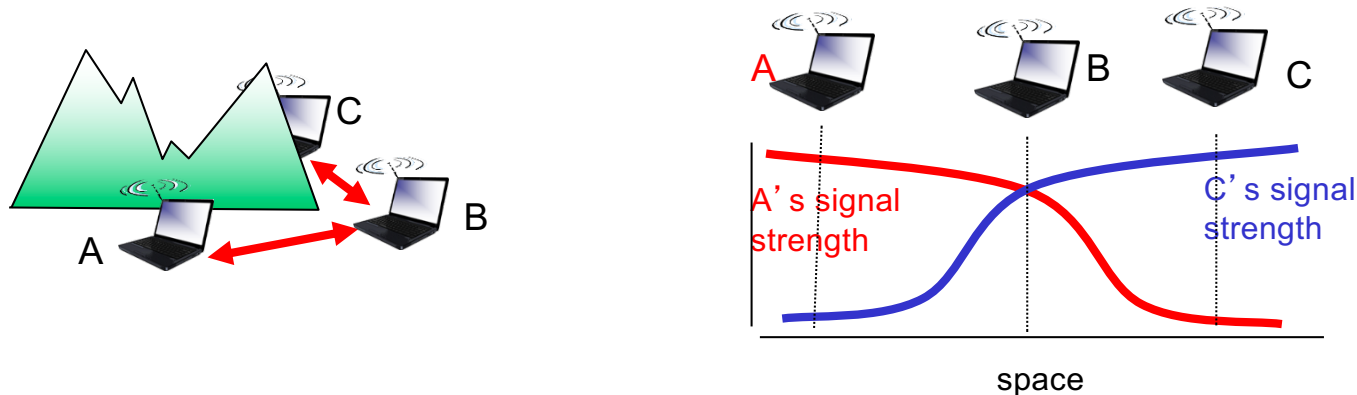
# Ethernet CSMA/CD algorithm

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1. NIC receives datagram from network layer, creates frame
2. If NIC senses channel idle, starts frame transmission. If NIC senses channel busy, waits until channel idle, then transmits.
3. If NIC transmits entire frame without detecting another transmission, NIC is done with frame !
4. If NIC detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, NIC enters **binary (exponential) backoff:**
  - after  $m^{\text{th}}$  collision, NIC chooses  $K$  at random from  $\{0, 1, 2, \dots, 2^m - 1\}$ . NIC waits  $K \cdot 512$  bit times, returns to Step 2
  - longer backoff interval with more collisions

# CSMA/CD fails in WLANs

- ❖ In WLANs collision detection does not work properly!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
- ❖ Goal: avoid collisions - CSMA/C(ollision)A(voidance)
- ❖ CSMA - sense before transmitting
  - don't collide with ongoing transmission by other node
- ❖ CA – scheme based on proper timing and ACKs (see IEEE 802.11)



# “Taking turns” MAC protocols

## channel partitioning MAC protocols:

- share channel efficiently and fairly at high load
- inefficient at low load: delay in channel access,  $1/N$  bandwidth allocated even if only 1 active node!

## random access MAC protocols

- efficient at low load: single node can fully utilize channel
- high load: collision overhead

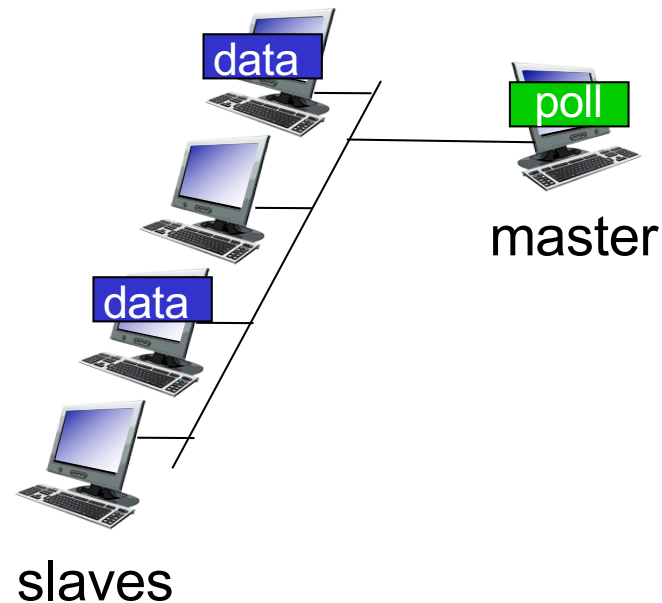
## “taking turns” protocols

look for best of both worlds!

# “Taking turns” MAC protocols

## polling:

- ❖ master node “invites” slave nodes to transmit in turn
- ❖ typically used with “dumb” slave devices
- ❖ concerns:
  - polling overhead
  - latency
  - single point of failure (master)

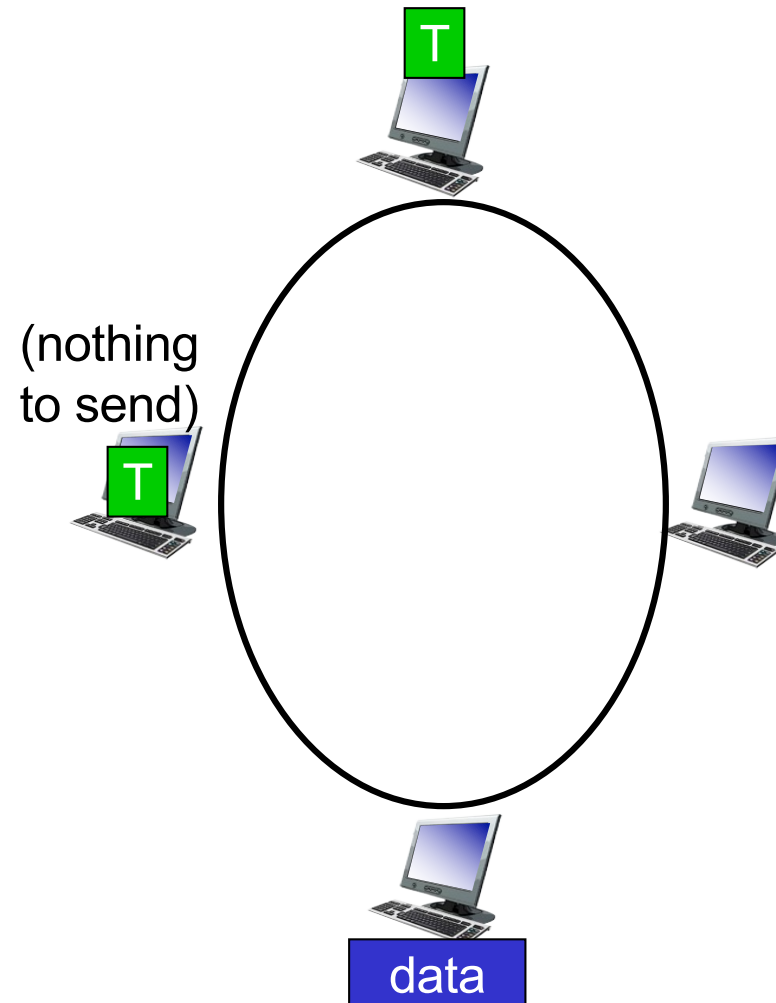




# “Taking turns” MAC protocols

## token passing:

- control *token* passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)



# Summary of MAC protocols

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- ❖ **channel partitioning**, by time, frequency (or code)
  - Time Division, Frequency Division
- ❖ **random access** (dynamic),
  - ALOHA, S-ALOHA, CSMA, CSMA/CD
  - carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in 802.11
- ❖ **taking turns**
  - polling from central site
  - token passing: bluetooth, FDDI, token ring

# Link layer, LANs: outline

6.1 introduction, services

6.2 error detection,  
correction

6.3 multiple access protocols

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- addressing, ARP
- Ethernet
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6.6 data center networking

6.7 a day in the life of a web  
request

# MAC addresses and ARP

## ❖ 32-bit IP address:

- network-layer address for interface
- used for layer 3 (network layer) forwarding

## ❖ MAC (or LAN or physical or Ethernet) address:

- function: **used locally to get frame from one interface to another physically-connected interface (same network, in IP-addressing sense)**
- 48 bit MAC address (for most LANs) burned in NIC ROM, also sometimes software settable
- e.g.: 1A-2F-BB-76-09-AD, also as company\_ID-76-09-AD

identifica o responsável pelo endereço

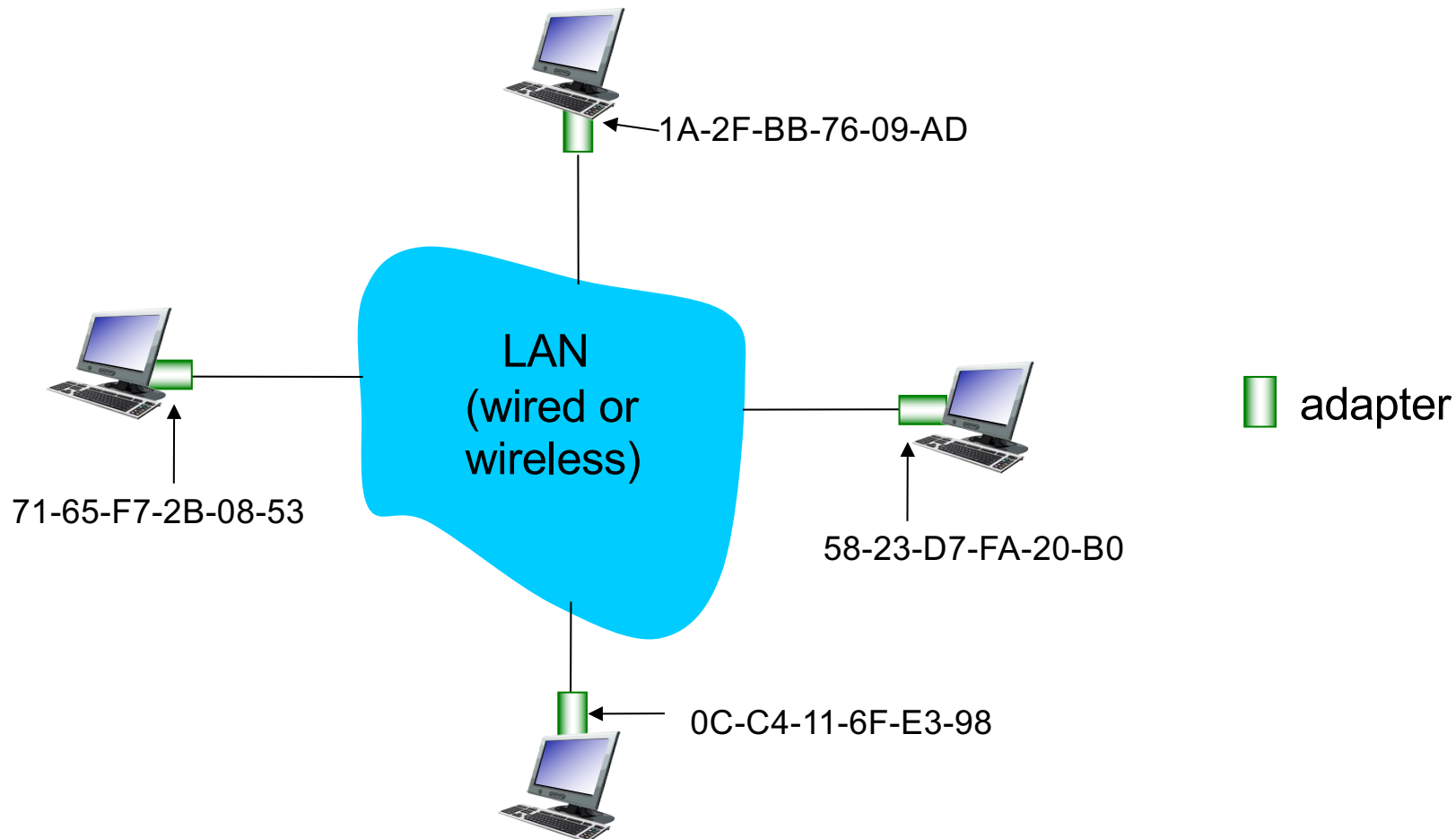
hexadecimal (base 16) notation  
(each “number” represents 4 bits)

1<sup>st</sup> 3 octets represent company\_ID  
(e.g. D-Link, Cisco, HP, Intel, etc. )

→ se uma máquina não tiver ligada à LAN não é possível aceder ao seu IP

# LAN addresses and ARP

each adapter on LAN has unique LAN address



## LAN addresses (more)

- ❖ MAC address allocation administered by IEEE
- ❖ manufacturer buys portion of MAC address space (to assure uniqueness)
- ❖ analogy:
  - MAC address: like Social Security Number
  - IP address: like postal address
- ❖ MAC flat address → portability
  - can move LAN card from one LAN to another
- ❖ IP hierarchical address not portable
  - address depends on IP subnet to which node is attached

# ARP: address resolution protocol

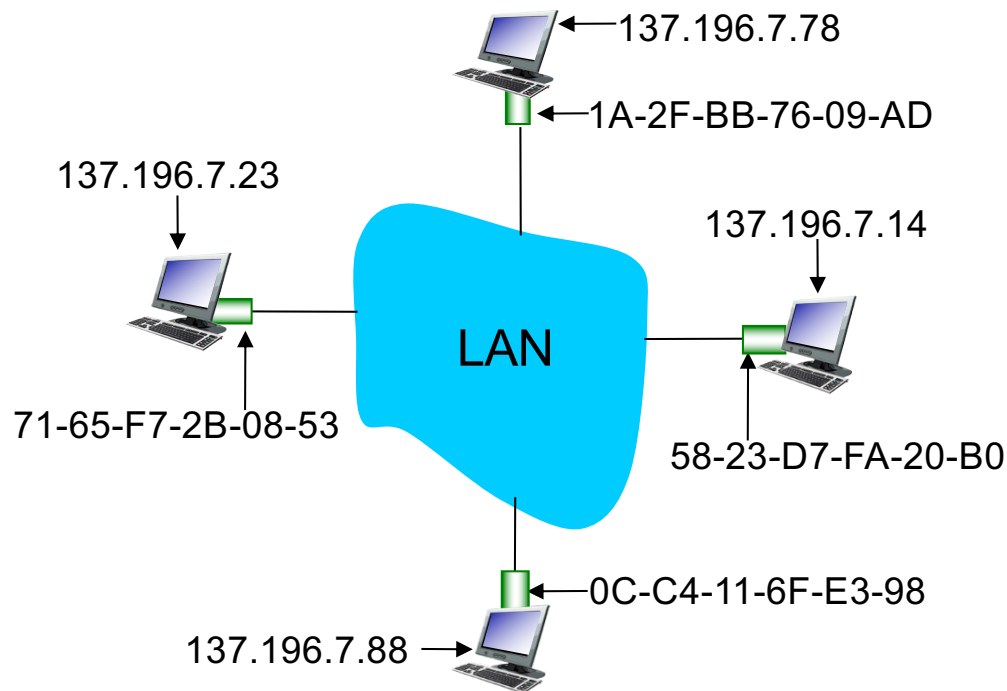
**Question:** how to determine interface's MAC address, knowing its IP address?

**ARP table:** each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:

< IP address; MAC address; TTL >

- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)



# ARP protocol: same LAN

- ❖ A wants to send datagram to B
  - B's MAC address not in A's ARP table.
- ❖ A **broadcasts** ARP query packet, containing B's IP address
  - destination MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query
- ❖ B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's MAC address (unicast)
- ❖ A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed
- ❖ ARP is “plug-and-play”:
  - nodes create their ARP tables without intervention from net administrator

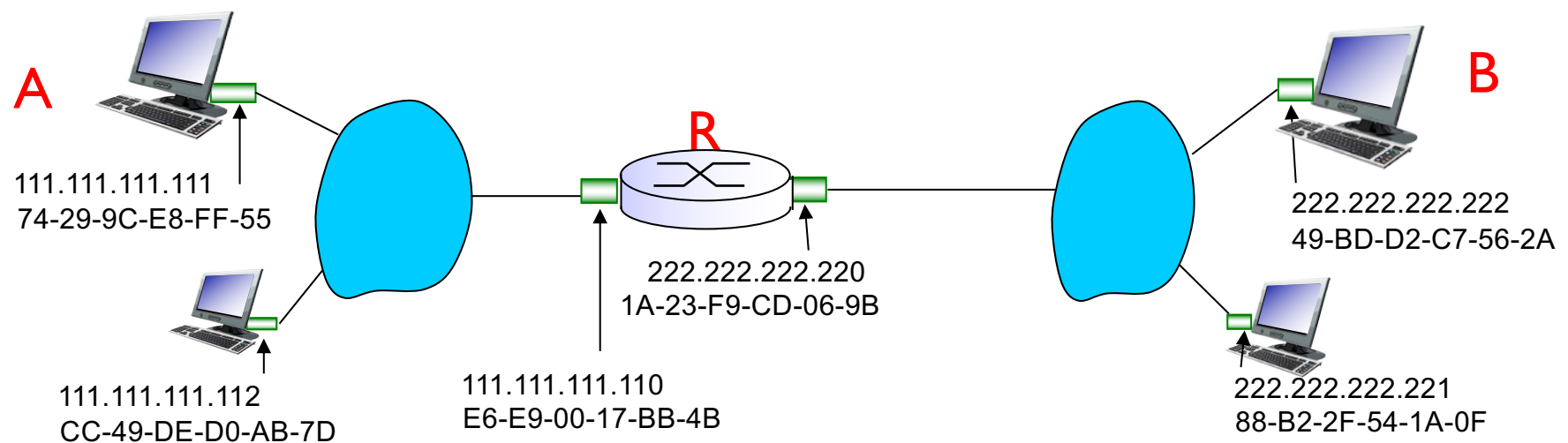


# Addressing: routing to another LAN

→ entrega entre 2 nodes  
que não são adjacentes

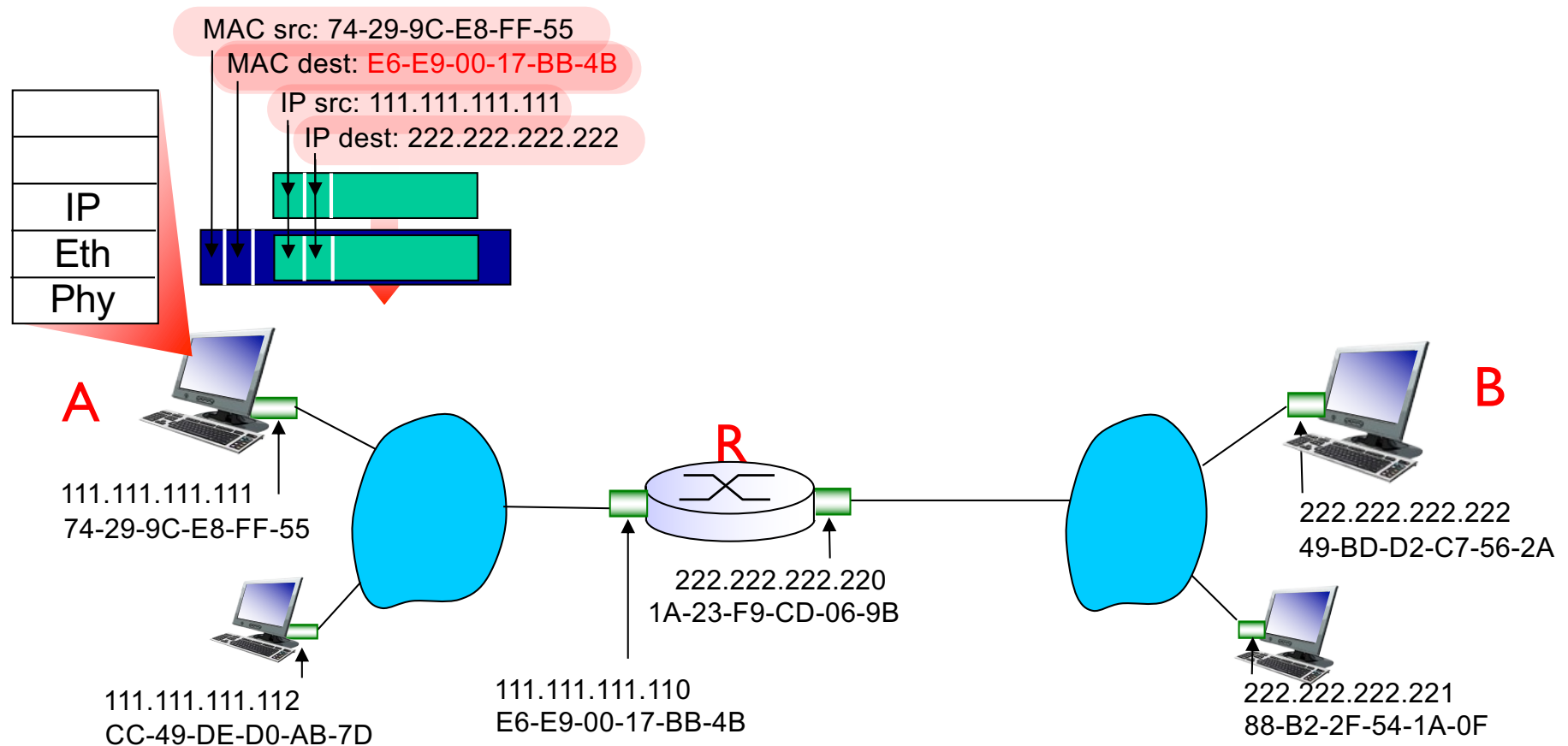
walkthrough: **send datagram from A to B via R**

- focus on addressing – at IP (datagram) and MAC layer (frame)
- assume A knows B's IP address
- assume A knows IP address of first hop router, R (how?)
- assume A knows R's MAC address (how?)



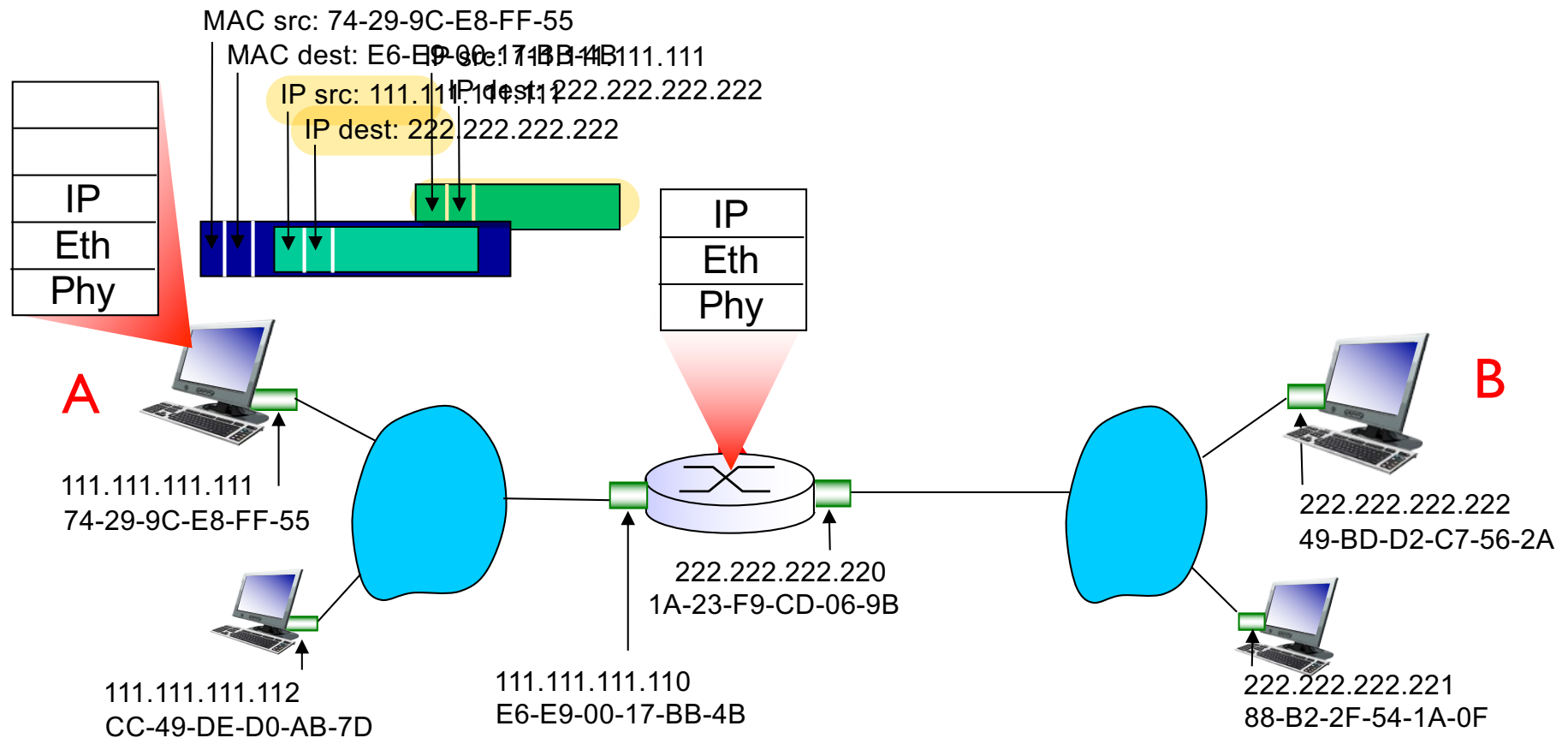
# Addressing: routing to another LAN

- A creates IP datagram with IP source A, destination B
- A creates link-layer frame with R's MAC address as destination address, frame contains A-to-B IP datagram



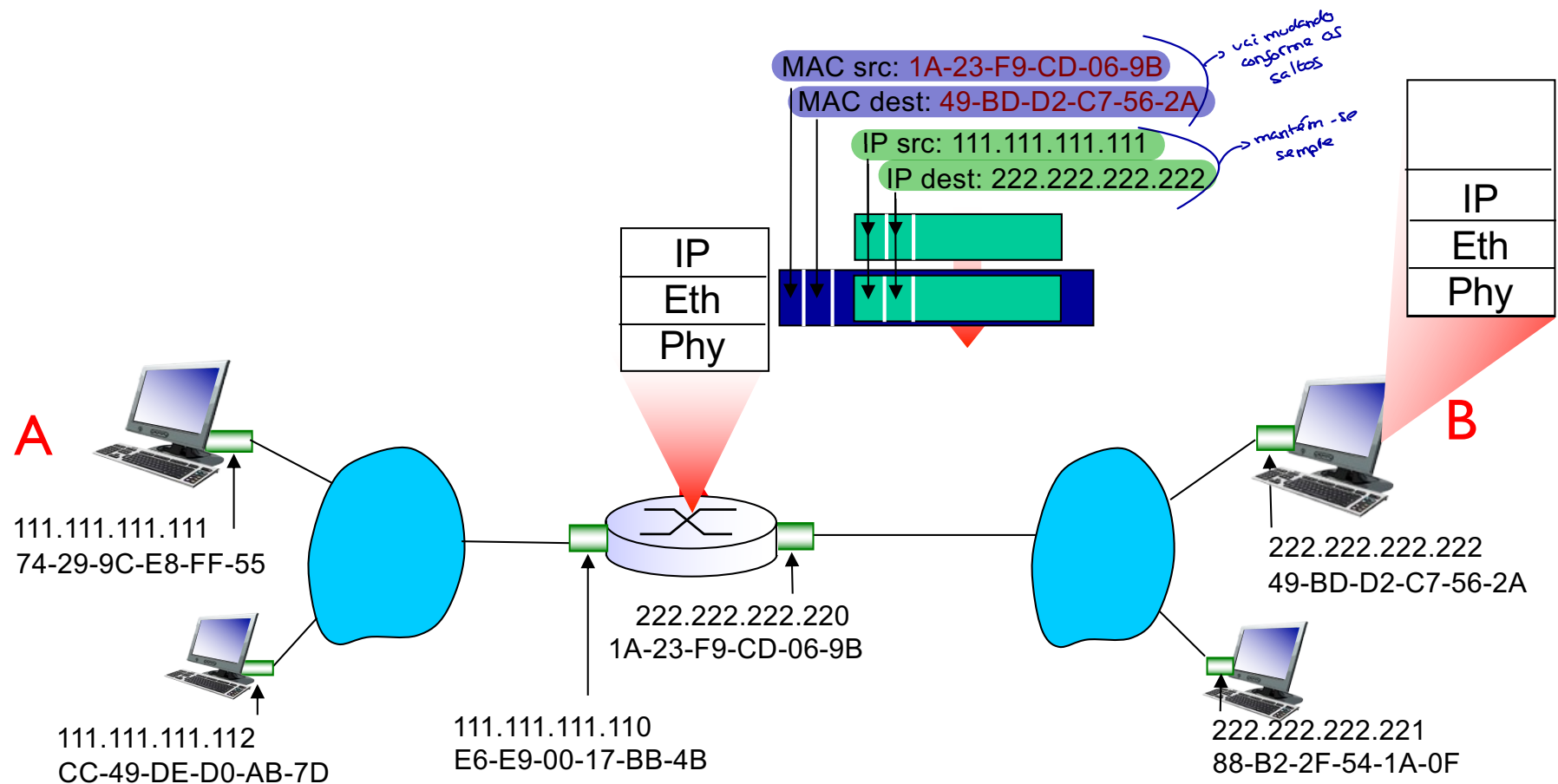
# Addressing: routing to another LAN

- frame sent from A to R
- frame received at R, datagram removed, passed up to IP



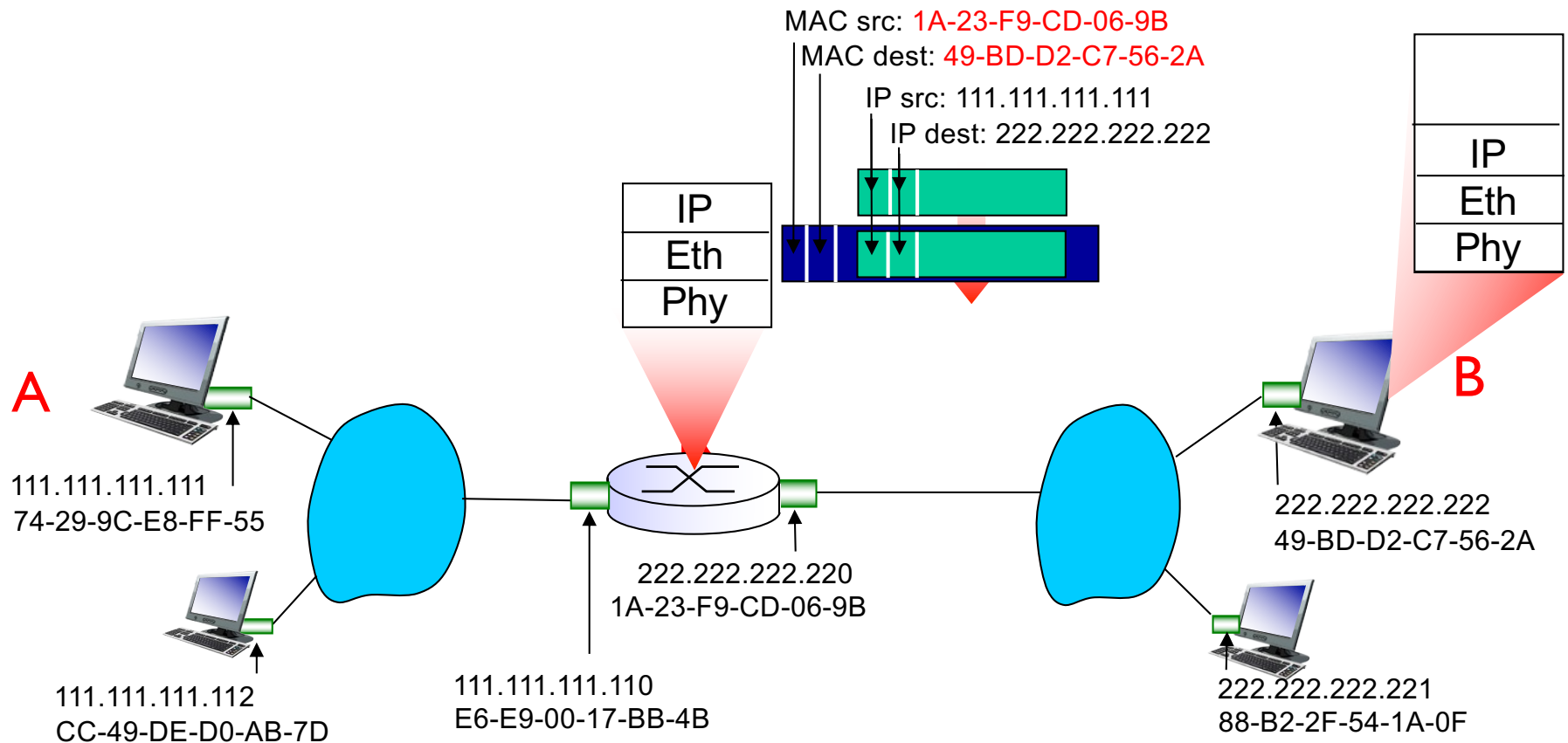
# Addressing: routing to another LAN

- R forwards datagram with IP source A, destination B
- R creates link-layer frame with B's MAC address as destination address, frame contains A-to-B IP datagram



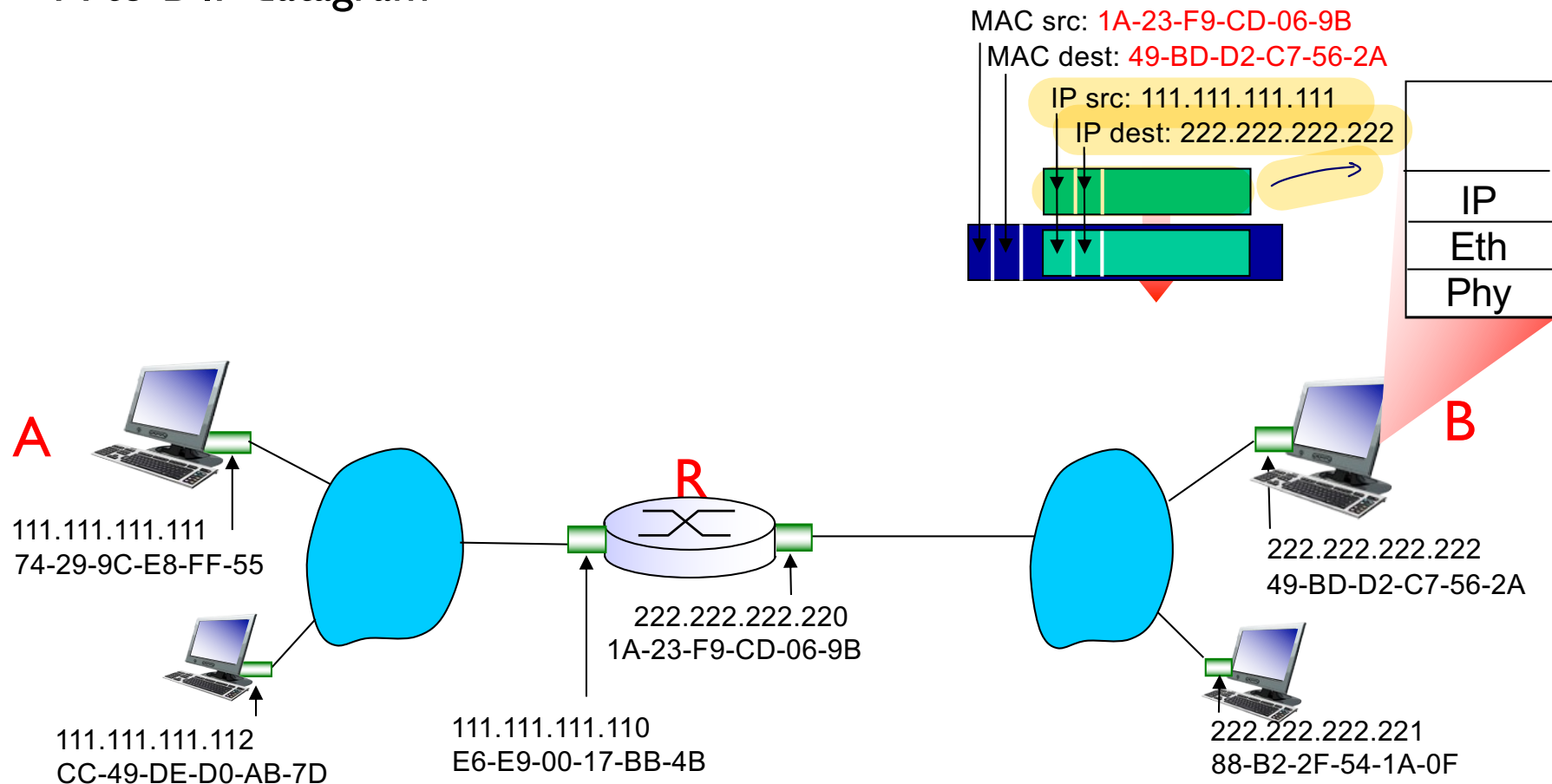
# Addressing: routing to another LAN

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# Addressing: routing to another LAN

- R forwards datagram with IP source A, destination B
- R creates link-layer frame with B's MAC address as dest, frame contains A-to-B IP datagram



\* Check out the online interactive exercises for more examples:  
[http://gaia.cs.umass.edu/kurose\\_ross/interactive/](http://gaia.cs.umass.edu/kurose_ross/interactive/)

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6.3 multiple access  
protocols

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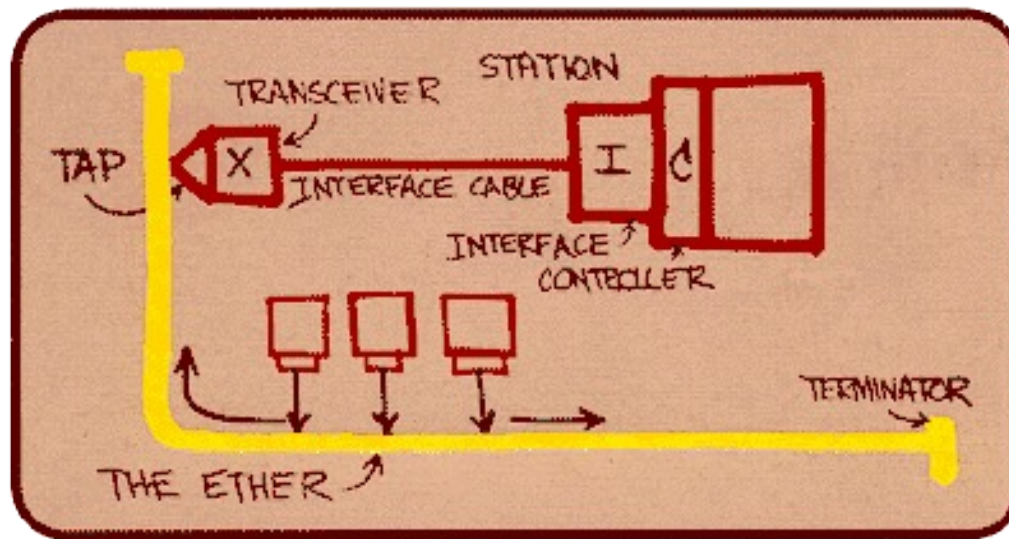
6.6 data center networking

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request

# Ethernet

“dominant” wired LAN technology:

- ❖ first widely used LAN technology
- ❖ simple, cheap
- ❖ single chip, multiple speeds (e.g., Broadcom BCM5761)
- ❖ kept up with speed race: 10 Mbps – 40 Gbps

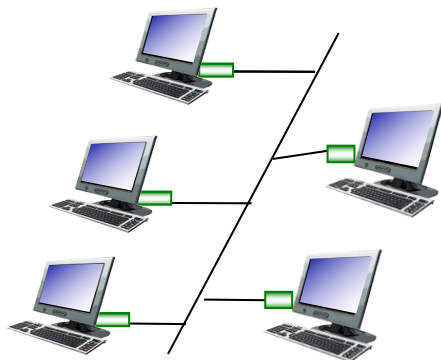


Metcalfe's Ethernet hand sketch, 1976

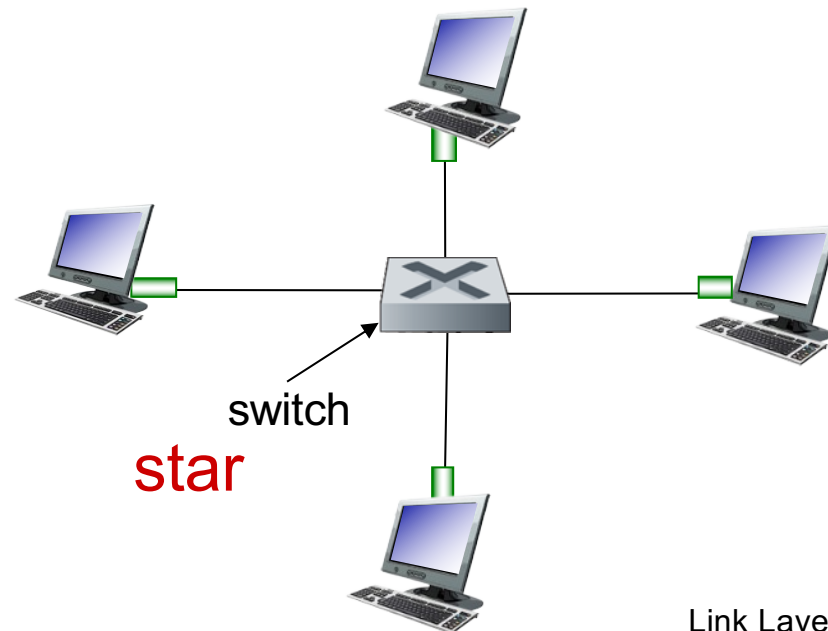


# Ethernet: physical topology

- ❖ **bus**: popular through mid 90s
  - all nodes in same collision domain (can collide with each other)
- ❖ **star**: prevails today
  - active **switch** in center
  - each “spoke” runs a (separate) Ethernet protocol (nodes do not collide with each other)



**bus**: coaxial cable



# Ethernet frame structure

sending adapter encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frame**

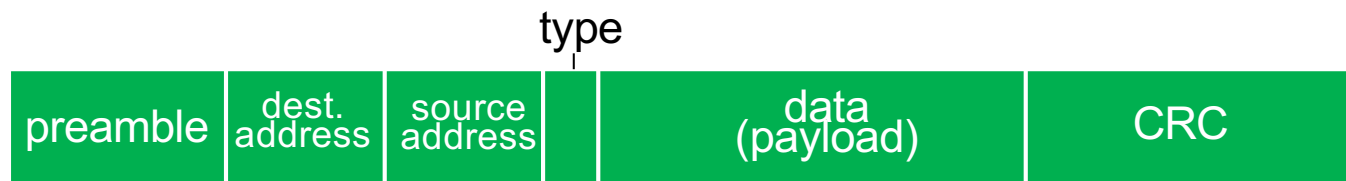


## preamble:

- ❖ 7 bytes with pattern 10101010 followed by one byte with pattern 10101011
- ❖ used to synchronize receiver, sender clock rates

# Ethernet frame structure (more)

- ❖ **addresses:** 6 byte source, destination MAC addresses
  - if adapter receives frame with matching destination address, or with broadcast address (e.g. ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- ❖ **type:** indicates higher layer protocol (mostly IP but others possible, e.g., ARP, Novell IPX, AppleTalk)
- ❖ **CRC:** cyclic redundancy check at receiver
  - aka Frame Check Sequence (FCS)
  - error detected: frame is dropped



# Ethernet: unreliable, connectionless

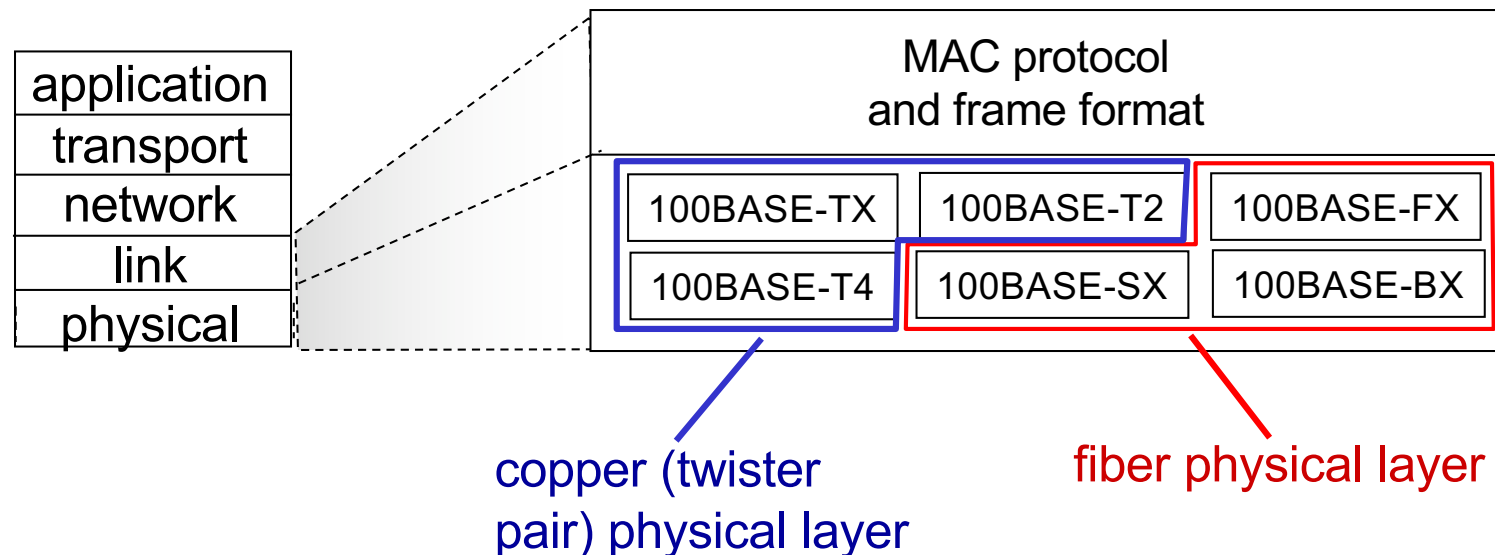
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- ❖ **connectionless**: no handshaking between sending and receiving NICs
- ❖ **unreliable**: receiving NIC doesn't send acks or negative acks (nacks) to sending NIC
  - data in dropped frames recovered only if initial sender uses higher layer reliable data transfer (rdt) protocol (e.g., TCP), otherwise dropped data is lost
- ❖ Ethernet's MAC protocol: unslotted **CSMA/CD (Carrier Sense Multiple Access / Collision Detection)** with binary backoff.

## 802.3 Ethernet standards: link & physical layers

### ❖ many different Ethernet standards

- common MAC protocol and frame format
- different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1 Gbps, 10Gbps, 40 Gbps
- different physical layer media: fiber, cable



# Link layer, LANs: outline

6.1 introduction, services

6.2 error detection,  
correction

6.3 multiple access  
protocols

6.4 LANs

- addressing, ARP
- Ethernet
- switches
- VLANs

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web  
request

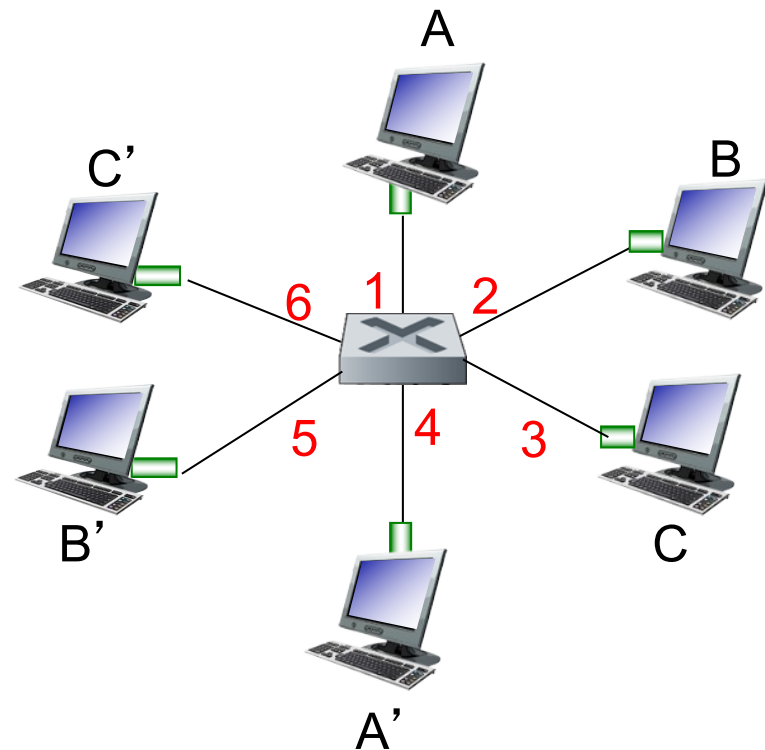
# Ethernet switch

- ❖ link-layer device: takes an active role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, **selectively** forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- ❖ transparent
  - hosts are unaware of presence of switches
- ❖ plug-and-play, self-learning
  - switches do not need to be configured

# Switch: multiple simultaneous transmissions

---

- ❖ hosts have dedicated, direct connection to switch
- ❖ switches buffer packets
- ❖ Ethernet protocol used on each incoming link, but no collisions; full duplex
  - each link is its own collision domain
- ❖ **switching:** A-to-A' and B-to-B' can transmit simultaneously, without collisions



switch with six interfaces  
(1,2,3,4,5,6)



# Switch forwarding table

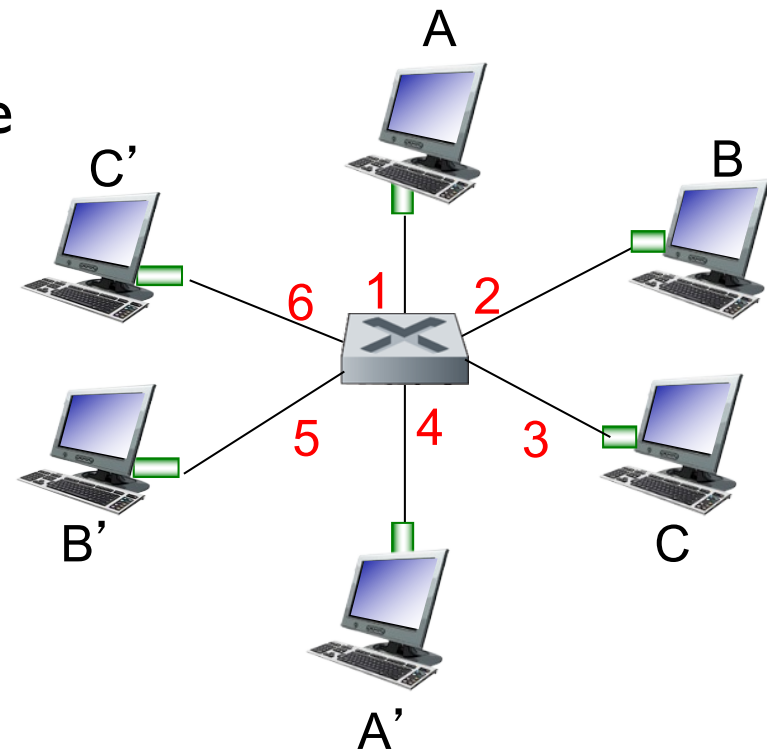
Q: how does switch know A' reachable via interface 4, B' reachable via interface 5?

❖ A: each switch has a **switch table**, each entry:

- (MAC address of host, interface to reach host, timestamp)
- looks like a routing table!

Q: how are entries created, maintained in switch table?

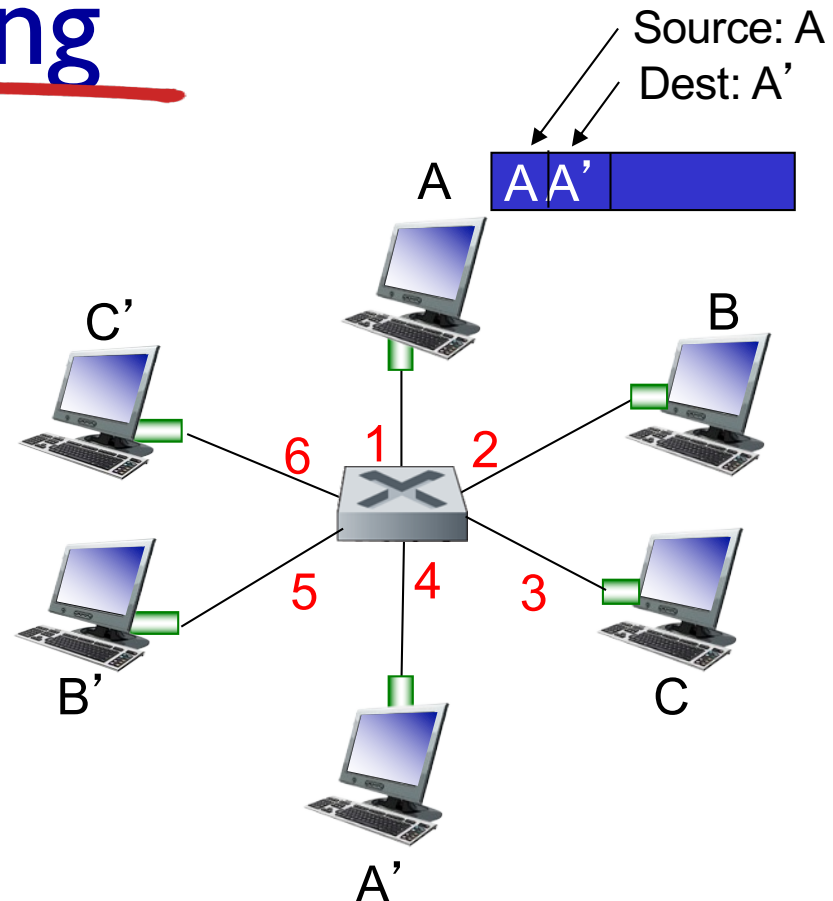
- something like a routing protocol?



switch with six interfaces  
(1,2,3,4,5,6)

# Switch: self-learning

- switch *learns* which hosts can be reached through which interfaces
  - when frame received, switch “learns” location of sender: incoming LAN segment
  - records sender/location pair in switch table



MAC addr	interface	TTL
A	1	60

*Switch table  
(initially empty)*

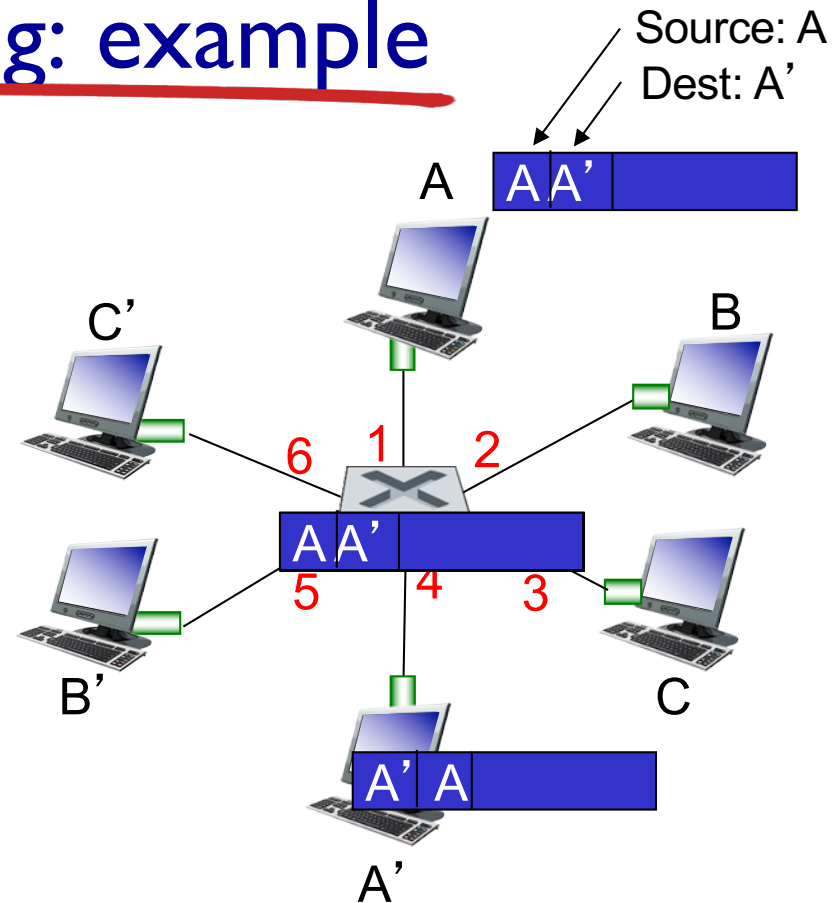
# Switch: frame filtering/forwarding

when frame received at switch:

1. record incoming link, MAC address of sending host
2. index switch table using MAC destination address
3. if entry found for destination  
    then {  
        if destination on segment from which frame arrived  
            then drop frame  
            else forward frame on interface indicated by entry  
        }  
    else flood /\* forward on all interfaces except arriving  
                    interface \*/

# Self-learning, forwarding: example

- frame destination, A', location unknown: *flood*
- destination A location known: *selectively send on just one link*

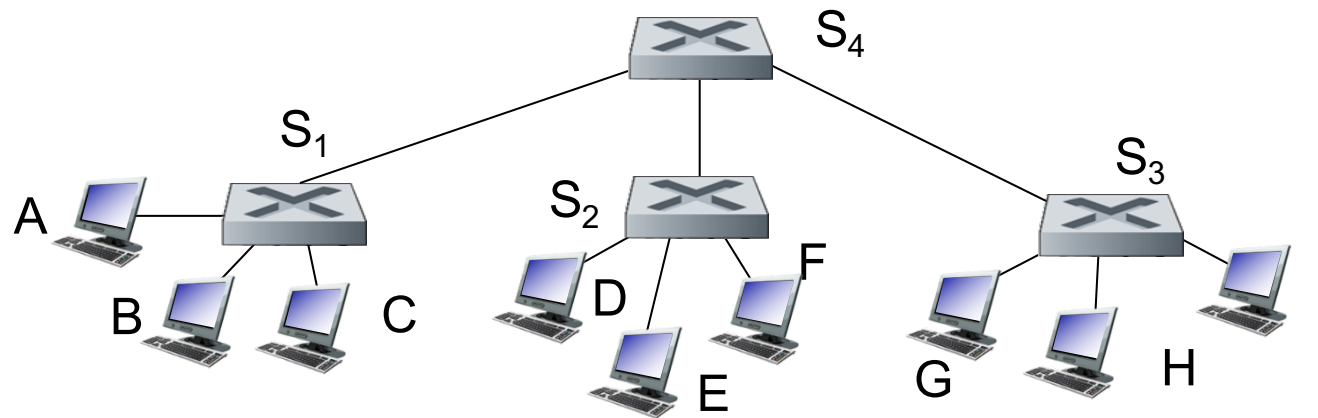


MAC addr	interface	TTL
A	1	60
A'	4	60

*switch table  
(initially empty)*

# Interconnecting switches

- ❖ switches can be connected together

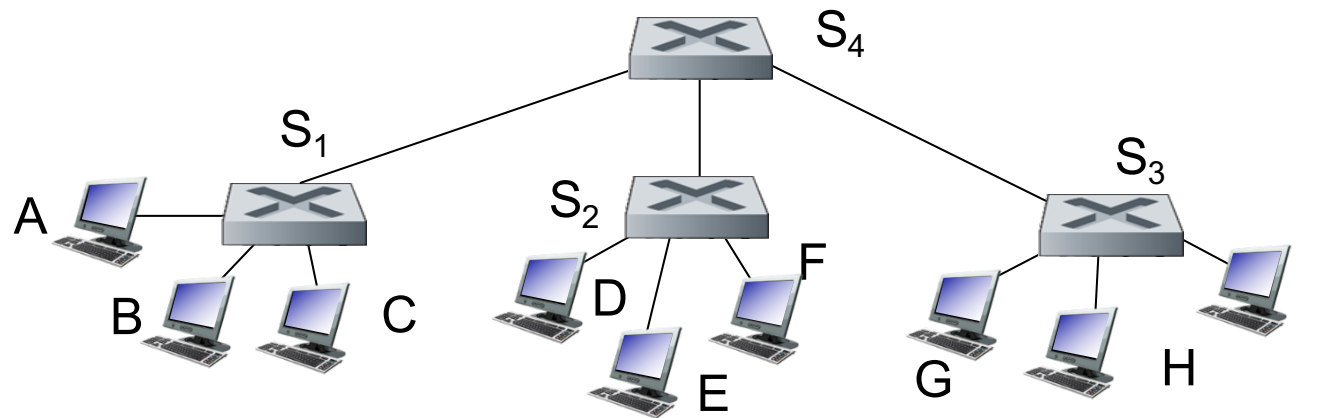


**Q:** sending from A to G - how does S<sub>1</sub> know to forward frame destined to G via S<sub>4</sub> and S<sub>3</sub>?

❖ **A:** self learning! (works exactly the same as in single-switch case!)

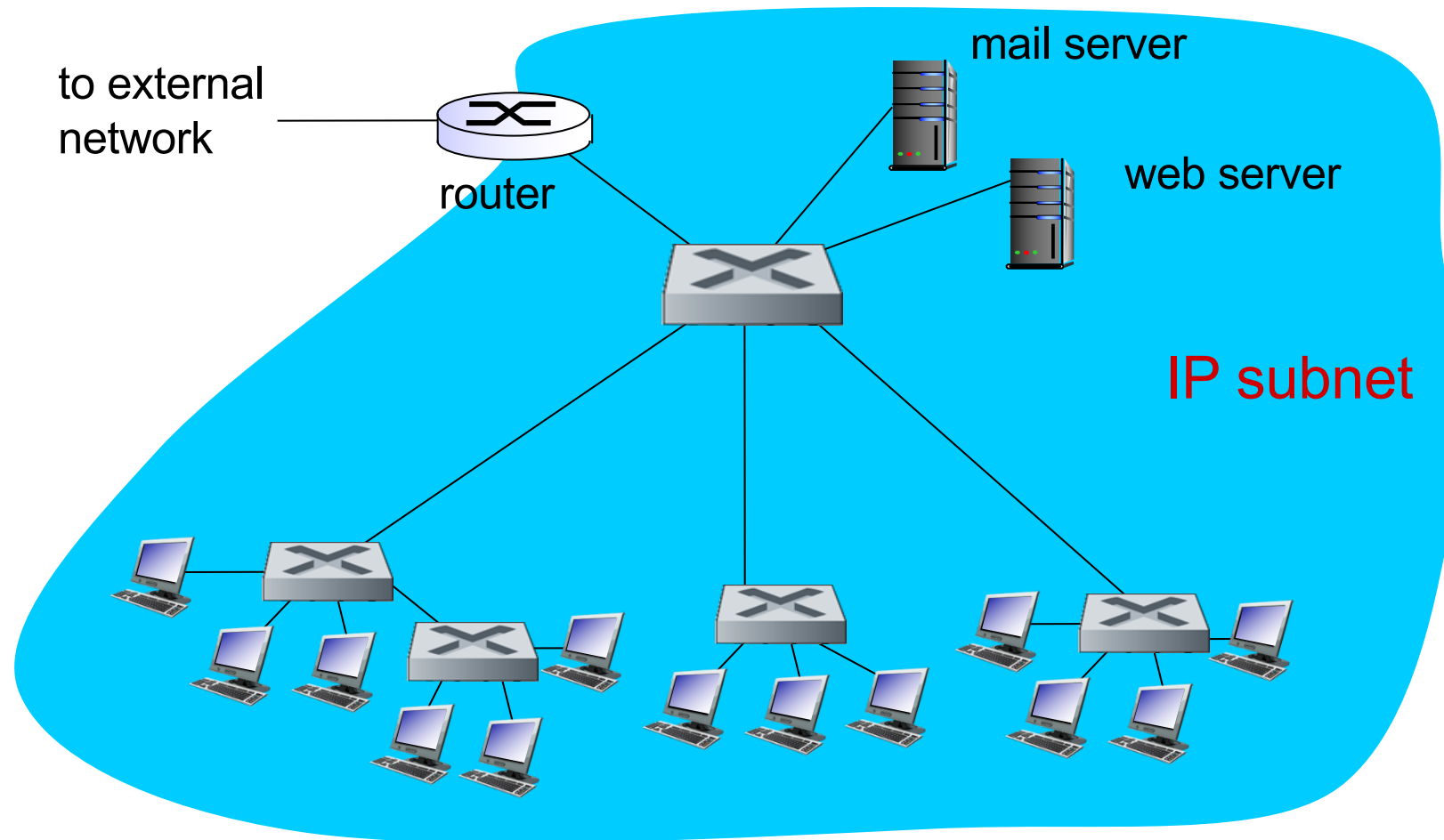
# Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



- ❖ Q: show switch tables and packet forwarding in S<sub>1</sub>, S<sub>2</sub>, S<sub>3</sub>, S<sub>4</sub>

# Institutional network



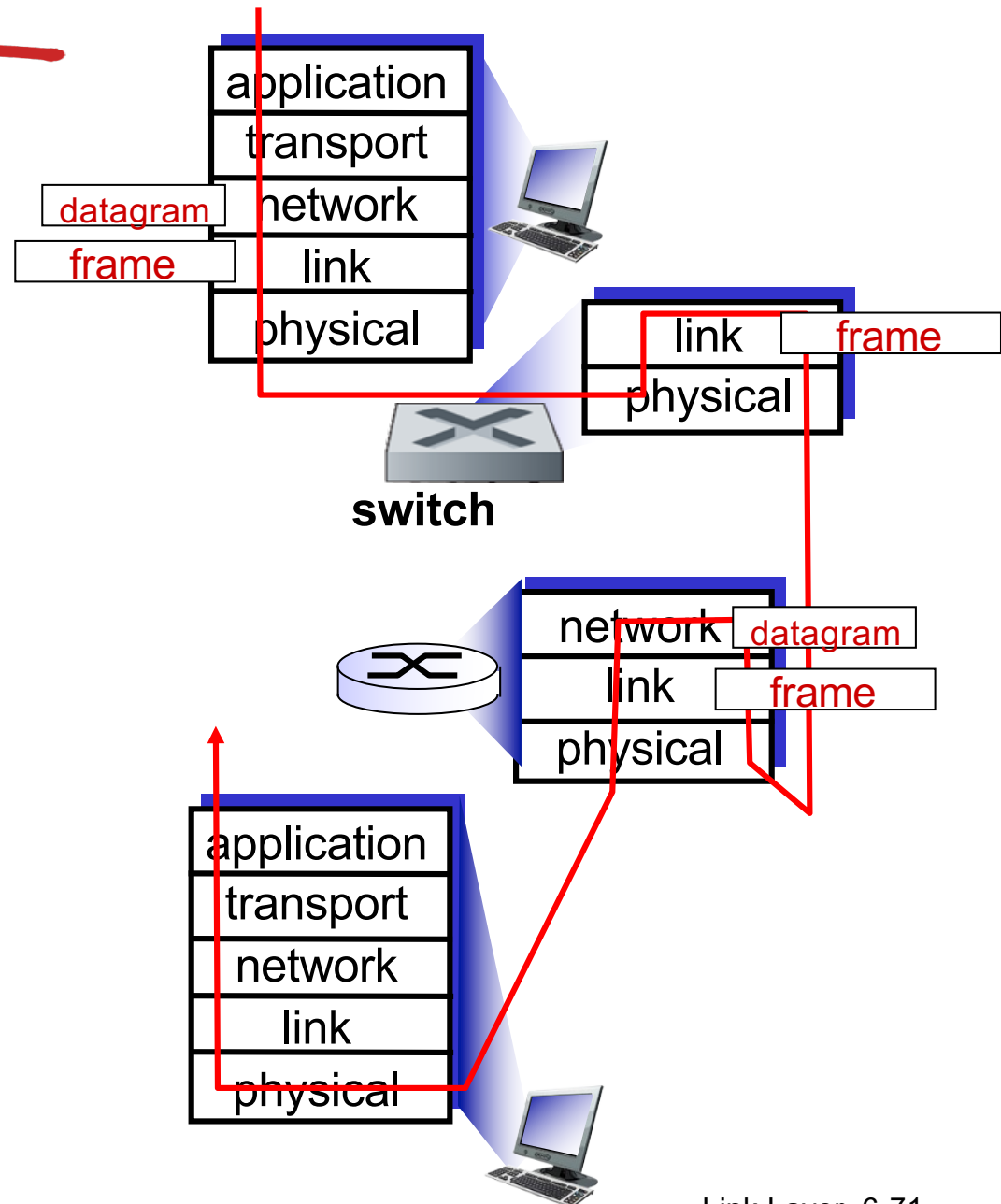
# Switches vs. routers

both are store-and-forward:

- **routers:** network-layer devices (examine network-layer headers)
- **switches:** link-layer devices (examine link-layer headers)

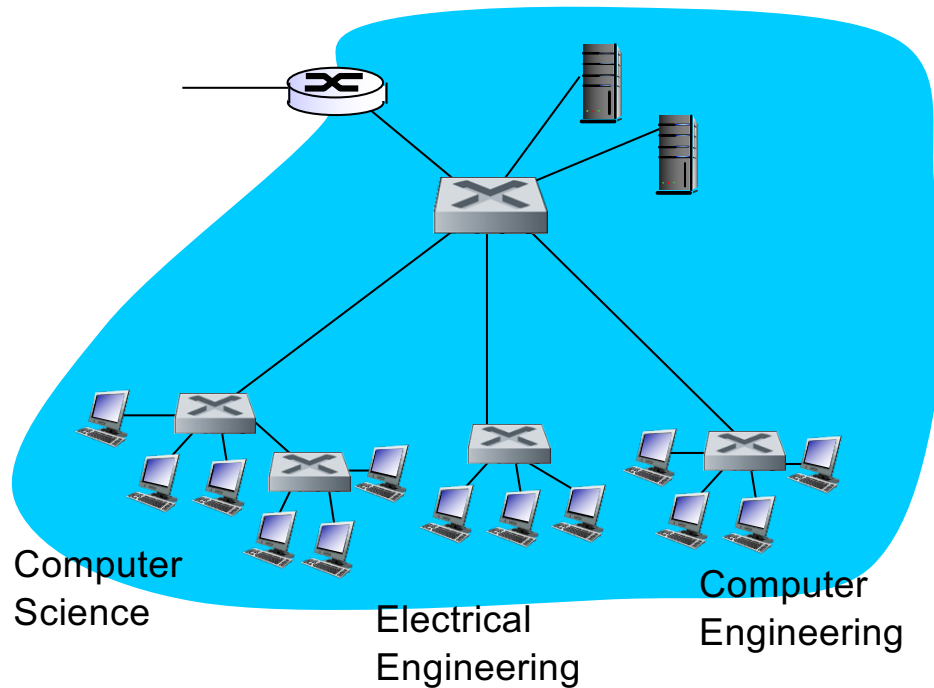
both have forwarding tables:

- **routers:** compute tables using routing algorithms, IP addresses
- **switches:** learn forwarding table using flooding, learning, MAC addresses





# VLANs: motivation



## consider:

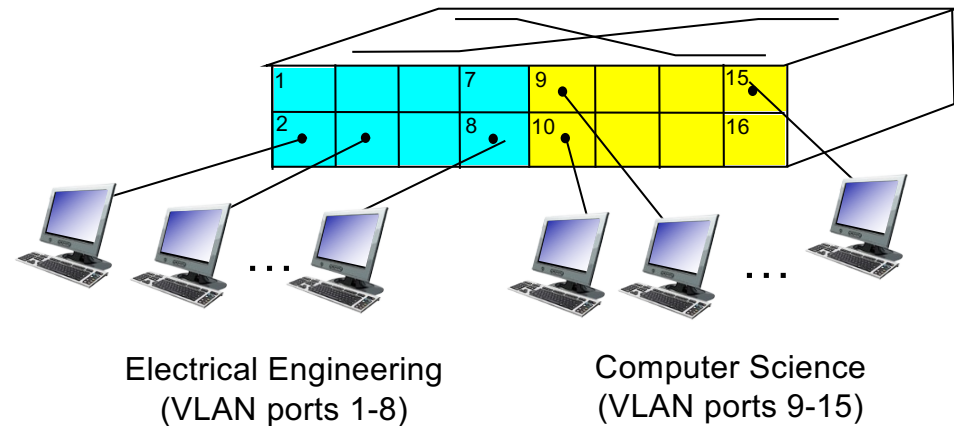
- ❖ CS user moves office to EE, but wants connect to CS switch?
- ❖ single broadcast domain:
  - all layer-2 broadcast traffic (ARP, DHCP, unknown location of destination MAC address) must cross entire LAN
  - security/privacy, efficiency issues

# VLANs

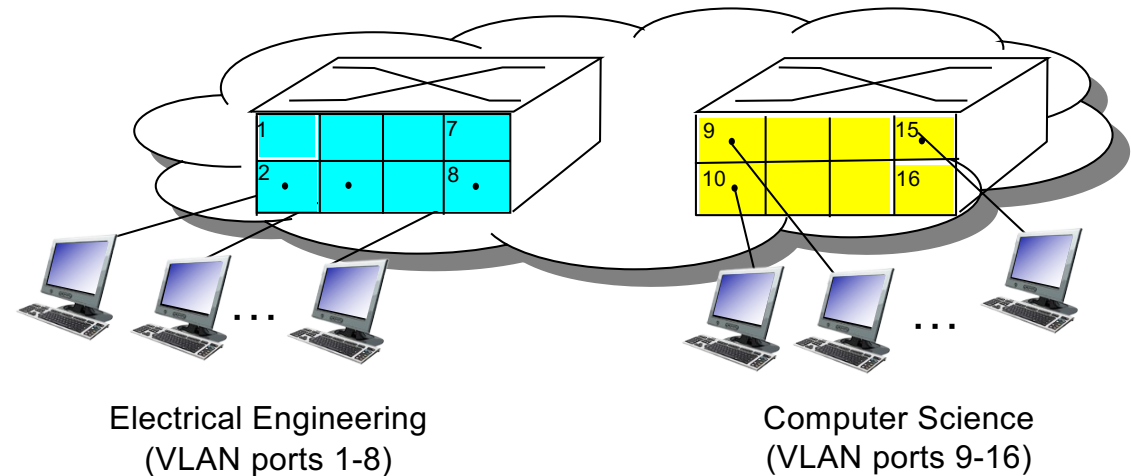
## Virtual Local Area Network

switch(es) supporting VLAN capabilities can be configured to define multiple **virtual** LANS over single physical LAN infrastructure.

**port-based VLAN:** switch ports grouped (by switch management software) so that **single** physical switch .....

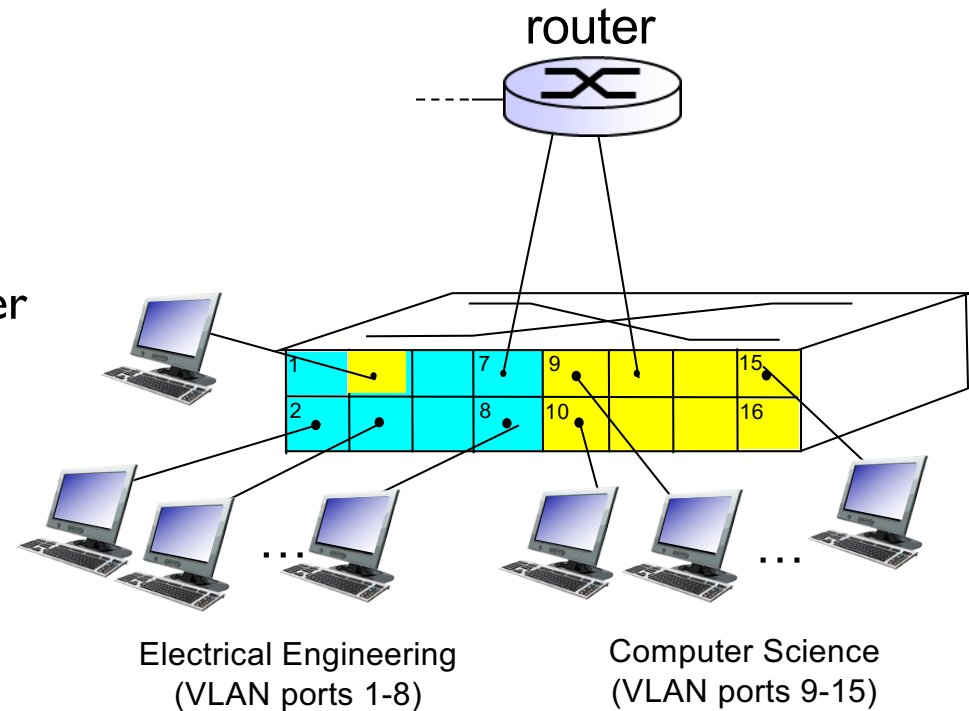


... operates as **multiple** virtual switches

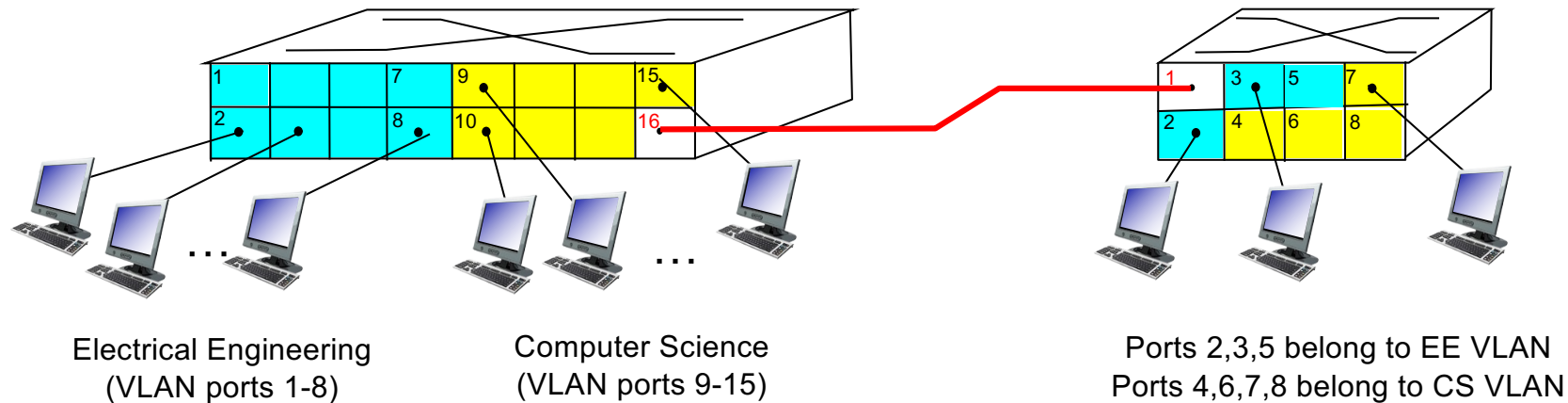


# Port-based VLAN

- ❖ **traffic isolation:** frames to/from ports 1-8 can only reach ports 1-8
  - can also define VLAN based on MAC addresses of endpoints, rather than switch port
- ❖ **dynamic membership:** ports can be dynamically assigned among VLANs
- ❖ **forwarding between VLANs:** done via routing (just as with separate switches)
  - in practice vendors sell combined switches plus routers

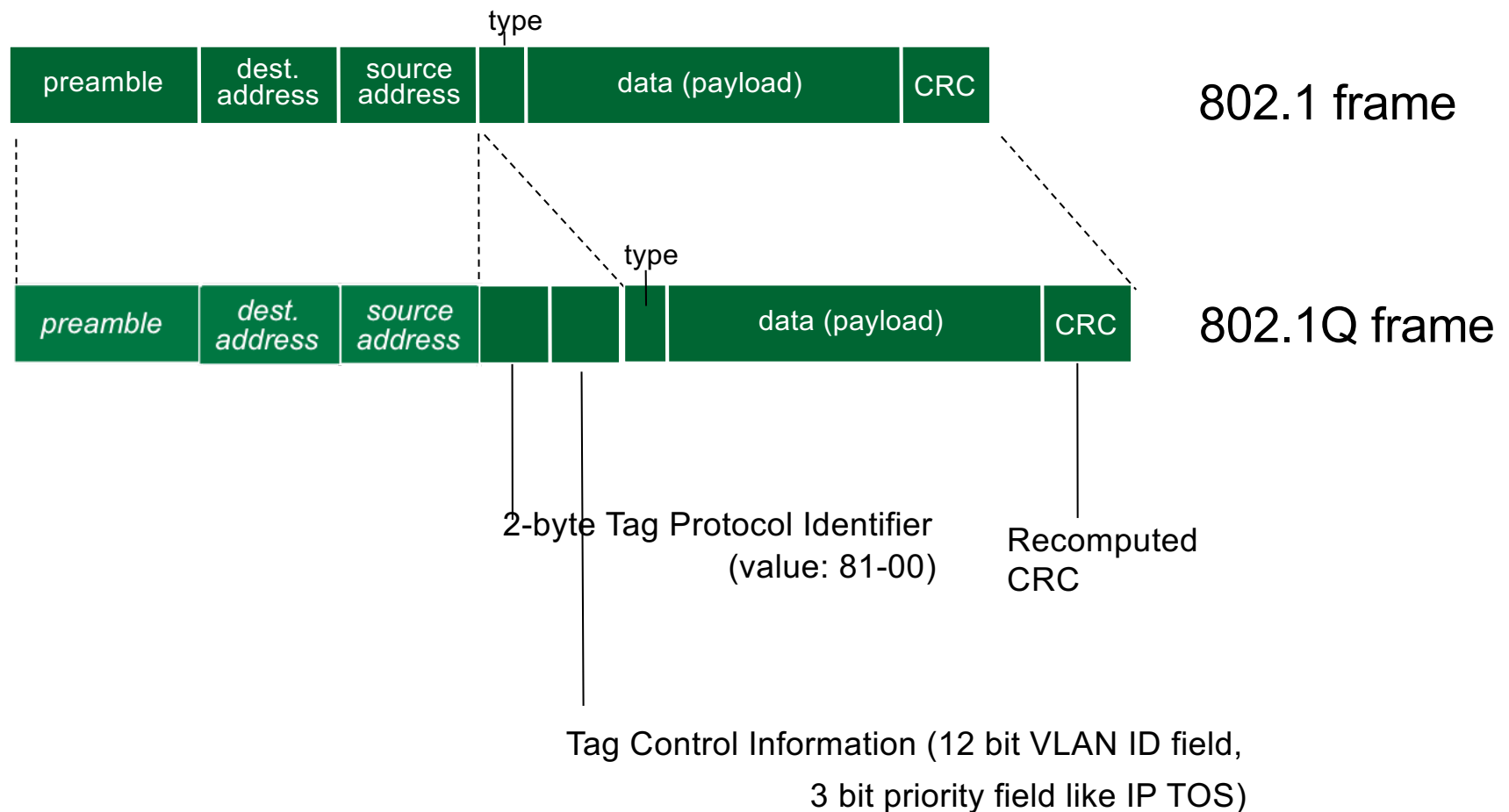


# VLANs spanning multiple switches



- ❖ **trunk port:** carries frames between VLANs defined over multiple physical switches
  - frames forwarded within VLAN between switches can't be vanilla 802.1 frames (must carry VLAN ID info)
  - 802.1q protocol adds/removed additional header fields for frames forwarded between trunk ports

# 802.1Q VLAN frame format



# Link layer, LANs: outline

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correction

5.3 multiple access protocols

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- Ethernet
- switches
- VLANs

5.5 link virtualization: MPLS

5.6 data center networking

5.7 a day in the life of a web  
request

Fim do capítulo para RC

# Chapter 5: Summary

- ❖ principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
- ❖ instantiation and implementation of various link layer technologies
  - Ethernet
  - switched LANS, VLANs
  - virtualized networks as a link layer: MPLS
- ❖ synthesis: a day in the life of a web request