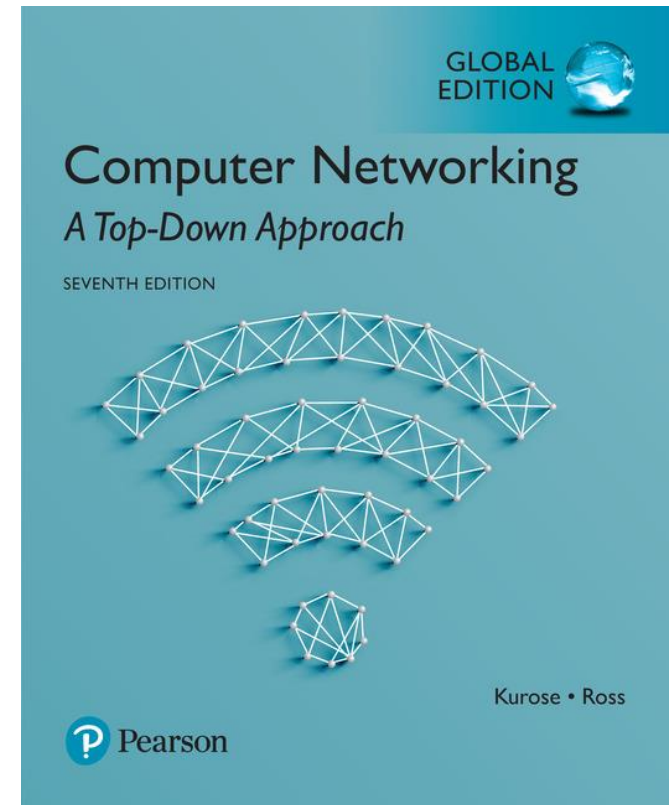# Chapter 6
The Link Layer and LANs

A note on the use of these Powerpoint slides:

We're making these slides freely available to all (faculty, students, readers). They're in PowerPoint form so you see the animations; and can add, modify, and delete slides (including this one) and slide content to suit your needs. They obviously represent a *lot* of work on our part. In return for use, we only ask the following:

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- If you post any slides on a www site, that you note that they are adapted from (or perhaps identical to) our slides, and note our copyright of this material.
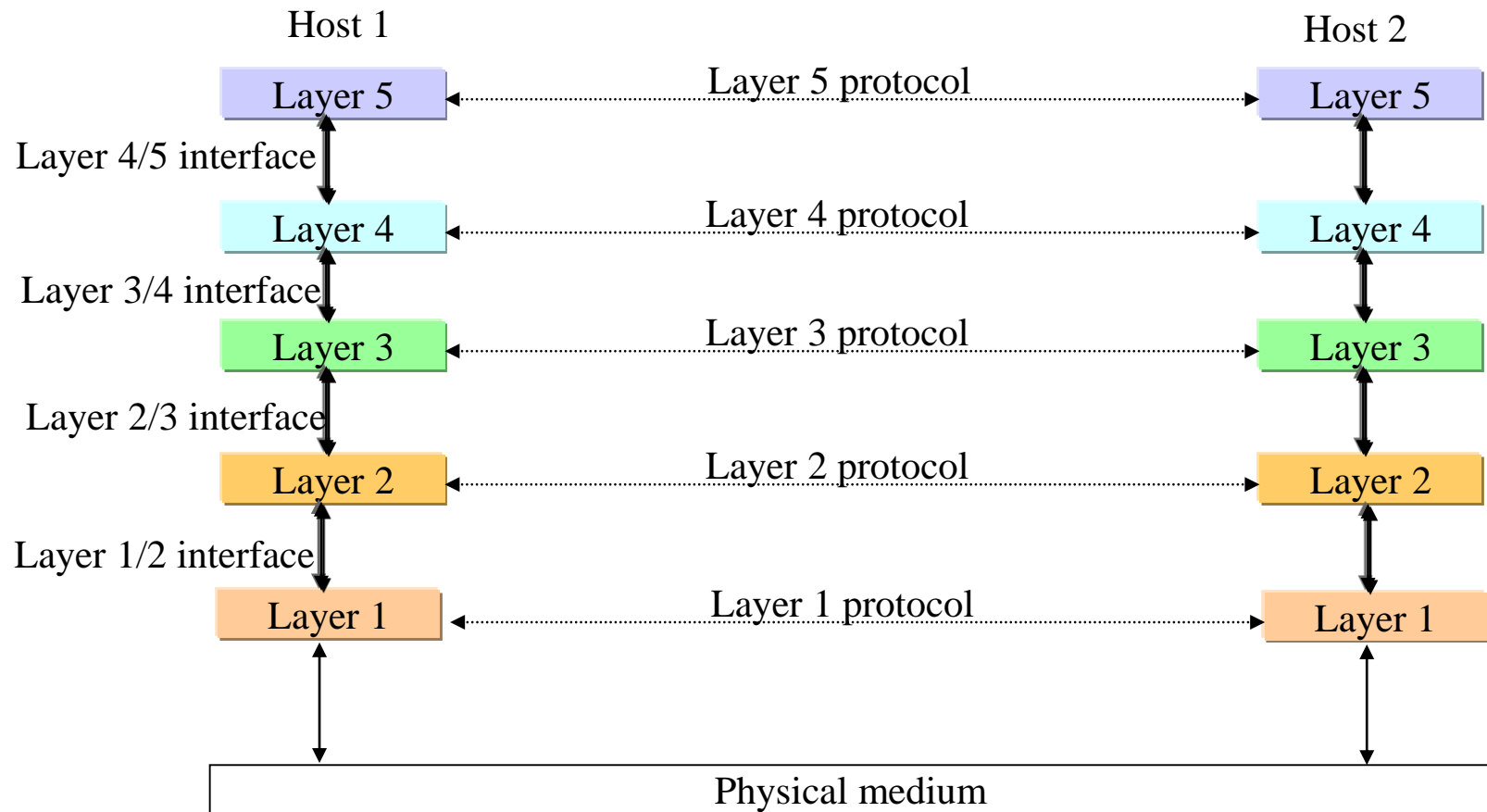
Thanks and enjoy! JFK/KWR

Computer Networking: A Top Down Approach

7th Edition, Global Edition
Jim Kurose, Keith Ross
Pearson
April 2016

Layers, Protocol, and Interfaces

Host 1   Host 2

| Layer 5 | ←······· Layer 5 protocol ·······→ | Layer 5 |

Layer 4/5 interface

| Layer 4 | ←······· Layer 4 protocol ·······→ | Layer 4 |

Layer 3/4 interface

| Layer 3 | ←······· Layer 3 protocol ·······→ | Layer 3 |

Layer 2/3 interface

| Layer 2 | ←······· Layer 2 protocol ·······→ | Layer 2 |

Layer 1/2 interface

| Layer 1 | ←······· Layer 1 protocol ·······→ | Layer 1 |

Physical medium

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
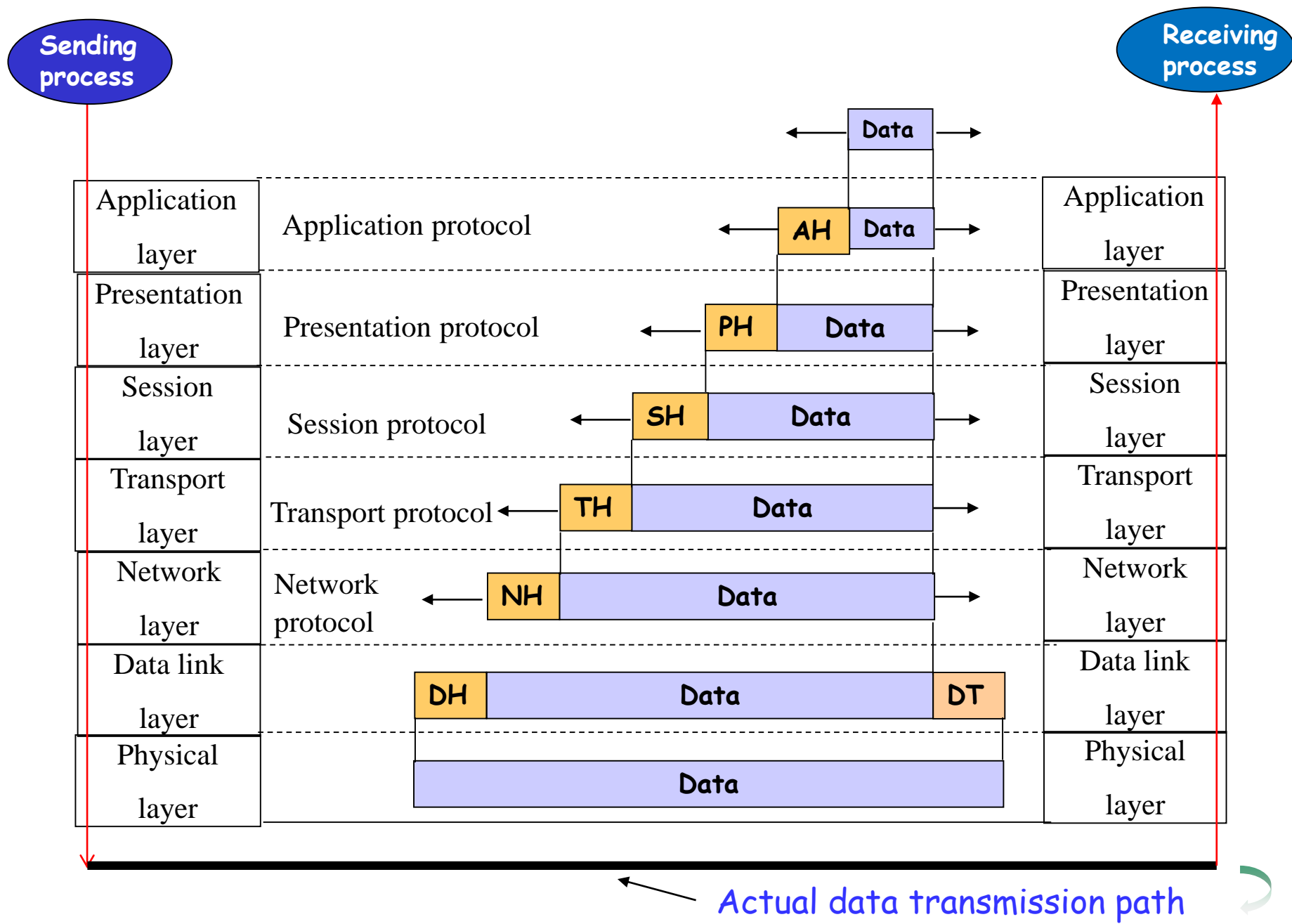
Link layer: introduction

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**

Sending process

Receiving process

Application layer	Application protocol	AH	Data
Presentation layer	Presentation protocol	PH	Data
Session layer	Session protocol	SH	Data
Transport layer	Transport protocol	TH	Data
Network layer	Network protocol	NH	Data
Data link layer		DH	Data	DT
Physical layer		Data

Data

Actual data transmission path
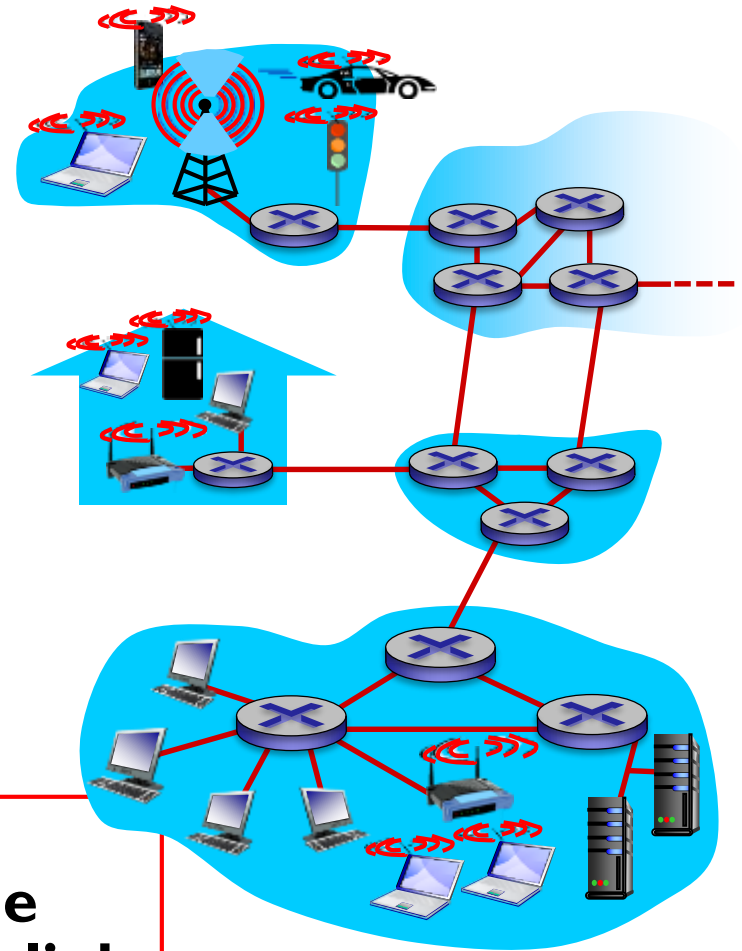
Link layer: context

- 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
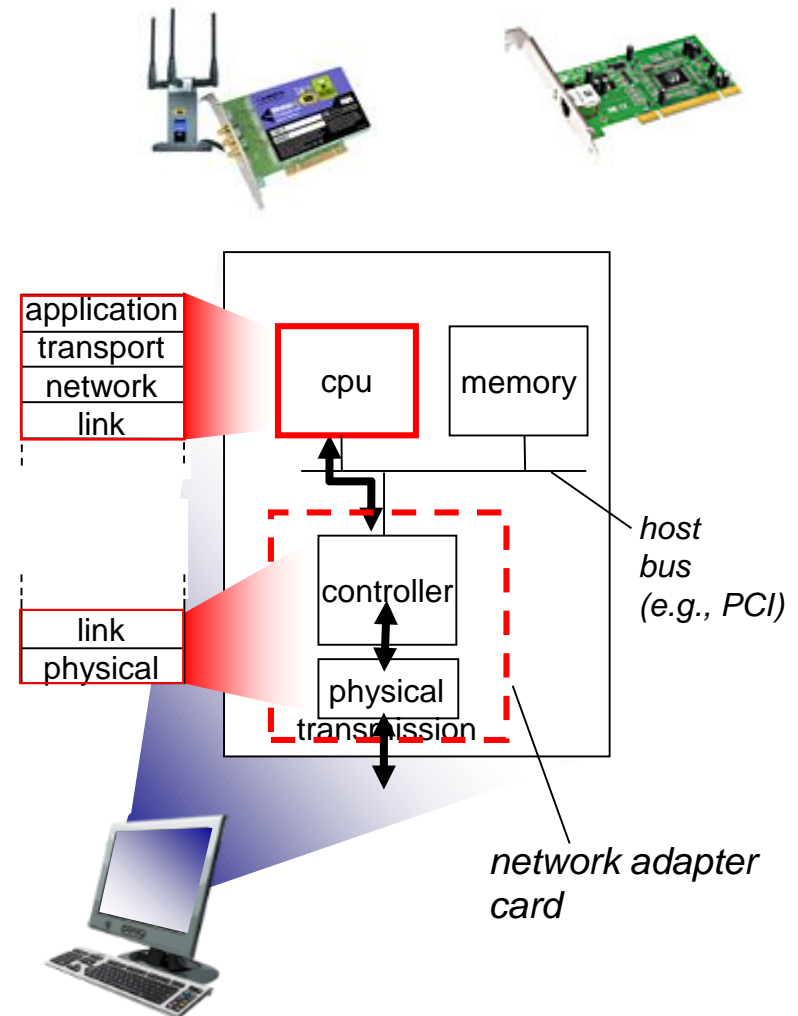   - e.g., may or may not provide rdt (reliable data transfer) over link
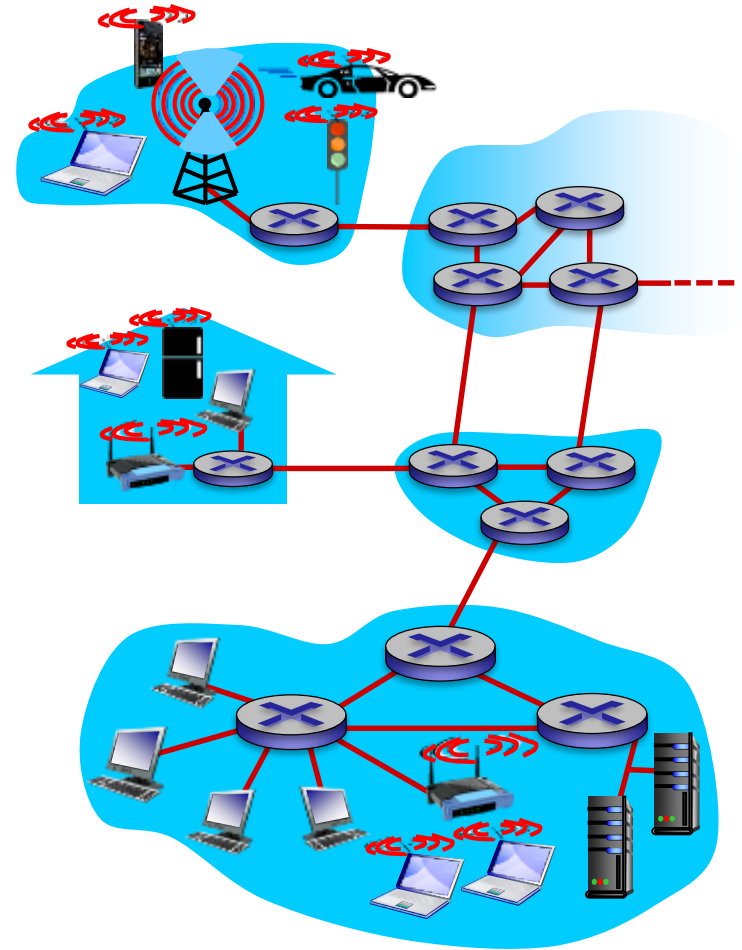
Link layer services

- *framing,* *link access:*
  - <u>encapsulate</u> datagram into frame, adding header, trailer
  - 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 rates**
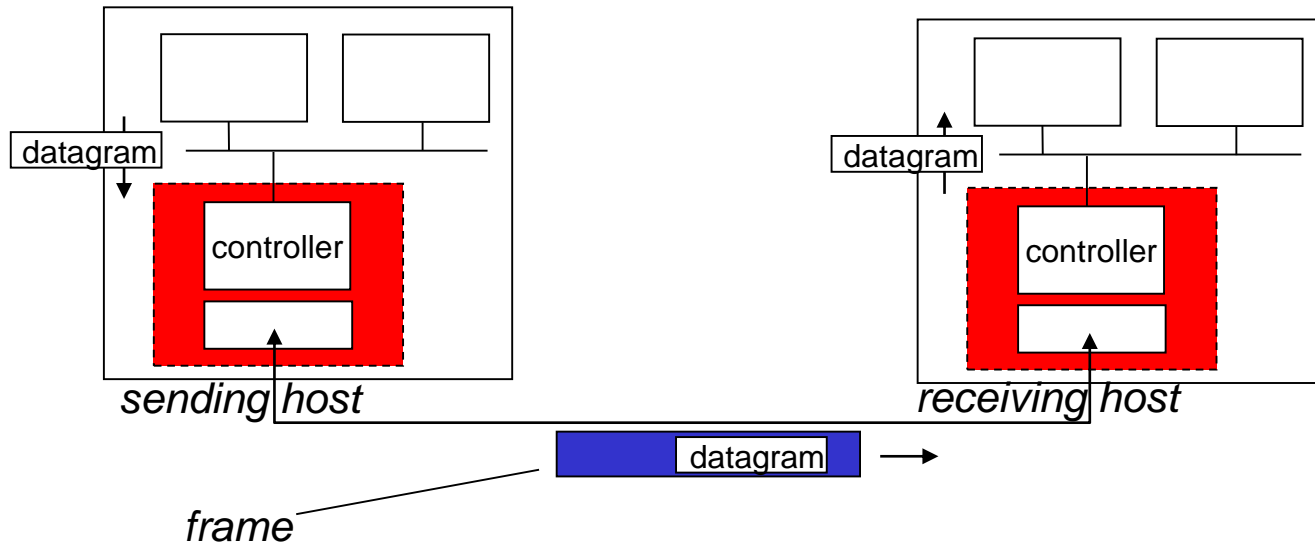
Link layer services (more)

- *flow control:*
  - pacing between adjacent sending and receiving nodes
- *error detection:*
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame
- *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
  - 802.11 chipset, Ethernet chipset
  - implements link, physical layer
- attaches into host's system buses
- combination of hardware, software, firmware

application
transport
network
link

cpu   memory

host
bus
(e.g., PCI)

link
physical

controller

physical
transmission

network adapter
card

Adaptors communicating

- sending side:
  - **encapsulates** datagram in frame
  - **adds** error checking bits, rdt, flow control, etc.

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

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

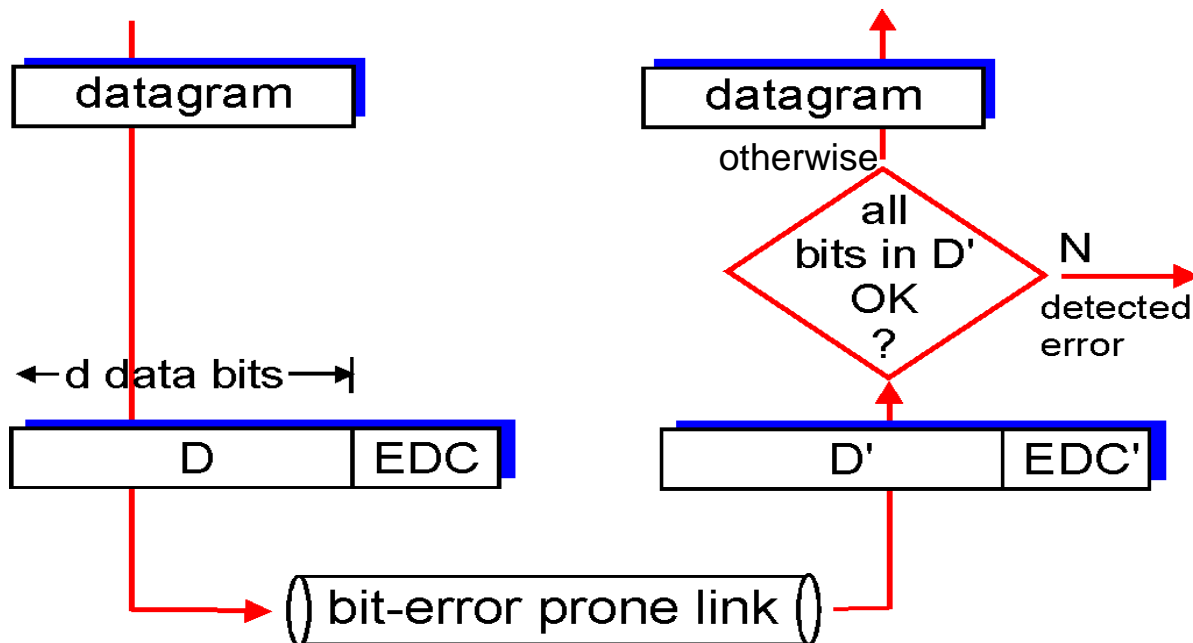6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

Error detection

EDC= **Error Detection and Correction bits** (redundancy)
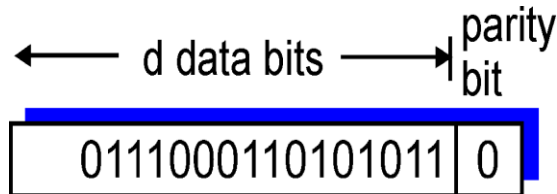D   = **Data** protected by error checking, may include header fields

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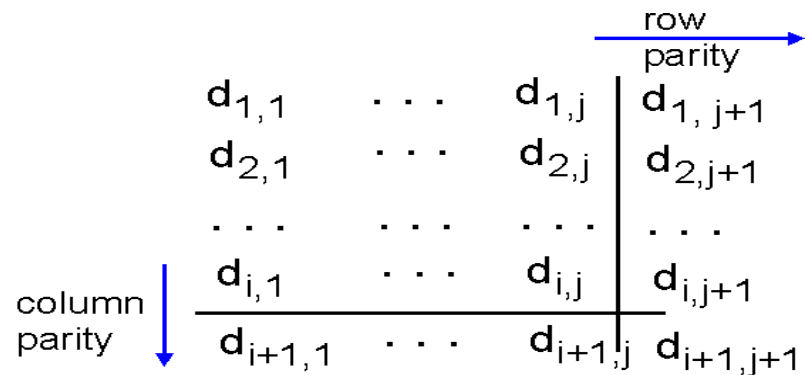   - larger EDC field yields better detection and correction

Parity checking

single bit parity:
- *d*etect **single bit** errors

two-dimensional bit parity:
- detect and correct single bit errors

row parity →

$$d_{1,1} \quad \cdots \quad d_{1,j} \quad | \quad d_{1,\,j+1}$$
$$d_{2,1} \quad \cdots \quad d_{2,j} \quad | \quad d_{2,j+1}$$
$$\cdots \quad \cdots \quad \cdots \quad | \quad \cdots$$
$$d_{i,1} \quad \cdots \quad d_{i,j} \quad | \quad d_{i,j+1}$$

column parity ↓

$$d_{i+1,1} \quad \cdots \quad d_{i+1,j} \quad d_{i+1,j+1}$$

d data bits → parity bit

| 011100011010101 1 | 0 |

```
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        parity
1 0 1 1 0 0    →     error
0 1 1 1 0 | 1
-----------
0 0 1 0 1 | 0
```
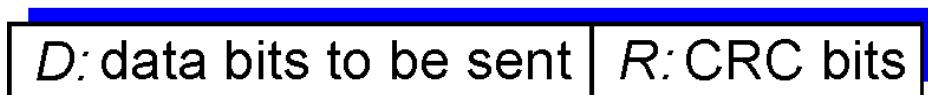parity error

correctable single bit error

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

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
  - <D,R> exactly divisible by G (modulo 2)
  - receiver knows G, divides <D,R> 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 bits → ← r bits →

| D: data bits to be sent | R: CRC bits |

bit pattern

$D * 2^r$ XOR   R

mathematical formula

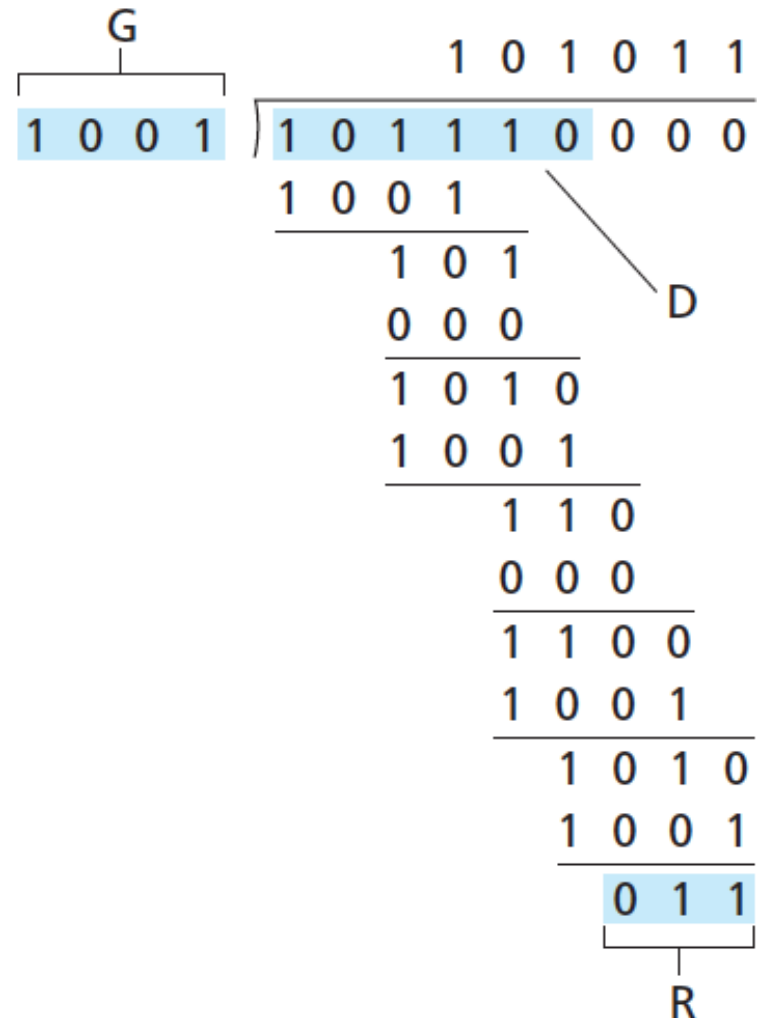# CRC example

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:

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

```
G
         1 0 1 0 1 1
1 0 0 1 ) 1 0 1 1 1 0 0 0 0
          1 0 0 1              D
          _____
            1 0 1
            0 0 0
          _____
            1 0 1 0
            1 0 0 1
          _____
              1 1 0
              0 0 0
          _____
              1 1 0 0
              1 0 0 1
          _____
                1 0 1 0
                1 0 0 1
          _____
                  0 1 1
                   R
```

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

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
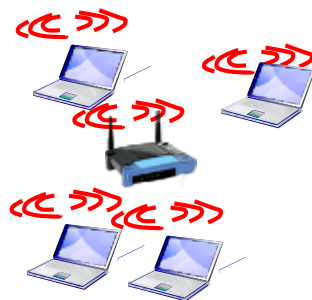
6.7 a day in the life of a web request

Multiple access links, protocols
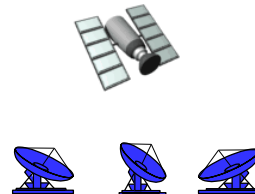
two types of "links":

- point-to-point
  - PPP for dial-up access
  - point-to-point link between Ethernet switch, host

- *broadcast (shared wire or medium)*
  - old-fashioned Ethernet
  - upstream HFC
  - 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:

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, code)
  - 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

- access to channel in "rounds"
- each station gets fixed length slot (length = packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle
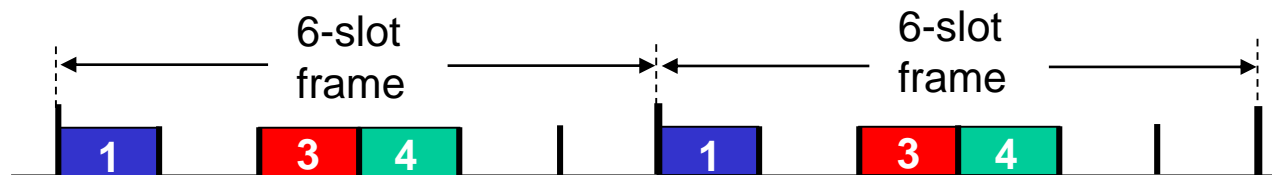
Channel partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

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

FDM cable

time

frequency bands
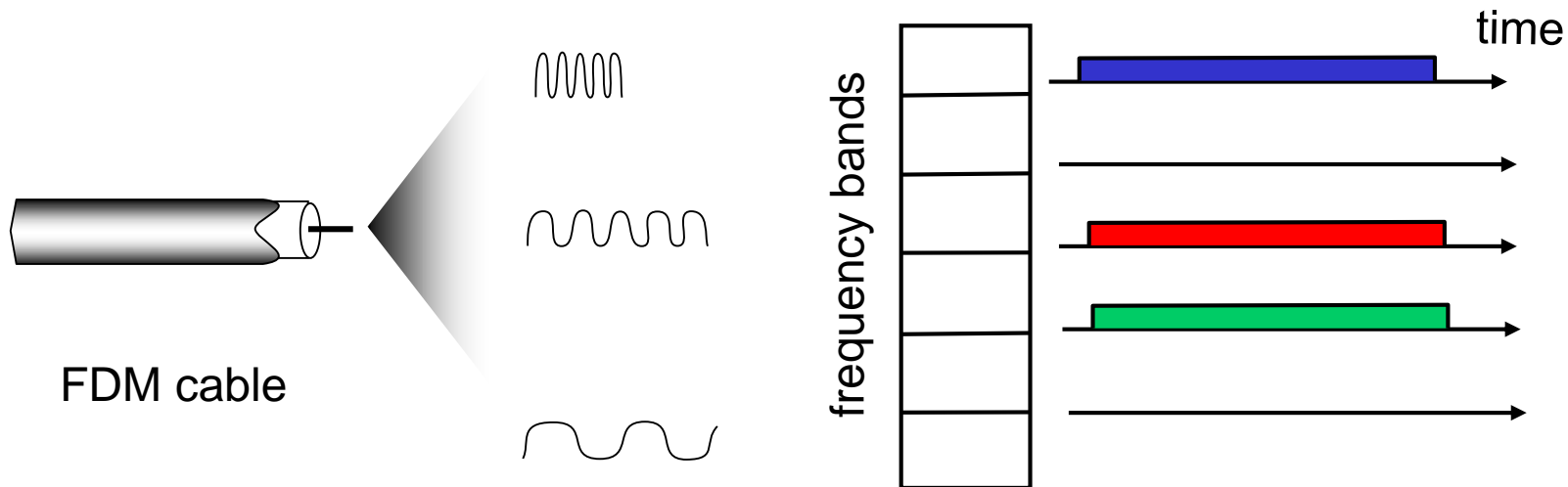
Random access protocols

- 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:
  - slotted ALOHA
  - ALOHA
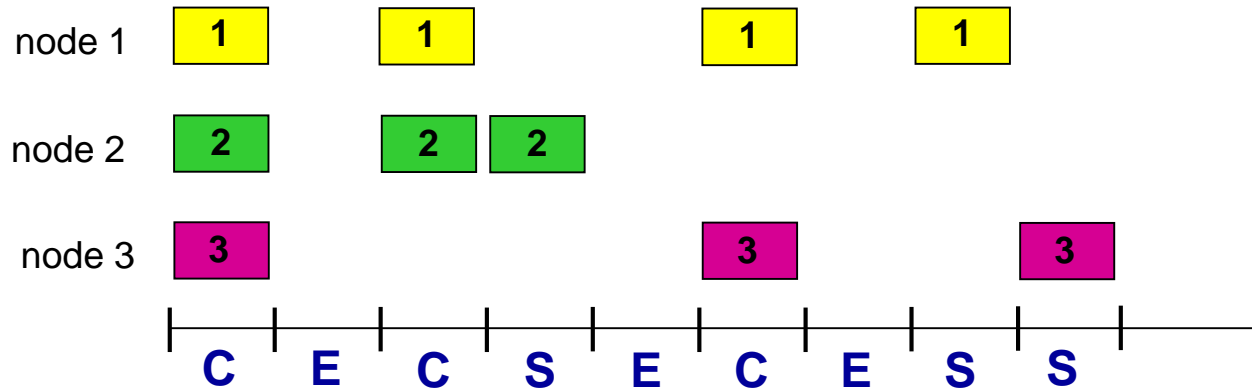 - CSMA, CSMA/CD, CSMA/CA

Slotted ALOHA
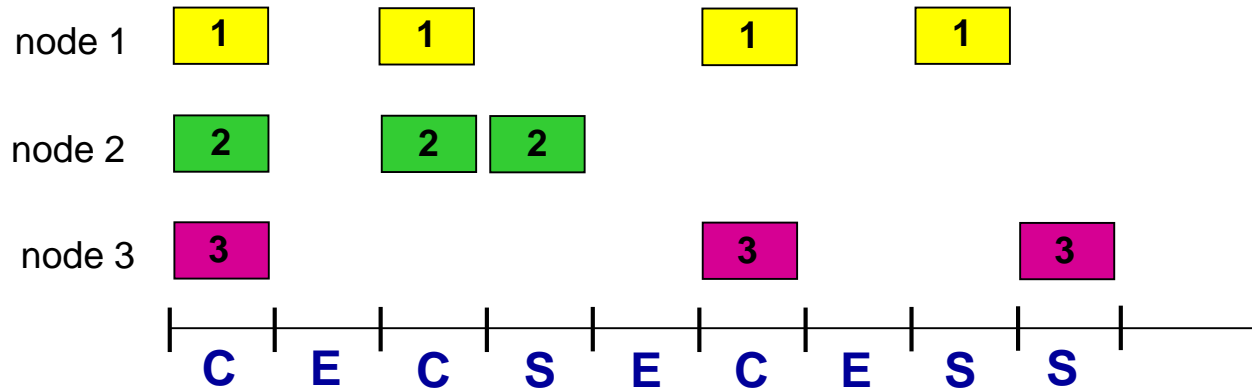
assumptions:

- all frames **same** size
- time divided into equal size **slots** (time to transmit 1 frame)
- nodes start to transmit only **slot beginning**
- nodes are **synchronized**
- if 2 or more nodes transmit in slot, all nodes detect collision
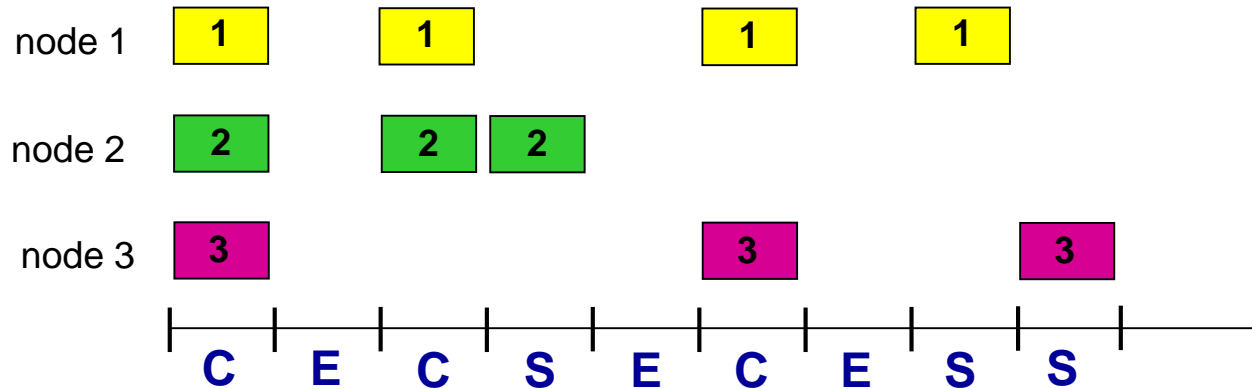
Slotted ALOHA

operation:

- when node obtains fresh frame, transmits in next slot
    - *if no collision:* node can send new frame in next slot
    - *if collision:* node retransmits frame in *each* subsequent slot with *prob. p* until success

Slotted ALOHA

node 1	**1**	**1**			**1**		**1**	
node 2	**2**	**2**	**2**					
node 3	**3**				**3**		**3**	

C   E   C   S   E   C   E   S   S

Pros:

- single active node can continuously transmit at full rate of channel
- highly decentralized: only slots in nodes need to be in sync
- simple

Cons:

- collisions, wasting slots
- idle slots
- nodes may be able to detect collision in less than time to transmit packet
- clock synchronization

Slotted ALOHA: efficiency

efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)

- *suppose:* N nodes with many frames to send, each transmits in slot with probability p

- prob that given node has success in a slot $= p(1-p)^{N-1}$

- prob that *any* node has a success $= Np(1-p)^{N-1}$

- max efficiency: find $p*$ that maximizes $Np(1-p)^{N-1}$

- for many nodes, take limit of $Np*(1-p*)^{N-1}$ as N goes to infinity, gives:
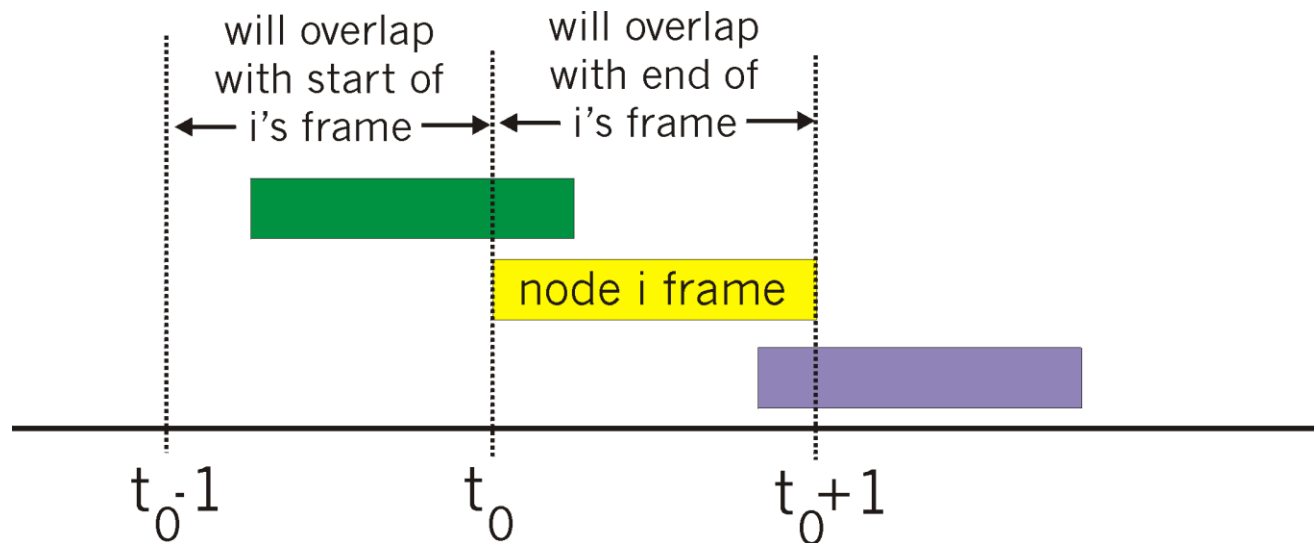
max efficiency = 1/e = .37

at best: channel used for useful transmissions 37% of time!

!

Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
  - transmit immediately
- collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$

Pure ALOHA efficiency

P(success by given node) = P(node transmits) .

P(no other node transmits in $[t_0-1,t_0]$.

P(no other node transmits in $[t_0-1,t_0]$

$$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$$

$$= p \cdot (1-p)^{2(N-1)}$$

… choosing optimum p and then letting $n \longrightarrow \infty$

$$= 1/(2e) = .18$$

even *worse* than slotted Aloha!

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

spatial layout of nodes

- 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 in determining collision probability

t_0

time

t_1
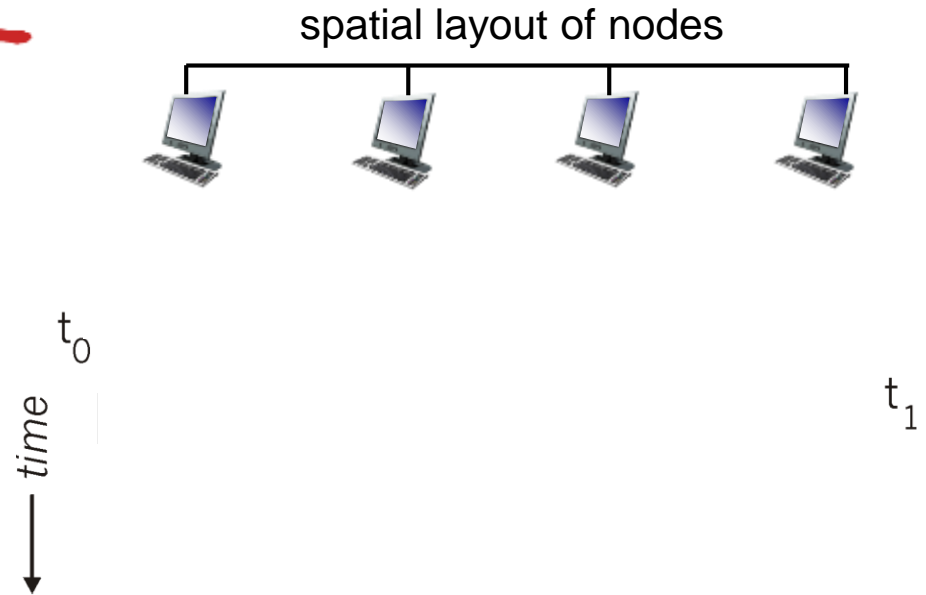
CSMA/CD (collision detection)

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

CSMA/CD (collision detection)

spatial layout of nodes

collision
detect/abort
time
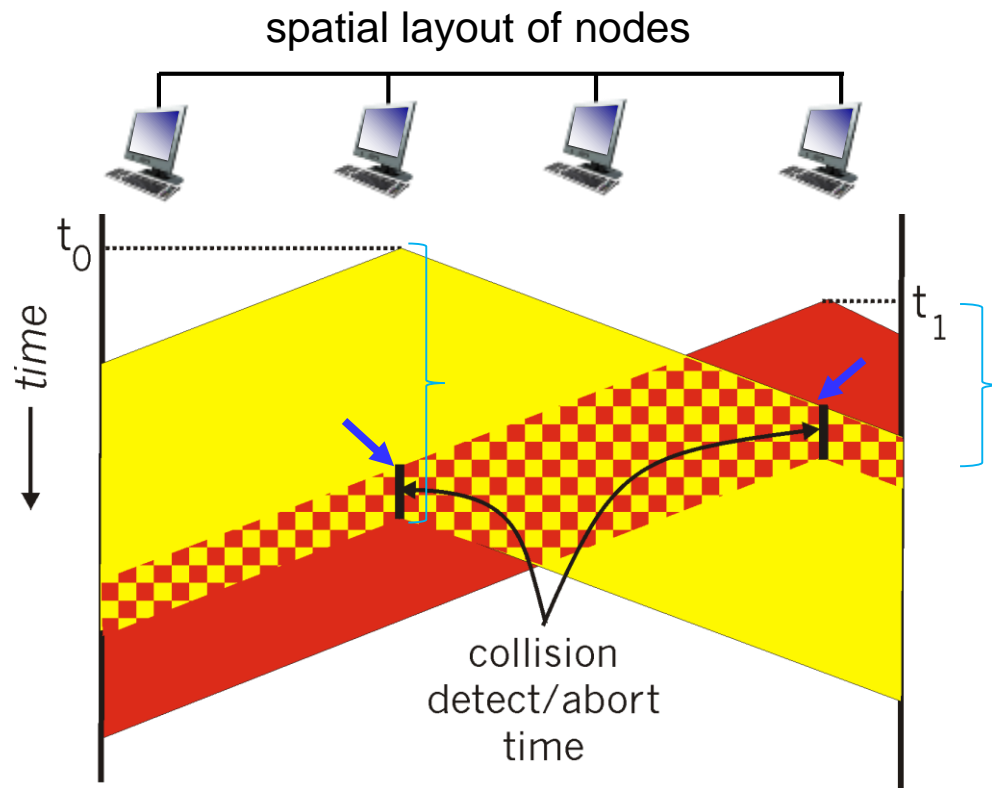
Ethernet CSMA/CD algorithm

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*th collision, NIC chooses *K* at random from {0,1,2, …, 2^m-1}. NIC **waits K·512 bit times**, returns to Step 2
   - **longer backoff interval with more collisions**

CSMA/CD efficiency

- T_{prop} = max prop delay between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame

$$efficiency = \frac{1}{1+5t_{prop}/t_{trans}}$$

- efficiency goes to 1
  - as t_{prop} goes to 0
  - as t_{trans} goes to infinity
- better performance than ALOHA: and simple, cheap, decentralized!

"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)

data

poll

master

data

slaves
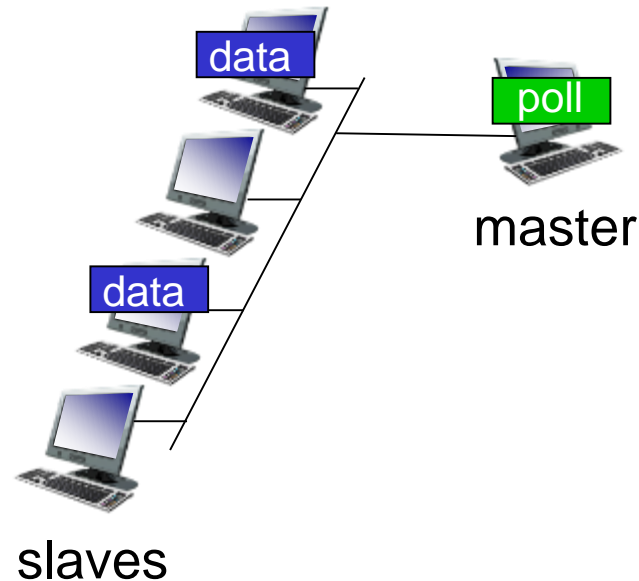
"Taking turns" MAC protocols

token passing:

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

(nothing to send)

data

Cable access network

Internet frames, TV channels, control transmitted downstream at different frequencies

cable headend

CMTS

cable modem termination system

ISP

splitter

cable modem

upstream Internet frames, TV control, transmitted upstream at different frequencies in time slots
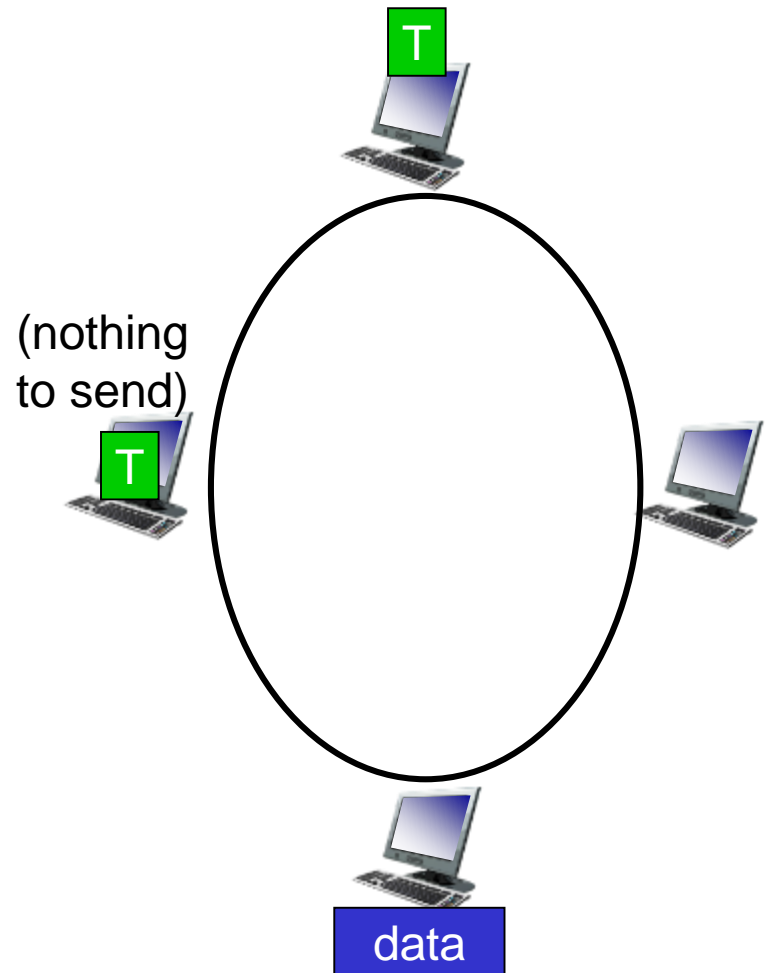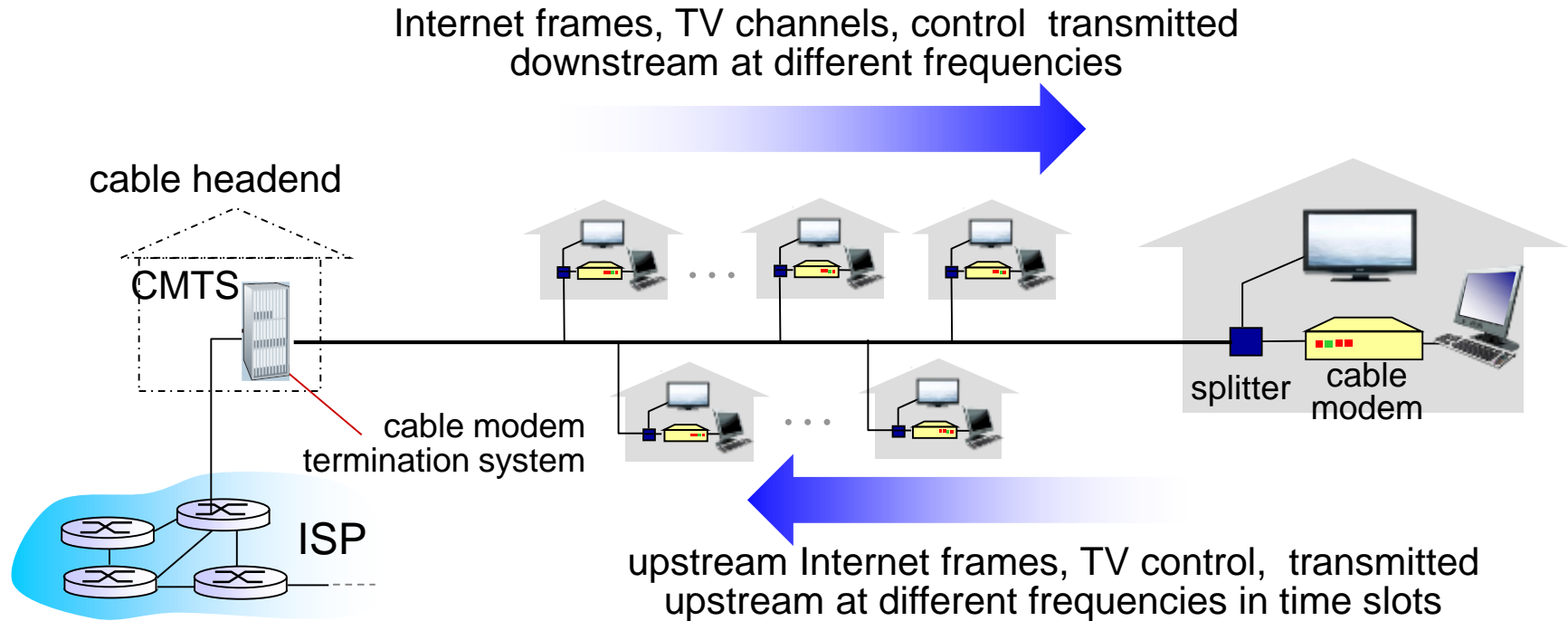
- multiple 40Mbps downstream (broadcast) channels
  - single CMTS transmits into channels
- **multiple 30 Mbps upstream channels**
  - multiple access: all users contend for certain upstream channel time slots (others assigned)

Cable access network

cable headend

MAP frame for Interval [t1, t2]

CMTS

Downstream channel i

Upstream channel j

t_1

t_2

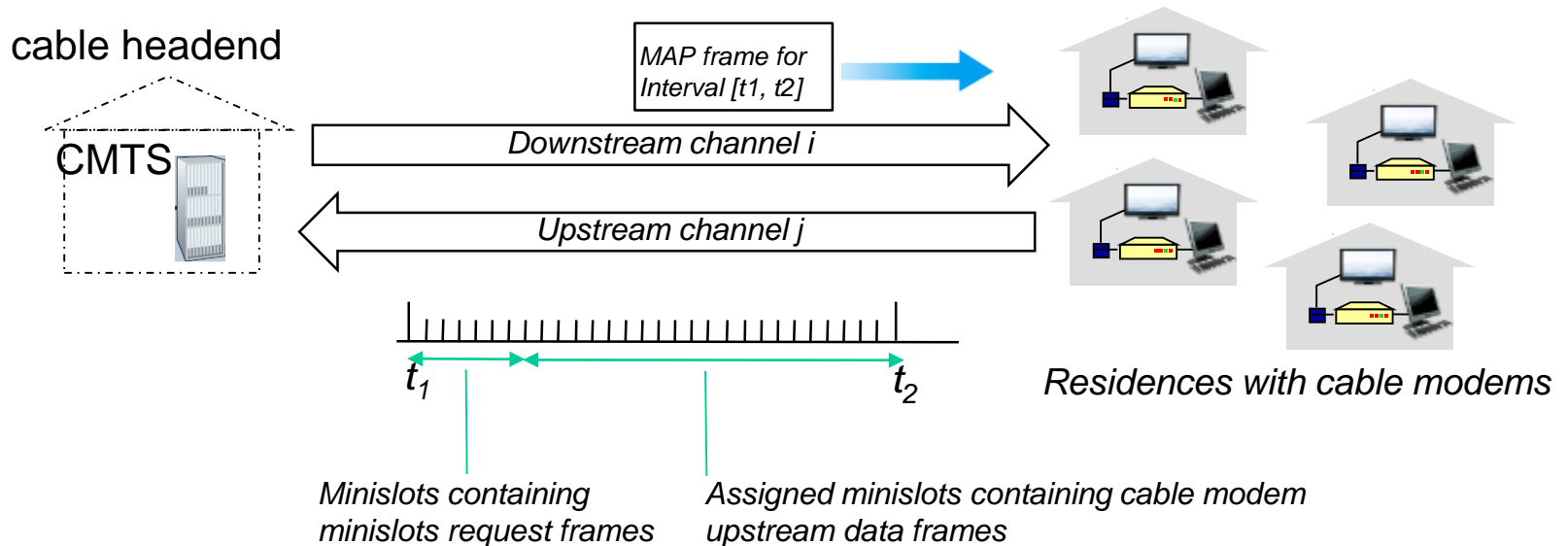*Residences with cable modems*

Minislots containing minislots request frames

Assigned minislots containing cable modem upstream data frames

DOCSIS: data over cable service interface spec
- FDM over upstream, downstream frequency channels
- TDM upstream: some slots assigned, some have contention
  - downstream MAP frame: assigns upstream slots
  - request for upstream slots (and data) transmitted random access (binary backoff) in selected slots

Summary of MAC protocols

- *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

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

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

hexadecimal (base 16) notation
(each "numeral" represents 4 bits)

LAN addresses and ARP

each adapter on LAN has unique *LAN* address

1A-2F-BB-76-09-AD

LAN
(wired or
wireless)

adapter

71-65-F7-2B-08-53

58-23-D7-FA-20-B0

0C-C4-11-6F-E3-98
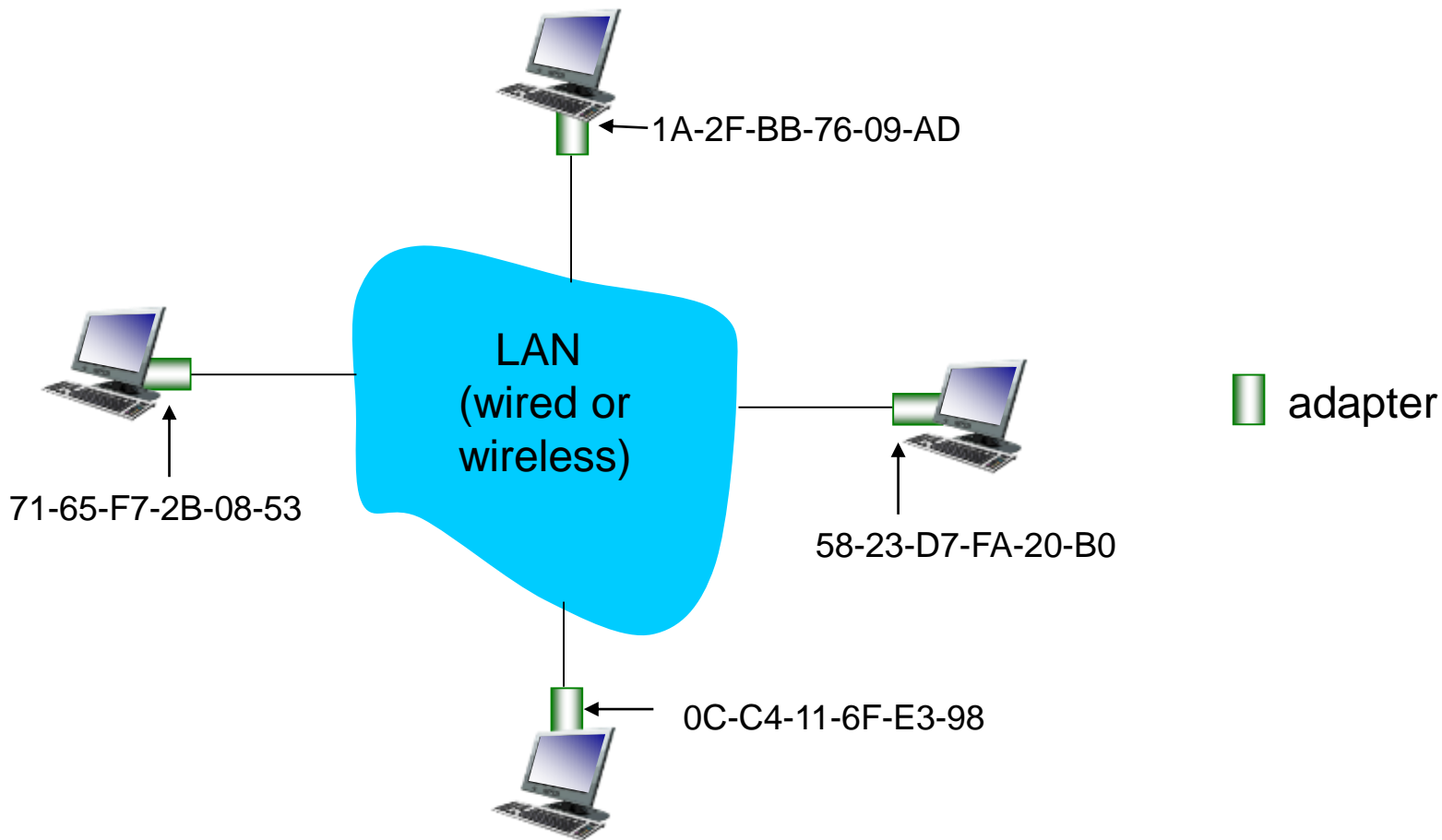
LAN addresses (more)

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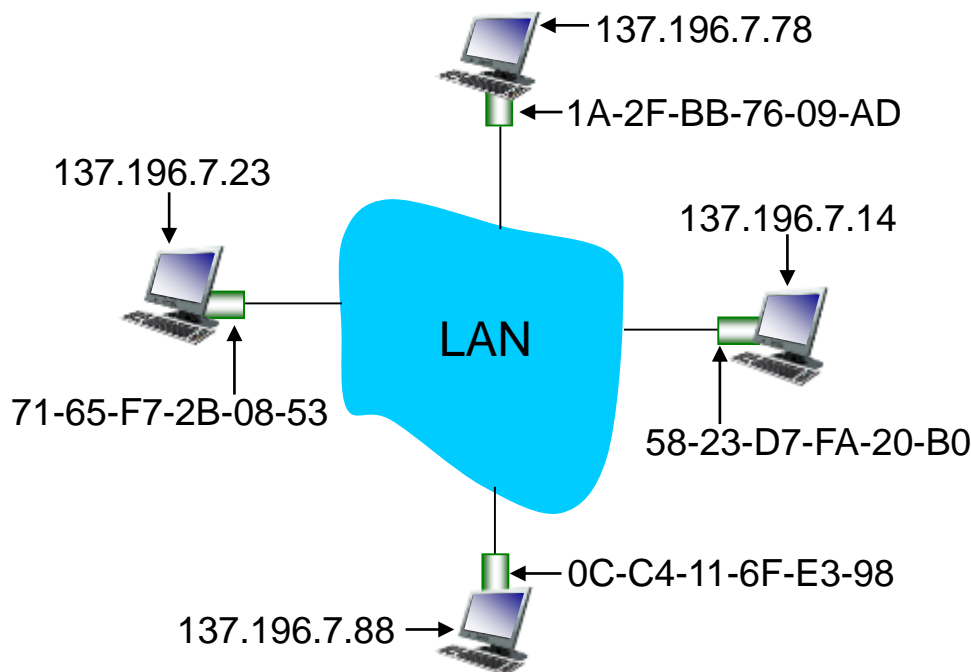
ARP table: each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:

  < IP address; MAC address; TTL>

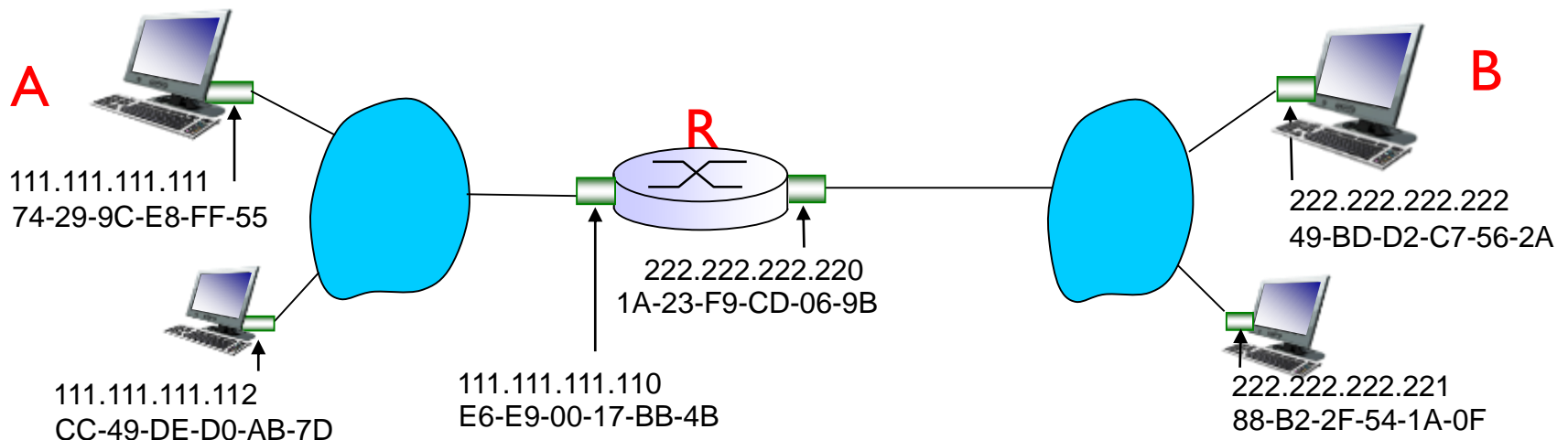- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

137.196.7.78

1A-2F-BB-76-09-AD

137.196.7.23

137.196.7.14

LAN

71-65-F7-2B-08-53

58-23-D7-FA-20-B0

0C-C4-11-6F-E3-98

137.196.7.88

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

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?)

A

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

R

222.222.222.220
1A-23-F9-CD-06-9B

111.111.111.110
E6-E9-00-17-BB-4B

B

222.222.222.222
49-BD-D2-C7-56-2A
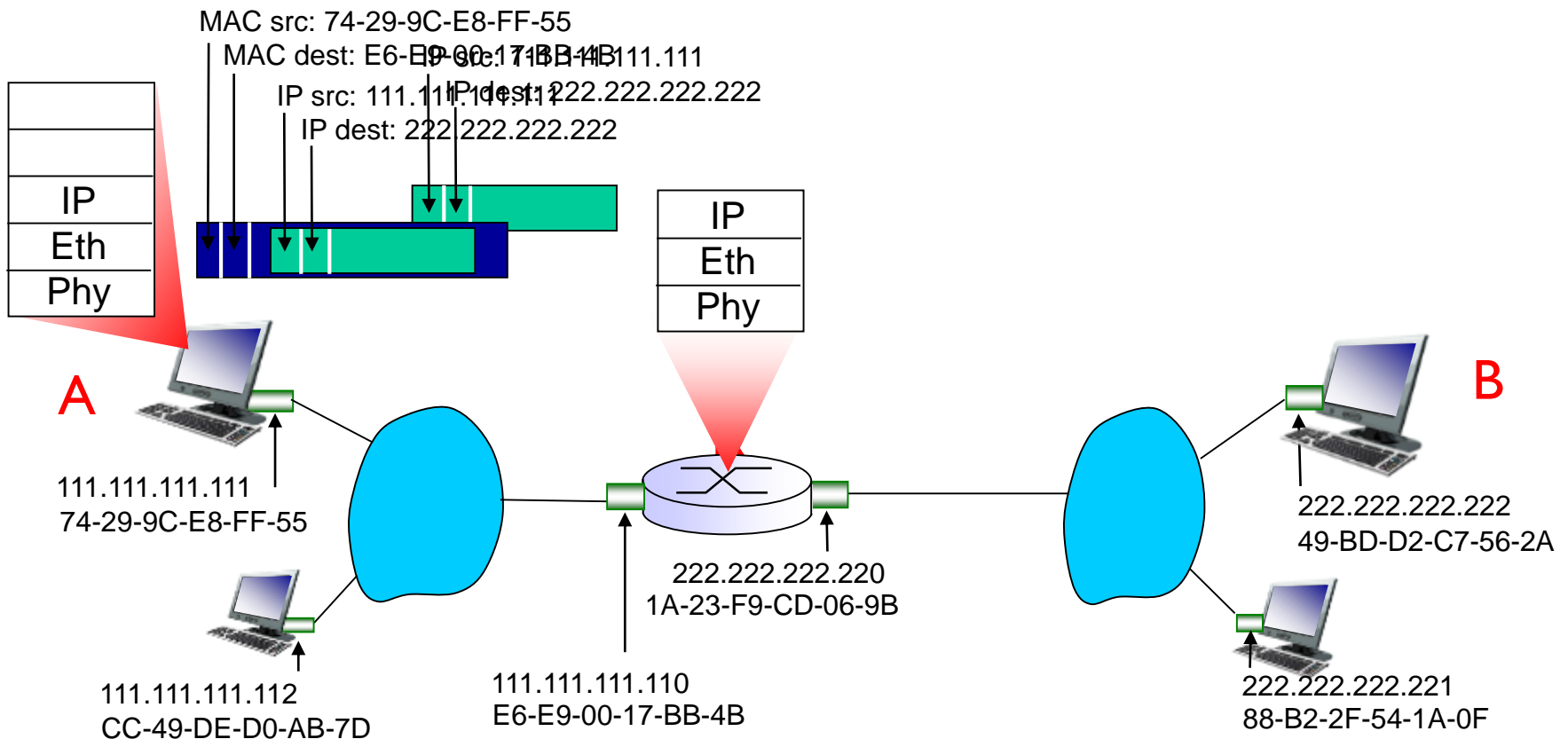
222.222.222.221
88-B2-2F-54-1A-0F

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

MAC src: 74-29-9C-E8-FF-55
MAC dest: E6-E9-00-17-BB-4B

IP src: 111.111.111.111
IP dest: 222.222.222.222

IP
Eth
Phy

A

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

R

222.222.222.220
1A-23-F9-CD-06-9B

111.111.111.110
E6-E9-00-17-BB-4B

B

222.222.222.222
49-BD-D2-C7-56-2A

222.222.222.221
88-B2-2F-54-1A-0F
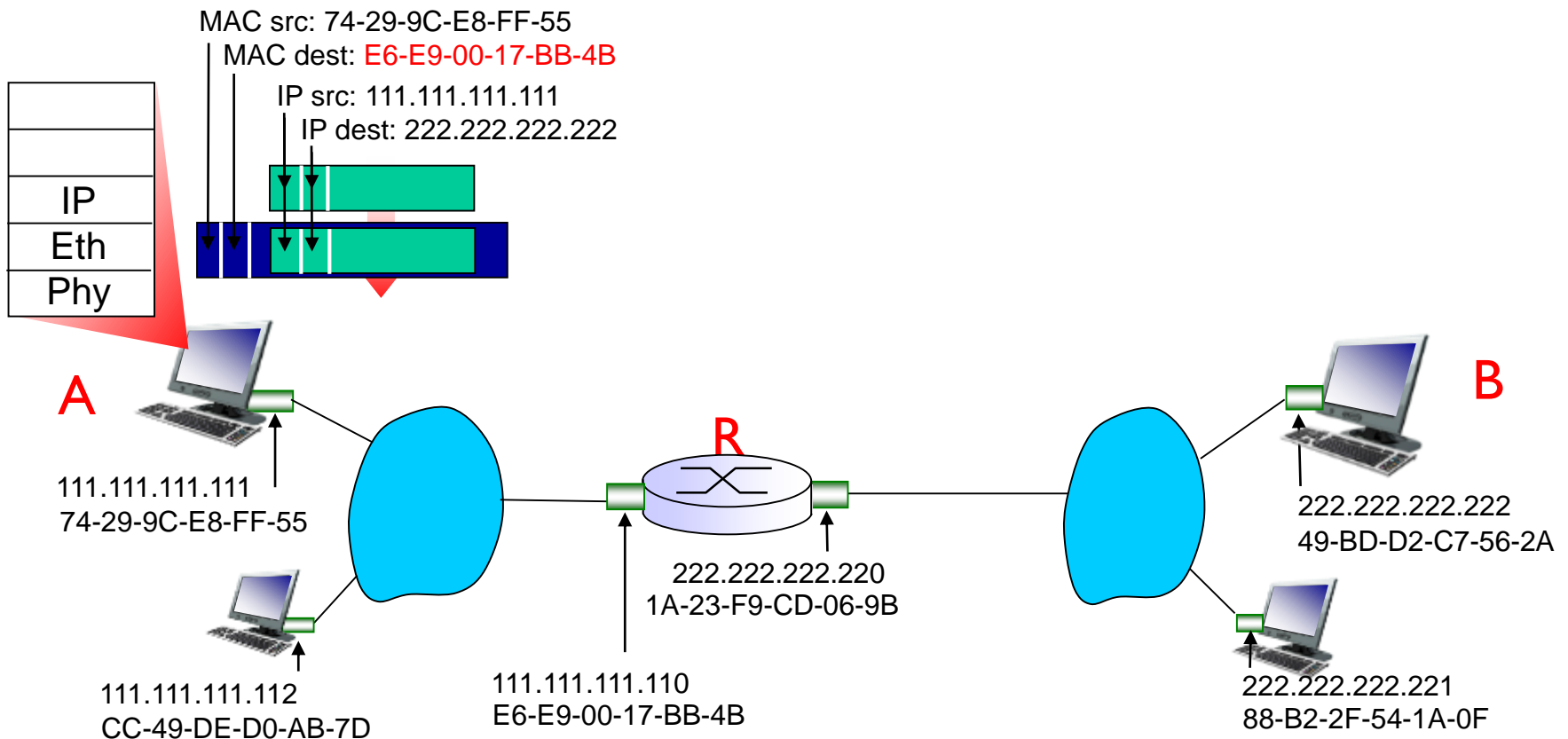
Addressing: routing to another LAN

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

MAC src: 74-29-9C-E8-FF-55
MAC dest: E6-E9-00-17-BB-4B

IP src: 111.111.111.111
IP dest: 222.222.222.222

IP src: 111.111.111.111
IP dest: 222.222.222.222

IP
Eth
Phy

IP
Eth
Phy

A

B

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

111.111.111.110
E6-E9-00-17-BB-4B

222.222.222.220
1A-23-F9-CD-06-9B

222.222.222.222
49-BD-D2-C7-56-2A

222.222.222.221
88-B2-2F-54-1A-0F

Addressing: routing to another LAN

- R forwards datagram with IP source A, destination B

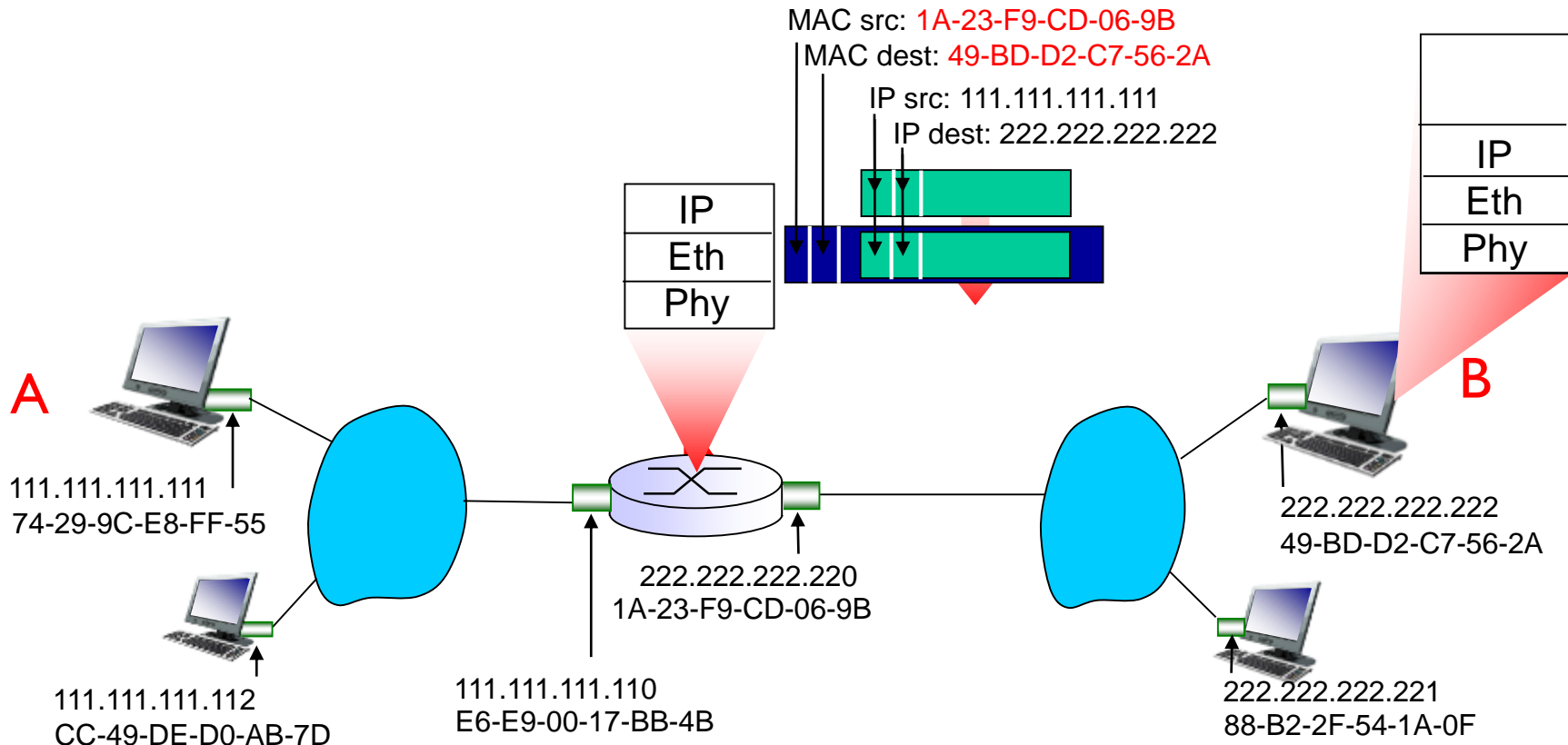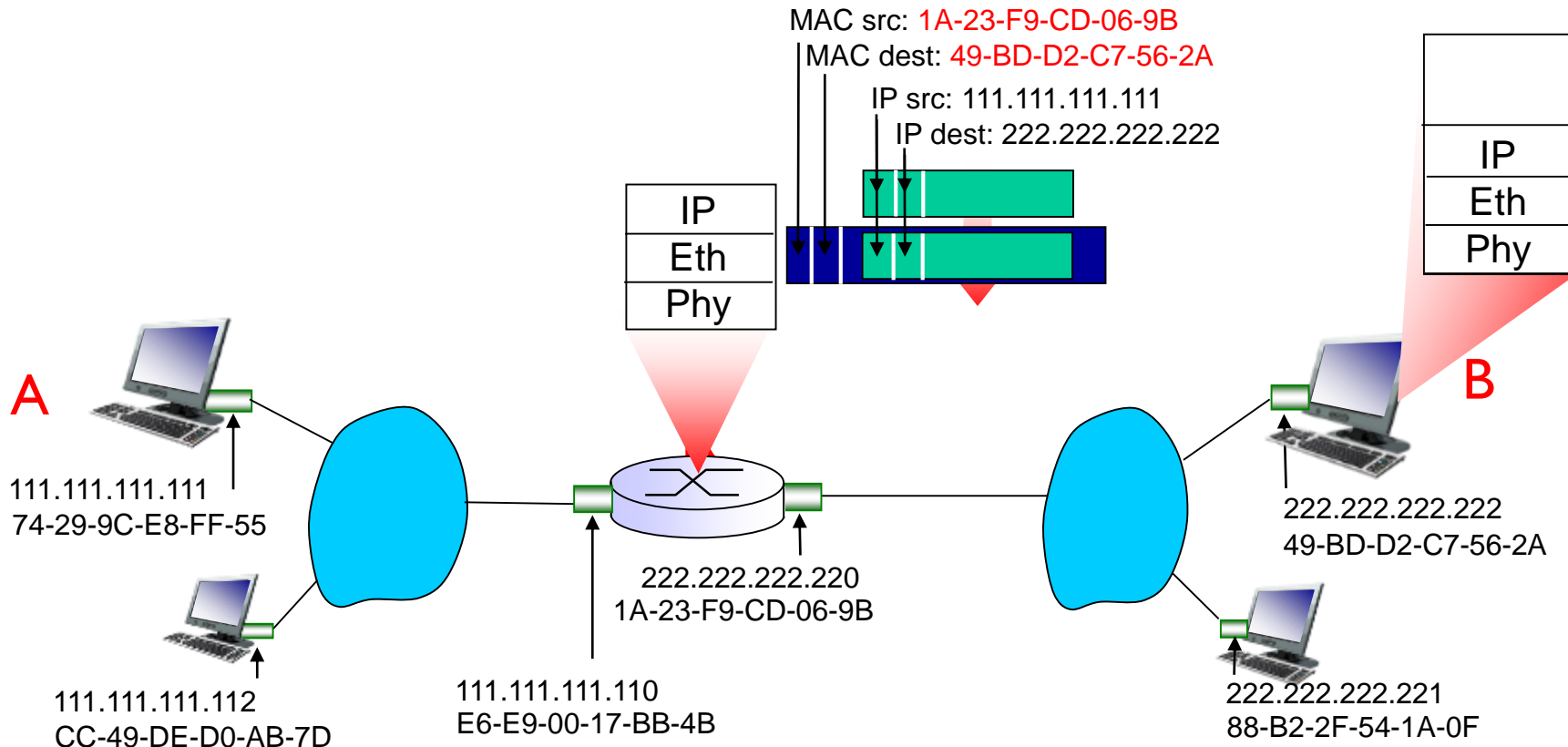- R creates link-layer frame with B's MAC address as destination address, frame contains A-to-B IP datagram

MAC src: 1A-23-F9-CD-06-9B
MAC dest: 49-BD-D2-C7-56-2A
IP src: 111.111.111.111
IP dest: 222.222.222.222

IP
Eth
Phy

IP
Eth
Phy

A

B

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

222.222.222.220
1A-23-F9-CD-06-9B

111.111.111.110
E6-E9-00-17-BB-4B

222.222.222.222
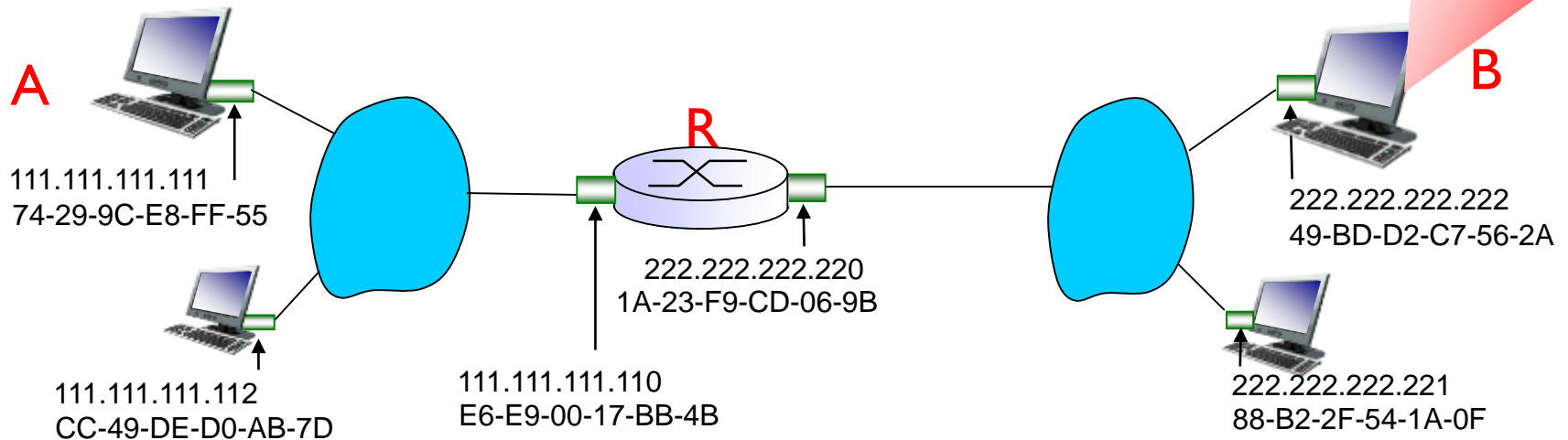49-BD-D2-C7-56-2A
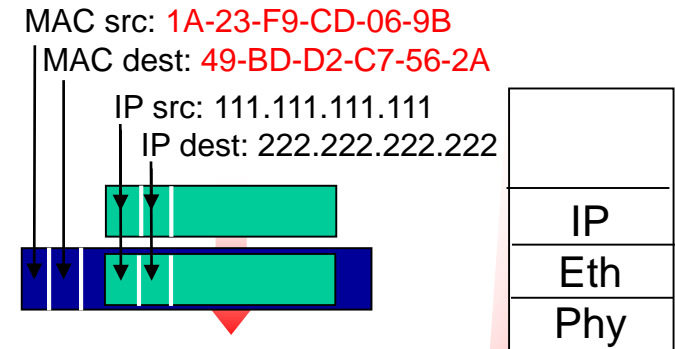
222.222.222.221
88-B2-2F-54-1A-0F

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

MAC src: 1A-23-F9-CD-06-9B
MAC dest: 49-BD-D2-C7-56-2A

IP src: 111.111.111.111
IP dest: 222.222.222.222

IP
Eth
Phy

IP
Eth
Phy

A

B

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

222.222.222.220
1A-23-F9-CD-06-9B

111.111.111.110
E6-E9-00-17-BB-4B

222.222.222.222
49-BD-D2-C7-56-2A

222.222.222.221
88-B2-2F-54-1A-0F

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

MAC src: 1A-23-F9-CD-06-9B
MAC dest: 49-BD-D2-C7-56-2A

IP src: 111.111.111.111
IP dest: 222.222.222.222

| IP |
| Eth |
| Phy |

A

111.111.111.111
74-29-9C-E8-FF-55

111.111.111.112
CC-49-DE-D0-AB-7D

R

222.222.222.220
1A-23-F9-CD-06-9B

111.111.111.110
E6-E9-00-17-BB-4B

B

222.222.222.222
49-BD-D2-C7-56-2A

222.222.222.221
88-B2-2F-54-1A-0F

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs
- addressing, ARP
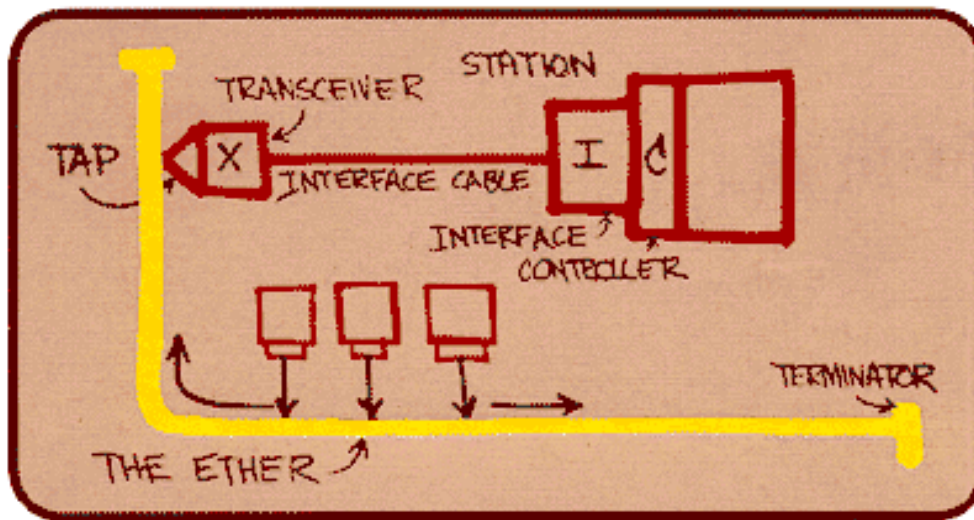- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request
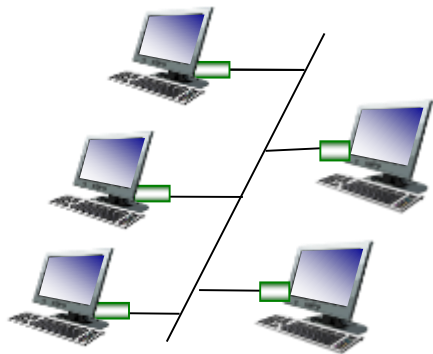
Ethernet

"dominant" wired LAN technology:

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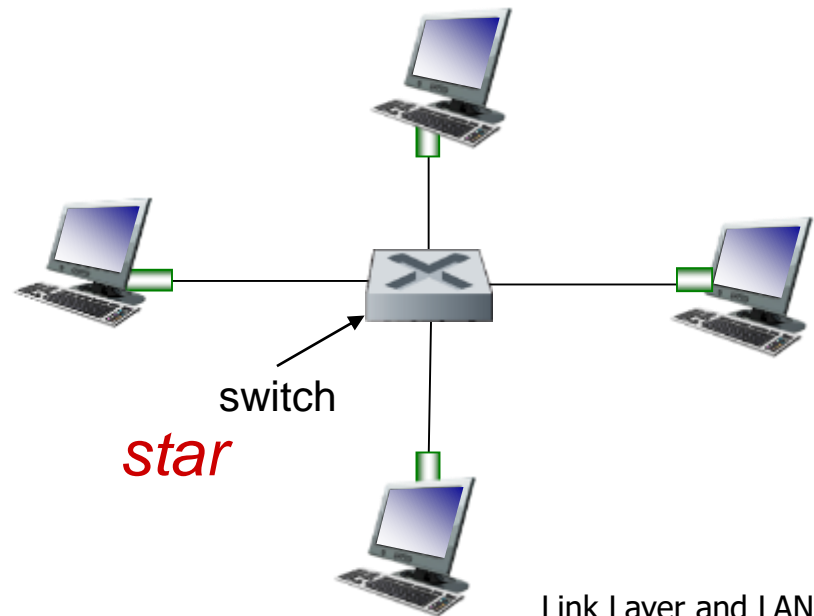- kept up with speed race: 10 Mbps – 10 Gbps

Metcalfe's Ethernet sketch

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

switch

star

Ethernet frame structure

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

preamble	dest. address	source address	*type*	data (payload)	CRC

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., Novell IPX, AppleTalk)
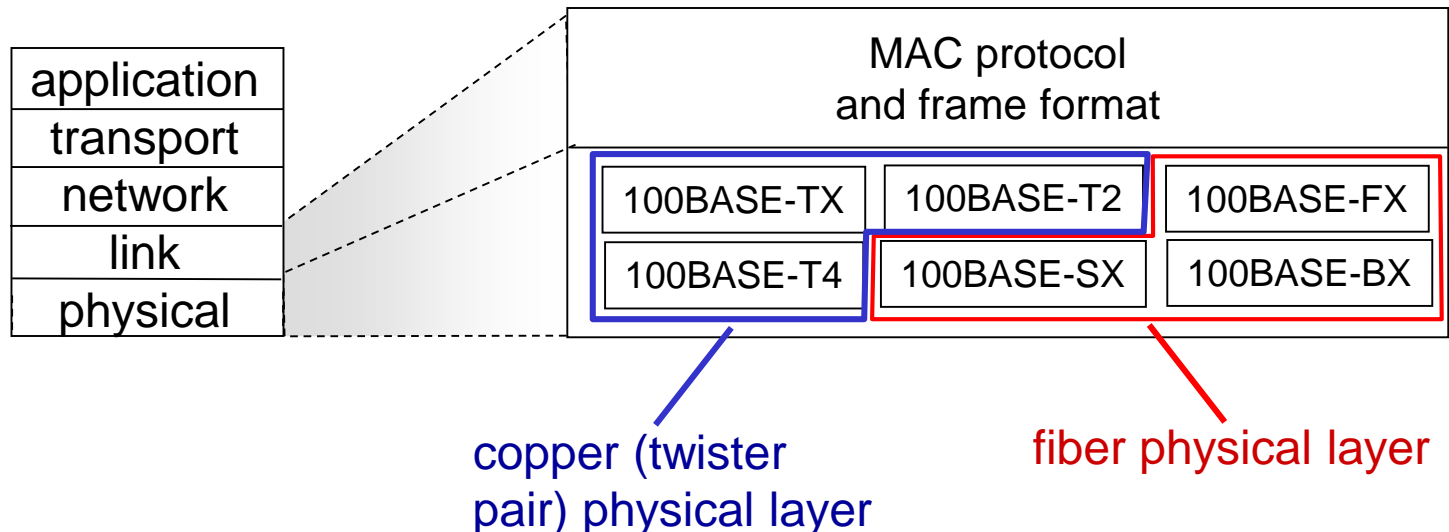- *CRC:* cyclic redundancy check at receiver
  - error detected: frame is dropped

type

preamble	dest. address	source address		data (payload)	CRC

Ethernet: unreliable, connectionless

- *connectionless:* no handshaking between sending and receiving NICs

- *unreliable:* receiving NIC doesn't send acks or nacks to sending NIC
  - data in dropped frames recovered only if initial sender uses higher layer rdt (e.g., TCP), otherwise dropped data lost

- Ethernet's MAC protocol: unslotted *CSMA/CD 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, 1Gbps, 10 Gbps, 40 Gbps
  - different physical layer media: fiber, cable

| application |
| transport |
| network |
| link |
| physical |

MAC protocol and frame format		
100BASE-TX	100BASE-T2	100BASE-FX
100BASE-T4	100BASE-SX	100BASE-BX

copper (twister pair) physical layer

fiber physical layer

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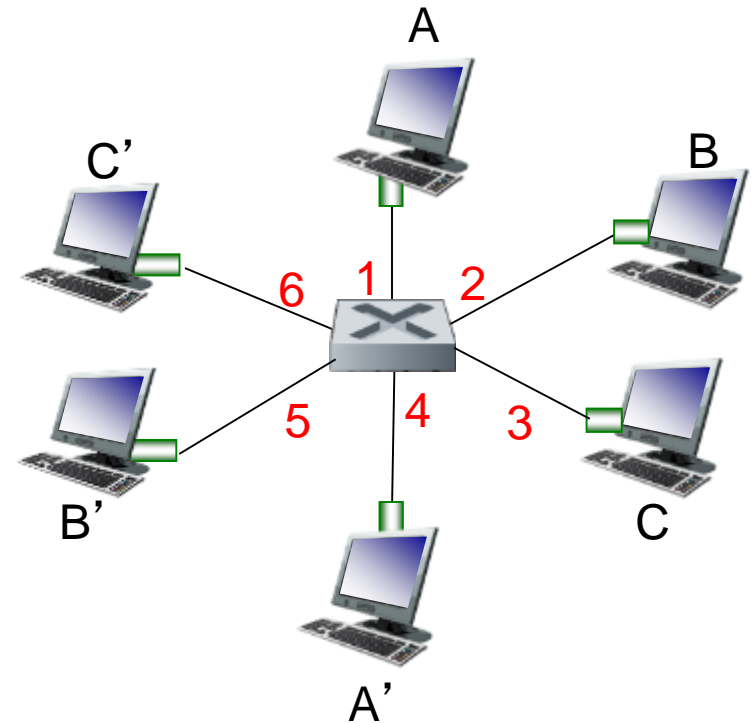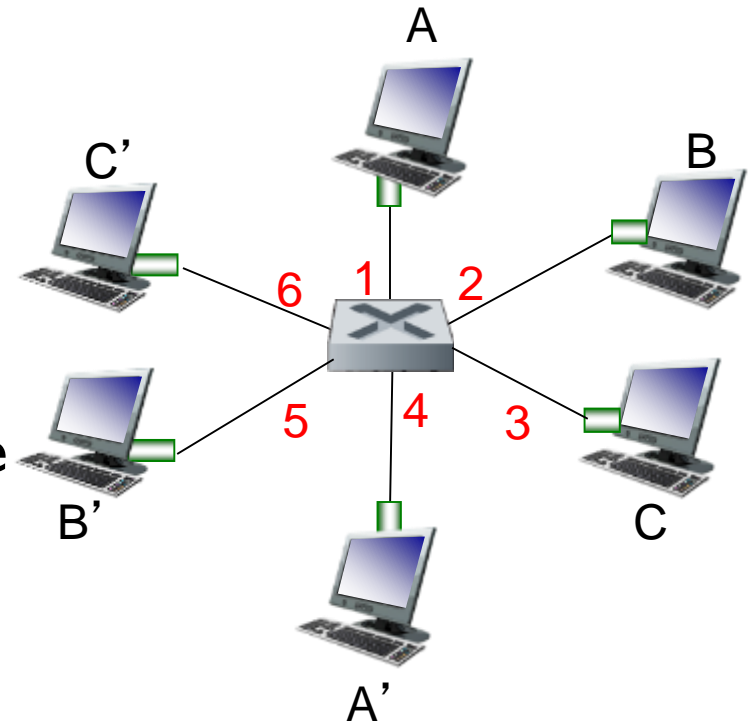
switch with six interfaces (1,2,3,4,5,6)

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, time stamp)
  - looks like a routing table!

Q: how are entries created,
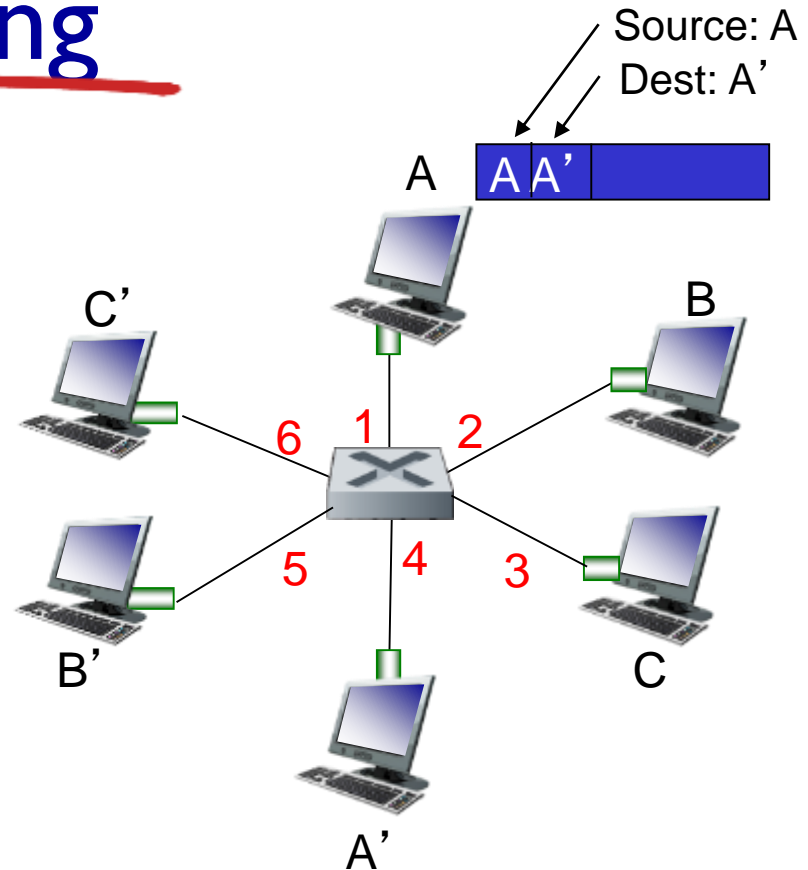maintained in switch table?
  - something like a routing
    protocol?

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

Switch: self-learning

Source: A
Dest: A'

A

A A'

- 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

C'

B

6   1   2

5   4   3

B'

C

A'

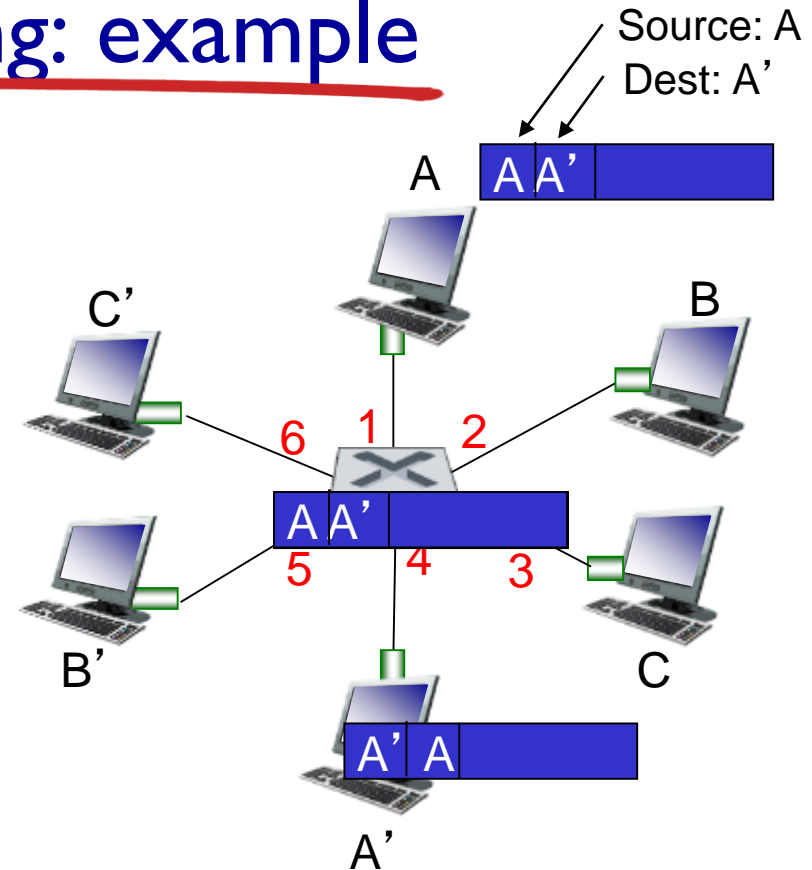| MAC addr	interface	TTL
A	*1*	*60*

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

Source: A
Dest: A'

- frame destination, A', location unknown: *flood*

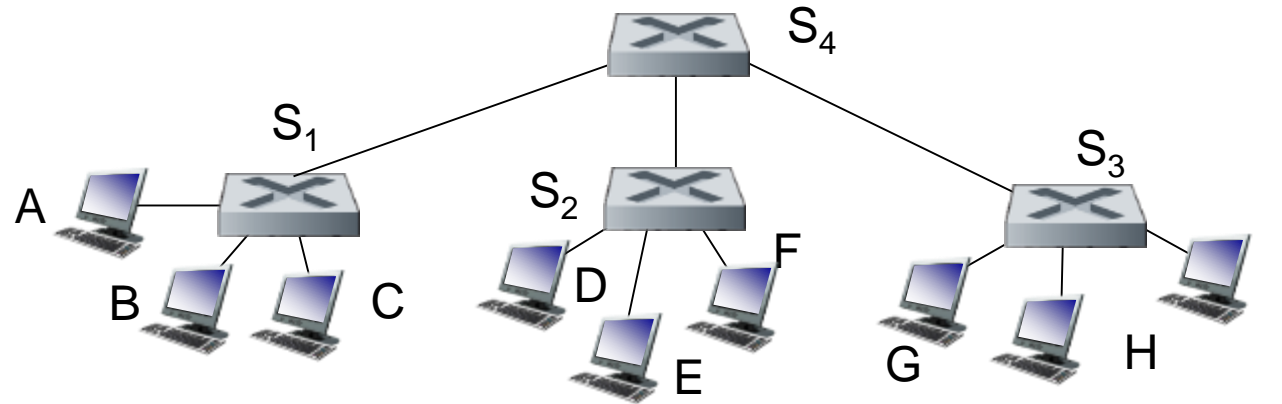- destination A location known: selectively send on just one link

MAC addr	interface	TTL
A	1	60
A'	4	60

switch table (initially empty)

Interconnecting switches

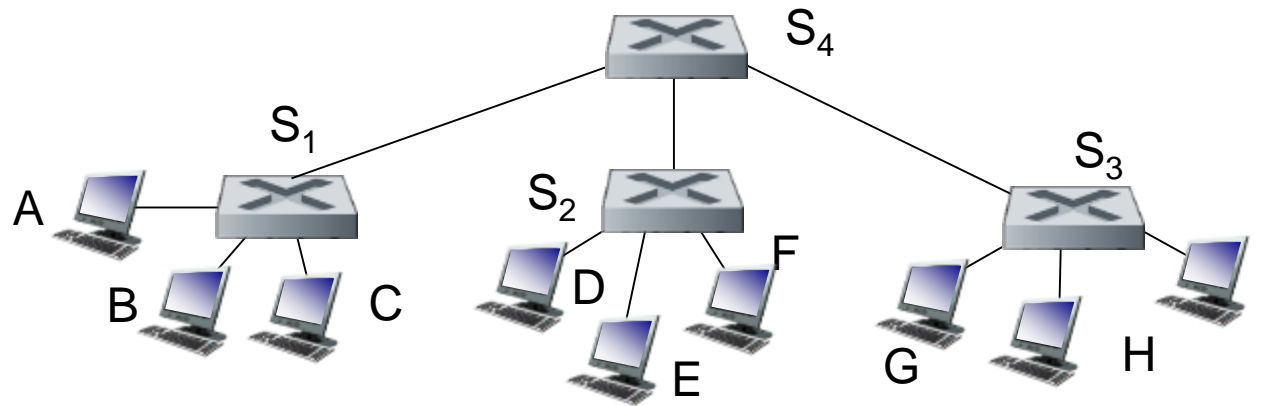self-learning switches can be connected together:

Q: sending from A to G - how does S_1 know to forward frame destined to G via S_4 and S_3?

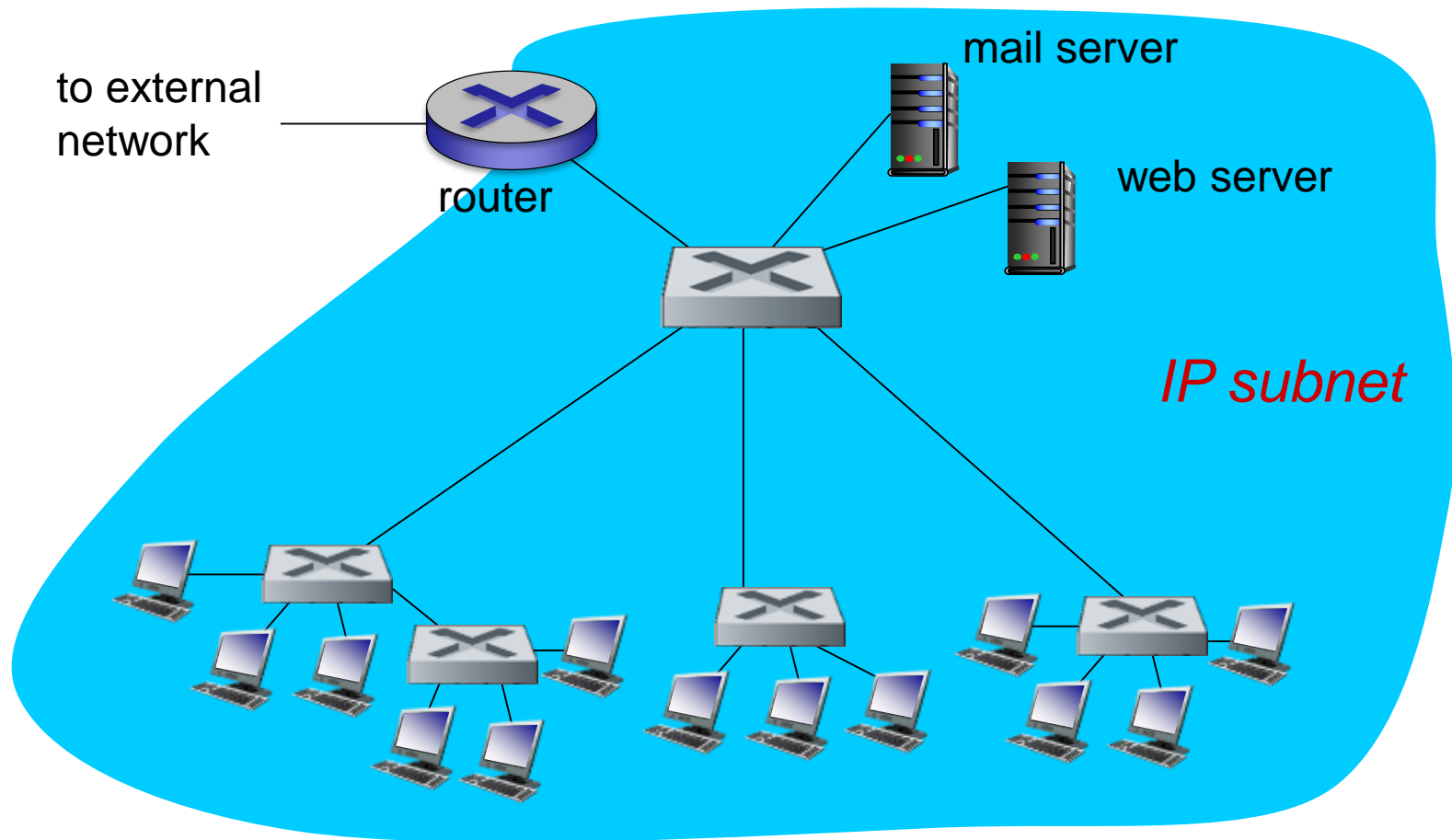- *A:* self learning! (works exactly the same as in single-switch case!)

Self-learning multi-switch example

Suppose C sends frame to I, I responds to C

- ■ Q: show switch tables and packet forwarding in S_1, S_2, S_3, S_4

Institutional network

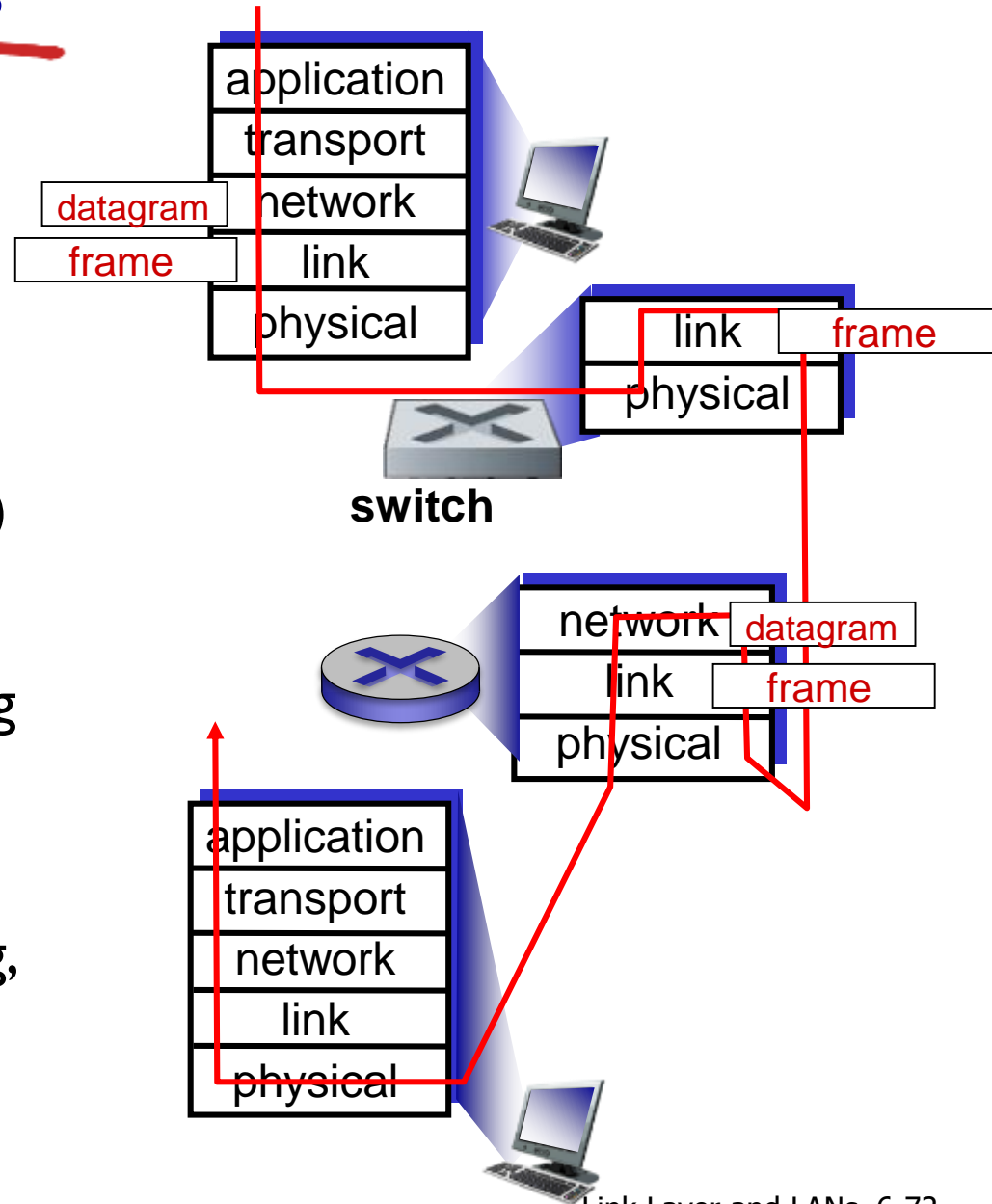to external network

router

mail server

web server

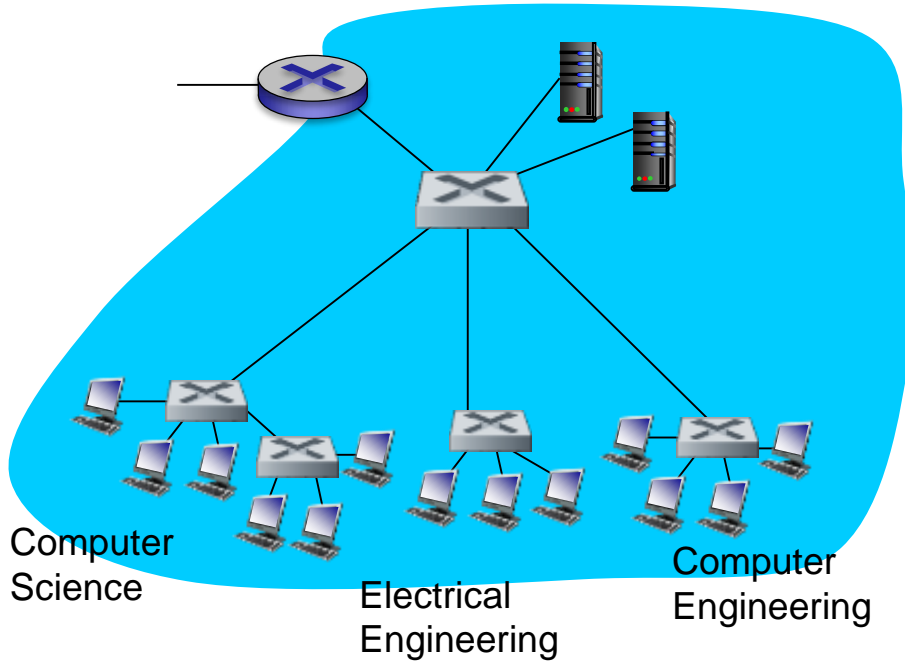*IP subnet*

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

| application |
| transport |
| network |
| link |
| physical |

datagram
frame

| link |
| physical |

frame

switch

| network |
| link |
| physical |

datagram
frame

| application |
| transport |
| network |
| link |
| physical |

VLANs: motivation

Computer
Science

Electrical
Engineering

Computer
Engineering

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
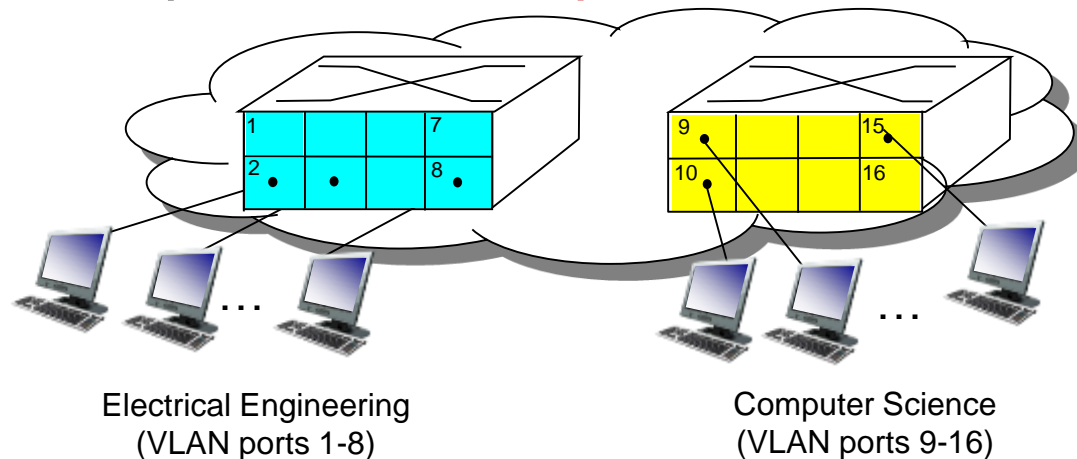 - security/privacy, efficiency issues

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 ……
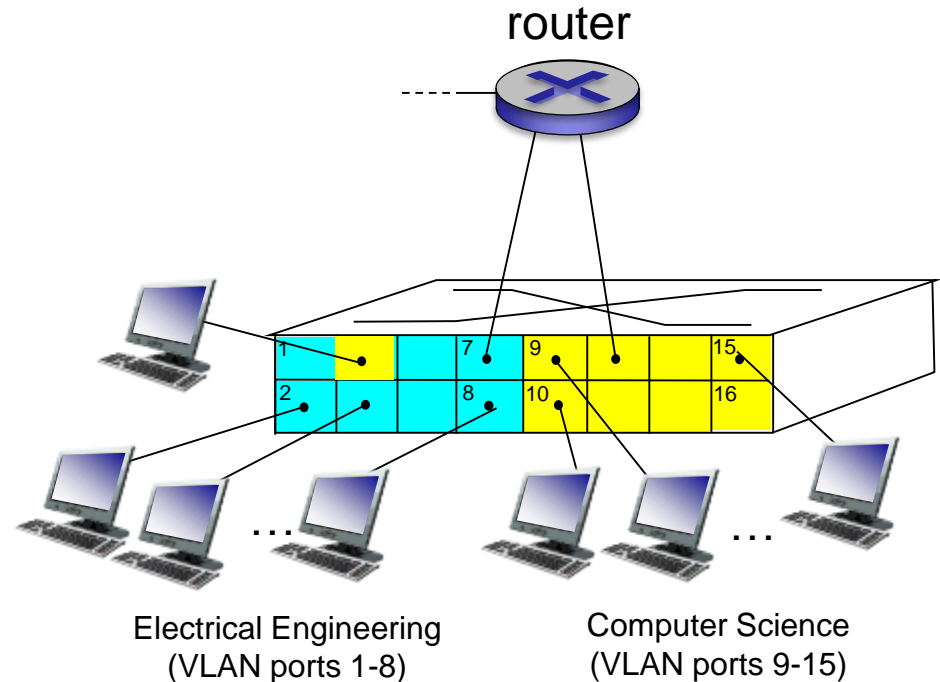

Electrical Engineering
(VLAN ports 1-8)

Computer Science
(VLAN ports 9-15)
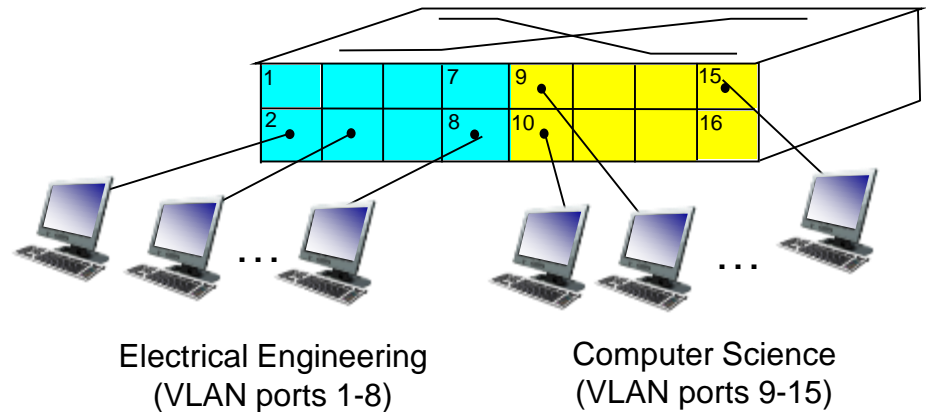
… operates as multiple virtual switches

Electrical Engineering
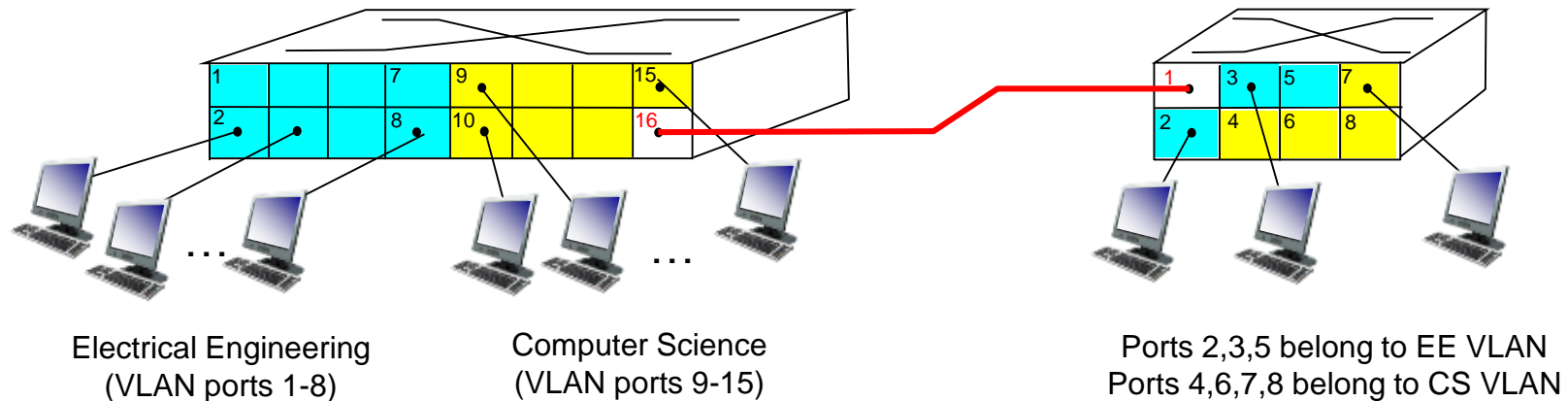(VLAN ports 1-8)

Computer Science
(VLAN ports 9-16)

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)
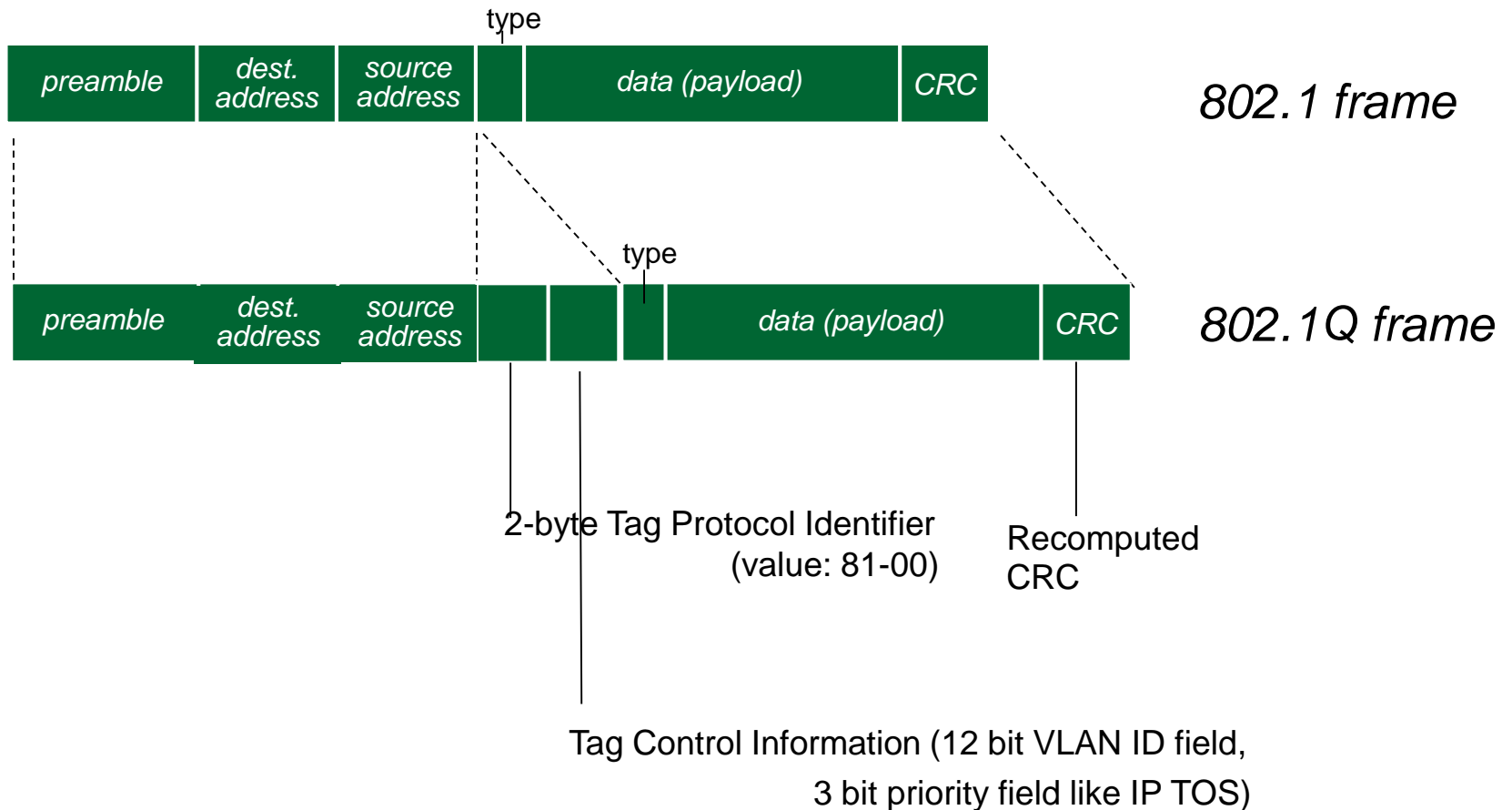 - in practice vendors sell combined switches plus routers

router

Electrical Engineering
(VLAN ports 1-8)

Computer Science
(VLAN ports 9-15)

VLANS spanning multiple switches

Electrical Engineering
(VLAN ports 1-8)

Computer Science
(VLAN ports 9-15)

Ports 2,3,5 belong to EE VLAN
Ports 4,6,7,8 belong to CS VLAN

- *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

type

| preamble | dest. address | source address | | data (payload) | CRC |

802.1 frame

type

| preamble | dest. address | source address | | | | data (payload) | CRC |

802.1Q frame

2-byte Tag Protocol Identifier
(value: 81-00)

Recomputed
CRC

Tag Control Information (12 bit VLAN ID field,
3 bit priority field like IP TOS)

The end. ☺

Homework #2

CH6

- R4, R5, P8, P10, P18, P21
- Wireshark Labs