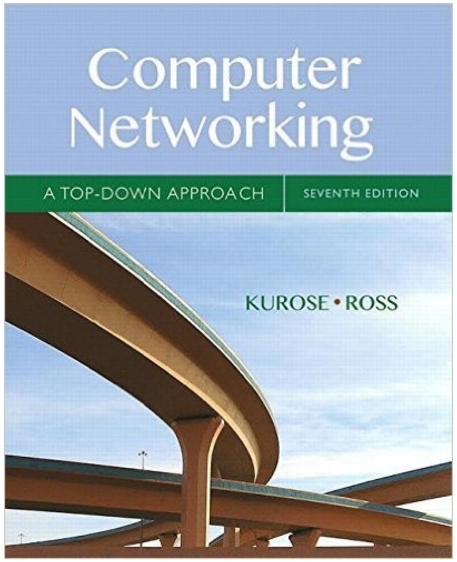
Chapter 5
Link Layer



A note on the use of these ppt 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:

- *If you use these slides (e.g., in a class) that you mention their source (after all, we'd like people to use our book!)*
- *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
Jim Kurose, Keith Ross
Addison-Wesley
April 2016

Link layer, LANs: outline

5.1 introduction, services

5.2 error detection, correction

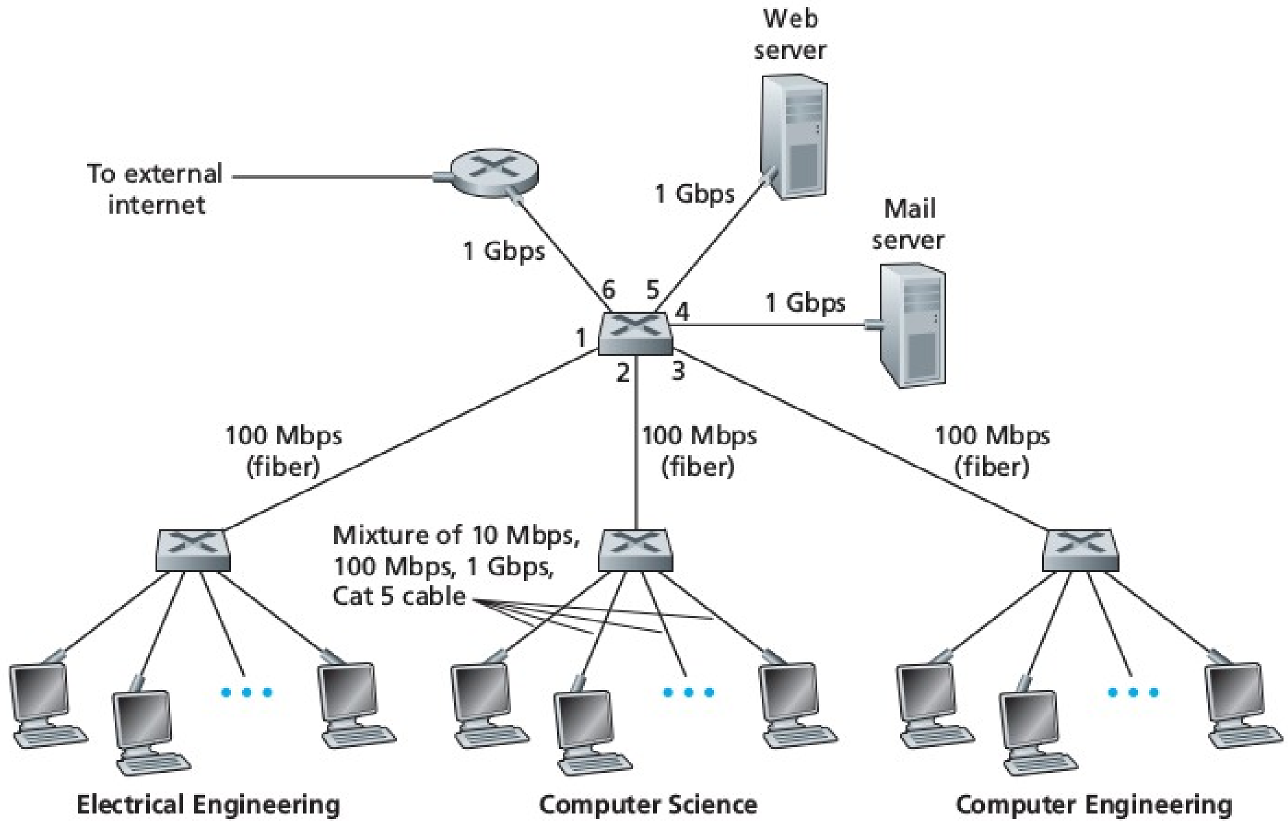
5.3 multiple access protocols

5.4 LANs

- *addressing, ARP*
- *Ethernet*
- *Switches*
- *VLANS*

Switched network, an example

Switches operate at link layer
They switch link-layer frames and DON'T use IP addresses…
Thus DON'T use routing algorithm (OSPF, RIP…)



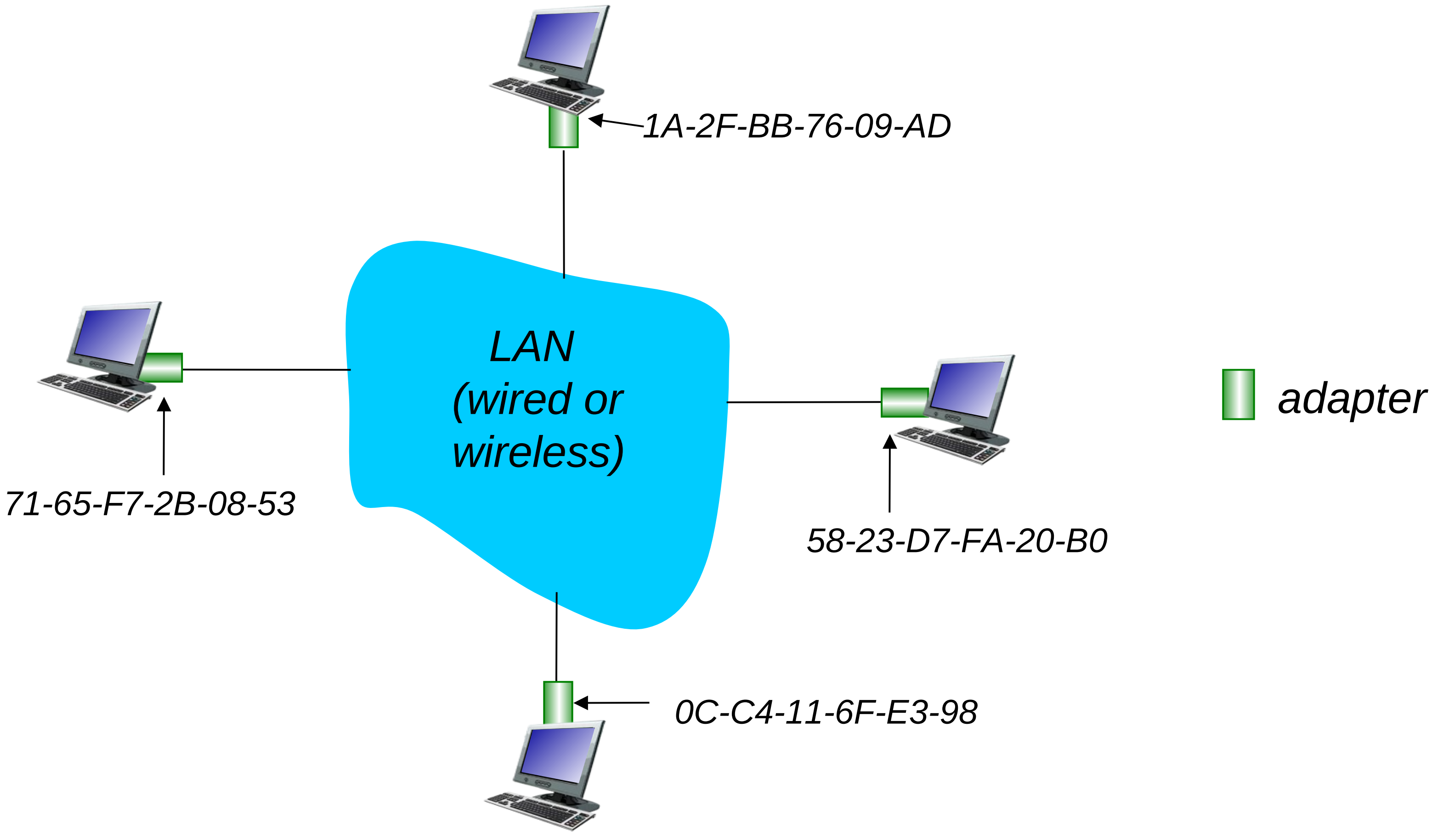
MAC addresses and ARP

- 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 “number” represents 4 bits)

LAN addresses and ARP

each adapter on LAN has unique LAN address

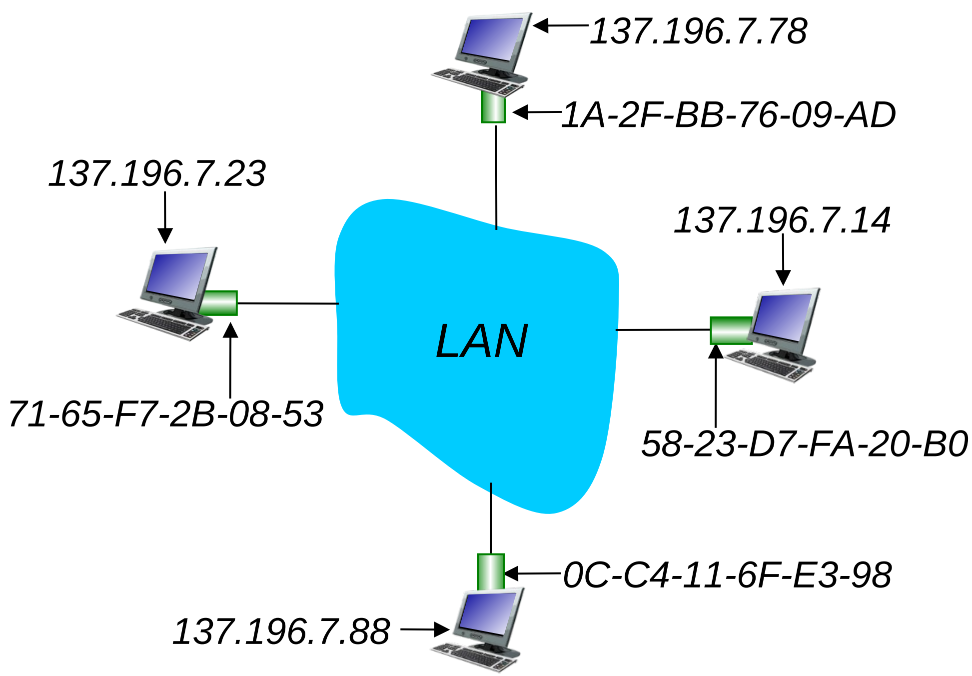


LAN addresses (more)

- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- analogy:
  - MAC address: like Fiscal Code
  - 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)

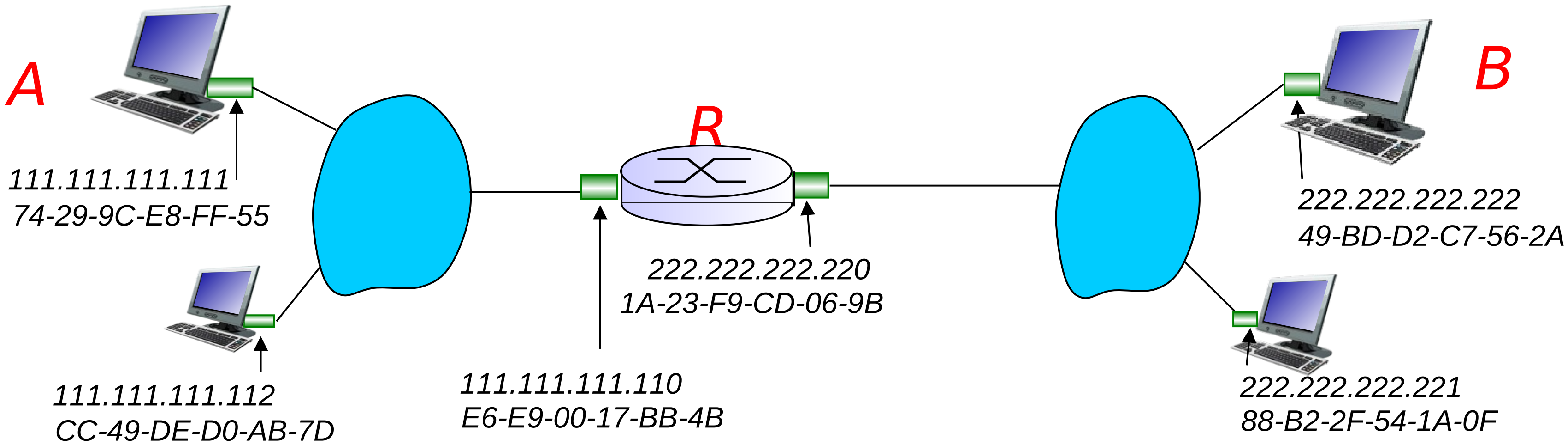
ARP protocol: same LAN

- *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*
  - *dest 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

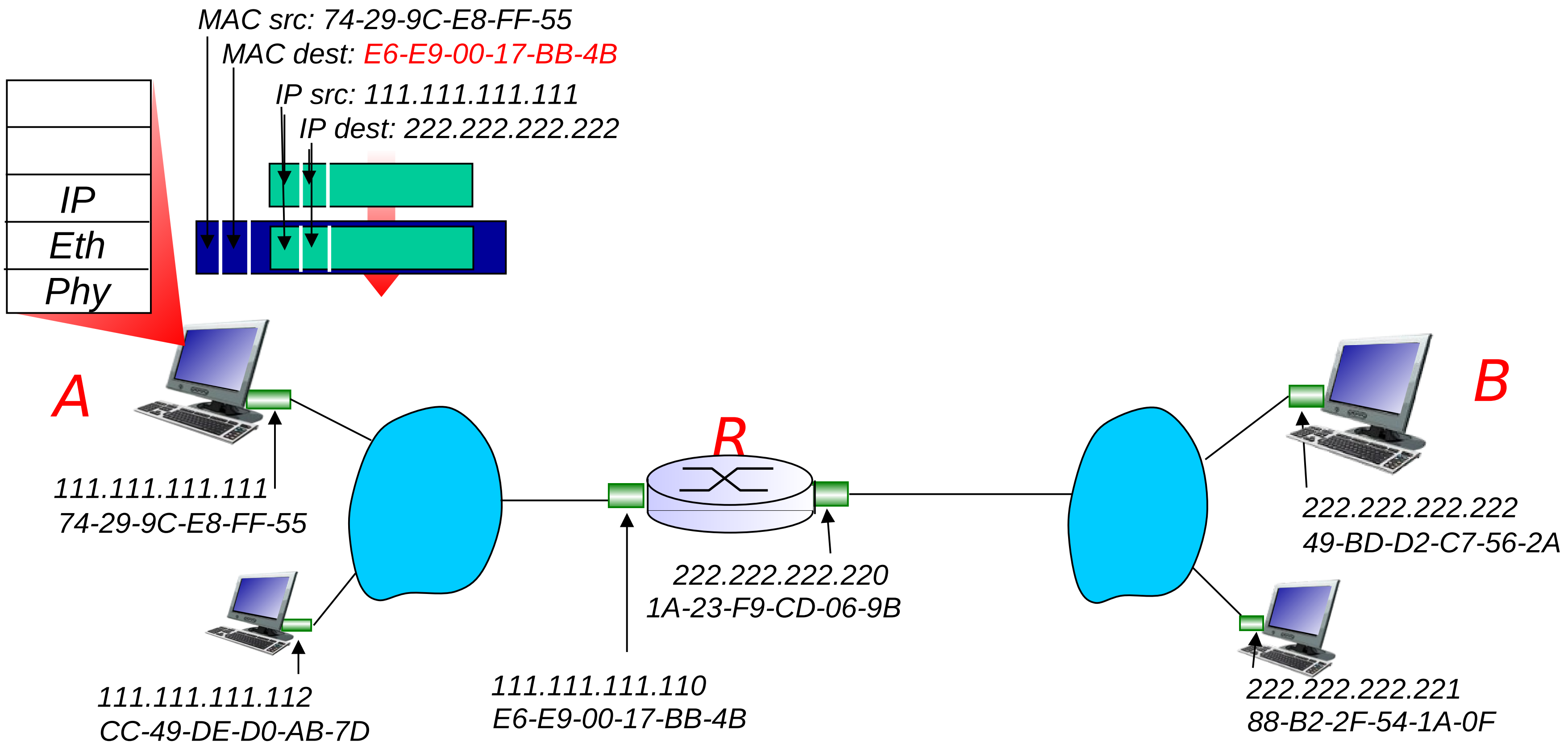
walkthrough: send datagram from A to B via R

- 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?)



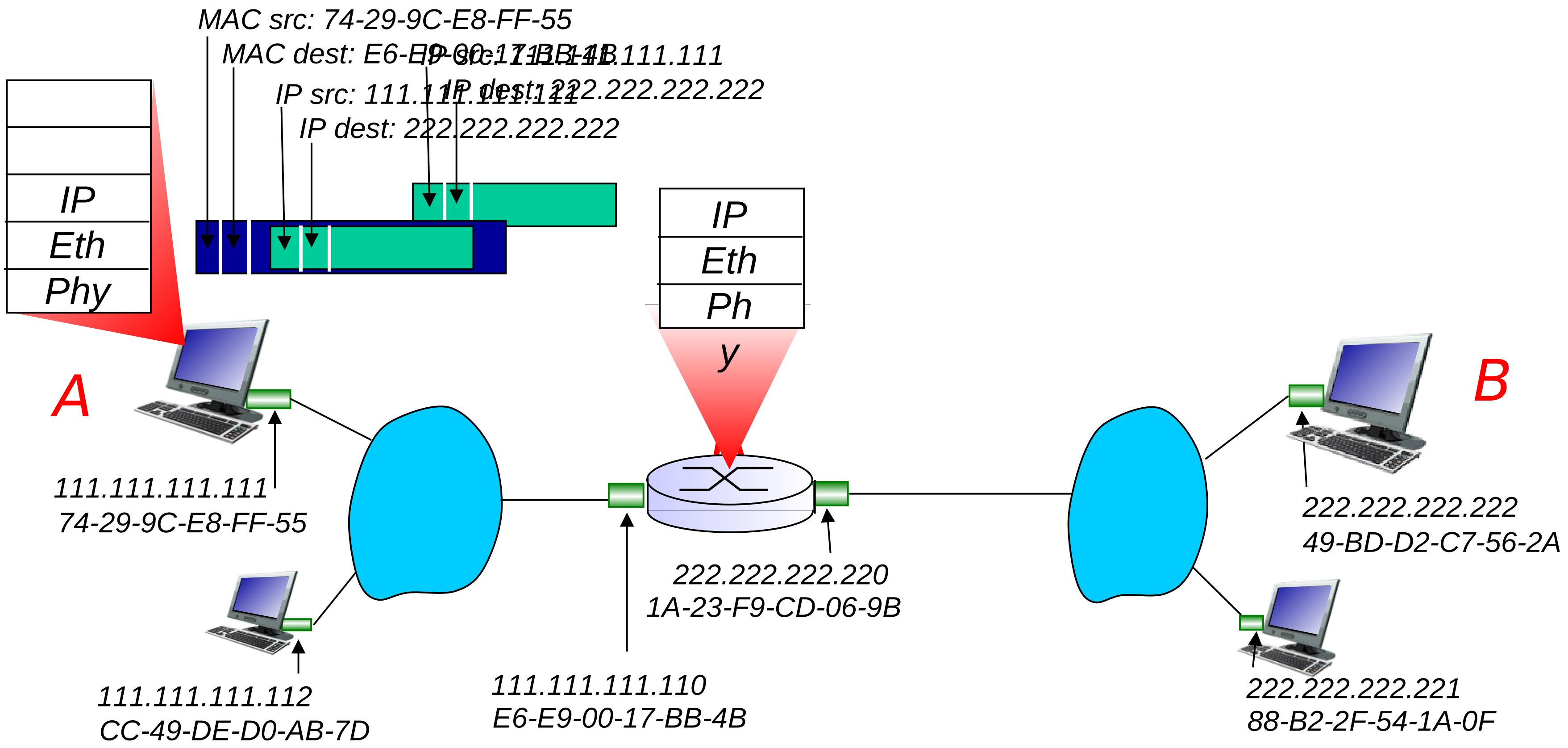
Addressing: routing to another LAN

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



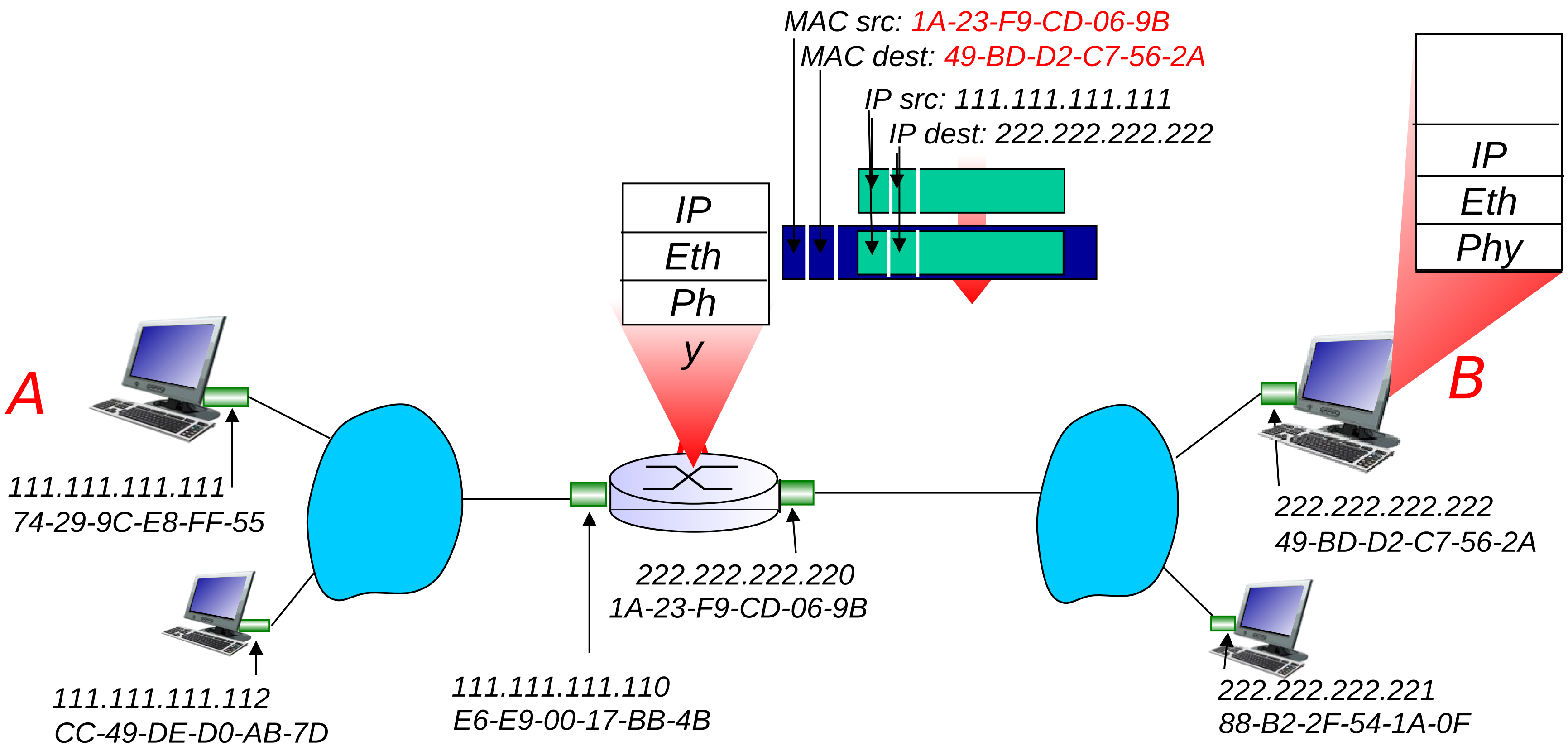
Addressing: routing to another LAN

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



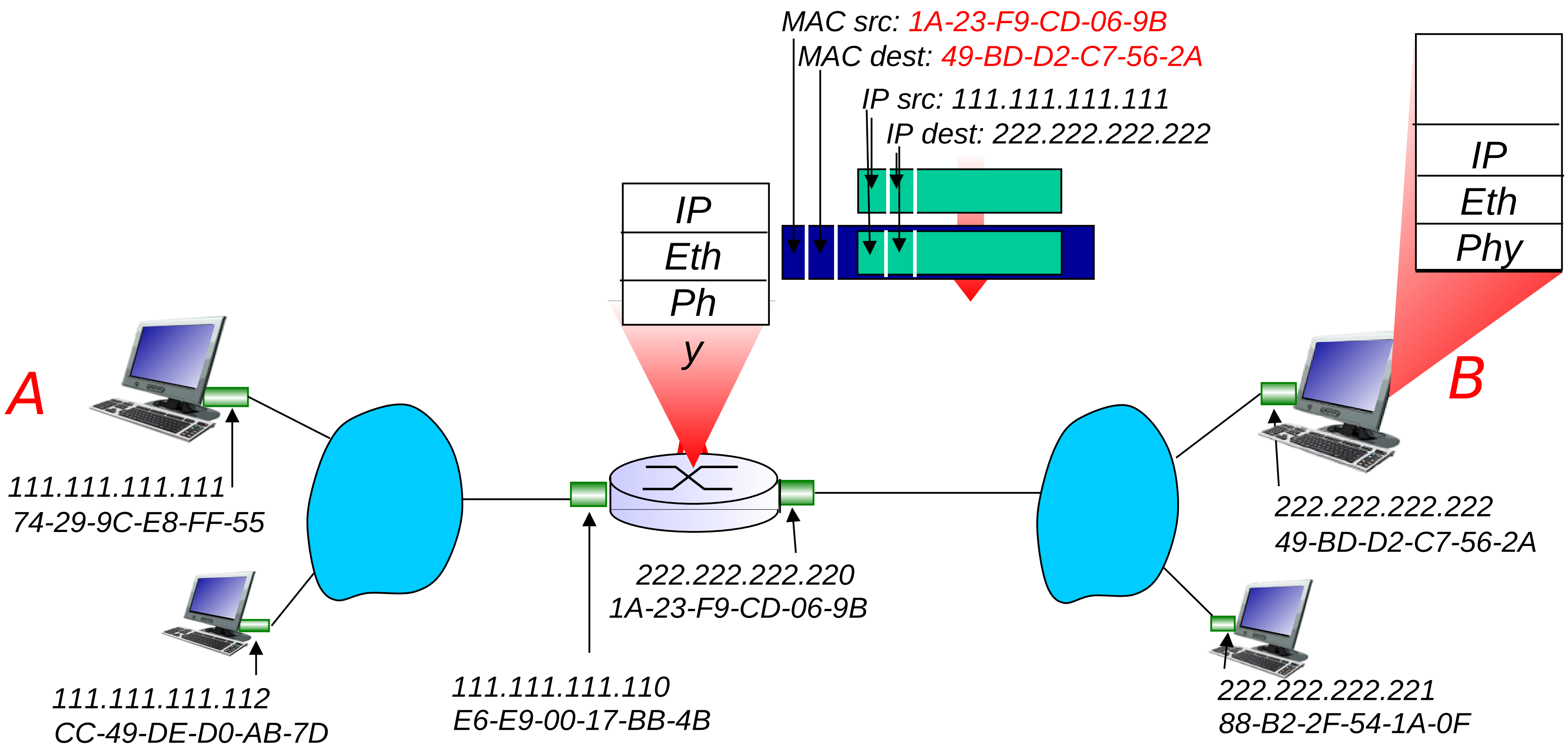
Addressing: routing to another LAN

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



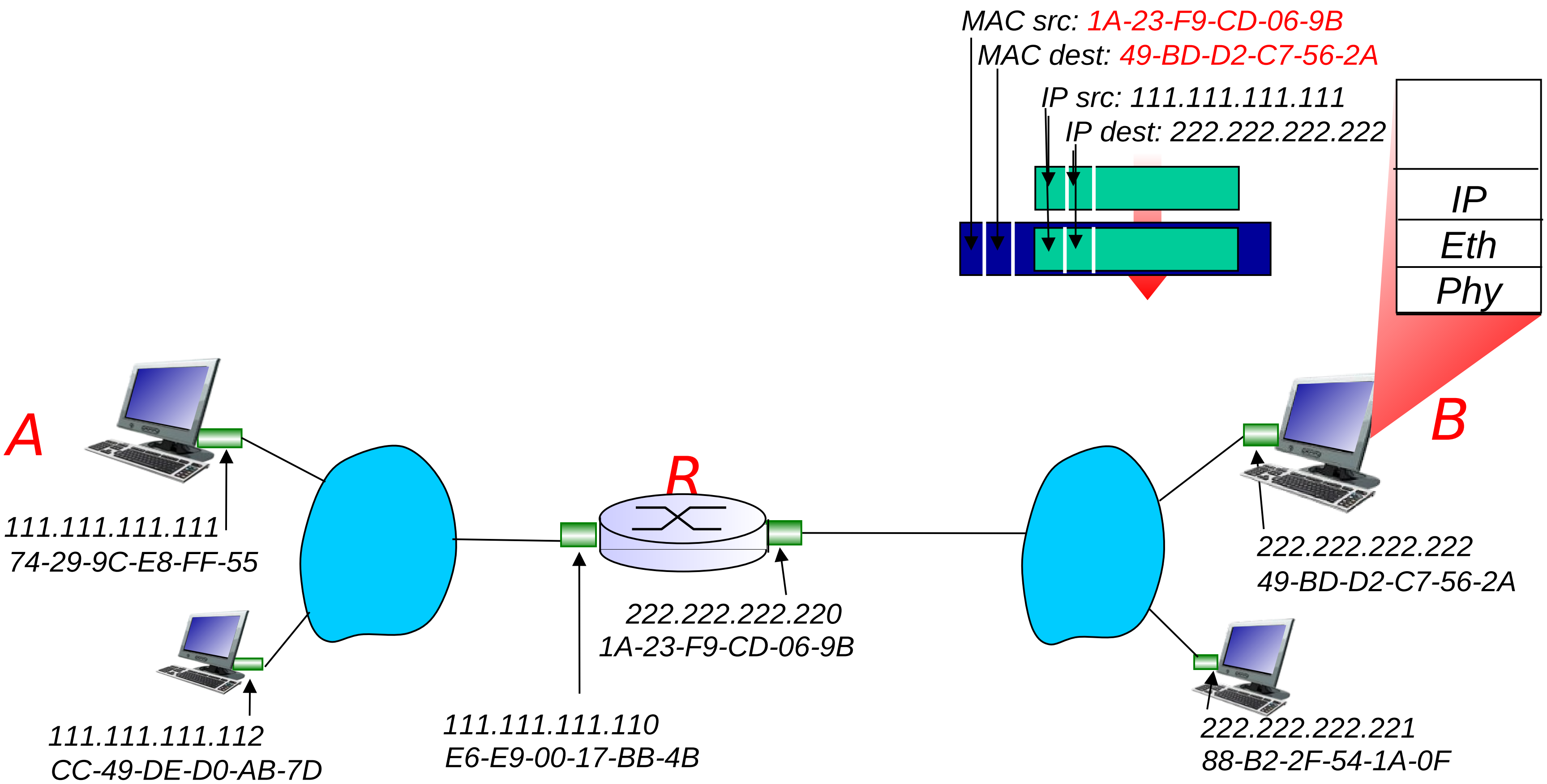
Addressing: routing to another LAN

- 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



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



Link layer, LANs: outline

5.1 introduction, services

5.2 error detection, correction

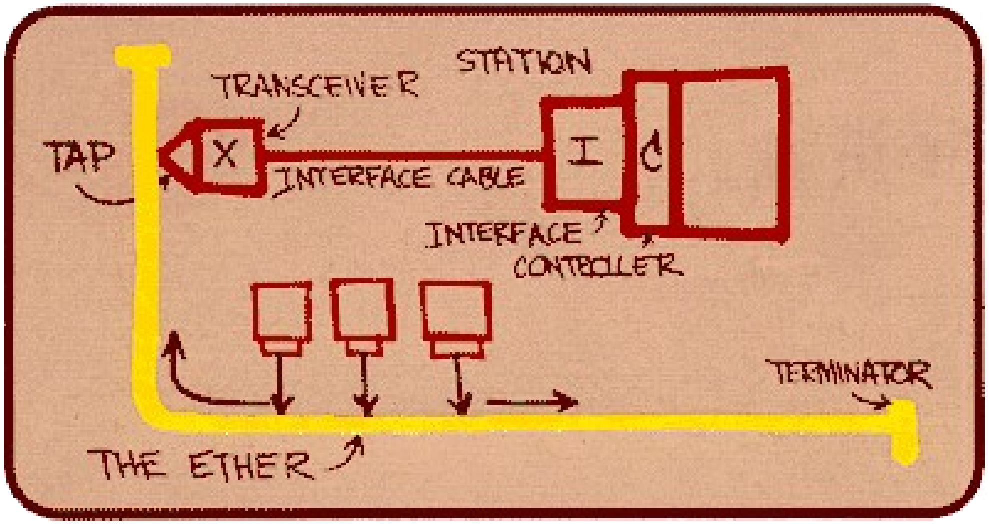
5.3 multiple access protocols

5.4 LANs
- addressing, ARP
- Ethernet
- Switches
- VLANS

Ethernet

"dominant" wired LAN technology:

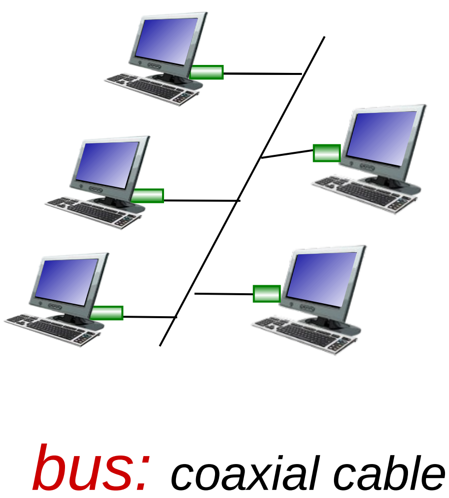
- *Cheap for NIC*
- *first widely used LAN technology*
- *simpler, cheaper than token ring LANs*
- *kept up with speed race: 10 Mbps – 10 Gbps*

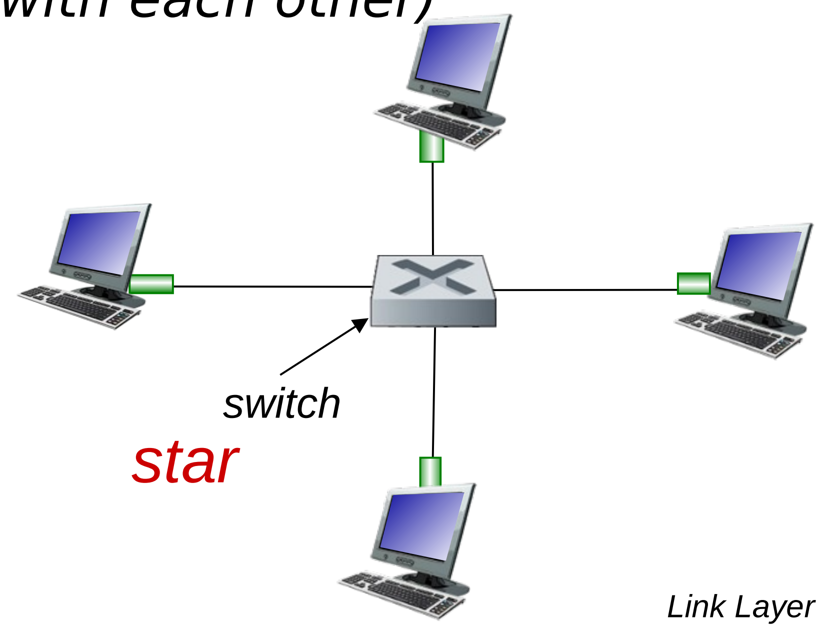


Metcalfe's Ethernet sketch

Ethernet: physical topology

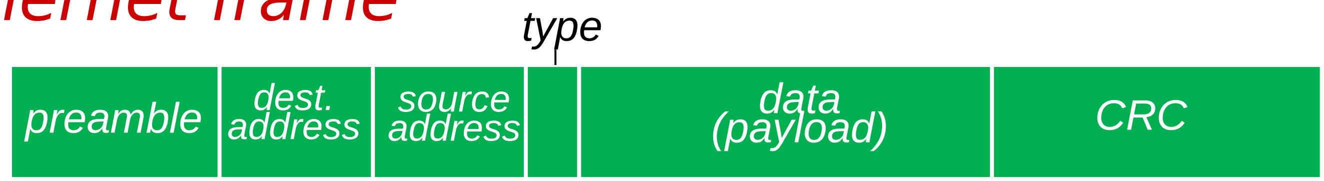
- *bus:* popular through mid 90s
  - all nodes in same collision domain (can collide with each other)
- *star:* prevails today
  - Earlier: *hub* in center (can collide)
  - Now: active *switch* in center
    - each "spoke" runs a (separate) Ethernet protocol (nodes do not collide with each other)





Ethernet frame structure

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

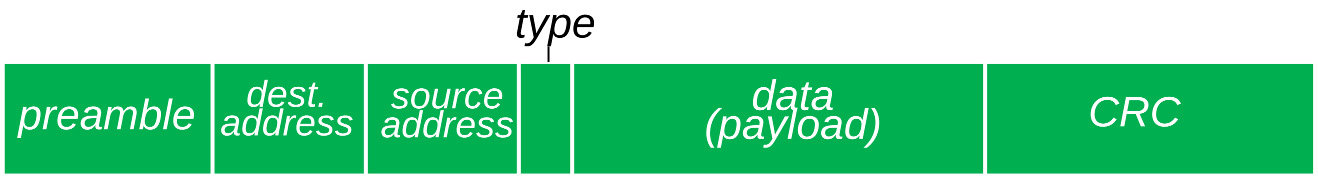


preamble:

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

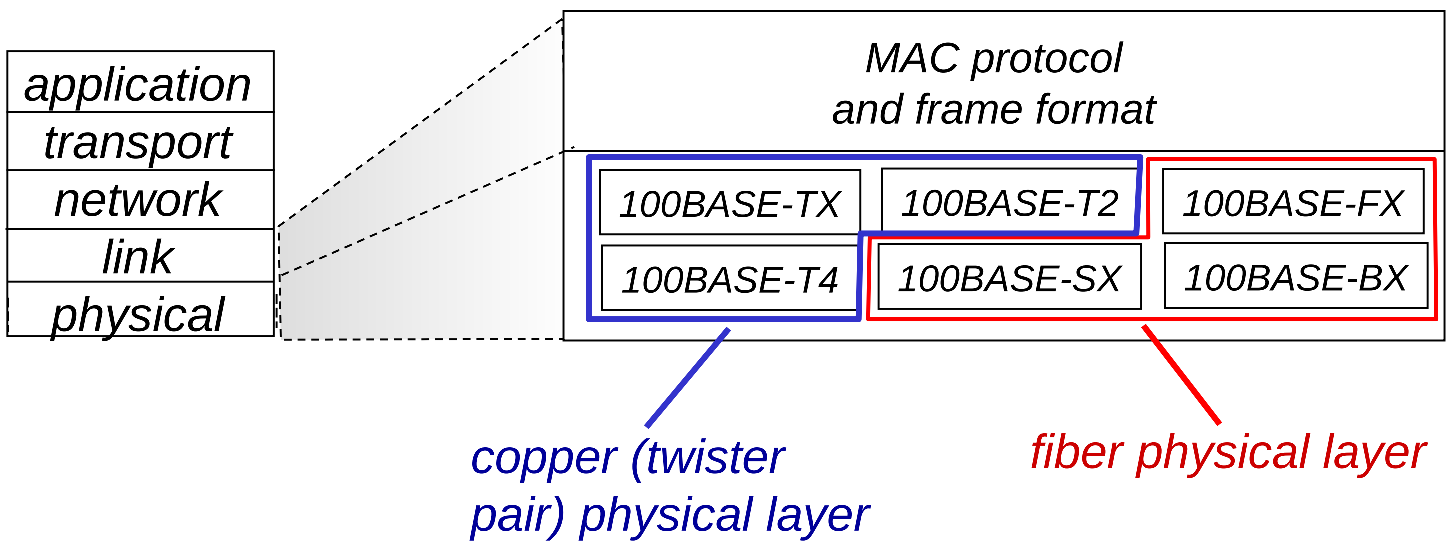


Ethernet: unreliable, connectionless

- *connectionless:* no handshaking between sending and receiving NICs
- *unreliable:* receiving NIC doesnt 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 wth 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, 10G bps
  - different physical layer media: fiber, cable



Link layer, LANs: outline

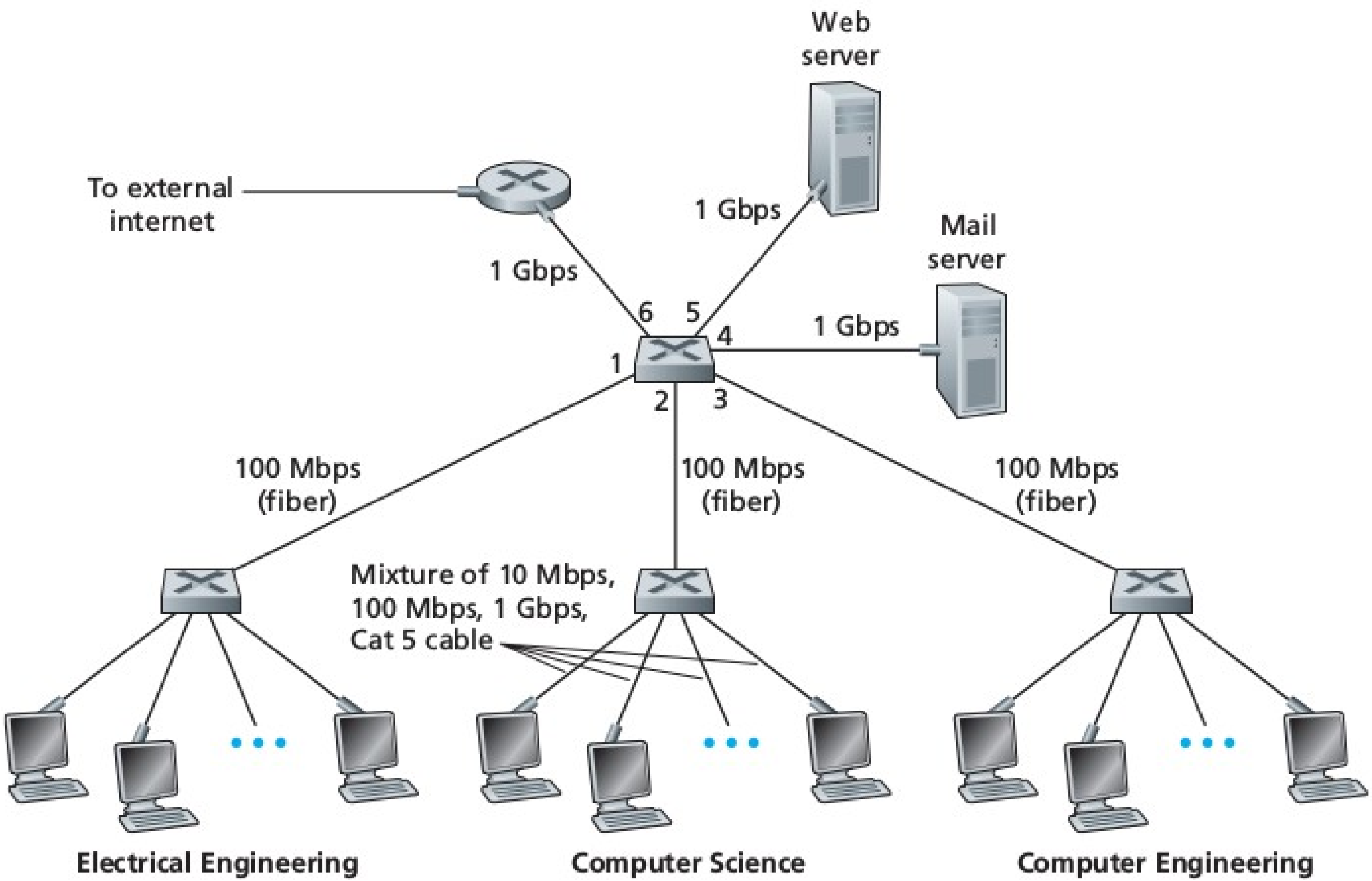
5.1 introduction, services

5.2 error detection, correction

5.3 multiple access protocols

5.4 LANs
- addressing, ARP
- Ethernet
- Switches
- VLANS

Switched network, an example

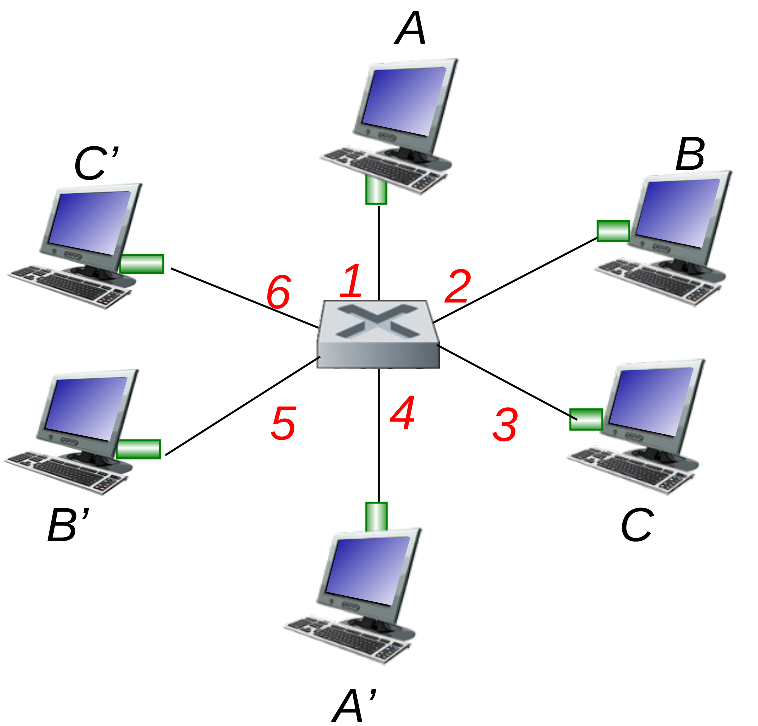


Ethernet switch

- *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*
- *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*

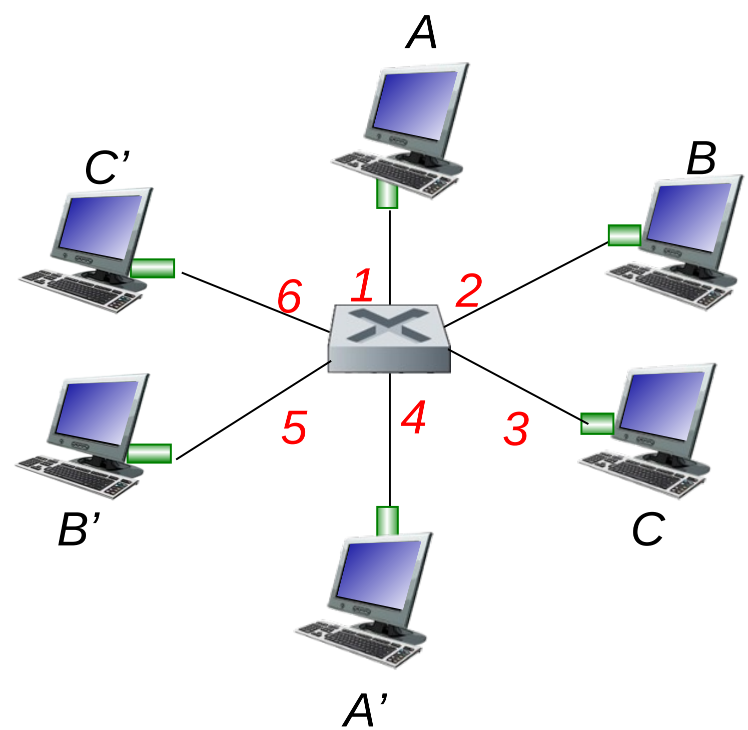


switch with six interfaces (1,2,3,4,5,6)

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!*



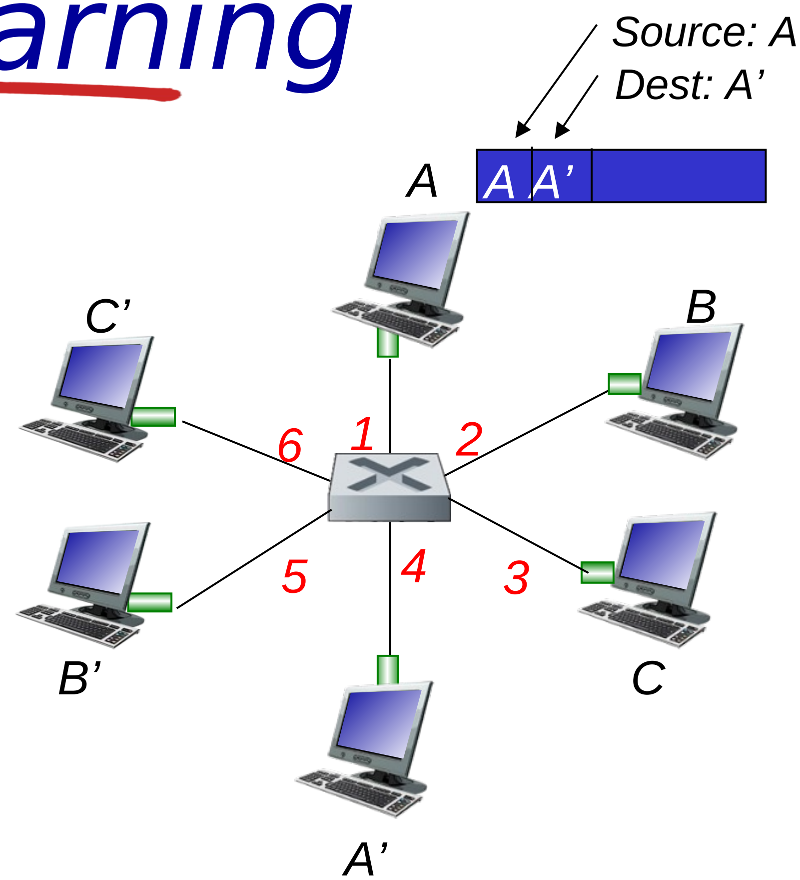
switch with six interfaces (1,2,3,4,5,6)

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

- *something like a routing protocol?*

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)

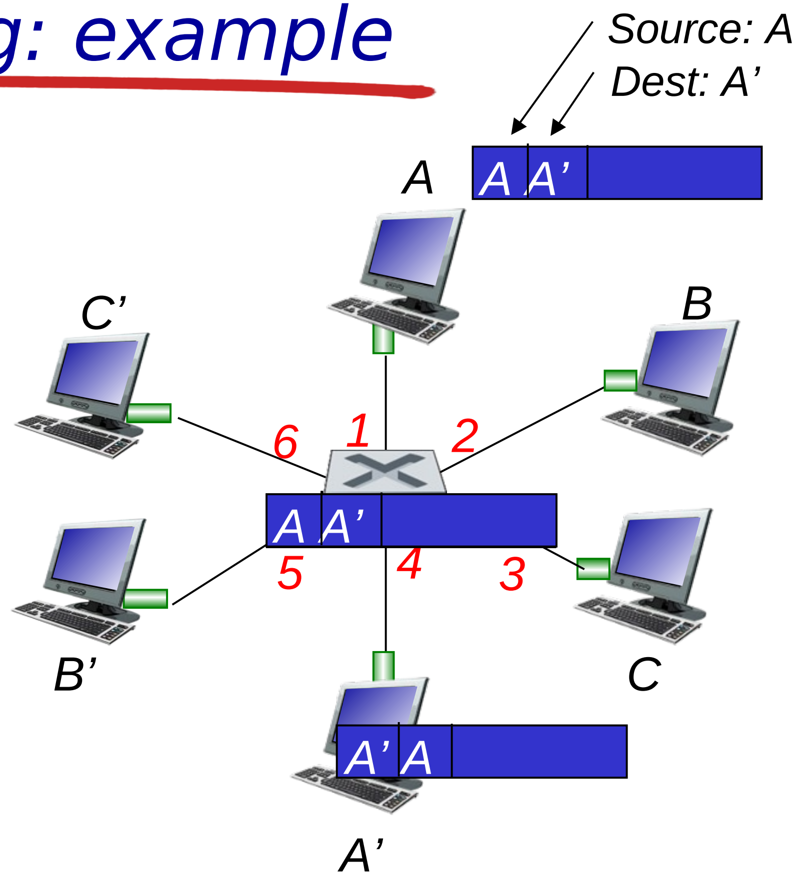
Switch: frame filtering/forwarding

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

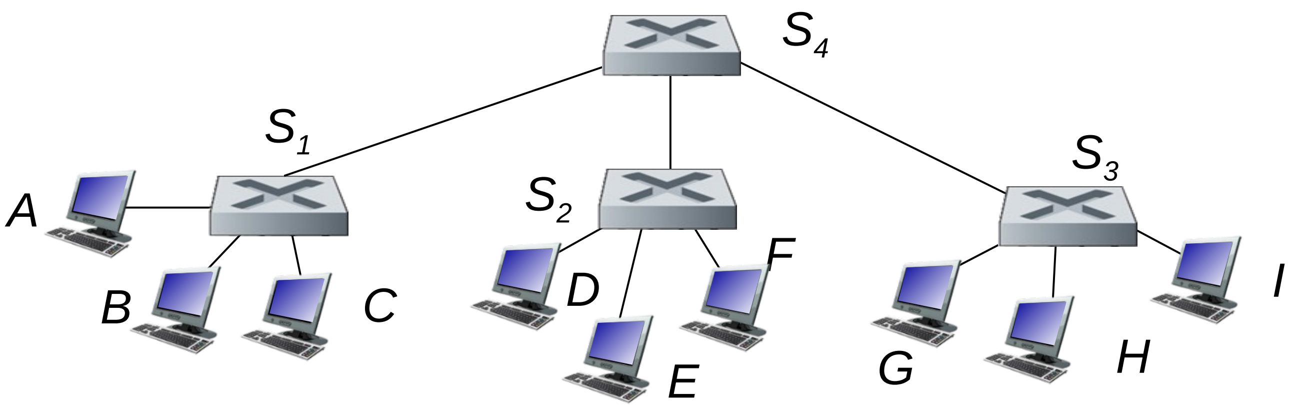


MAC addr	interface	TTL
A	1	60
A'	4	60

switch table
(initially empty)

Interconnecting switches

- switches can be connected together

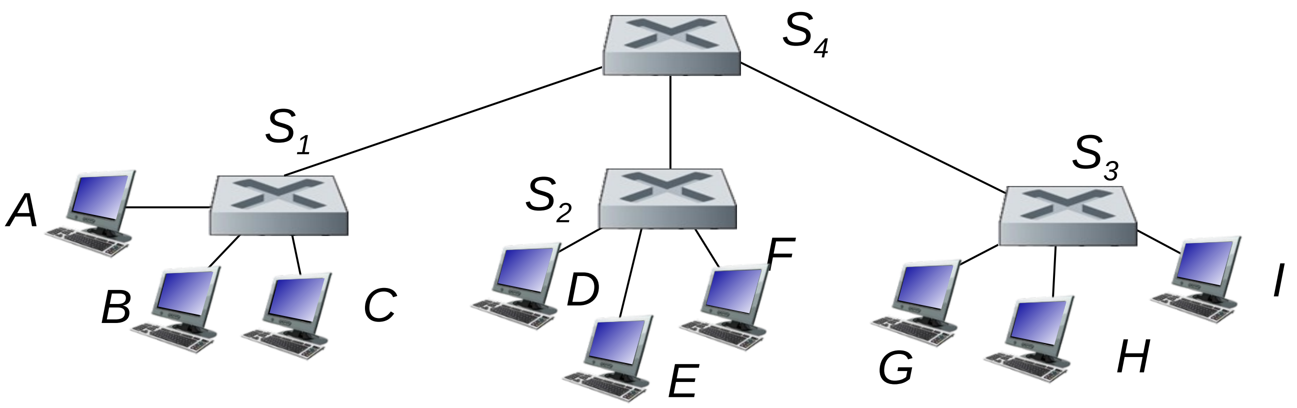


Q: sending from A to G - how does S_1 know to forward frame destined to F via S_4 and S_3?

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

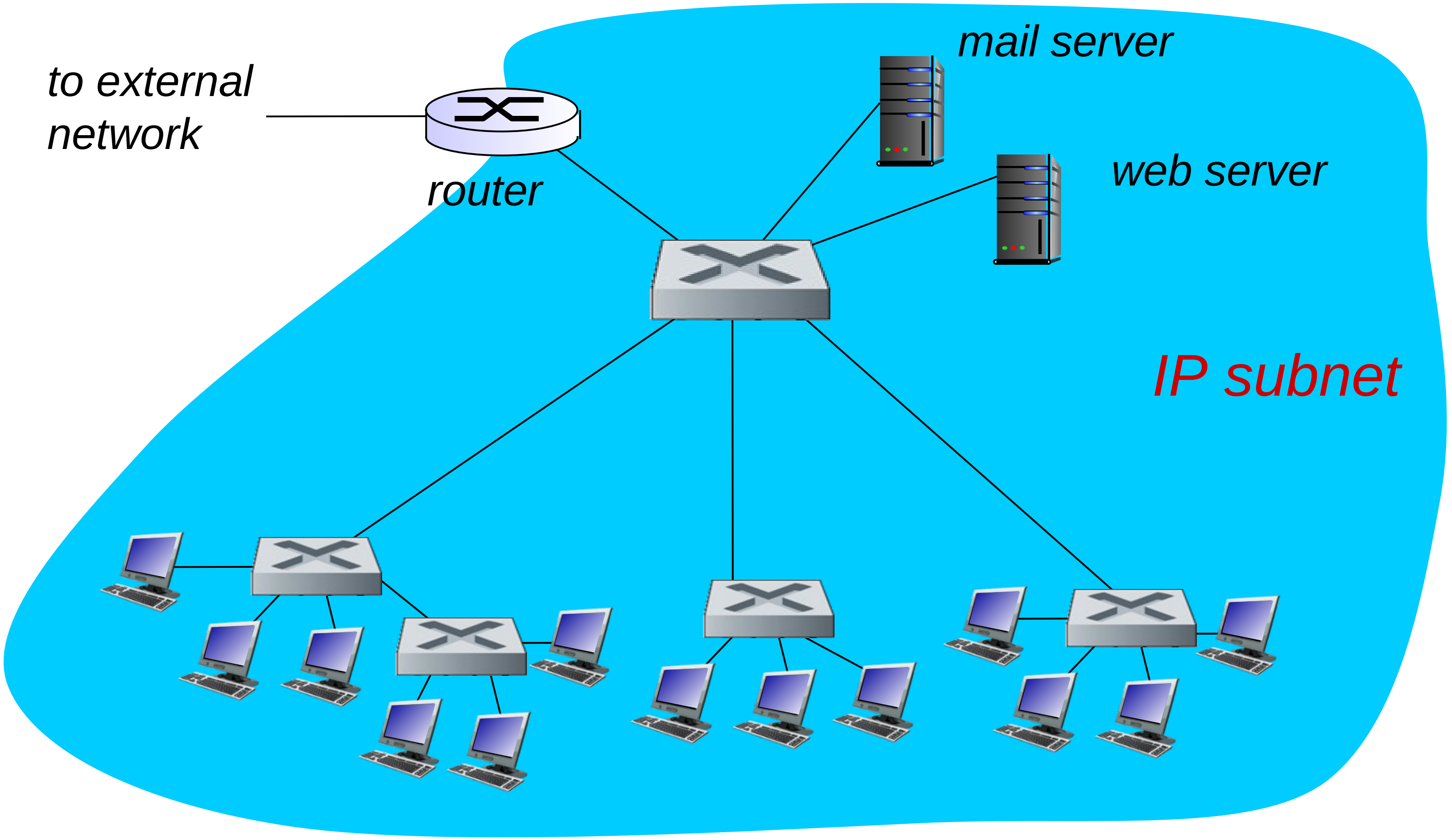
Self-learning multi-switch example

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



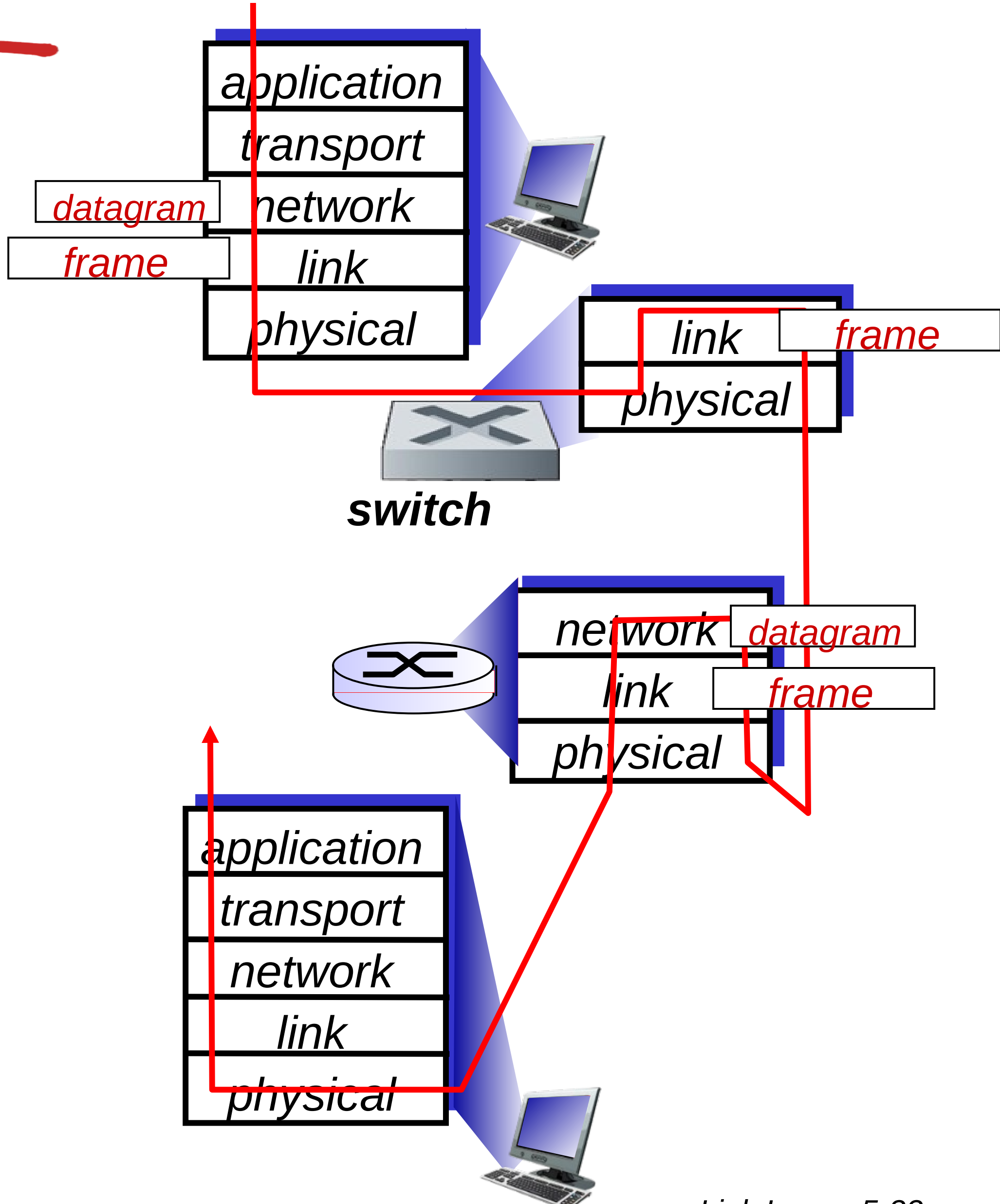
Switches vs. routers

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



Link layer, LANs: outline

5.1 introduction, services

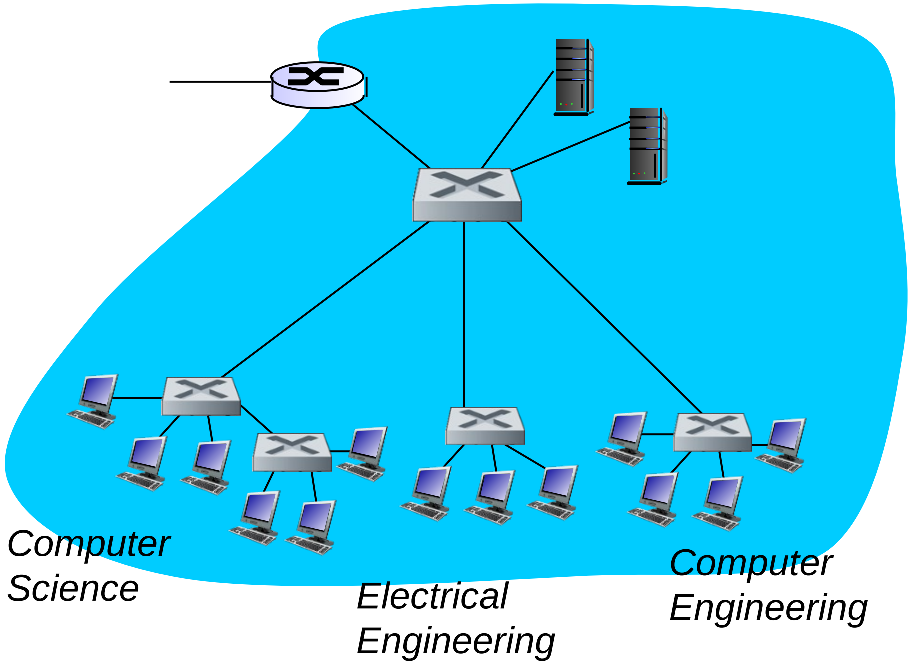
5.2 error detection, correction

5.3 multiple access protocols

5.4 LANs

- *addressing, ARP*
- *Ethernet*
- *Switches*
- *VLANS*

VLANs: motivation



consider:

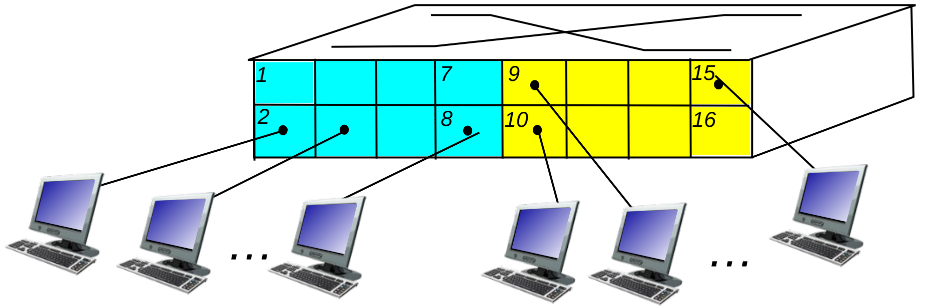
- *CS user moves office to EE, but wants connect to CS switch?*
- *single broadcast domain:*
  - *all layer-2 broadcast traffic (ARP, DHCP, unknown location of destination MAC address) must cross entire LAN*
  - *security/privacy, efficiency issues*

VLANs

Virtual Local Area Network

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

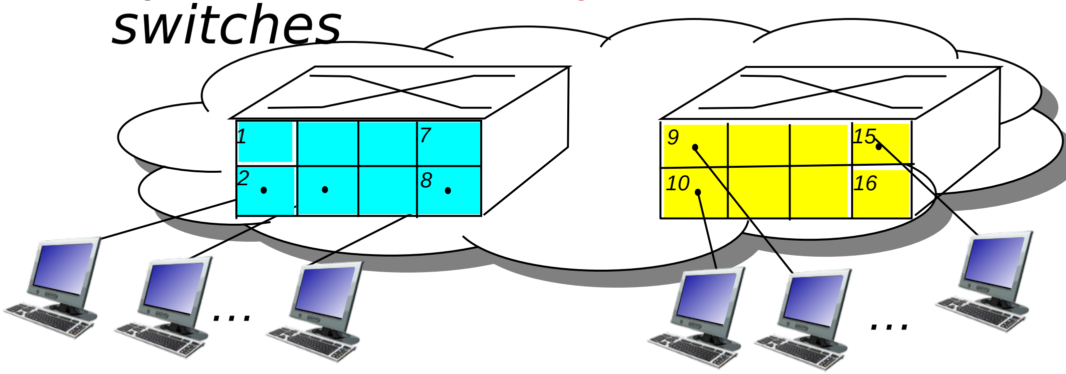
port-based VLAN: switch ports grouped (by switch management software) so that single physical switch ……



Electrical Engineering (VLAN ports 1-8)

Computer Science (VLAN ports 9-15)

… operates as multiple virtual switches

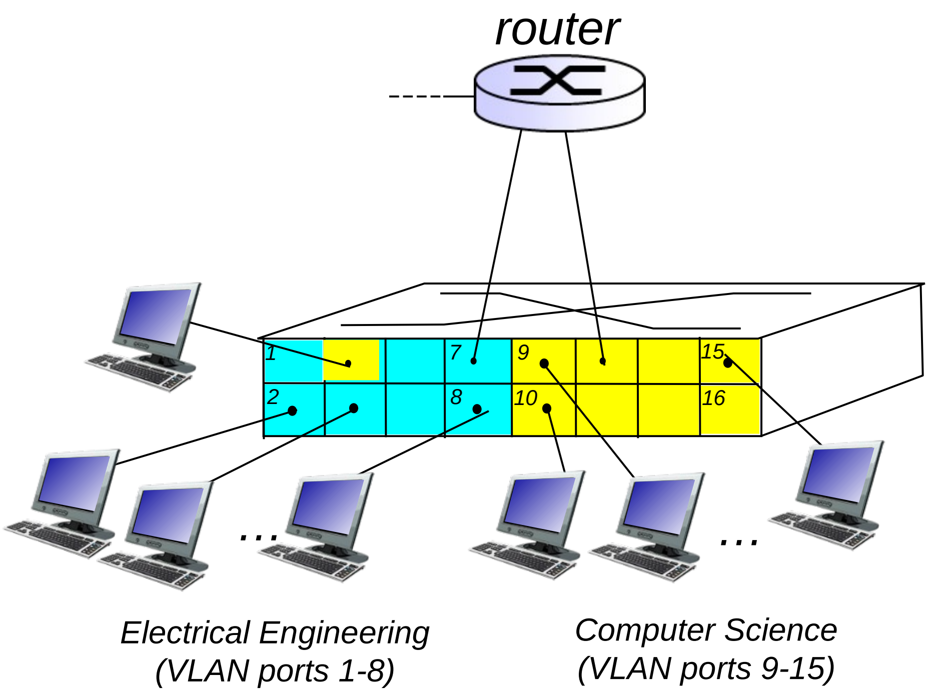


Electrical Engineering (VLAN ports 1-8)

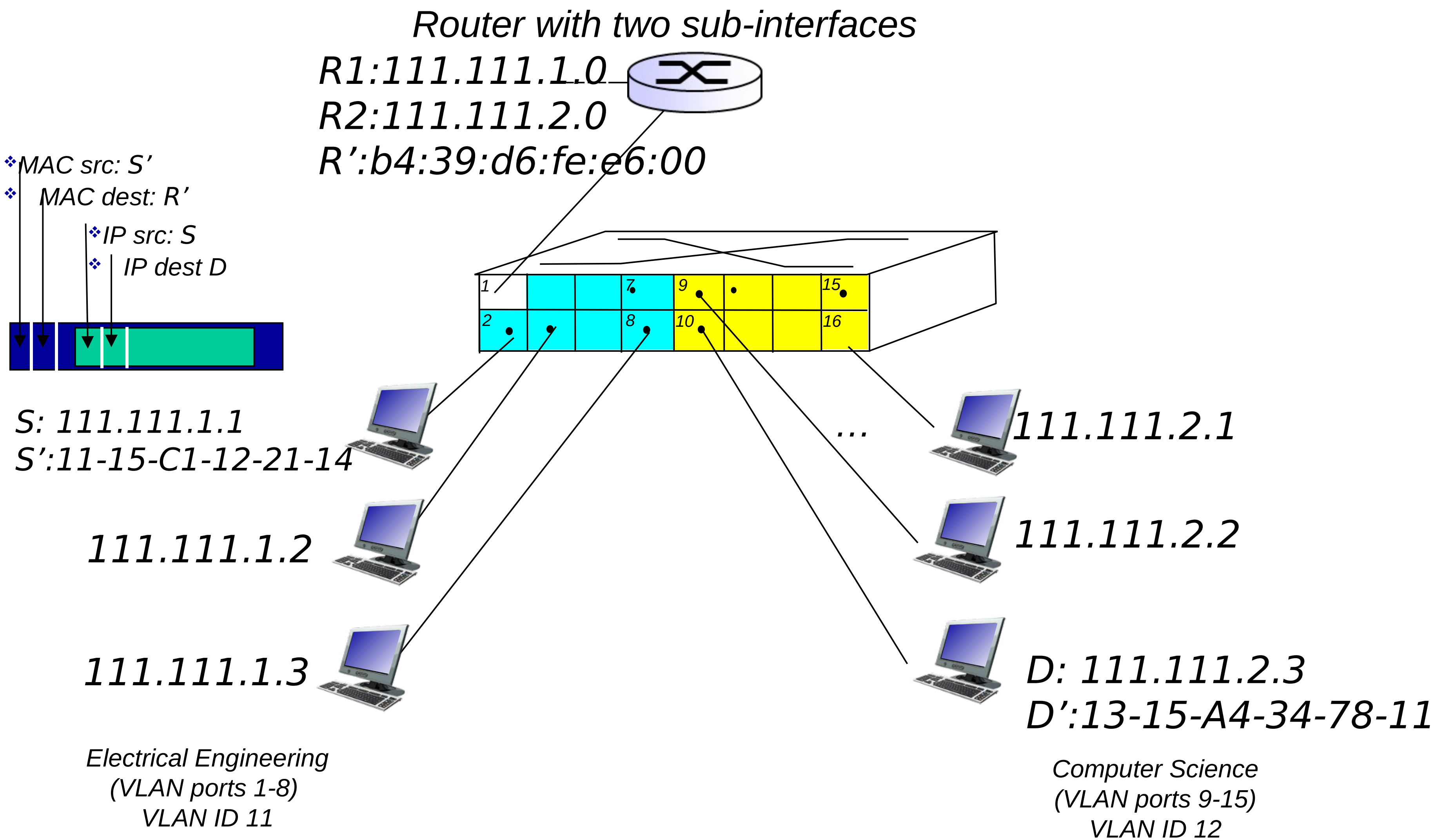
Computer Science (VLAN ports 9-16)

Port-based VLAN

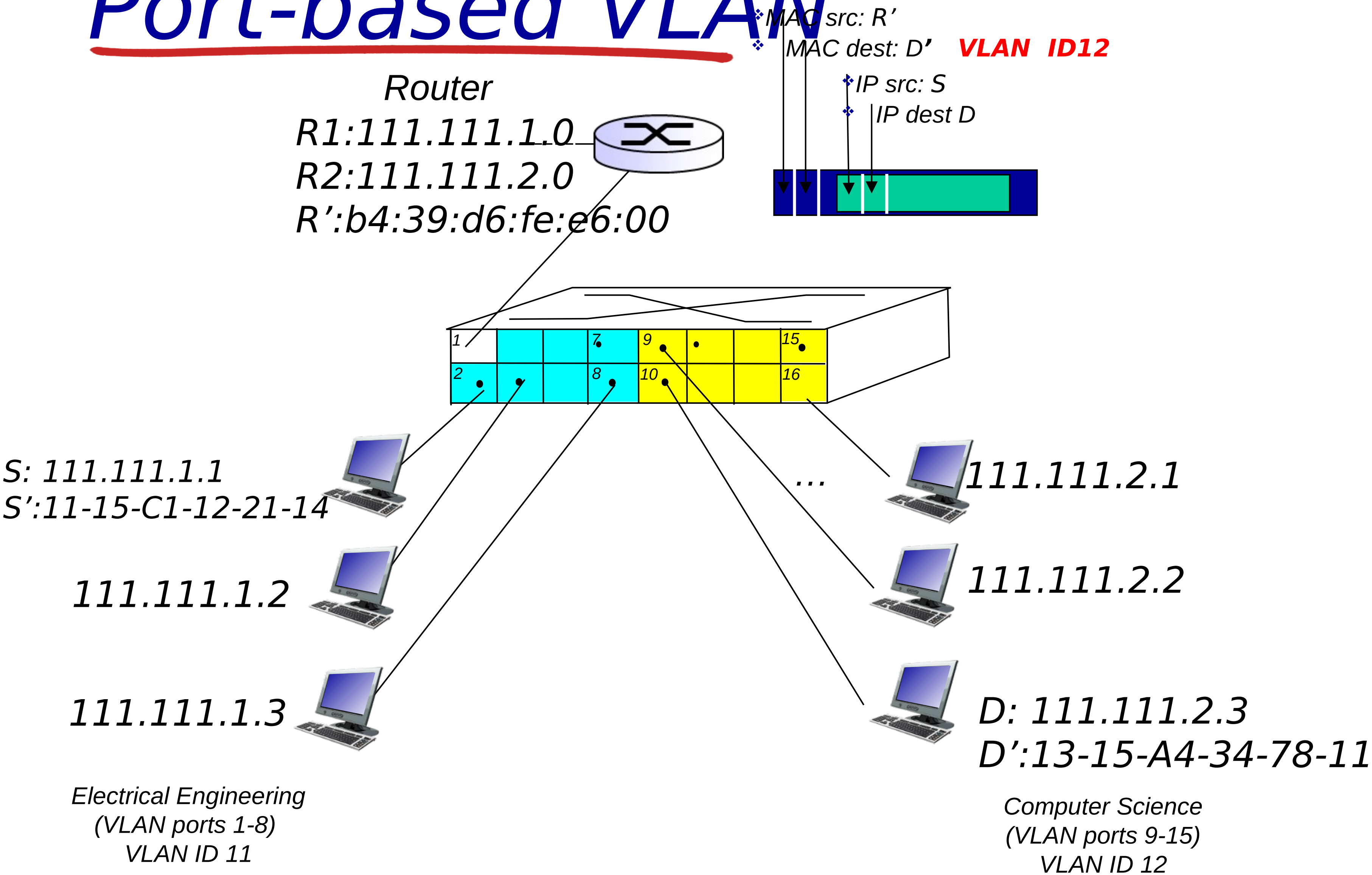
- *traffic isolation:* frames to/from ports 1-8 can only reach ports 1-8
  - can also define VLAN based on MAC addresses of endpoints, rather than switch port
- *dynamic membership:* ports can be dynamically assigned among VLANs
- *forwarding between VLANS:* done via routing (just as with separate switches)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



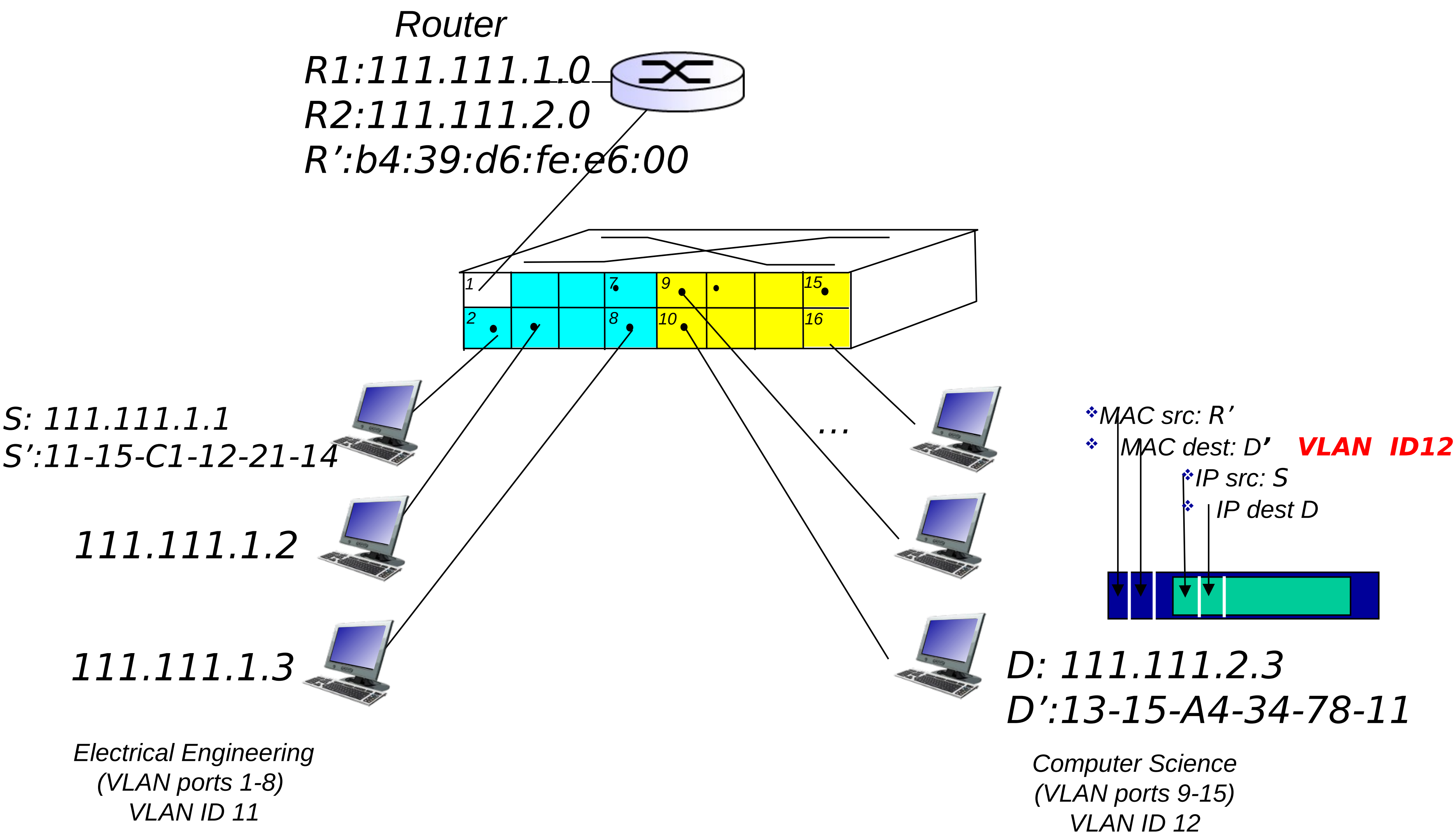
Port-based VLAN



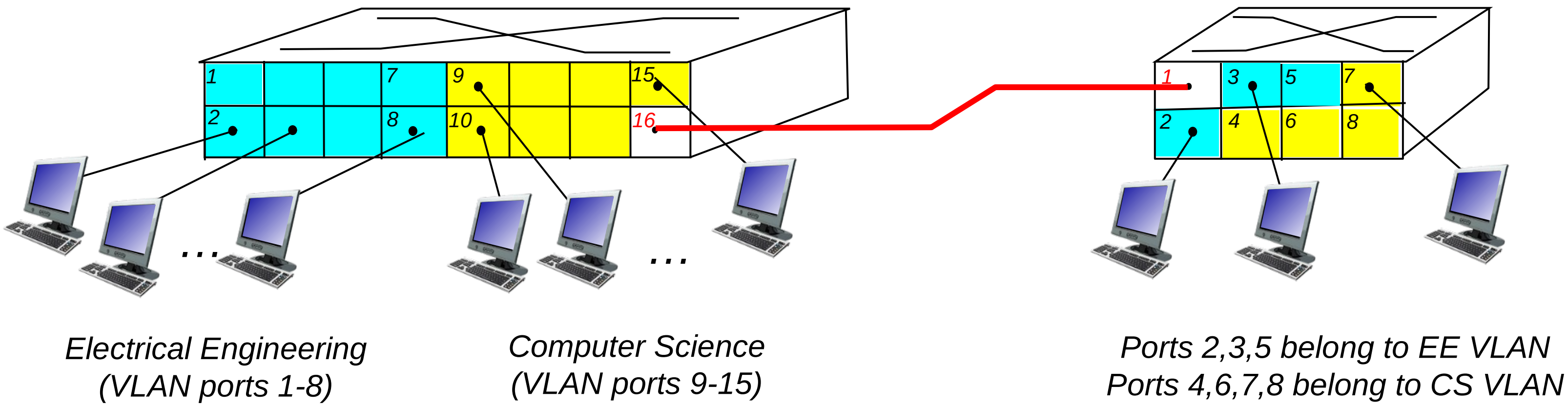
Port-based VLAN



Port-based VLAN

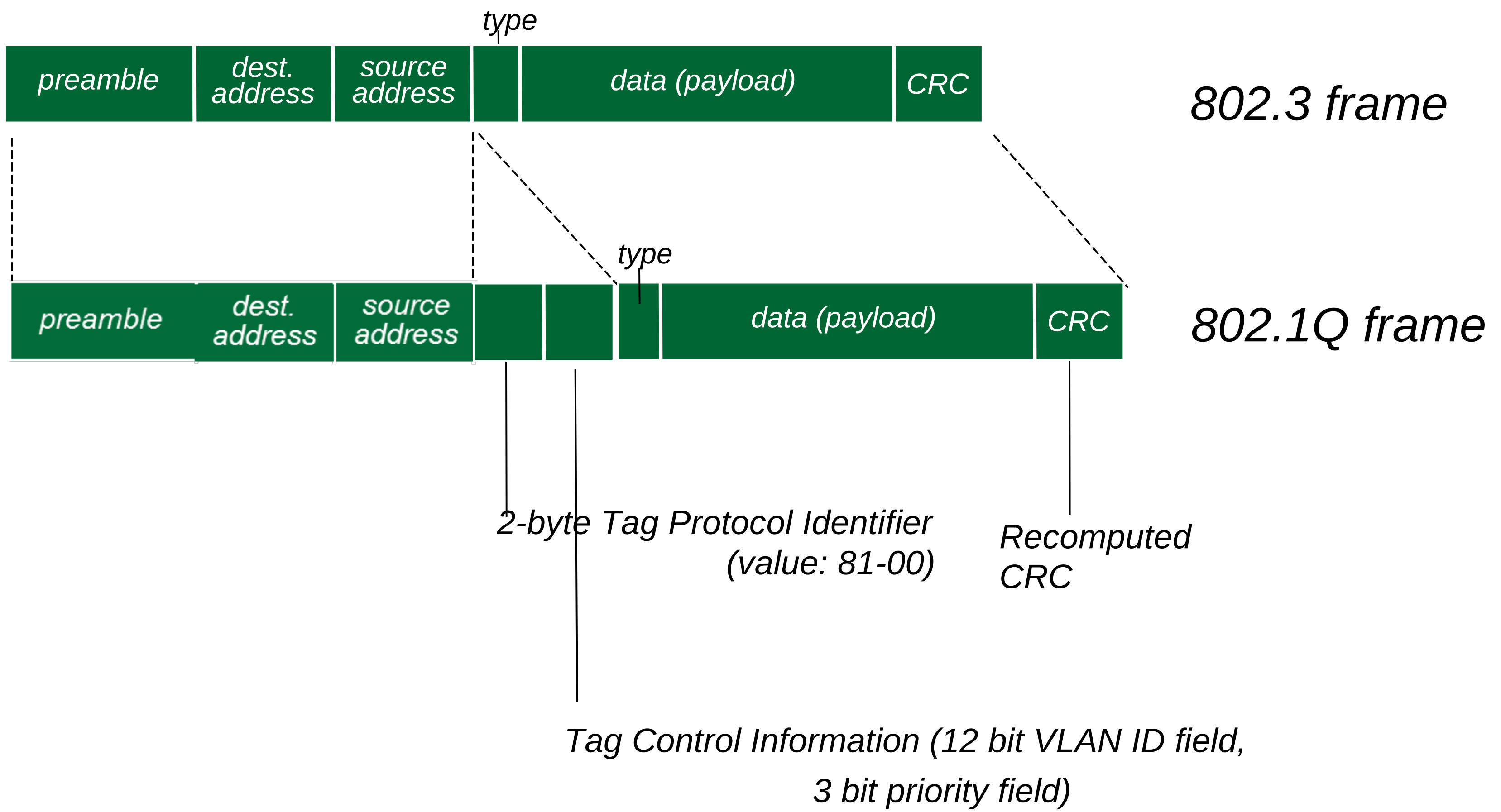


VLANS spanning multiple switches



- *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

5.1 introduction, services

5.2 error detection, correction

5.3 multiple access protocols

5.4 LANs

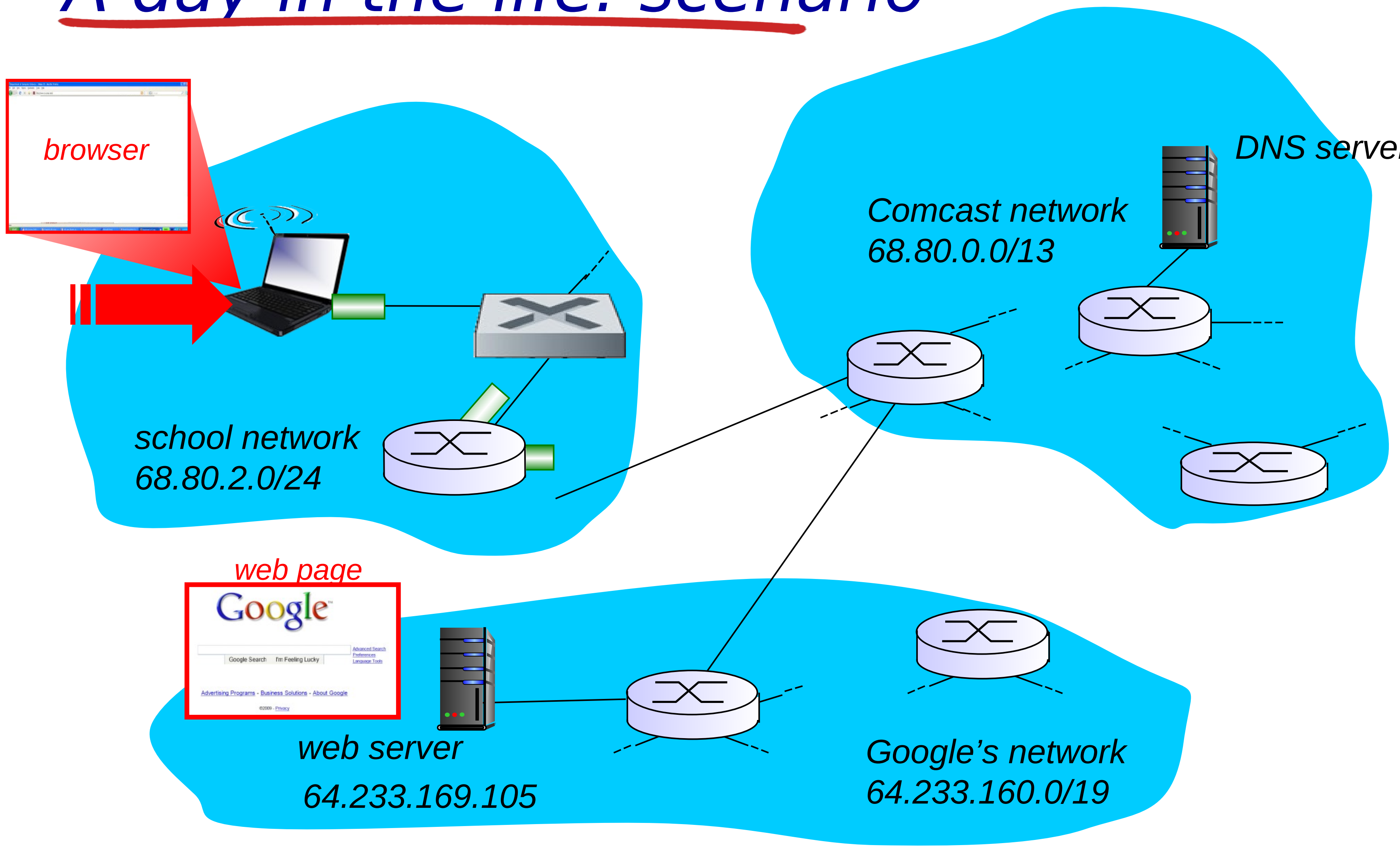
- addressing, ARP
- Ethernet
- switches
- VLANS

5.6 a day in the life of a web request

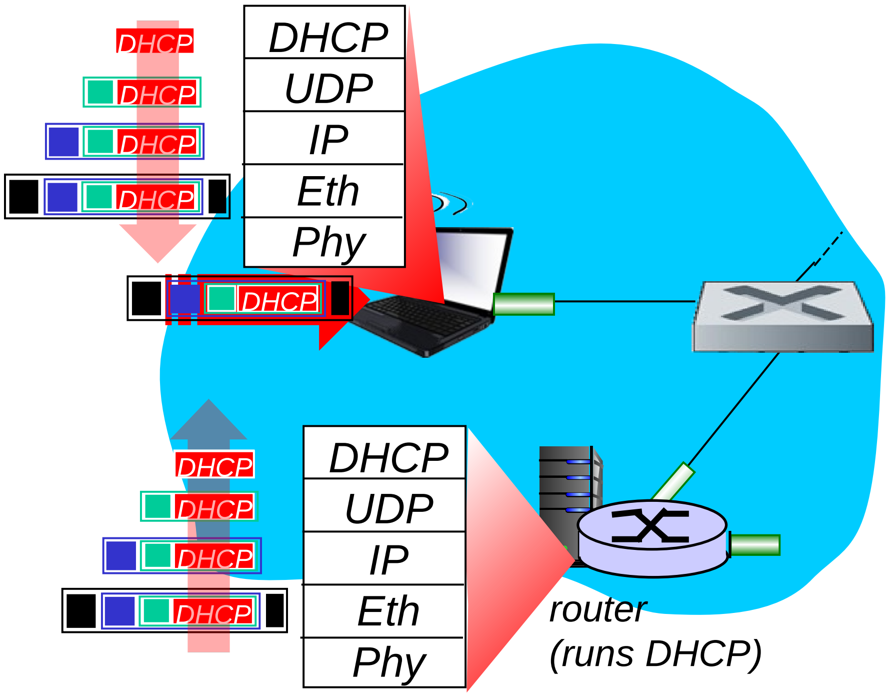
Synthesis: a day in the life of a web request

- *journey down protocol stack complete!*
  - *application, transport, network, link*
- *putting-it-all-together: synthesis!*
  - *goal: identify, review, understand protocols (at all layers) involved in seemingly simple scenario: requesting www page*
  - *scenario: student attaches laptop to campus network, requests/receives www.google.com*

A day in the life: scenario

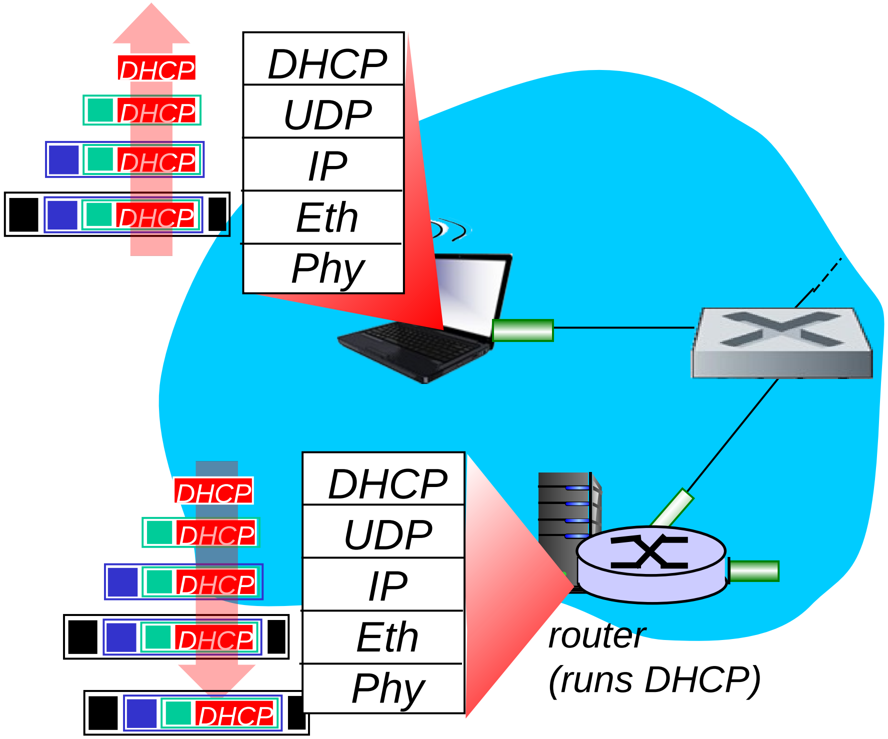


A day in the life... connecting to the Internet



- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use DHCP
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.3 Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

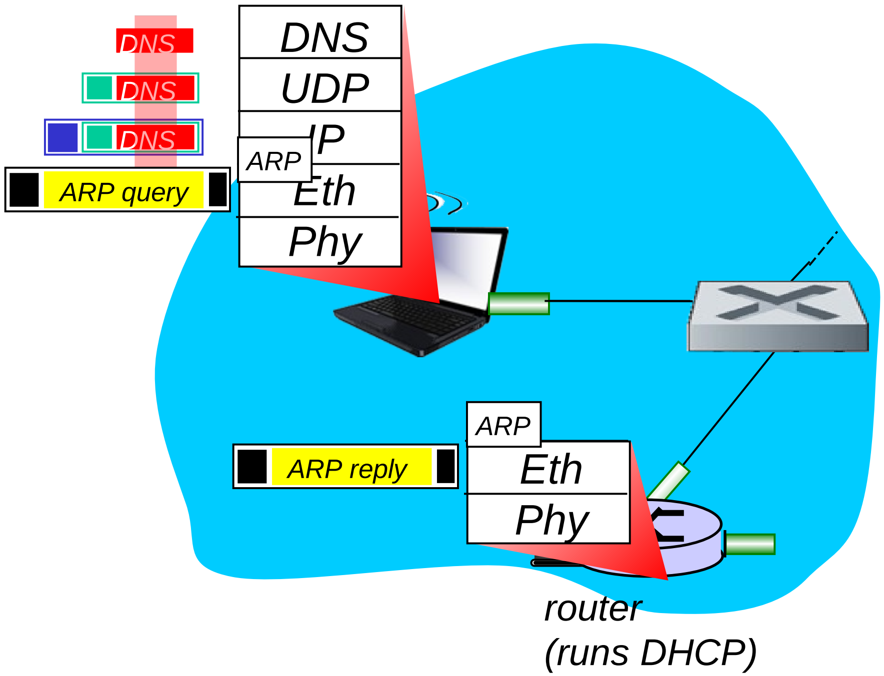
A day in the life... connecting to the Internet



- DHCP server formulates DHCP ACK containing client’s IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (switch learning) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply

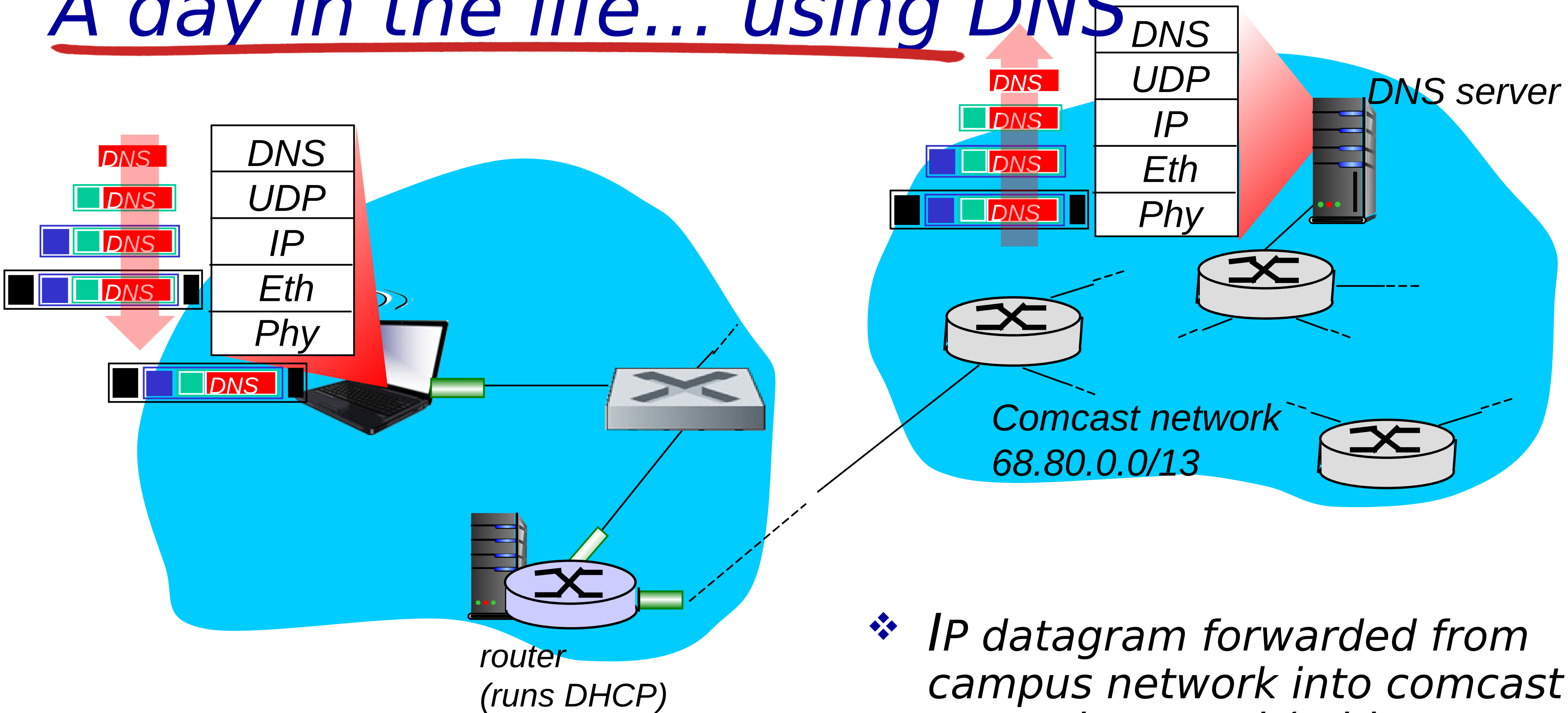
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

A day in the life... ARP (before DNS, before HTTP)



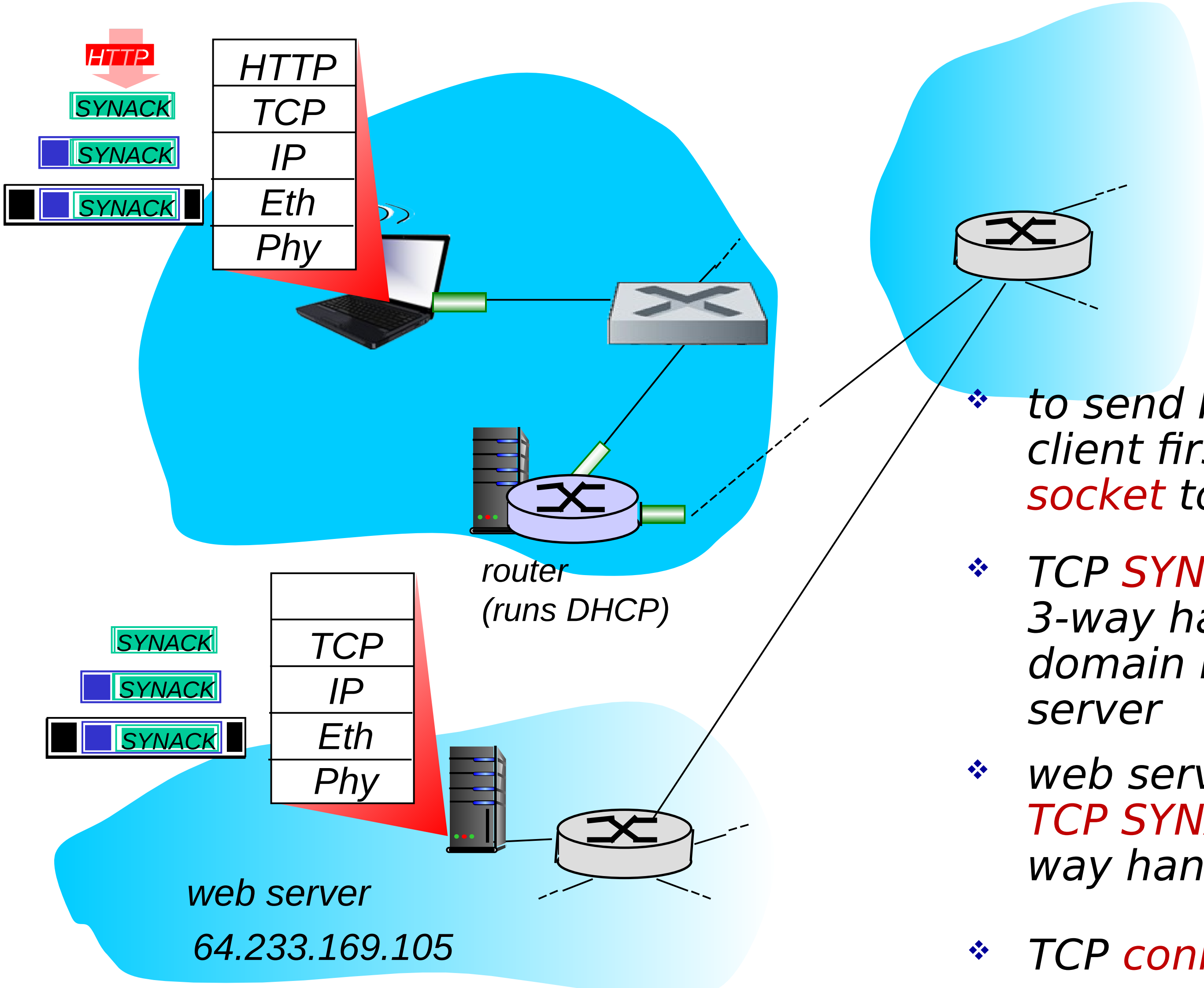
- before sending *HTTP* request, need IP address of www.google.com: *DNS*
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: *ARP*
- *ARP query* broadcast, received by router, which replies with *ARP reply* giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

A day in the life... using DNS



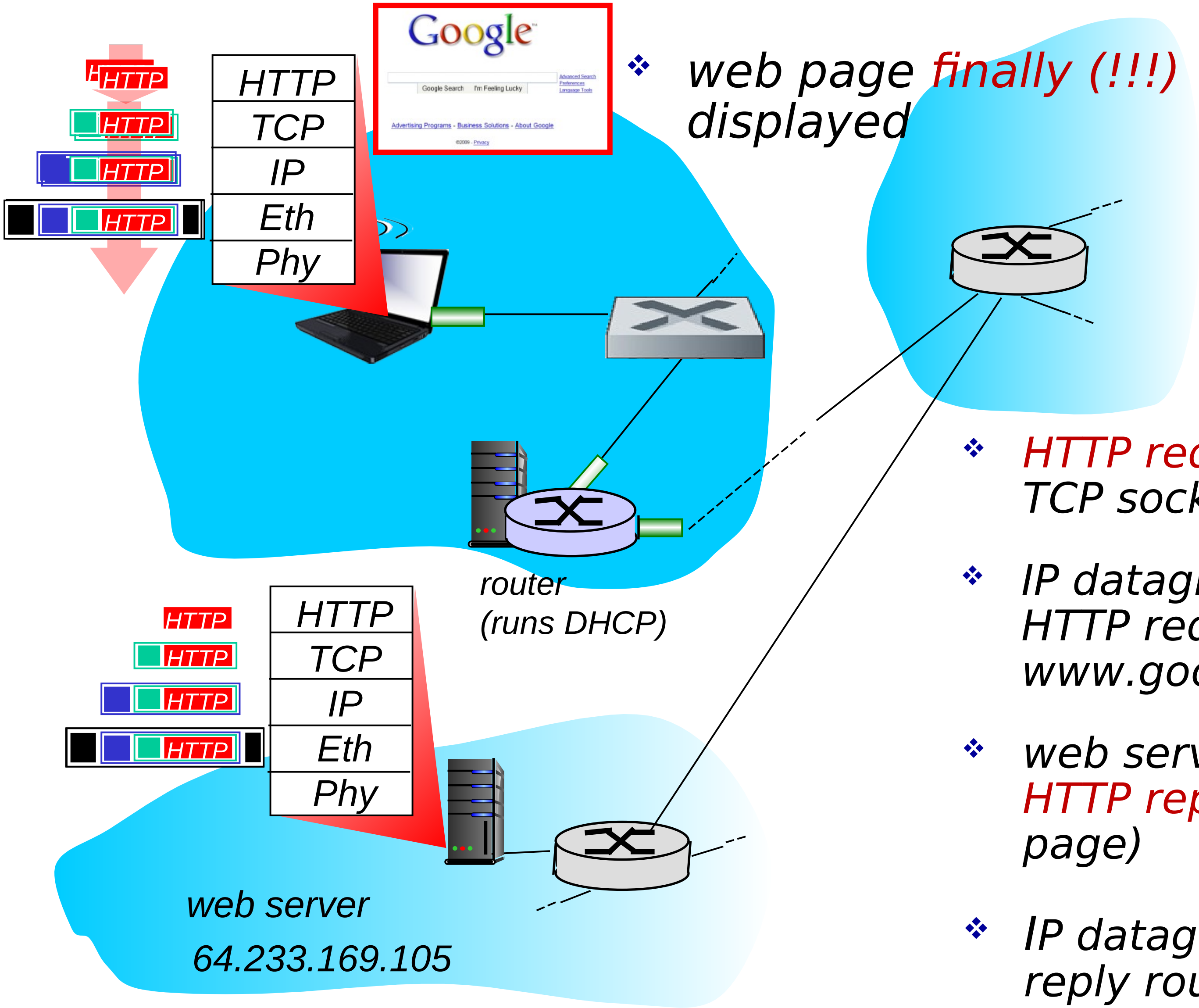
- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router
- IP datagram forwarded from campus network into comcast network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server
- demux'ed to DNS server
- DNS server replies to client with IP address of www.google.com

A day in the life...TCP connection carrying HTTP



- to send HTTP request, client first opens TCP socket to web server
- TCP SYN segment (step 1 in 3-way handshake) inter-domain routed to web server
- web server responds with TCP SYNACK (step 2 in 3-way handshake)
- TCP connection established!

A day in the life… HTTP request/reply



- web page *finally (!!!)* displayed
- *HTTP request* sent into TCP socket
- IP datagram containing HTTP request routed to www.google.com
- web server responds with *HTTP reply* (containing web page)
- IP datagram containing HTTP reply routed back to client

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
- synthesis: a day in the life of a web request

Chapter 5: let's take a breath

- *journey down protocol stack complete (except PHY)*
- *solid understanding of networking principles, practice*
- *..... could stop here .... but lots of interesting topics!*
  - *wireless*
  - *multimedia*