



Data Link Layers and LANs

Network Layer: 5-1

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: roadmap

- **introduction**
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
 - VLANs
- a day in the life of a web request

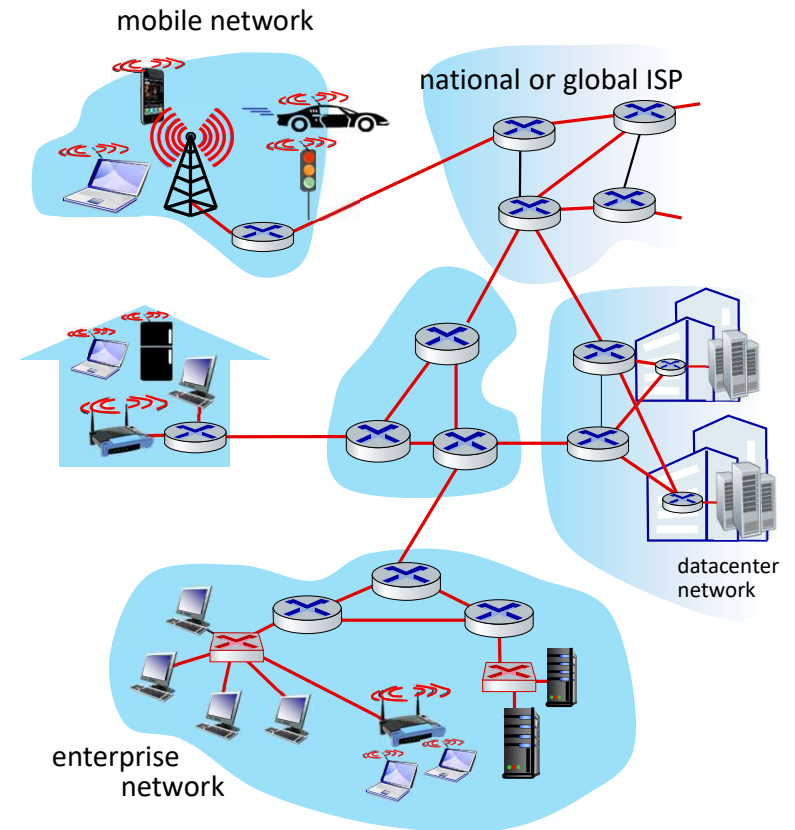


Link layer: introduction

terminology:

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

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



Link layer: context

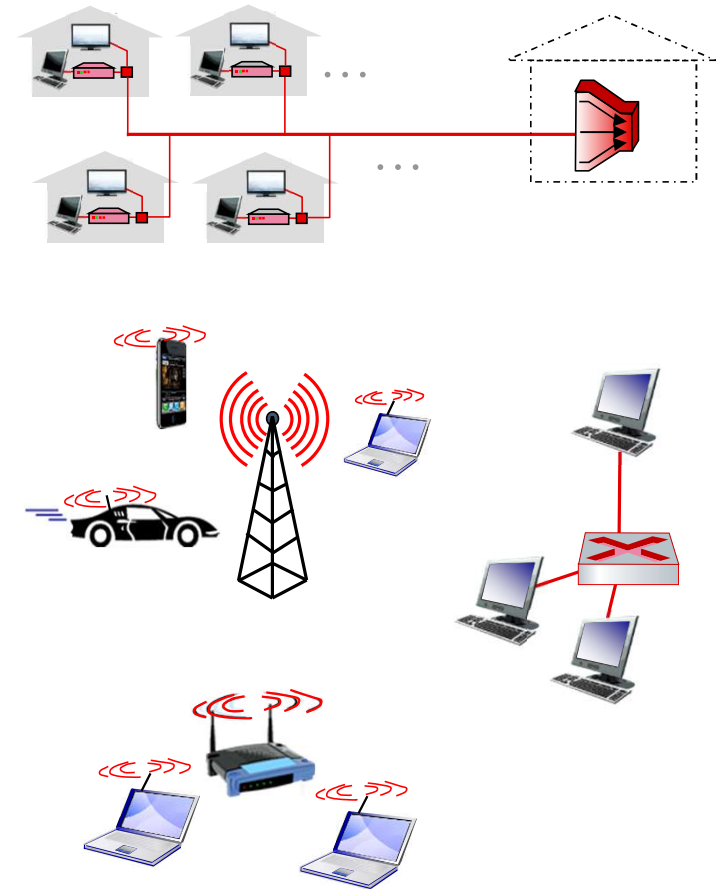
- datagram transferred by different link protocols over different links:
 - e.g., Wi-Fi on first link, Ethernet on next link
- each link protocol provides different services
 - e.g., may or may not provide reliable data transfer over link

transportation analogy:

- trip from Princeton to Lausanne
 - limo: 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**

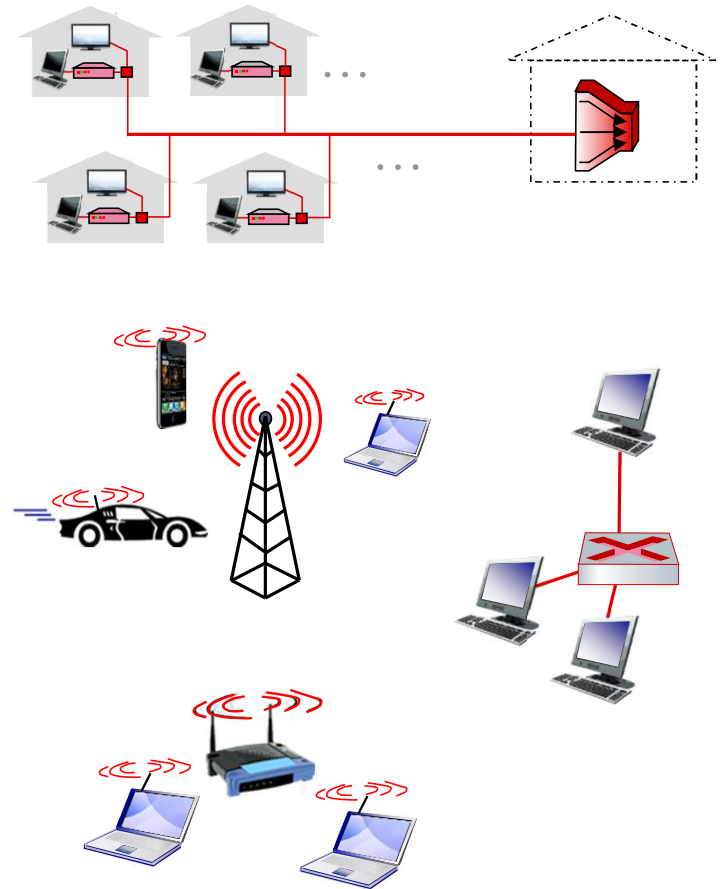
Link layer: services

- **framing, link access:**
 - encapsulate datagram into frame, adding header, trailer
 - channel access if shared medium
 - “MAC” addresses in frame headers identify source, destination (different from IP address!)
- **reliable delivery between adjacent nodes**
 - we already know how to do this!
 - seldom used on low bit-error links
 - wireless links: high error rates
 - Q: why both link-level and end-end reliability?



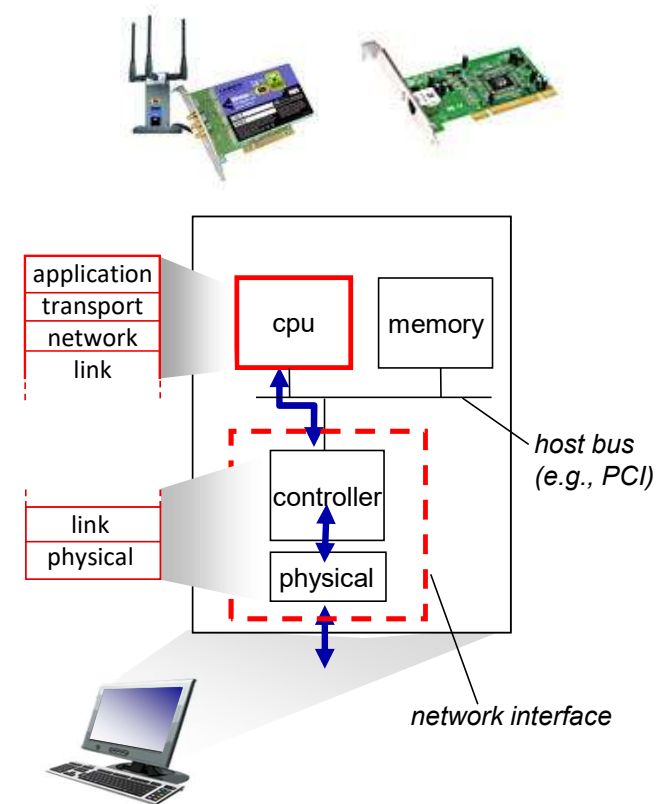
Link layer: services (more)

- **flow control:**
 - pacing between adjacent sending and receiving nodes
- **error detection:**
 - errors caused by signal attenuation, noise.
 - receiver detects errors, signals retransmission, or drops frame
- **error correction:**
 - receiver identifies *and corrects* bit error(s) without retransmission
- **half-duplex and full-duplex:**
 - with half duplex, nodes at both ends of link can transmit, but not at same time

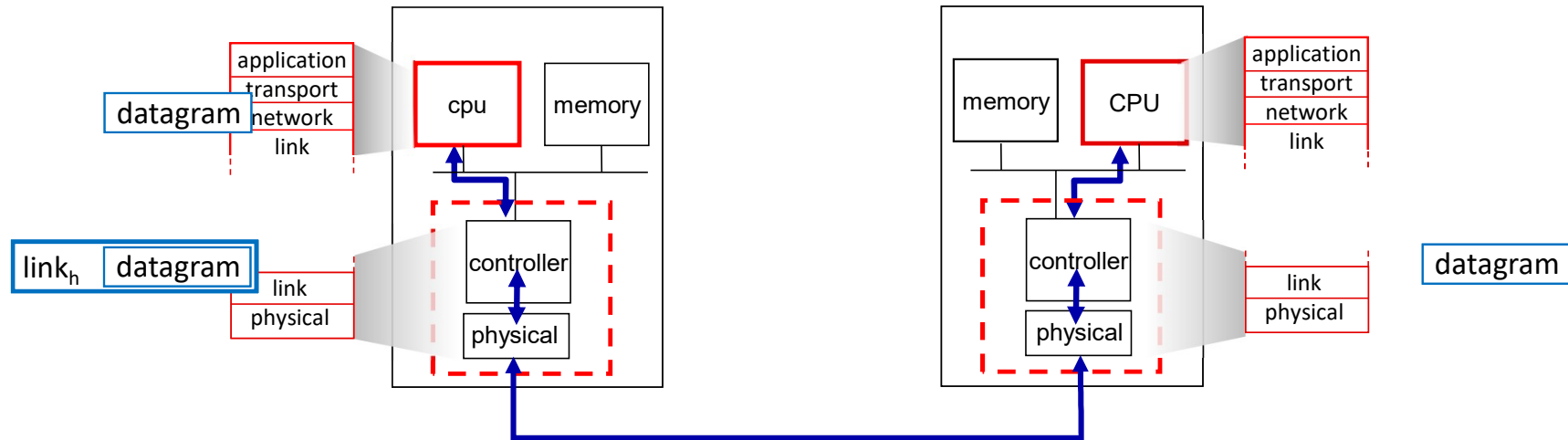


Where is the link layer implemented?

- in each-and-every host
- link layer implemented in *network interface card* (NIC) or on a chip
 - Ethernet, WiFi card or chip
 - implements link, physical layer
- attaches into host's system buses
- combination of hardware, software, firmware



Interfaces communicating



sending side:

- encapsulates datagram in frame
- adds error checking bits, reliable data transfer, flow control, etc.

receiving side:

- looks for errors, reliable data transfer, flow control, etc.
- extracts datagram, passes to upper layer at receiving side

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- **multiple access protocols**
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 - VLANs
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Multiple access links, protocols

two types of “links”:

- point-to-point
 - point-to-point link between Ethernet switch, host
 - PPP for dial-up access
- **broadcast (shared wire or medium)**
 - old-fashioned Ethernet
 - upstream HFC in cable-based access network
 - 802.11 wireless LAN, 4G/5G. satellite



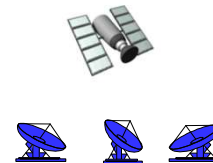
shared wire (e.g.,
cabled Ethernet)



shared radio: 4G/5G



shared radio: WiFi

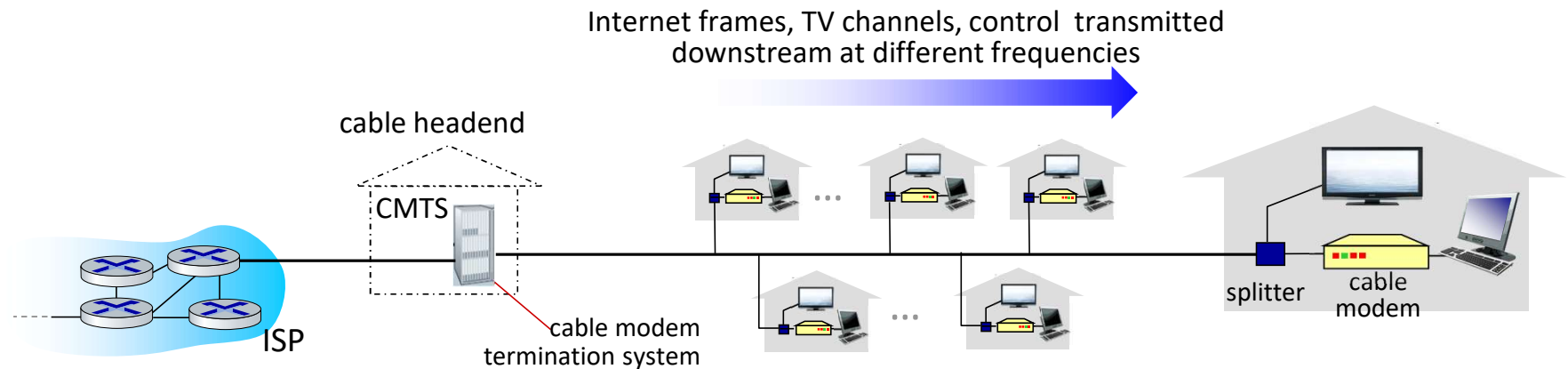


shared radio: satellite



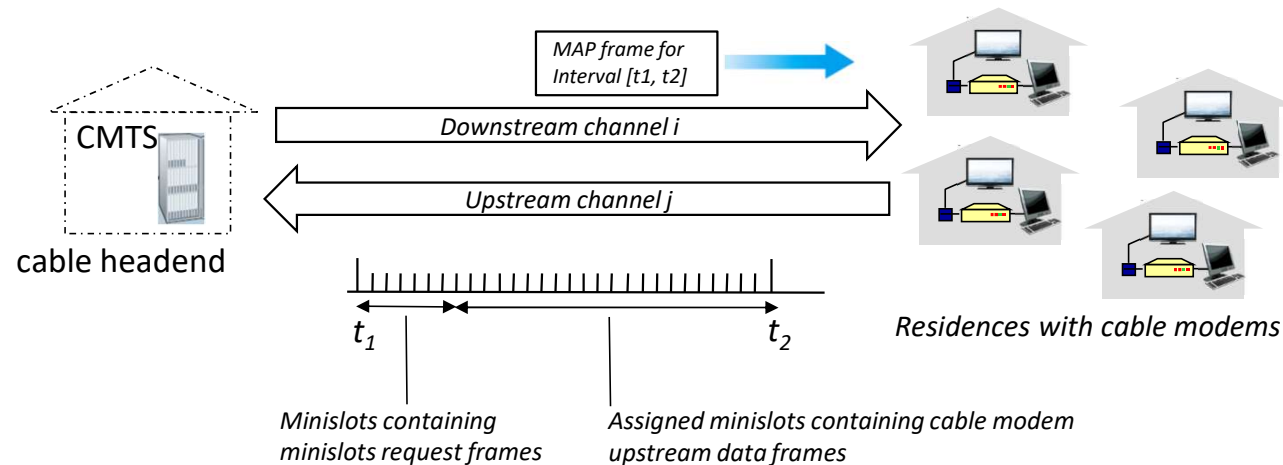
humans at a cocktail party
(shared air, acoustical)

Cable access network: FDM, TDM *and* random access!



- **multiple** downstream (broadcast) FDM channels: up to 1.6 Gbps/channel
 - single CMTS transmits into channels
- **multiple** upstream channels (up to 1 Gbps/channel)
 - **multiple access**: all users contend (random access) for certain upstream channel time slots; others assigned TDM

Cable access network:

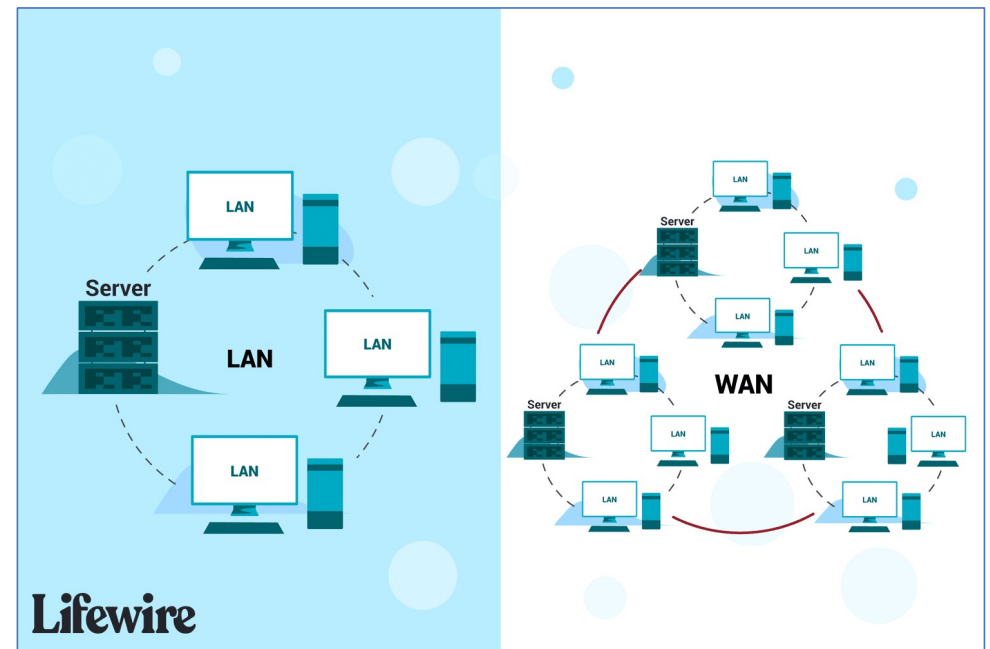


DOCSIS: data over cable service interface specification

- 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

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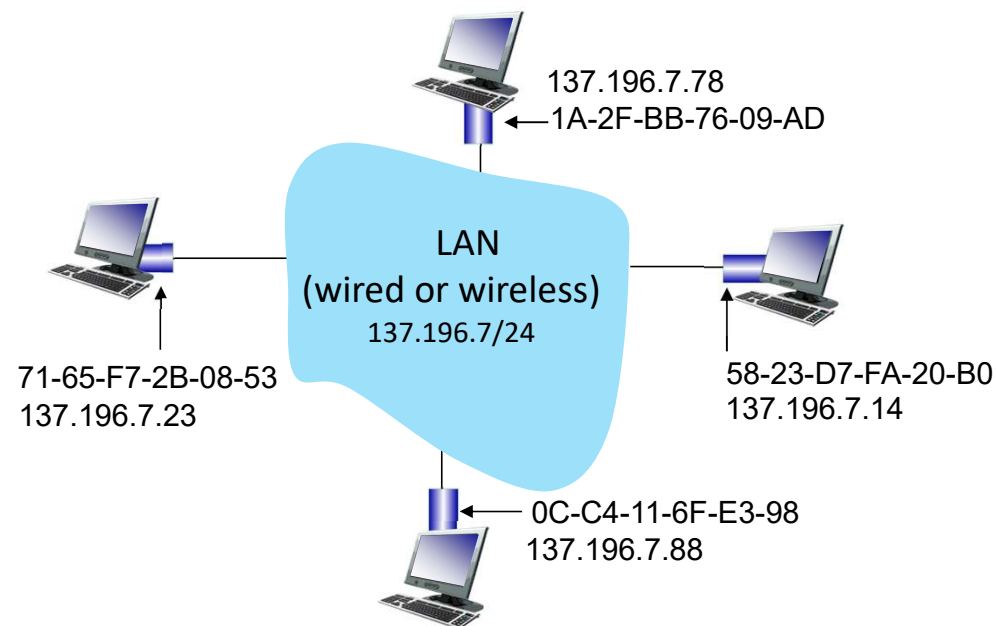
MAC addresses

- 32-bit IP address:
 - *network-layer* address for interface
 - used for layer 3 (network layer) forwarding
 - e.g.: 128.119.40.136
 - MAC (or LAN or physical or Ethernet) address:
 - function: used “locally” to get frame from one interface to another physically-connected interface (same subnet, 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)*

MAC addresses

each interface on LAN

- has unique 48-bit **MAC** address
- has a locally unique 32-bit IP address (as we've seen)

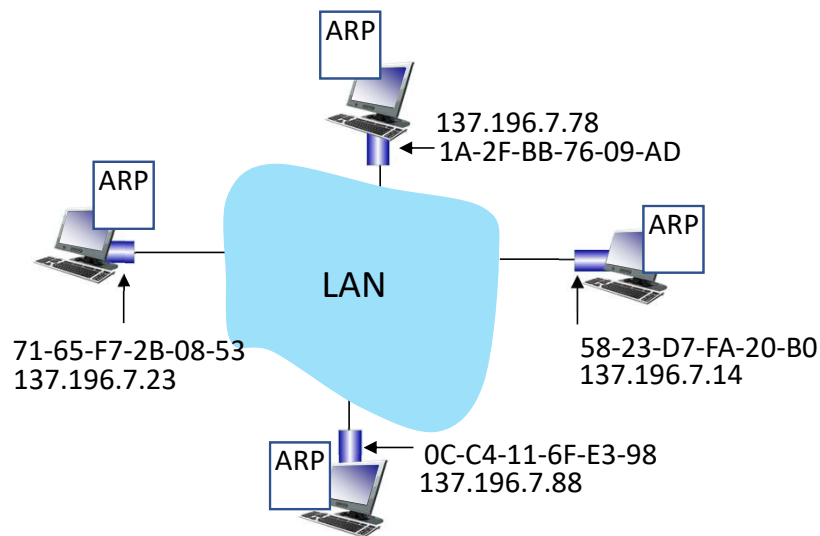


MAC addresses

- 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 interface from one LAN to another
 - recall IP address *not* portable: 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)

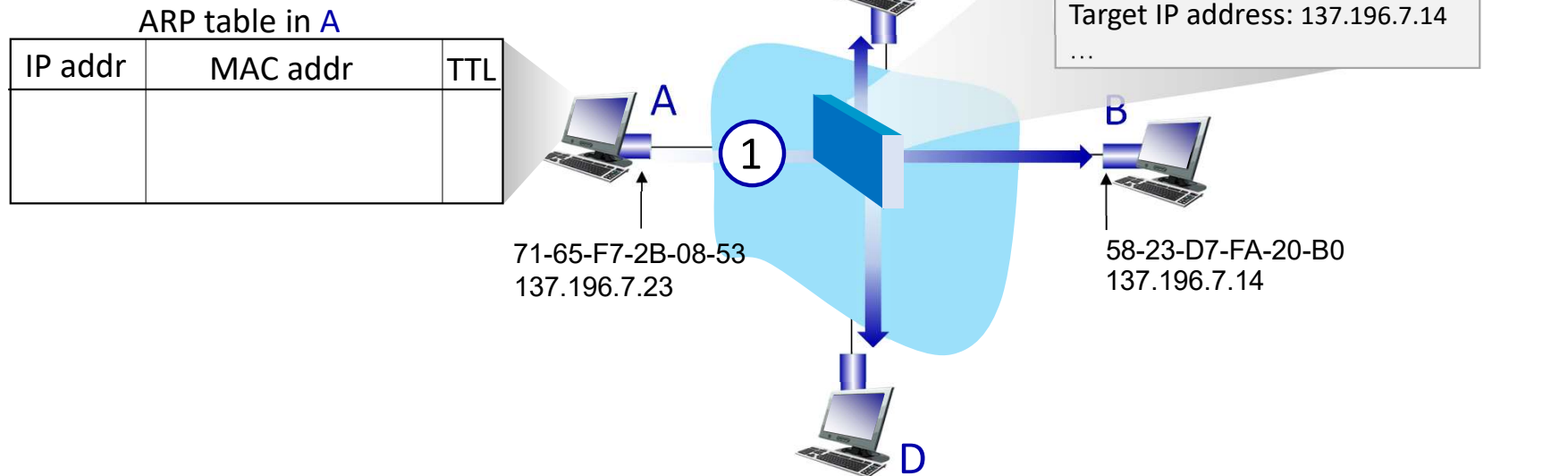
ARP protocol in action

example: A wants to send datagram to B

- B's MAC address not in A's ARP table, so A uses ARP to find B's MAC address

A broadcasts ARP query, containing B's IP addr

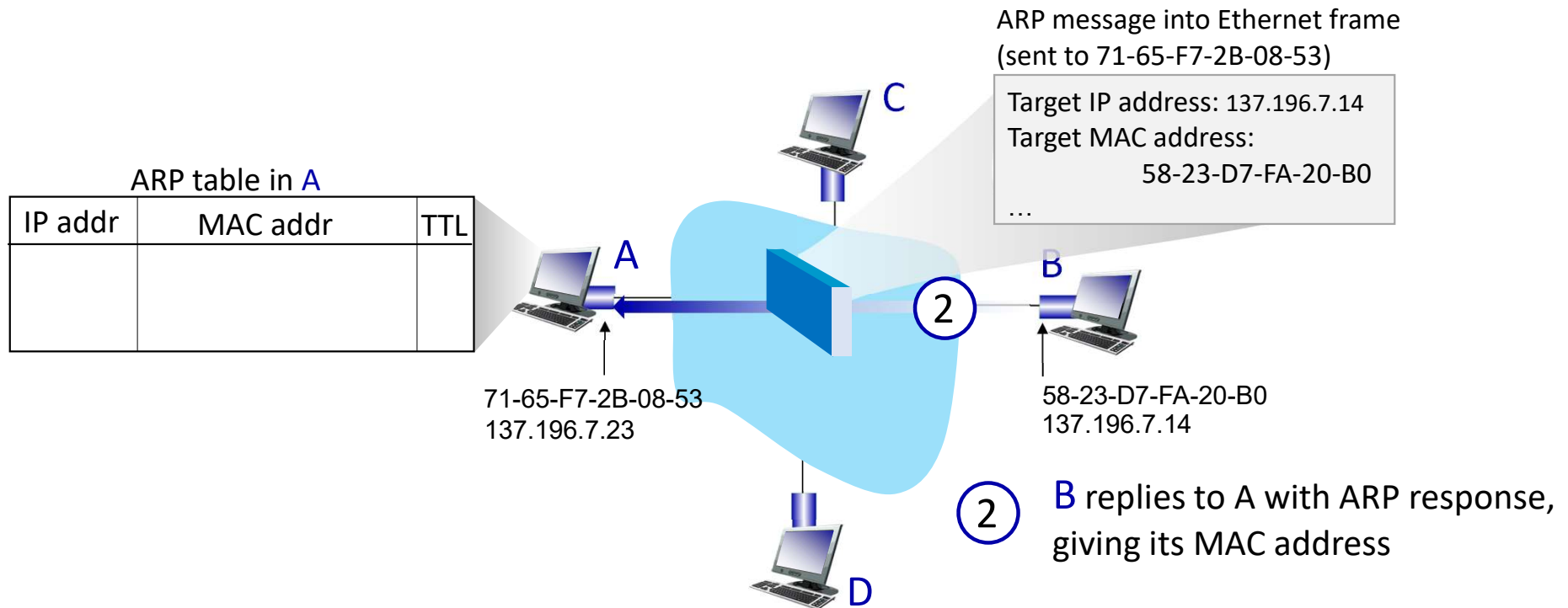
- ①
- destination MAC address = FF-FF-FF-FF-FF-FF
 - all nodes on LAN receive ARP query



ARP protocol in action

example: A wants to send datagram to B

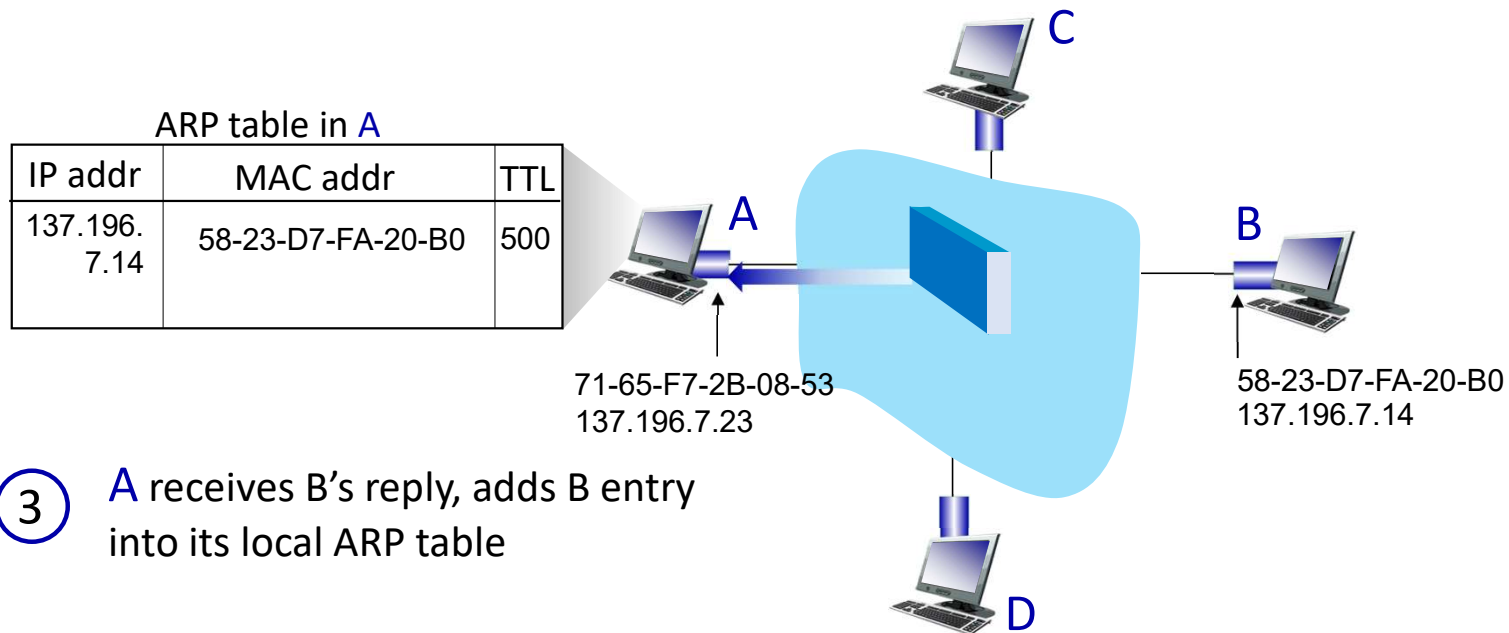
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ARP protocol in action

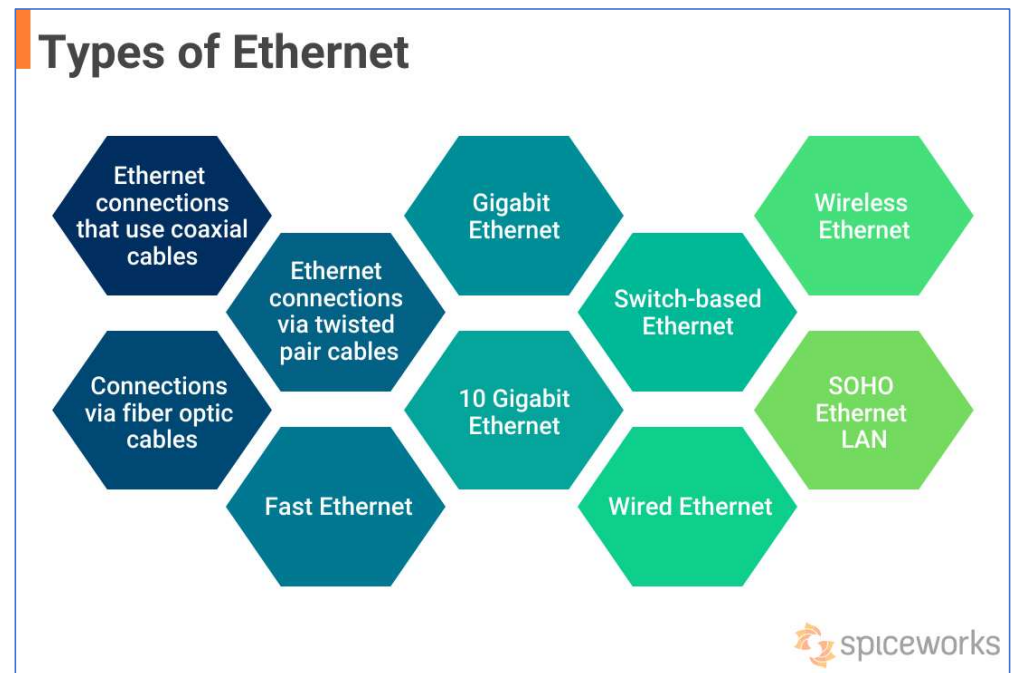
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Link layer, LANs: roadmap

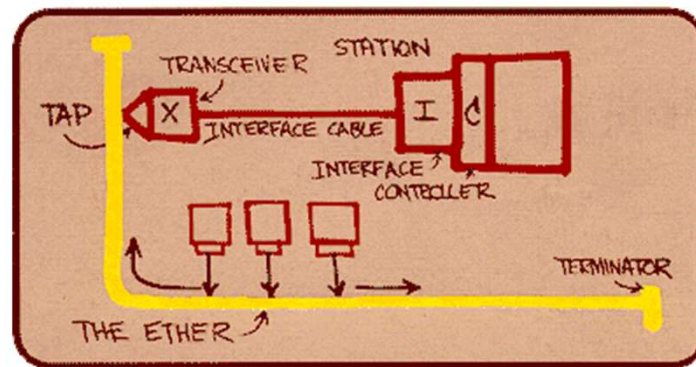
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Ethernet

“dominant” wired LAN technology:

- first widely used LAN technology
- simpler, cheap
- kept up with speed race: 10 Mbps – 400 Gbps
- single chip, multiple speeds (e.g., Broadcom BCM5761)

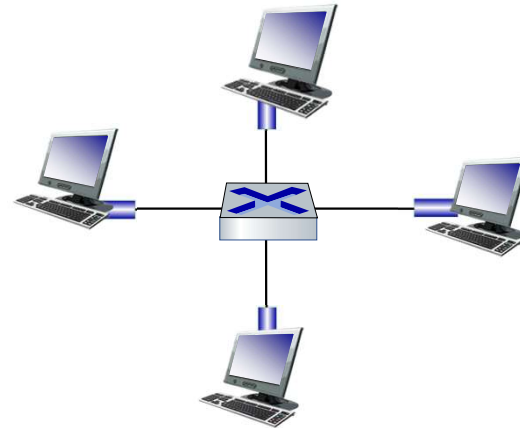
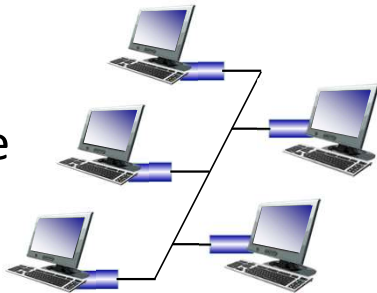


Metcalfe's Ethernet sketch

Ethernet: physical topology

- **bus:** popular through mid 90s
 - all nodes in same collision domain (can collide with each other)
- **switched:** prevails today
 - active link-layer 2 *switch* in center
 - each “spoke” runs a (separate) Ethernet protocol (nodes do not collide with each other)

bus: coaxial cable



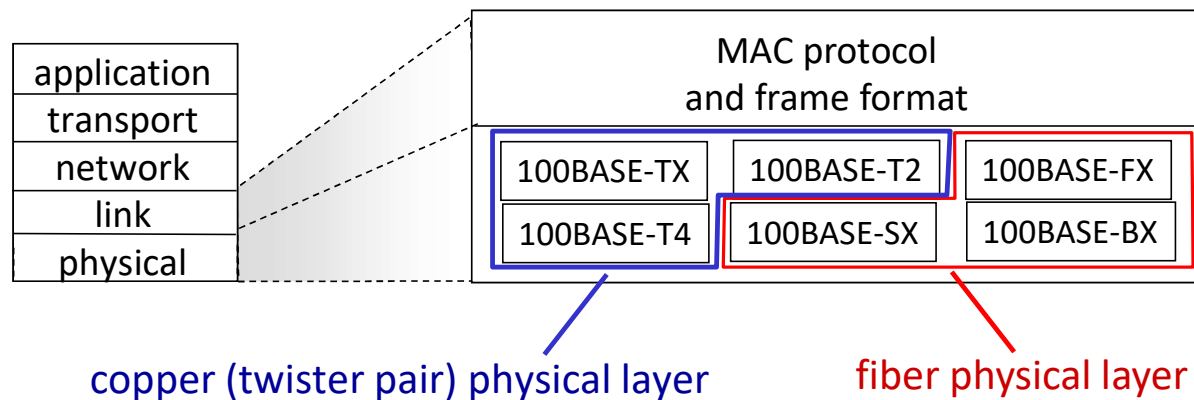
switched

Ethernet: unreliable, connectionless

- **connectionless**: no handshaking between sending and receiving NICs
- **unreliable**: receiving NIC doesn't send ACKs or NAKs 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



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 - Ethernet
 - **switches**
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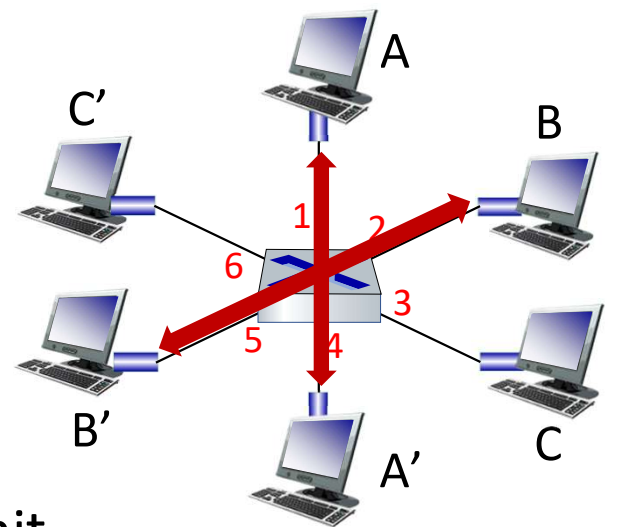


Ethernet switch

- Switch is a **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 *unaware* of presence of switches
- **plug-and-play, self-learning**
 - switches do not need to be configured

Switch: multiple simultaneous transmissions

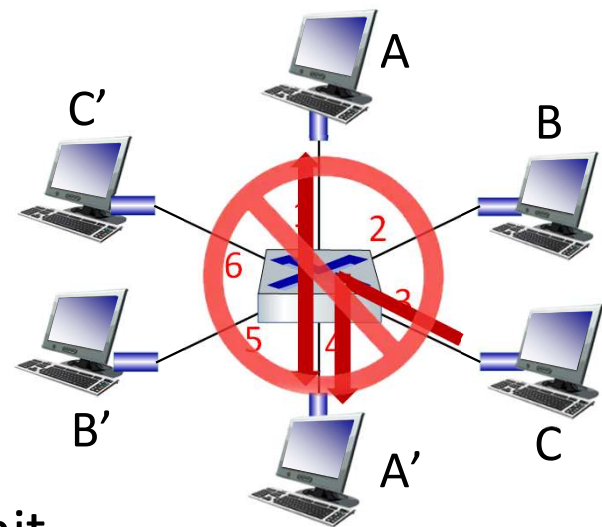
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, so:
 - no collisions; full duplex
 - each link is its own collision domain
- **switching:** A-to-A' and B-to-B' can transmit simultaneously, without collisions



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

Switch: multiple simultaneous transmissions

- hosts have dedicated, direct connection to switch
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- Ethernet protocol used on *each* incoming link, so:
 - no collisions; full duplex
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- **switching:** A-to-A' and B-to-B' can transmit simultaneously, without collisions
 - but A-to-A' and C to A' can *not* happen simultaneously



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

Switch forwarding table

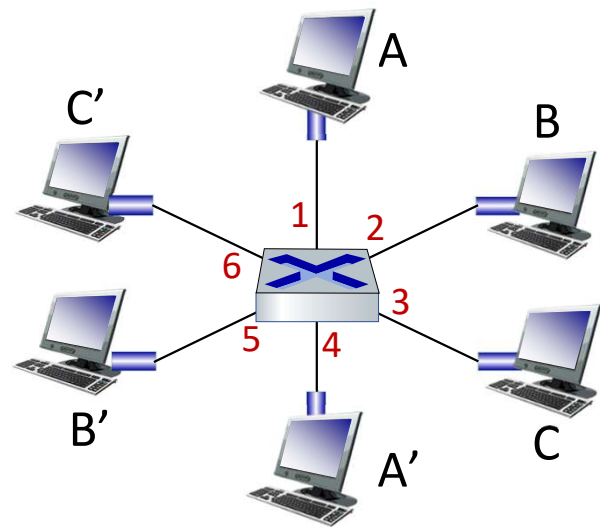
Q: how does switch know A' reachable via interface 4, B' reachable via interface 5?

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

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

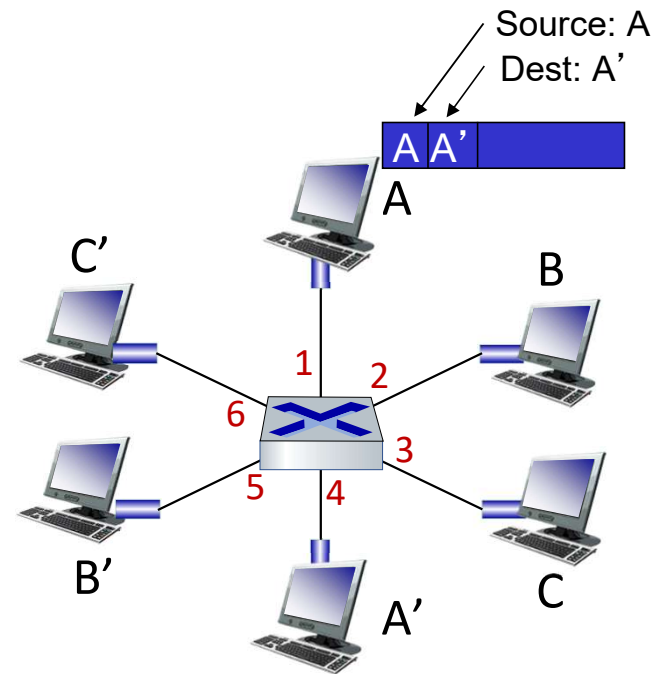
Q: how are entries created, maintained in switch table?

- something like a routing protocol?



Switch: 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)*

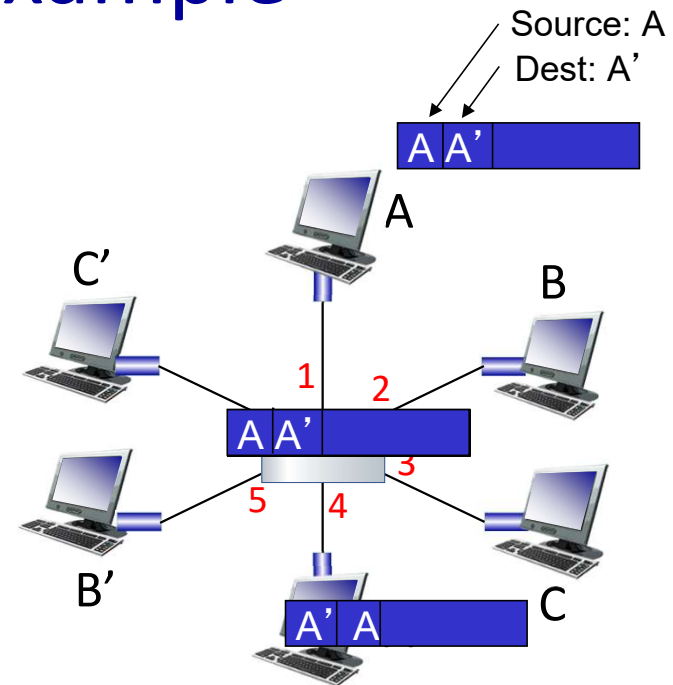
Switch: frame filtering/forwarding

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

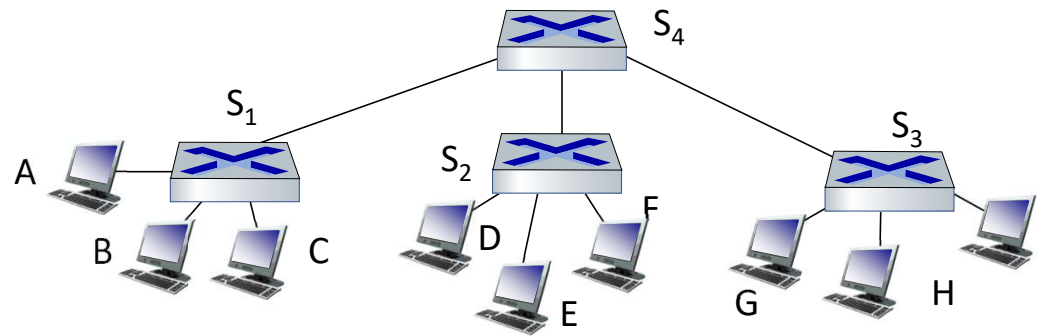


| MAC addr | interface | TTL |
|----------|-----------|-----|
| A | 1 | 60 |
| A' | 4 | 60 |

*switch table
(initially empty)*

Interconnecting switches

self-learning switches can be connected together:

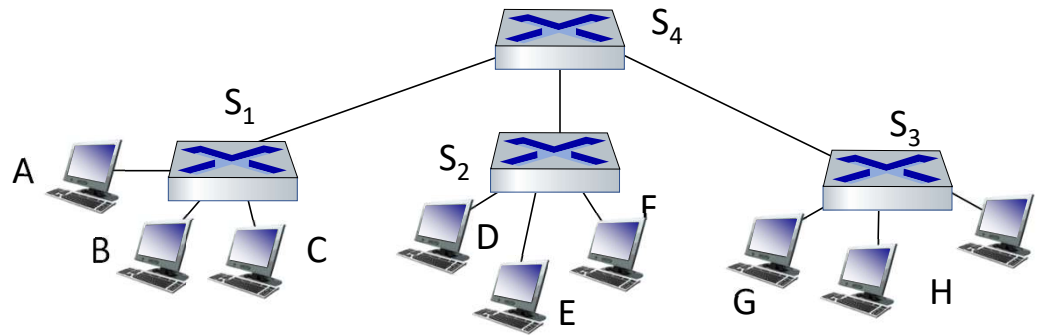


Q: sending from A to G - how does S₁ know to forward frame destined to G via S₄ and S₃?

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

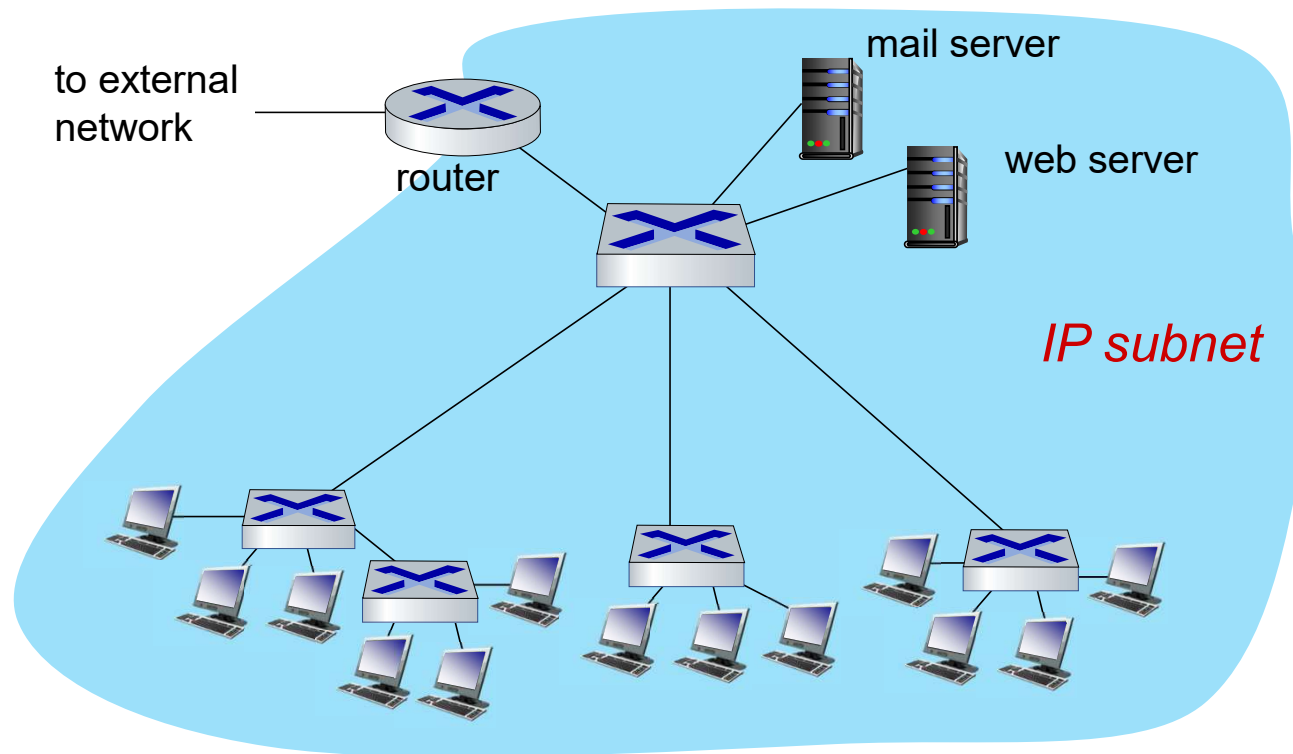
Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



Q: show switch tables and packet forwarding in S₁, S₂, S₃, S₄

Small institutional network



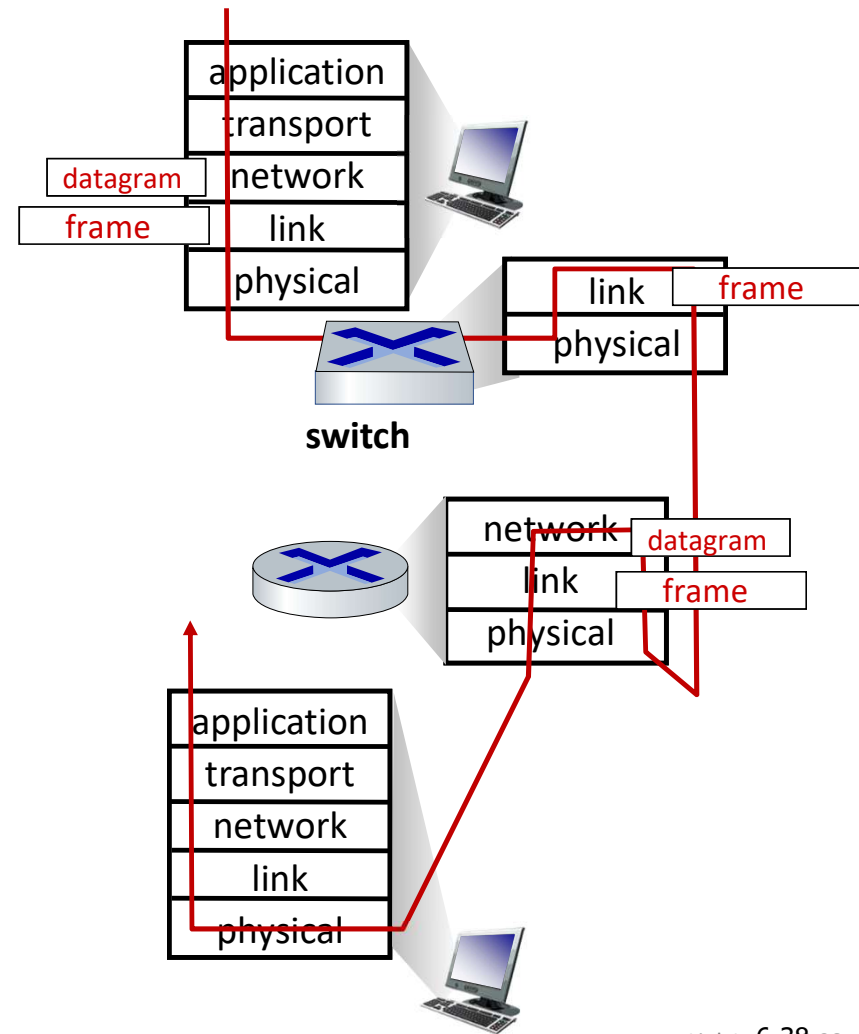
Switches vs. routers

both are store-and-forward:

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

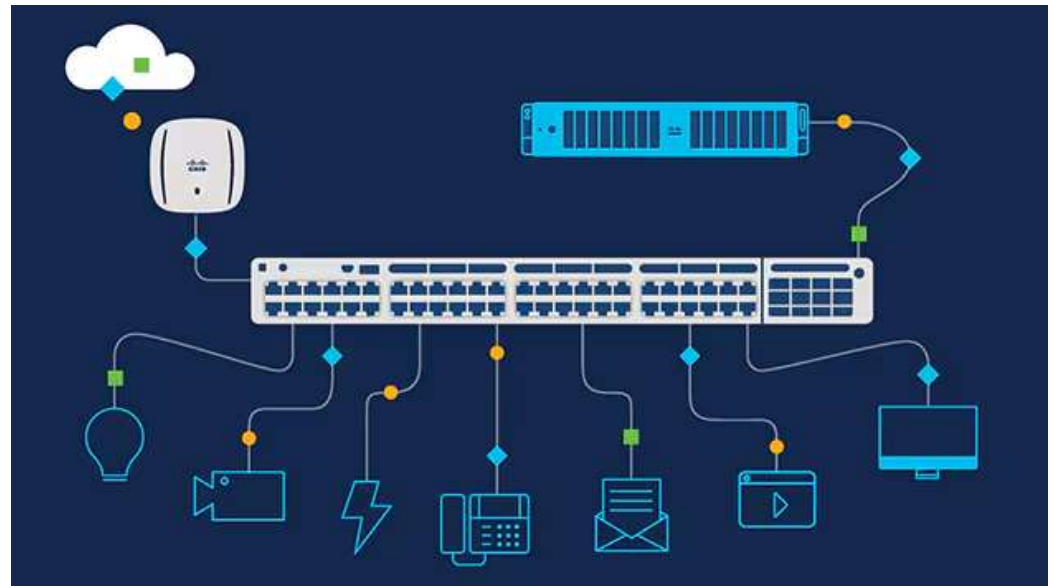
both have forwarding tables:

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



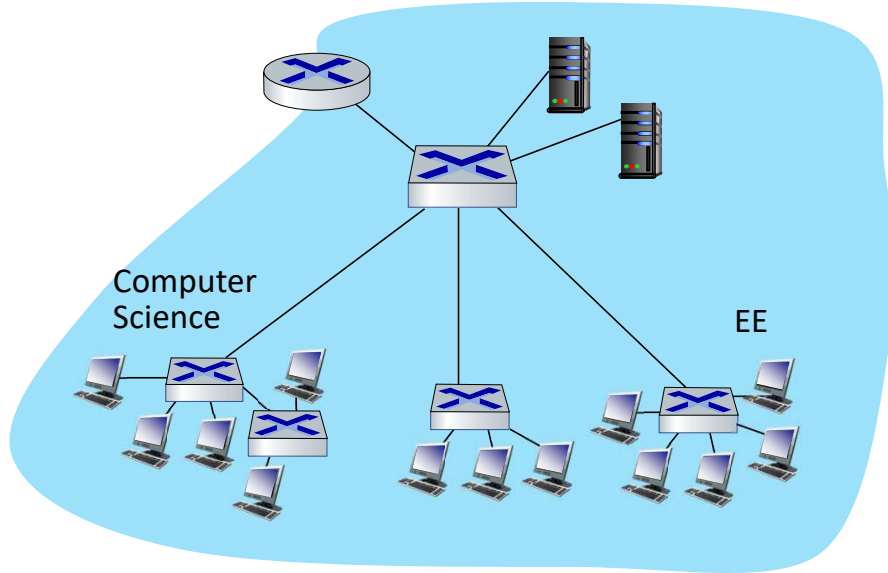
Link layer, LANs: roadmap

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- **LANs**
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 - **VLANs**
- a day in the life of a web request



Virtual LANs (VLANs): motivation

Q: what happens as LAN sizes scale, users change point of attachment?

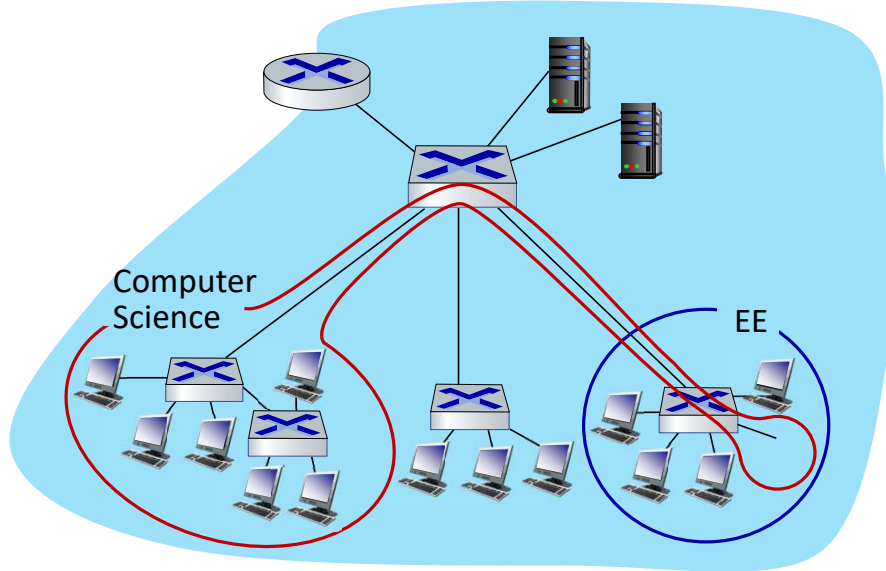


single broadcast domain:

- *scaling*: all layer-2 broadcast traffic (ARP, DHCP, unknown MAC) must cross entire LAN
- efficiency, security, privacy issues

Virtual LANs (VLANs): motivation

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single broadcast domain:

- *scaling*: all layer-2 broadcast traffic (ARP, DHCP, unknown MAC) must cross entire LAN
- efficiency, security, privacy, efficiency issues

administrative issues:

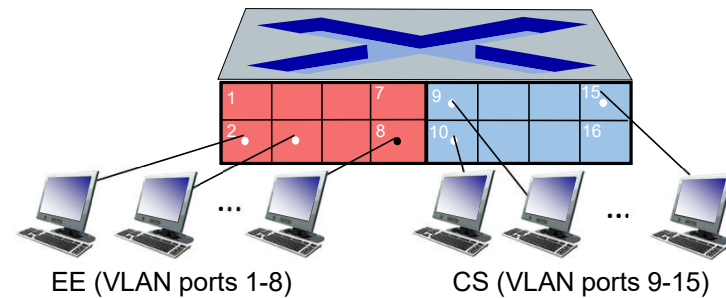
- CS user moves office to EE - *physically* attached to EE switch, but wants to remain *logically* attached to CS switch

Port-based VLANs

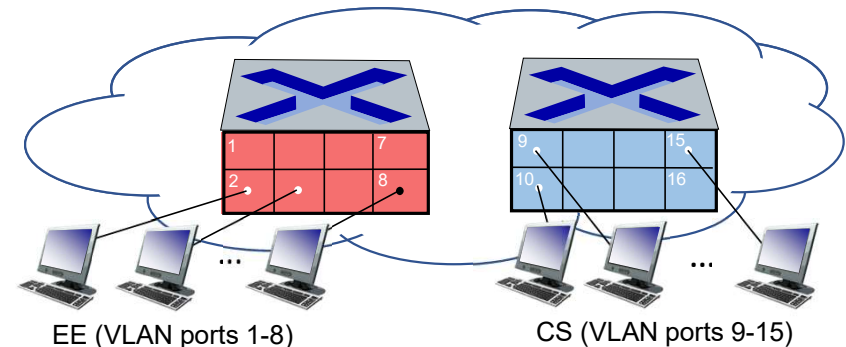
Virtual Local Area Network (VLAN)

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

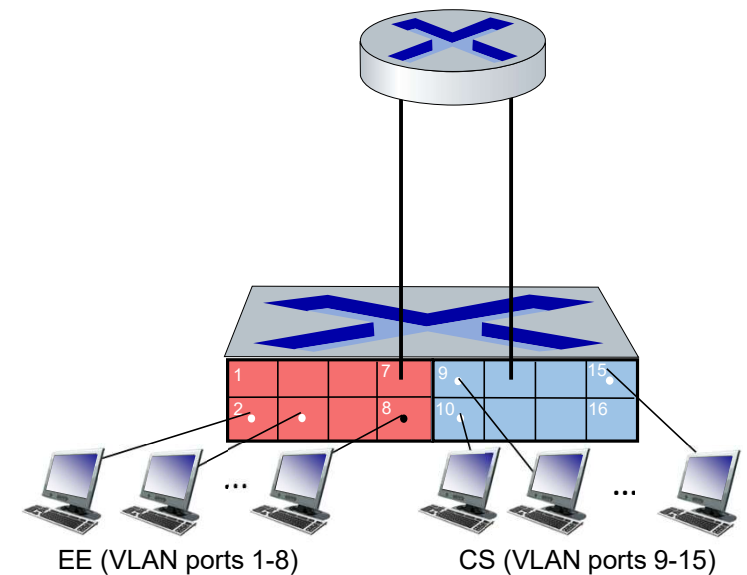


... operates as **multiple** virtual switches

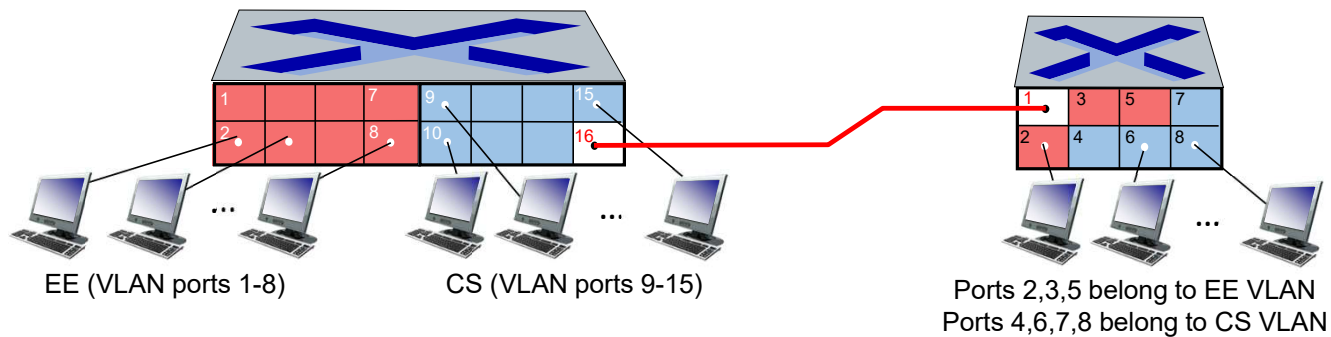


Port-based VLANs

- **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



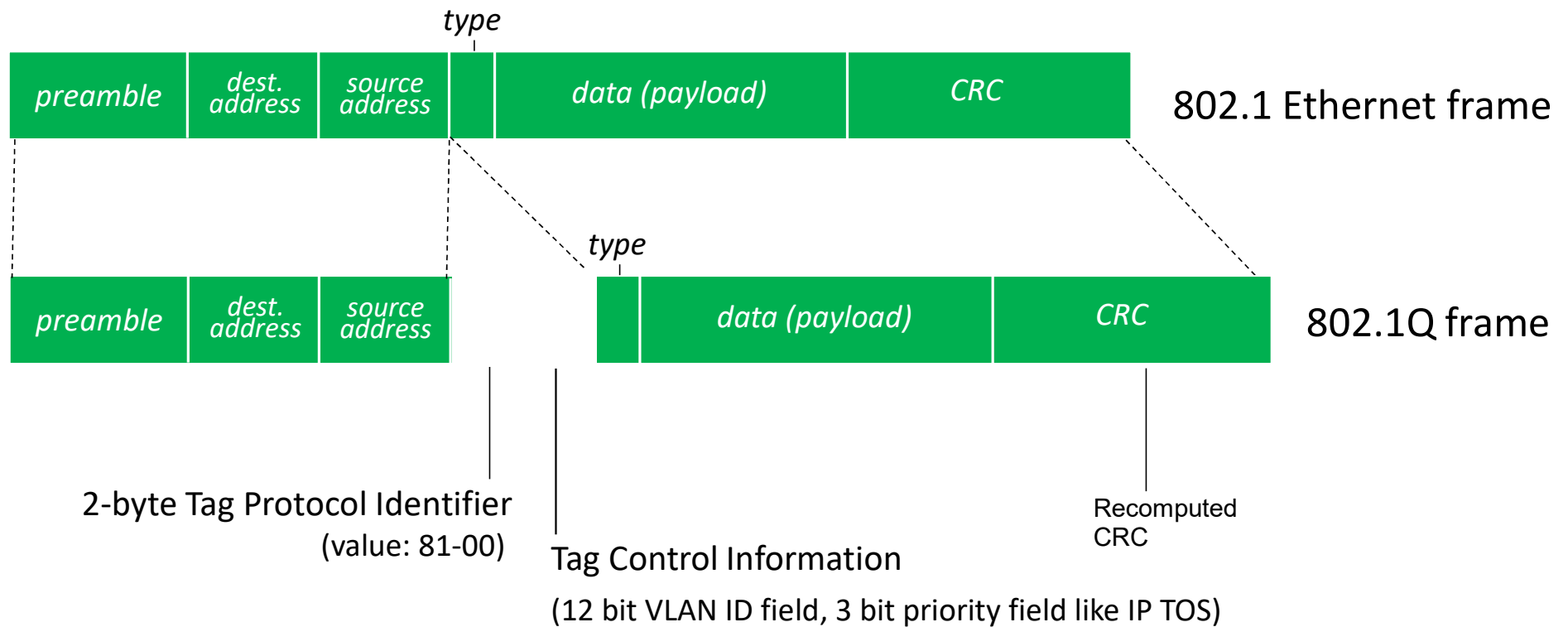
VLANs spanning multiple switches



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

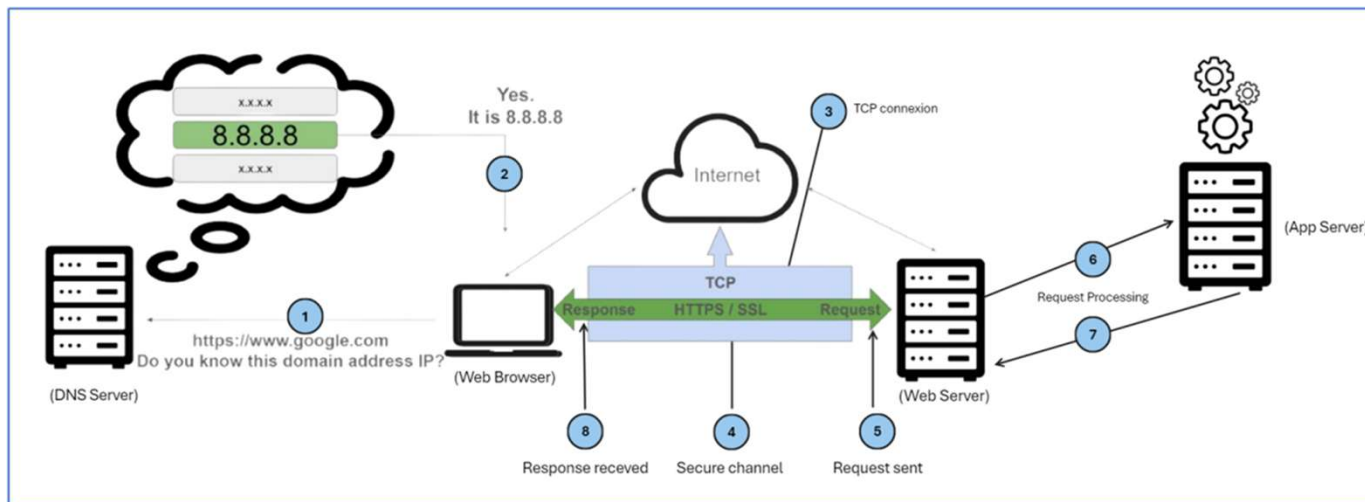




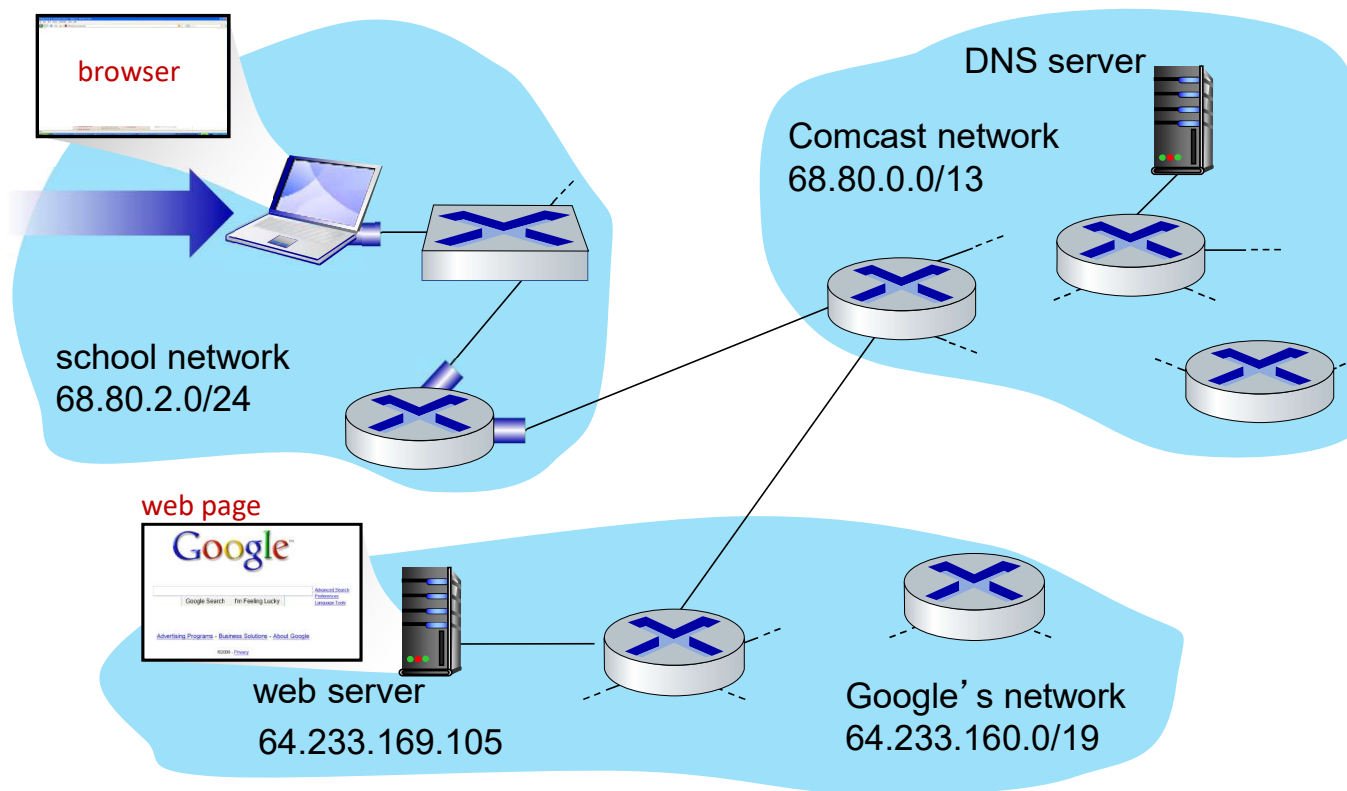
A day in the Life of Web Request

Synthesis: a day in the life of a web request

- our journey down the protocol stack is now 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

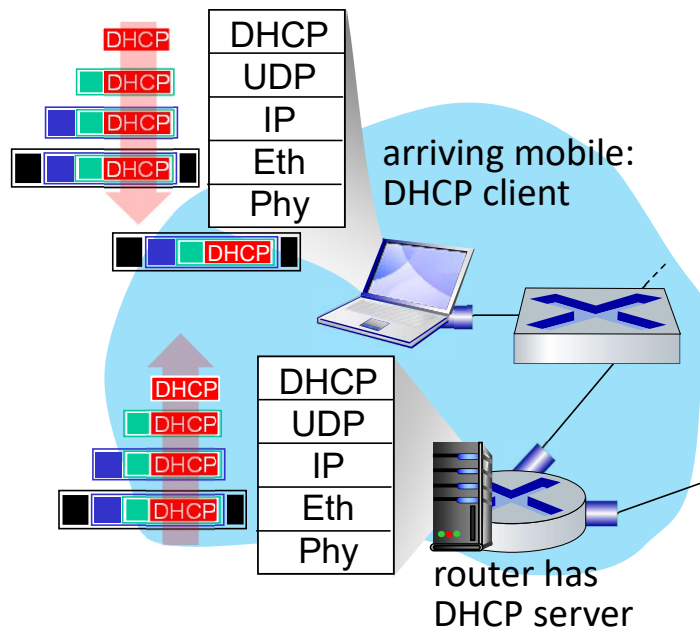


scenario:

- arriving mobile client attaches to network ...
- requests web page:
www.google.com

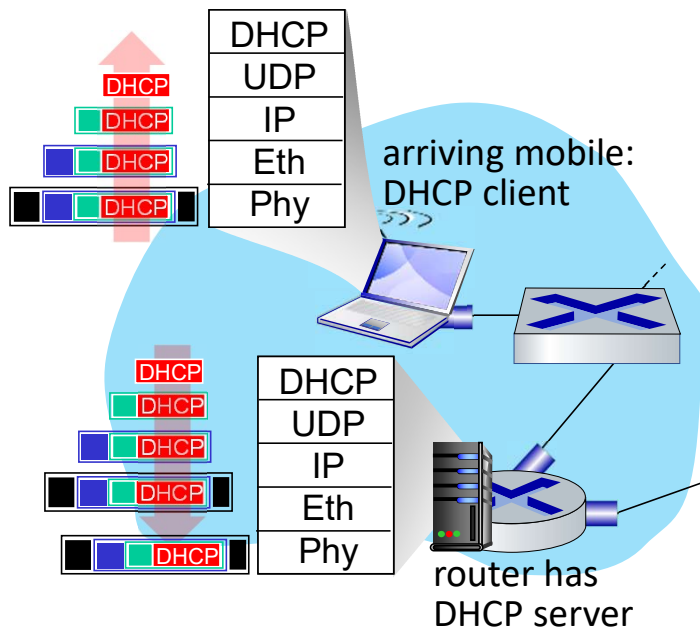
Sounds simple! 

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: FFFFFFFFFFFFFFFF) on LAN, received at router running **DHCP** server
- Ethernet **demuxed** to IP demuxed, UDP demuxed to DHCP

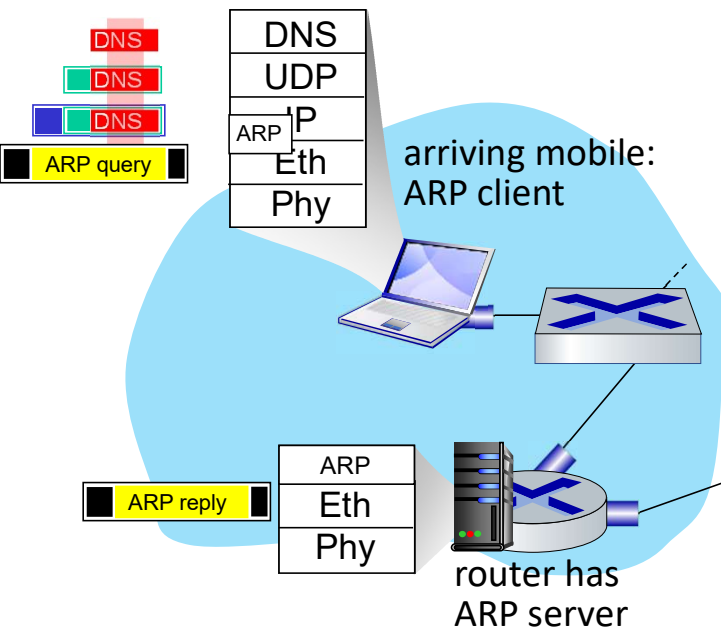
A day in the life: connecting to the Internet



- 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

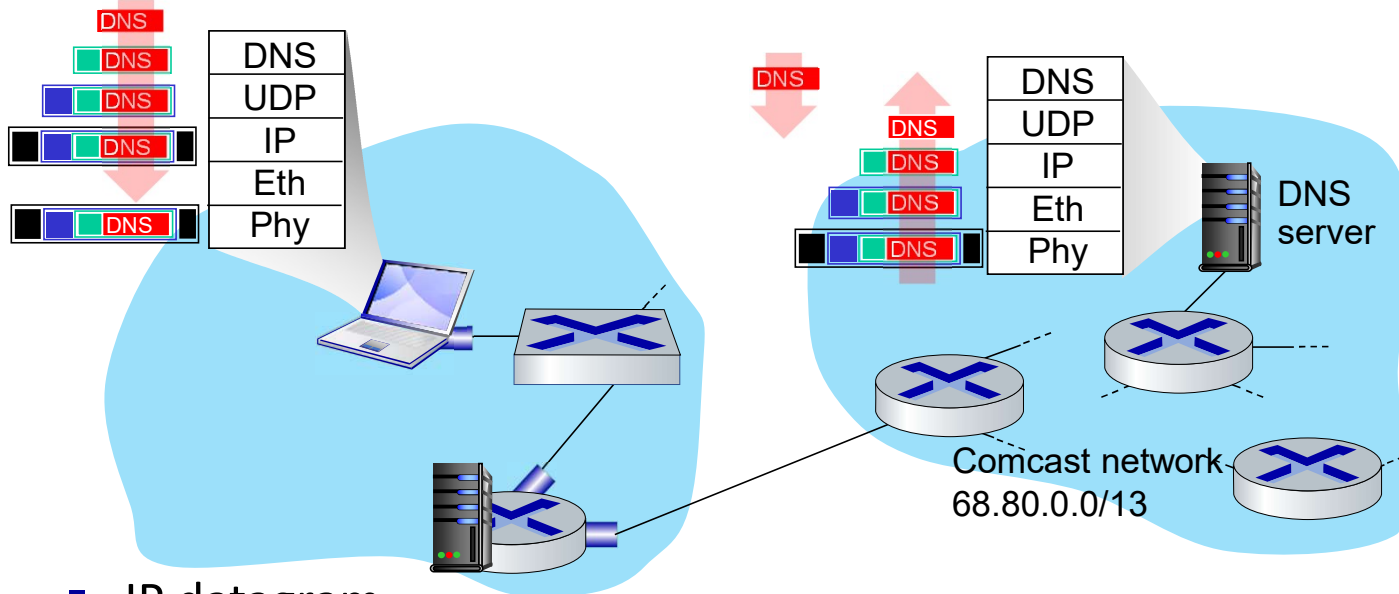
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

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

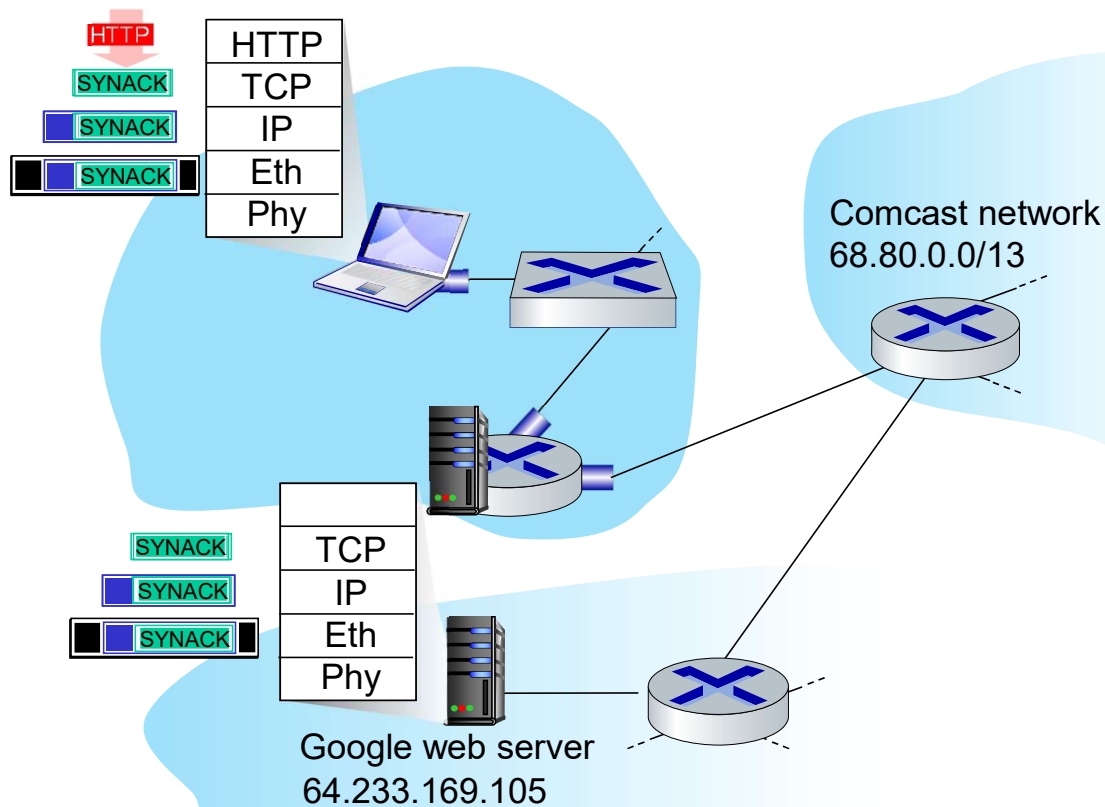
A day in the life... using DNS



- 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

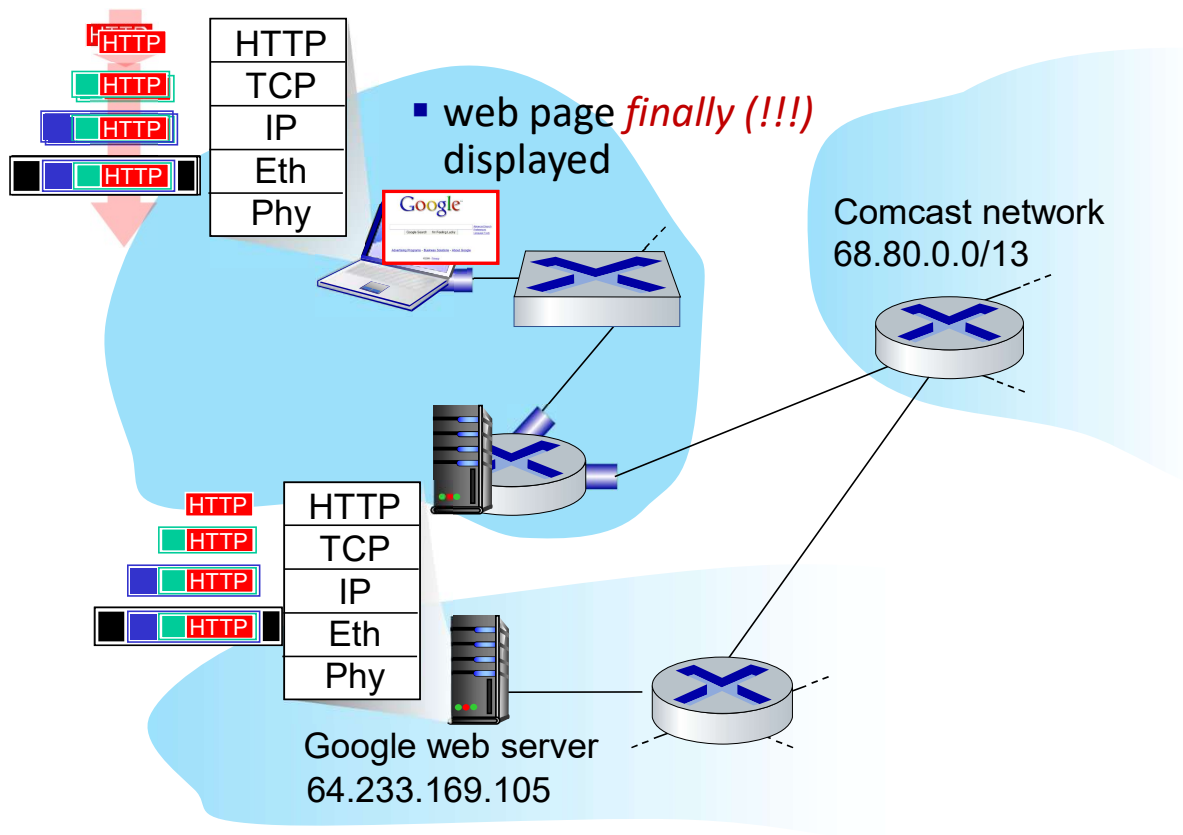
- demuxed to DNS
- DNS replies to client with IP address of www.google.com

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 TCP 3-way handshake) inter-domain routed to web server
- web server responds with **TCP SYNACK** (step 2 in TCP 3-way handshake)
- TCP **connection established!**

A day in the life... HTTP request/reply



- **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 6: Summary

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



Data Link Layers and LANs