

# Chapter 6

# The Link Layer

# and LANs

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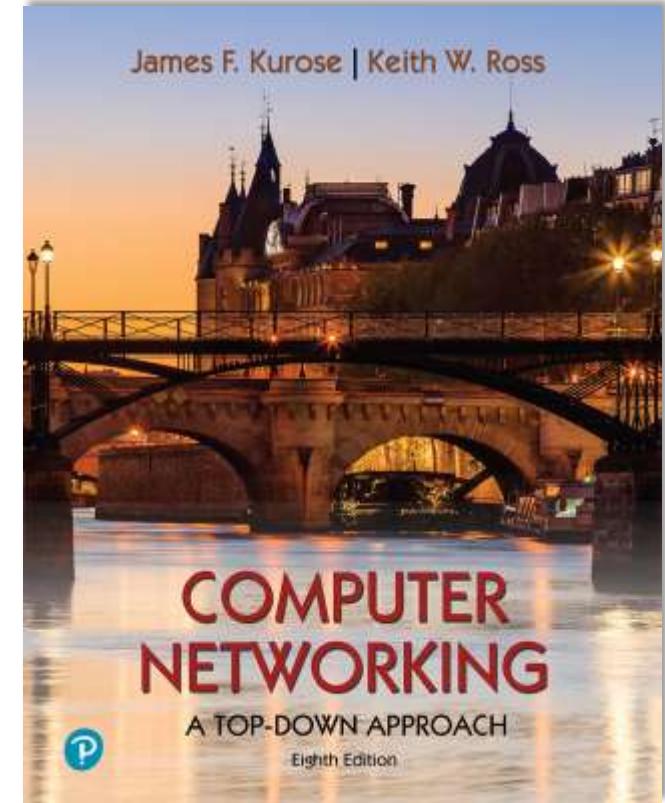
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*Computer Networking: A  
Top-Down Approach*  
8<sup>th</sup> edition  
Jim Kurose, Keith Ross  
Pearson, 2020

# 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
- datacenter networks
- instantiation, implementation of various link layer technologies



# Link layer, LANs: roadmap

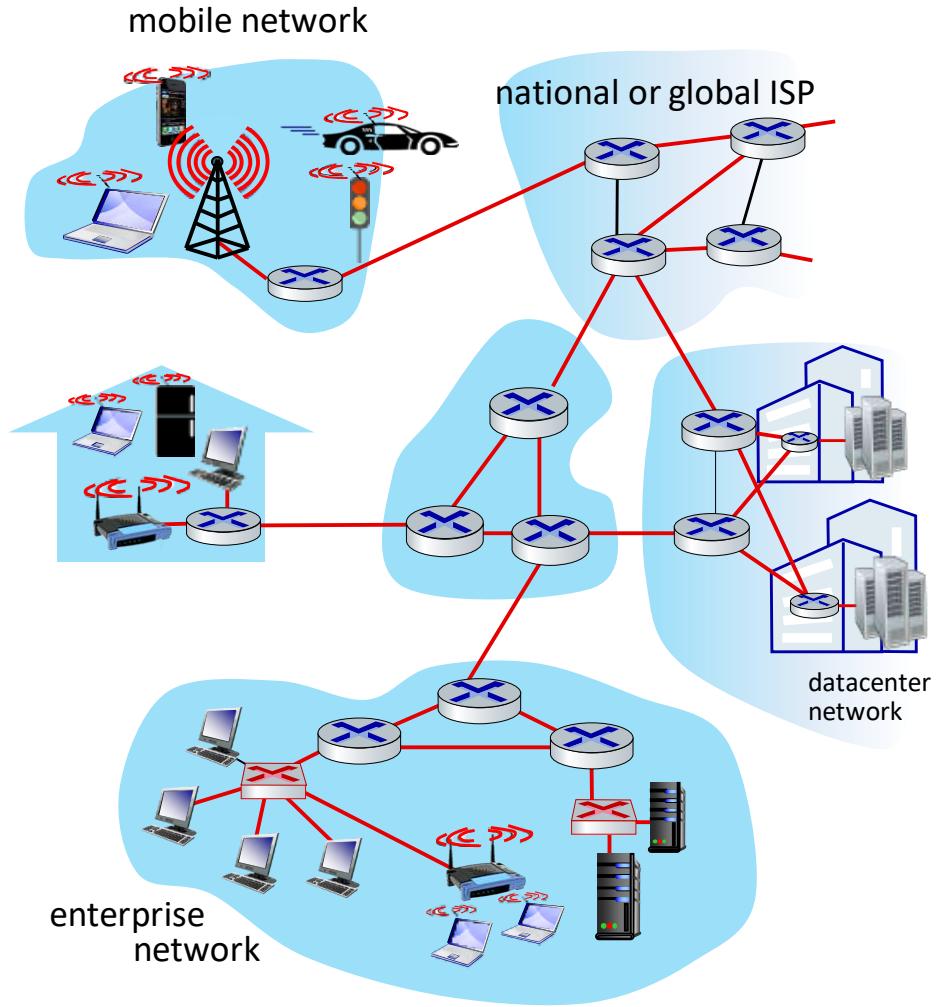
- introduction
  - error detection, correction
  - multiple access protocols
  - LANs
    - addressing, ARP
    - Ethernet
    - switches
    - VLANs
  - link virtualization: MPLS
  - data center networking
- 
- a day in the life of a web request

# 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

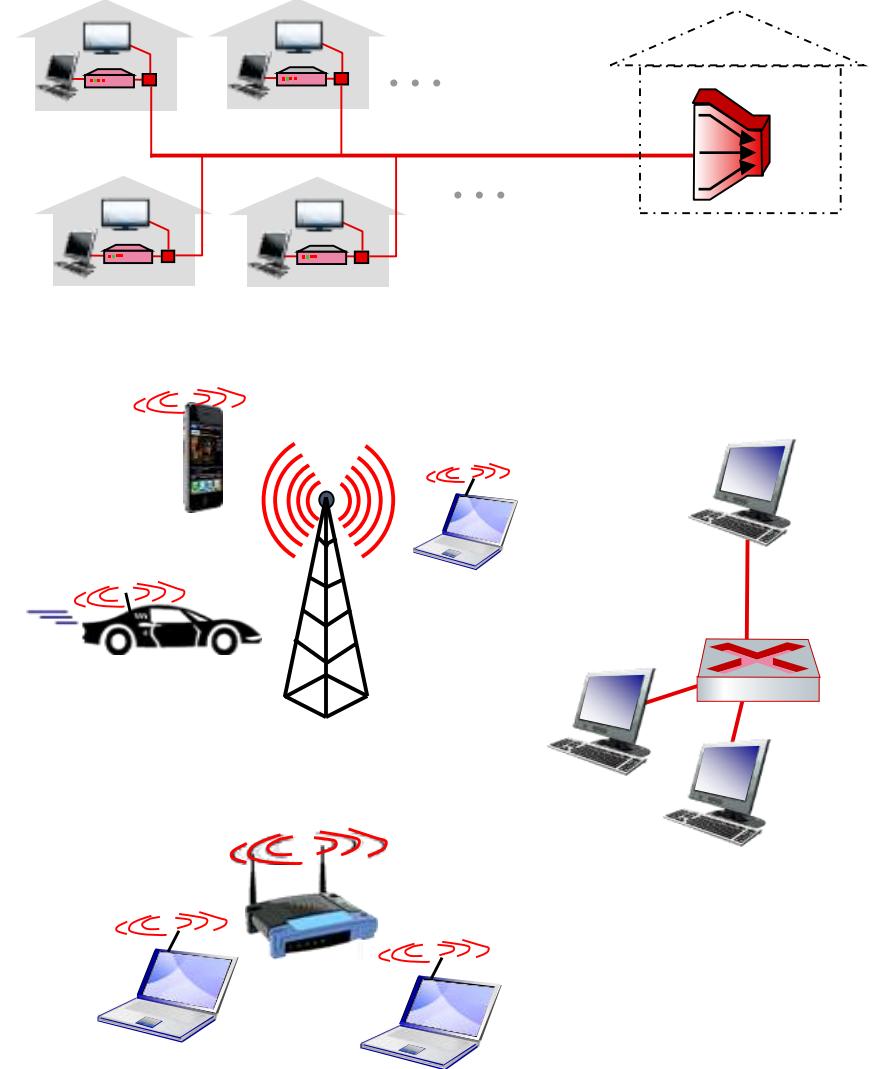
- datagram transferred by different link protocols over different links:
  - e.g., WiFi on first link, Ethernet on next link
- each link protocol provides different services
  - e.g., may or may not provide reliable data transfer over link

## 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**

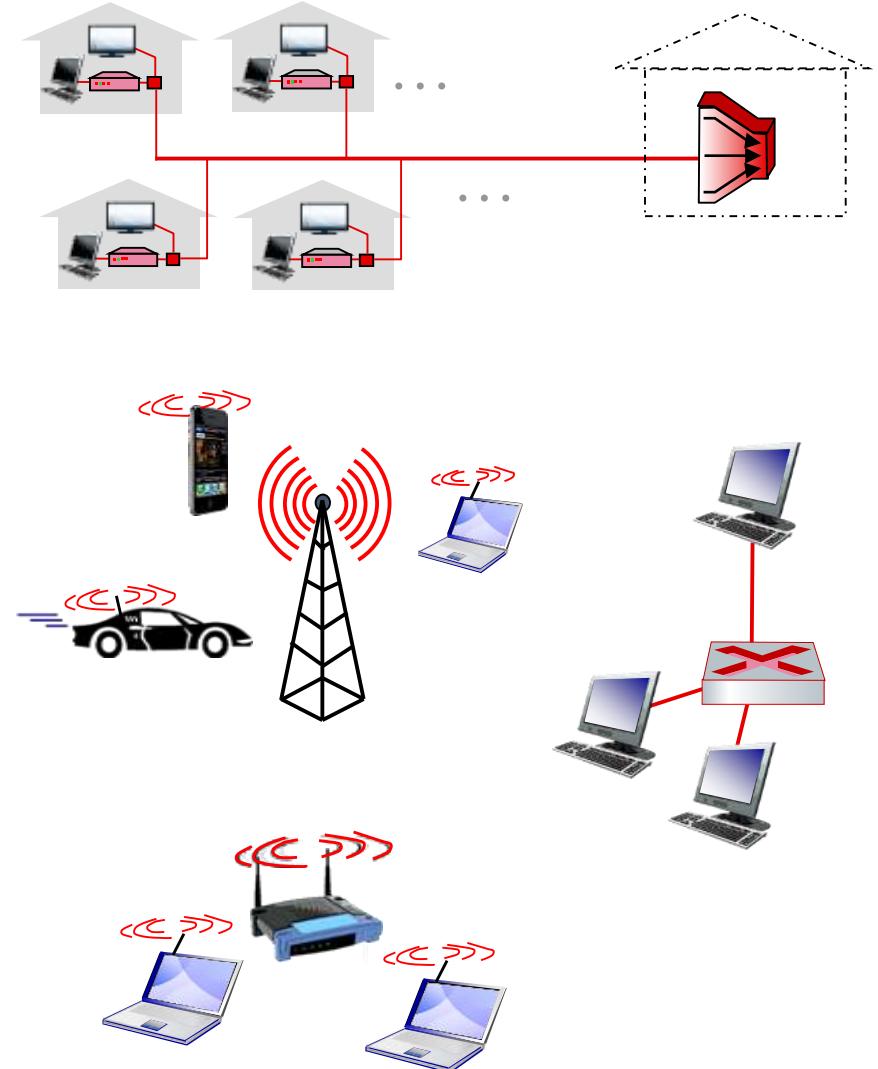
# Link layer: services

- **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?



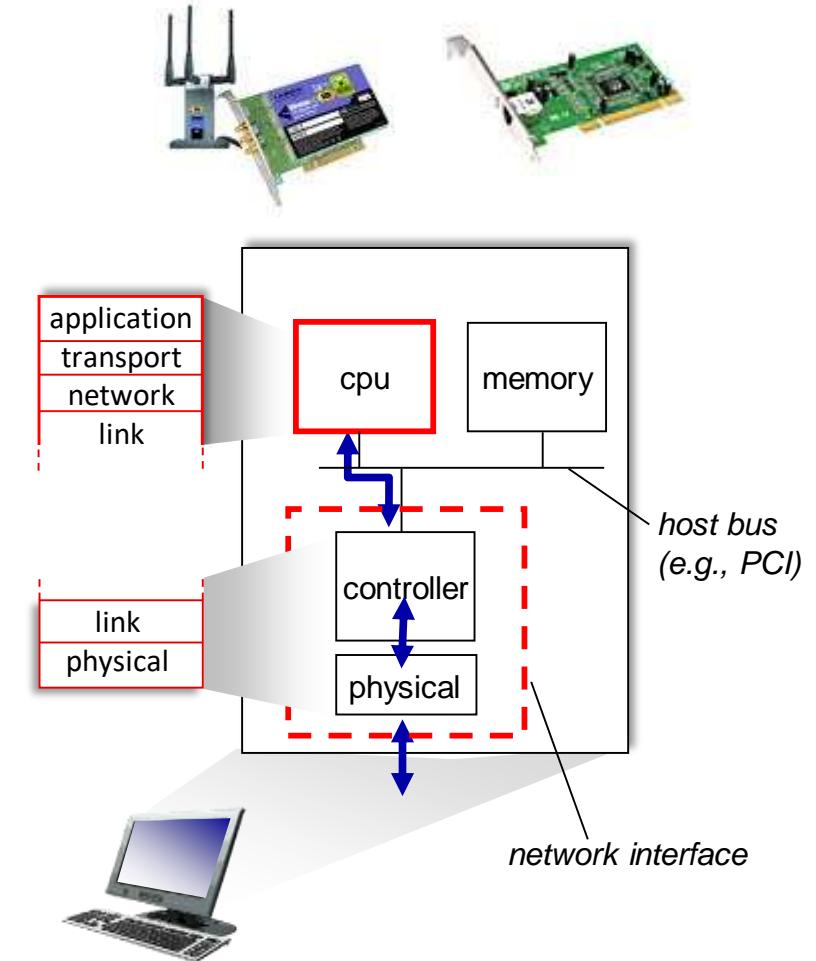
# Link layer: services (more)

- **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

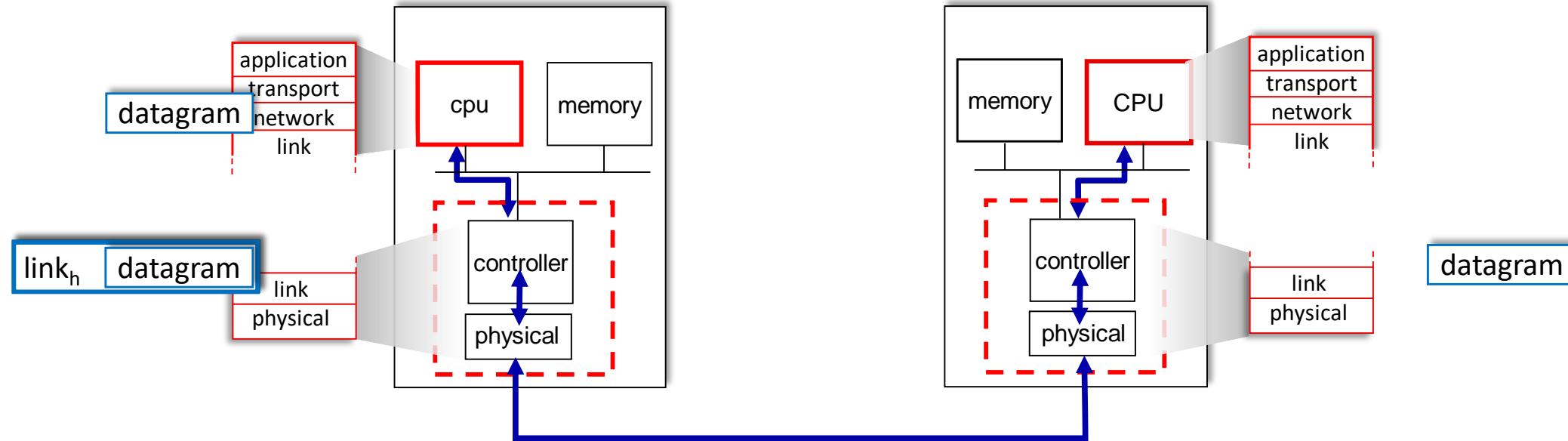


# Where is the link layer implemented?

- 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

# Link layer, LANs: roadmap

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- **error detection, correction**
- multiple access protocols
- LANs
  - addressing, ARP
  - Ethernet
  - switches
  - VLANs
- link virtualization: MPLS
- data center networking

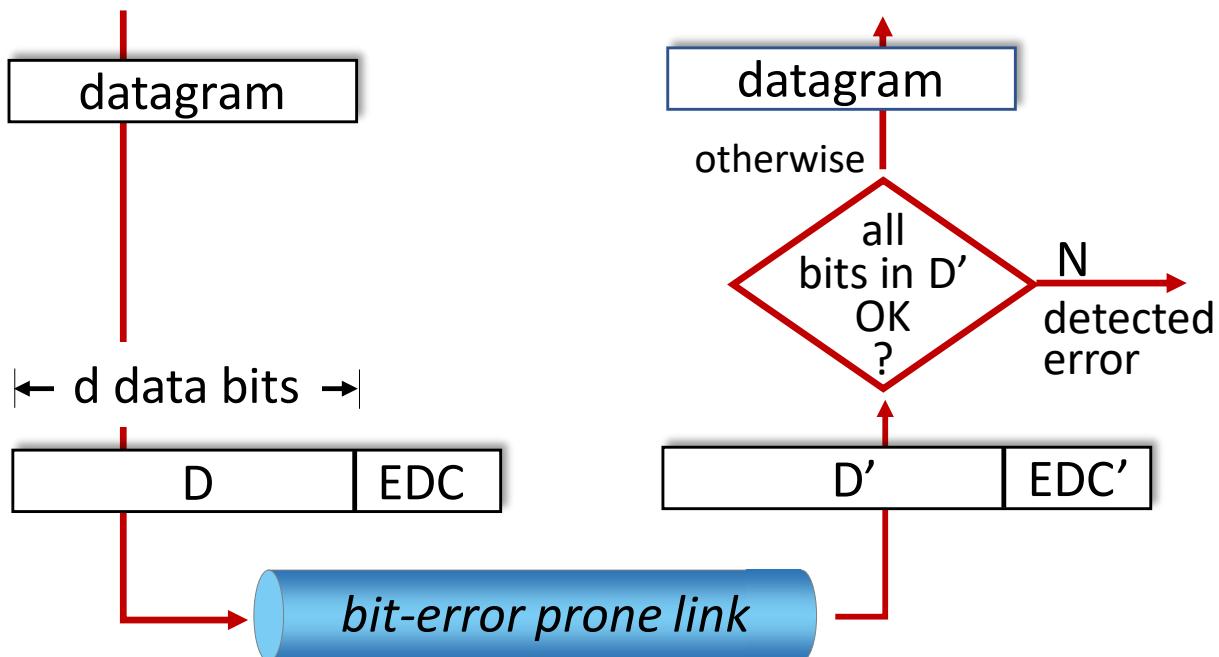


- a day in the life of a web request

# Error detection

EDC: error detection and correction bits (e.g., redundancy)

D: data protected by error checking, may include header fields



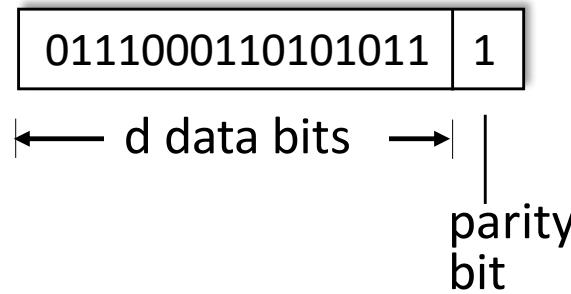
Error detection not 100% reliable!

- protocol may miss some errors, but rarely
- larger EDC field yields better detection and correction

# Parity checking

## single bit parity:

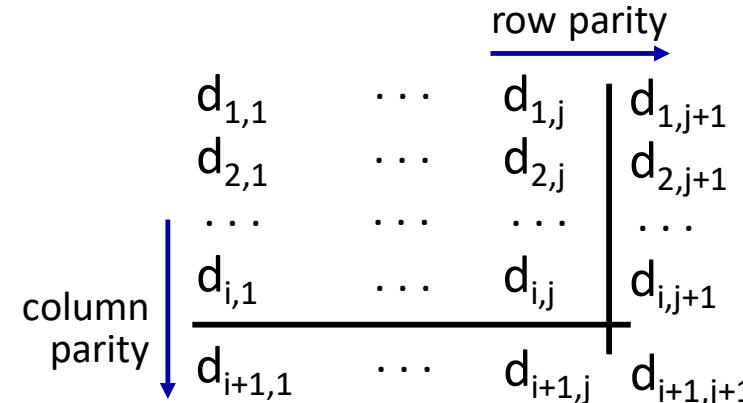
- detect single bit errors



Even parity: set parity bit so there is an even number of 1's

## two-dimensional bit parity:

- detect *and correct* single bit errors



no errors:	1 0 1 0 1   1
	1 1 1 1 0   0
	0 1 1 1 0   1
	1 0 1 0 1   0

detected  
and  
correctable  
single-bit  
error:

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

parity error

parity error

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

# Internet checksum (review)

**Goal:** detect errors (*i.e.*, flipped bits) in transmitted segment

sender:

- treat contents of UDP segment (including UDP header fields and IP addresses) as sequence of 16-bit integers
- **checksum:** addition (one's complement sum) of segment content
- checksum value put into UDP checksum field

receiver:

- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - not equal - error detected
  - equal - no error detected. *But maybe errors nonetheless?* More later ....

# Link layer, LANs: roadmap

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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/4G satellite



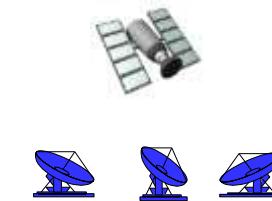
shared wire (e.g.,  
cabled Ethernet)



shared radio: 4G/5G



shared radio: WiFi



shared radio: satellite



humans at a cocktail party  
(shared air, acoustical)

# Link layer, LANs: roadmap

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# MAC addresses

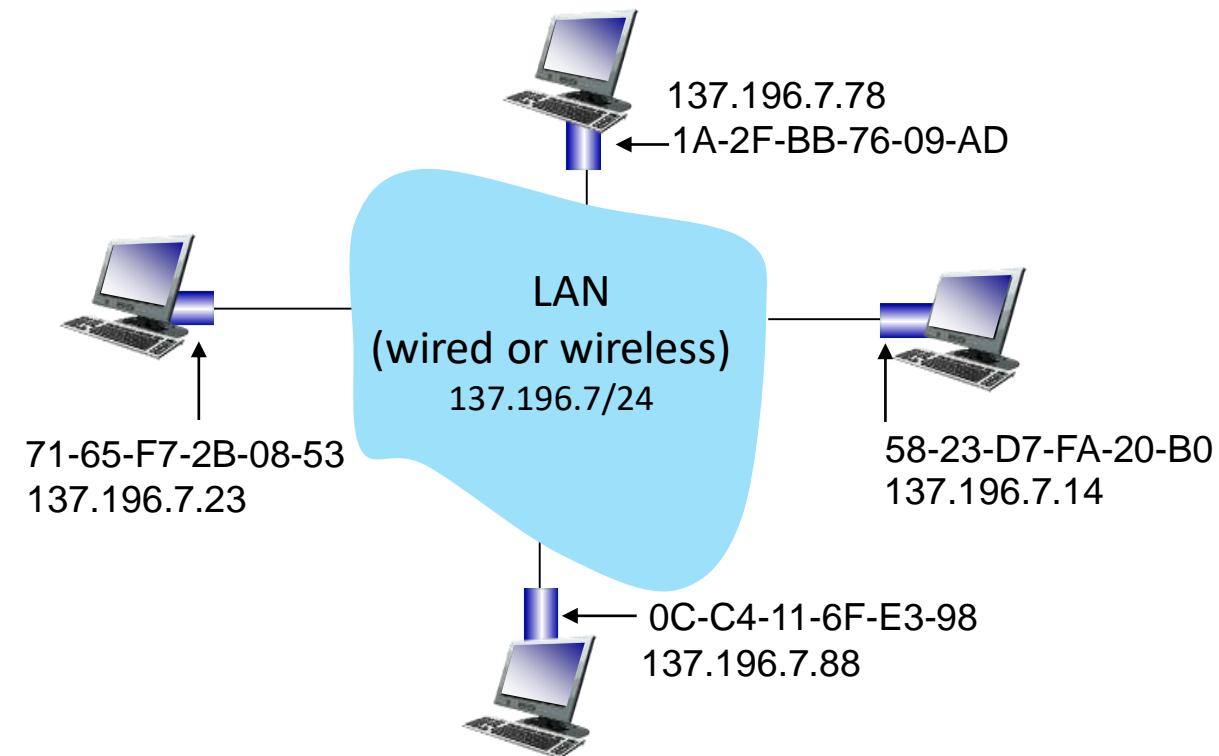
- 32-bit IP address:
  - *network-layer* address for interface
  - used for layer 3 (network layer) forwarding
  - e.g.: 128.119.40.136
- MAC (or LAN or physical or Ethernet) address:
  - function: used “locally” to get frame from one interface to another physically-connected interface (same subnet,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

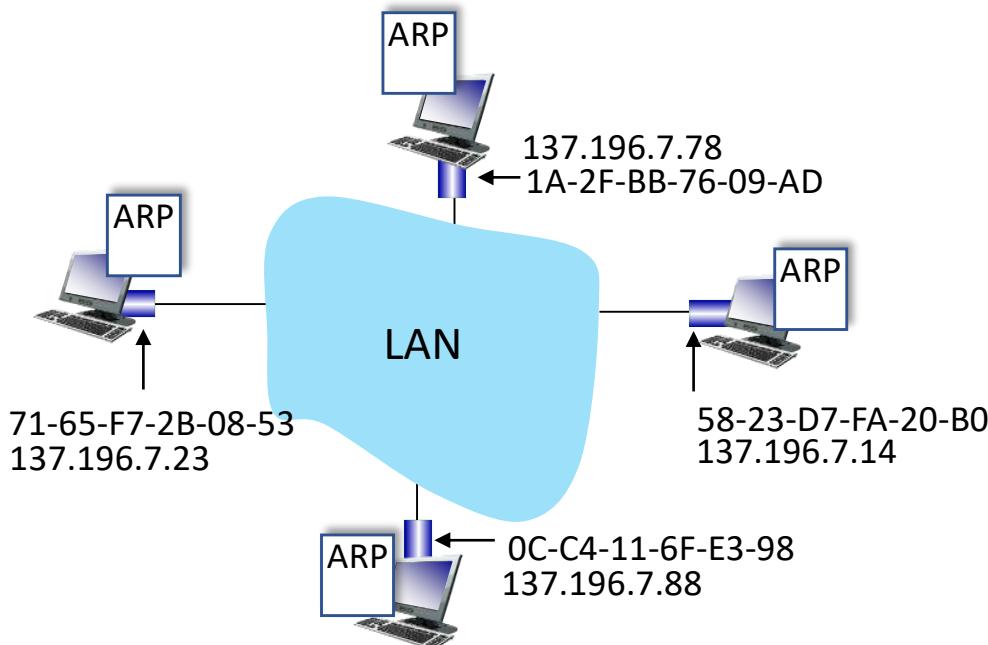


# MAC addresses

- 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)

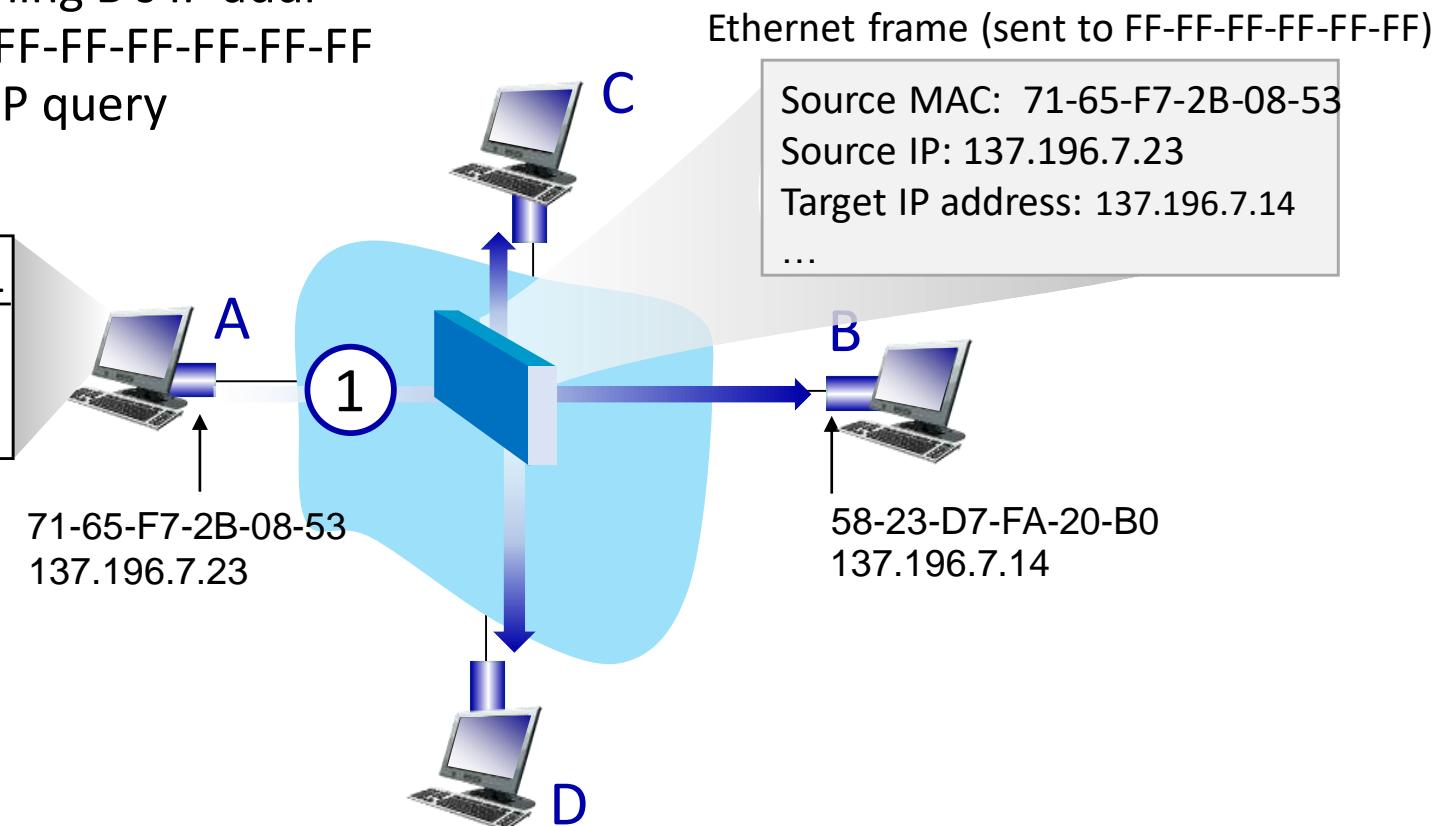
# ARP protocol in action

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

- ① A broadcasts ARP query, containing B's IP addr
- destination MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query

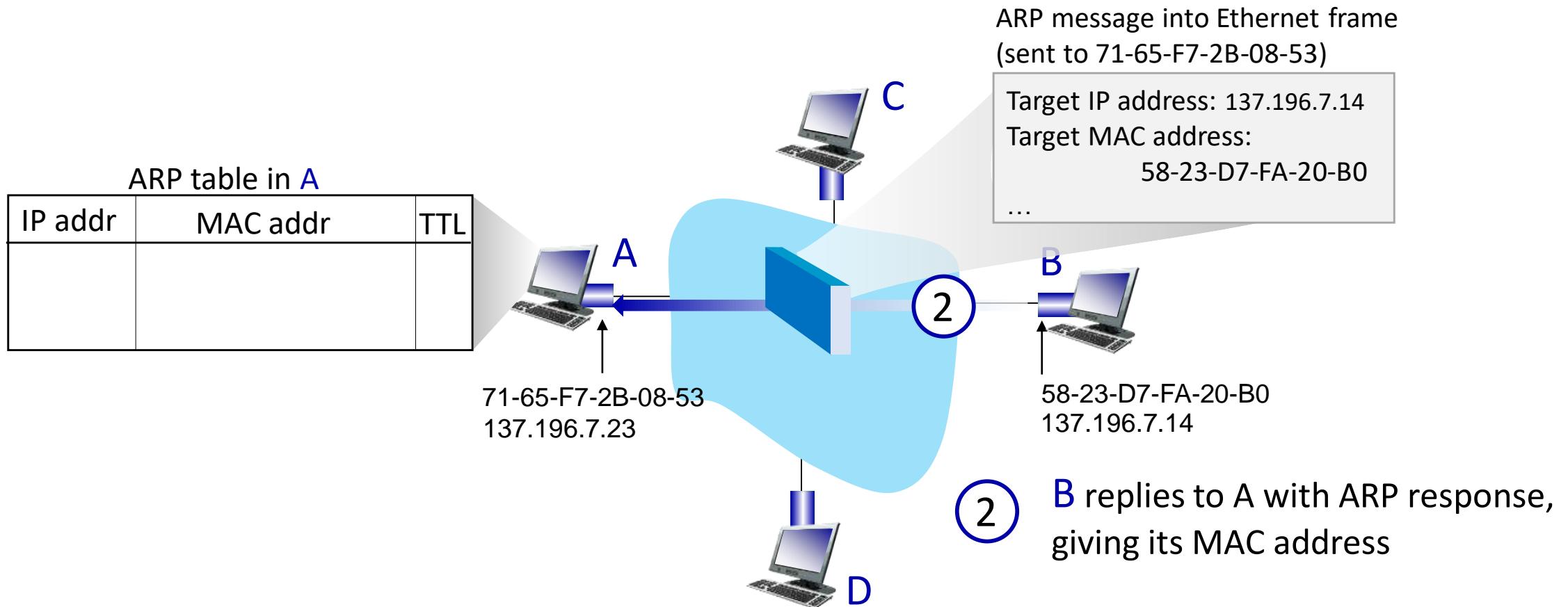
ARP table in A		
IP addr	MAC addr	TTL



# ARP protocol in action

example: A wants to send datagram to B

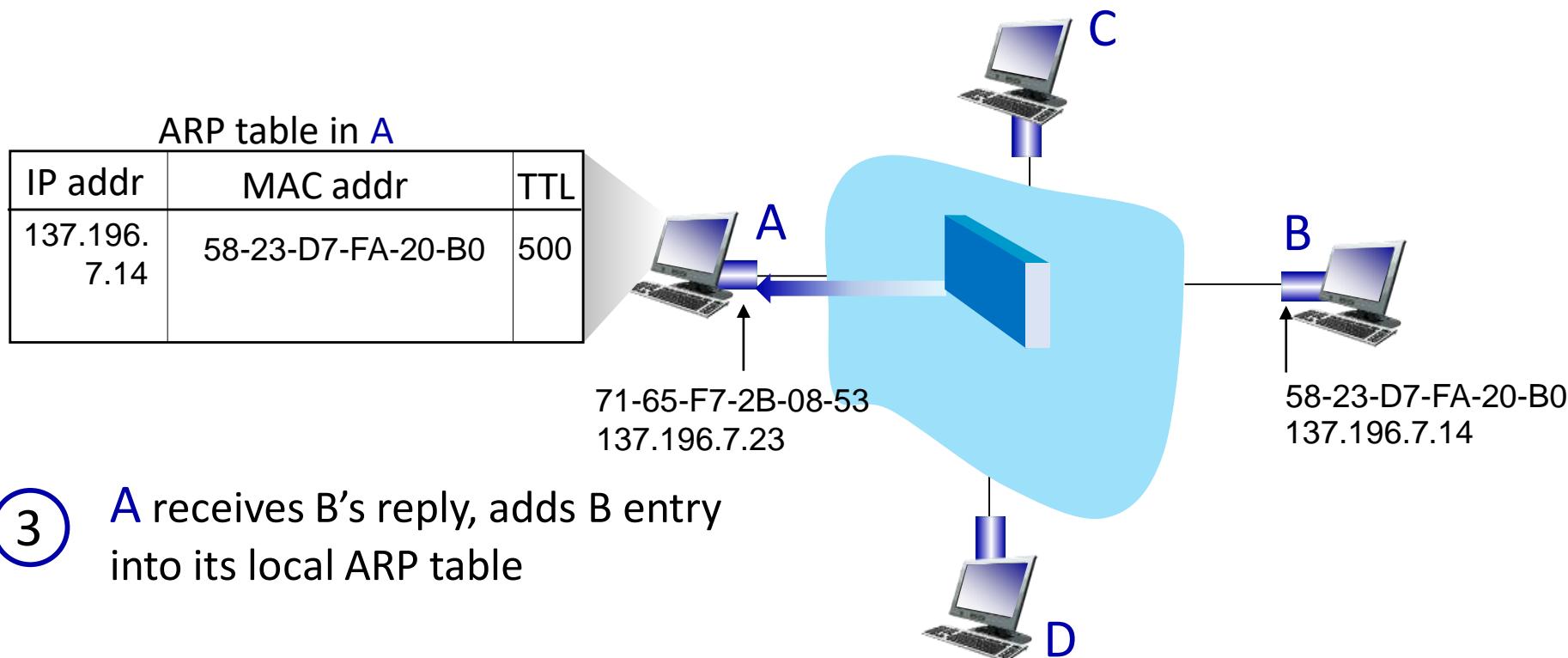
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# ARP protocol in action

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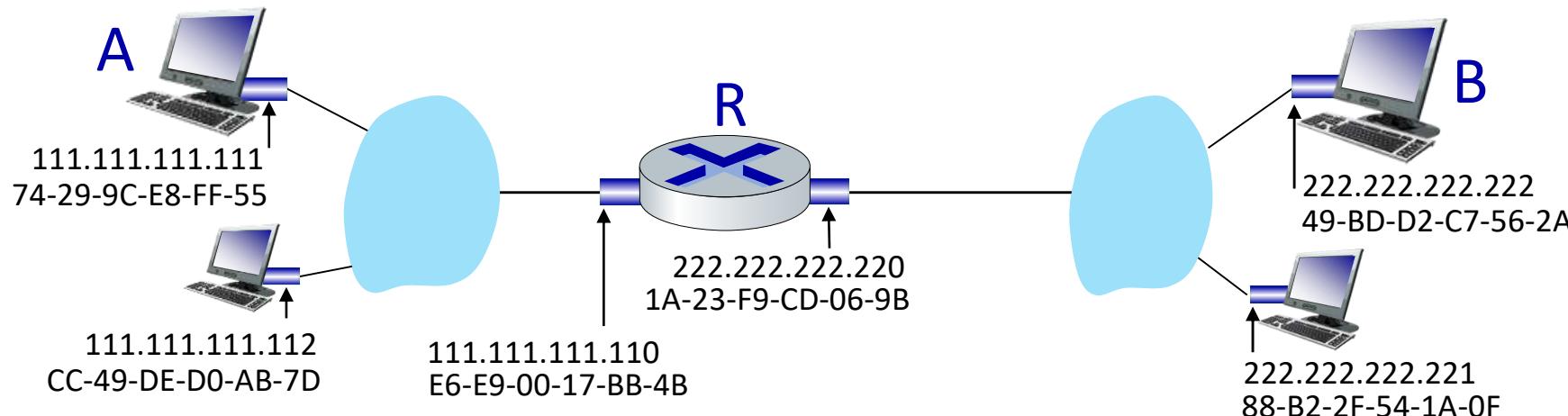
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# Routing to another subnet: addressing

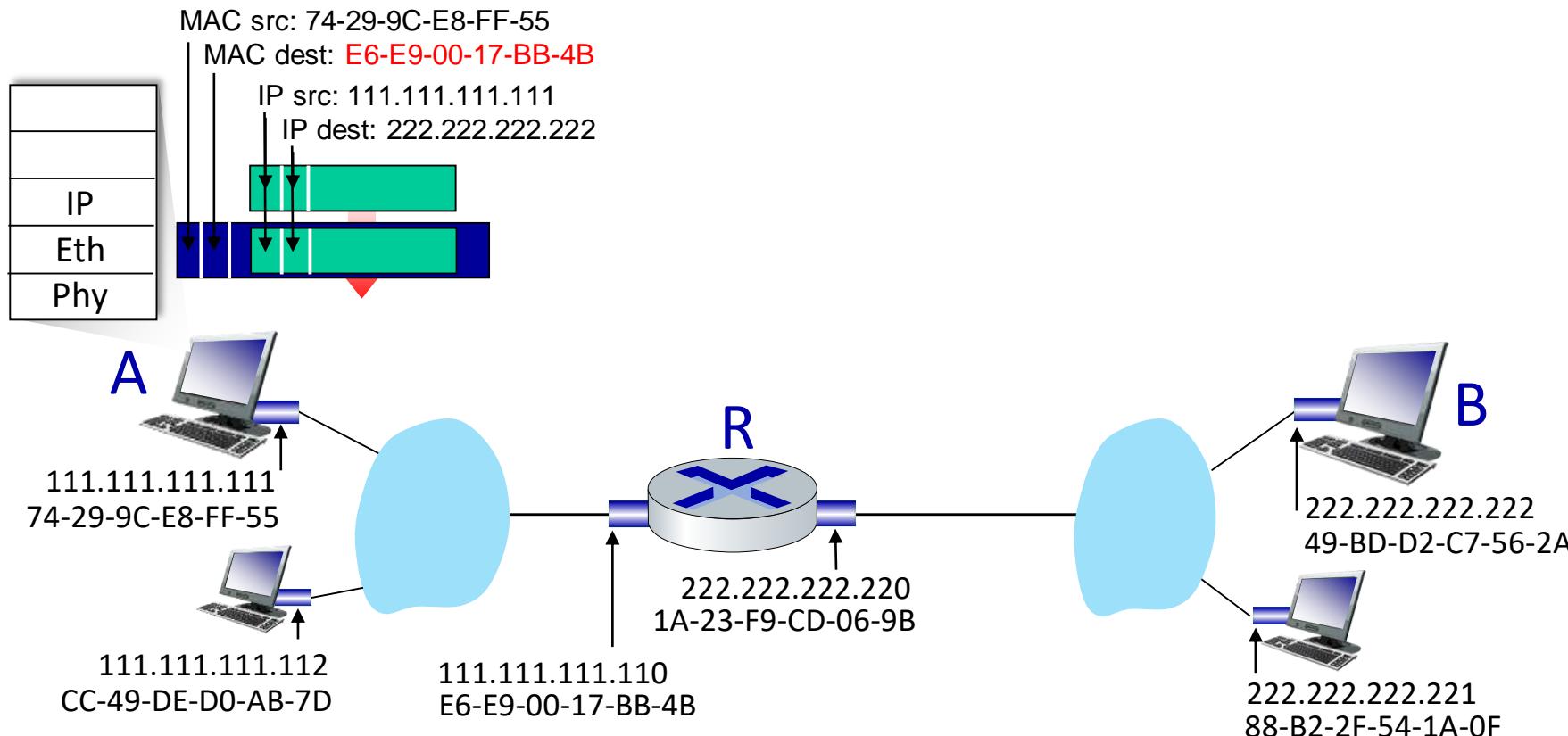
walkthrough: sending a datagram from *A* to *B* via *R*

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



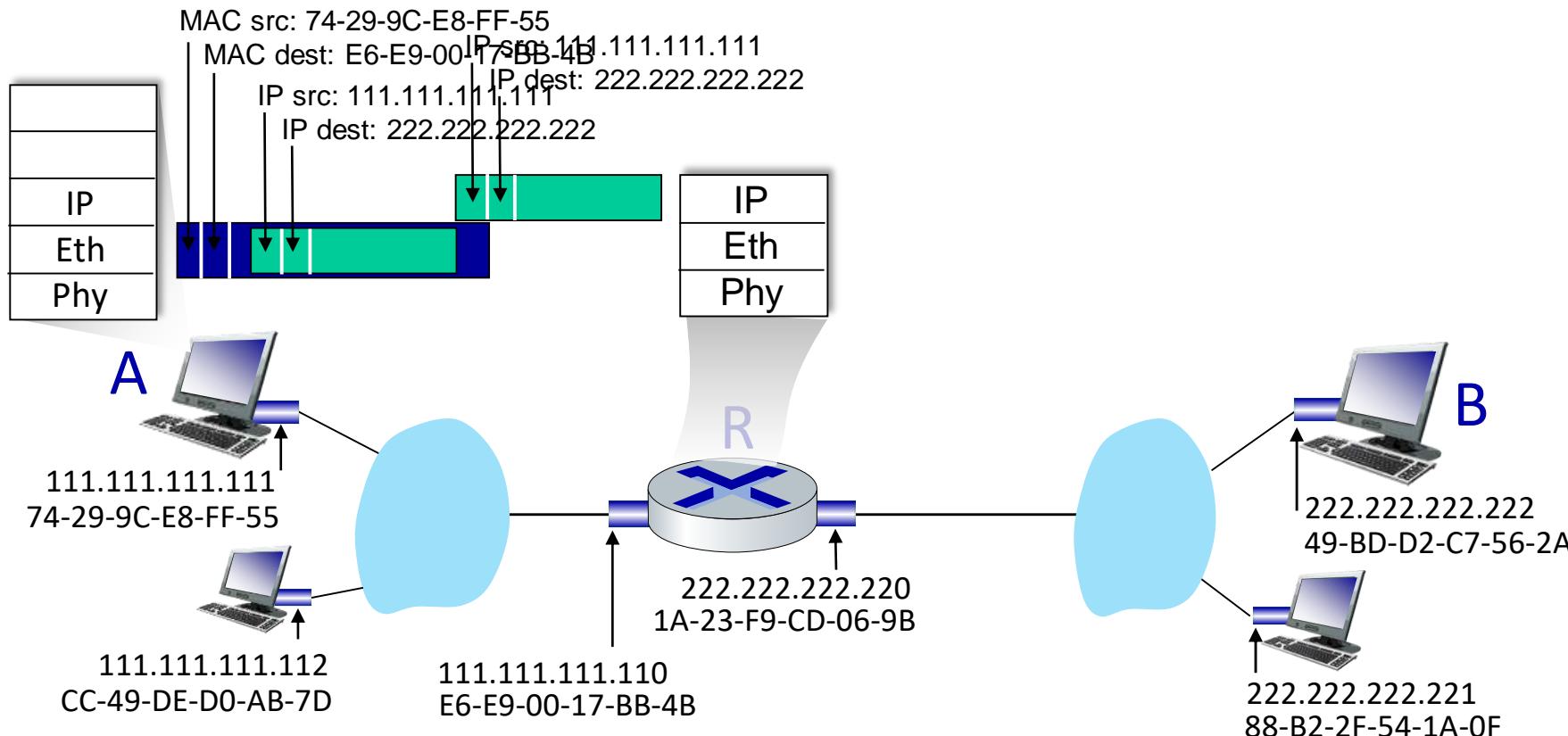
# Routing to another subnet: addressing

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



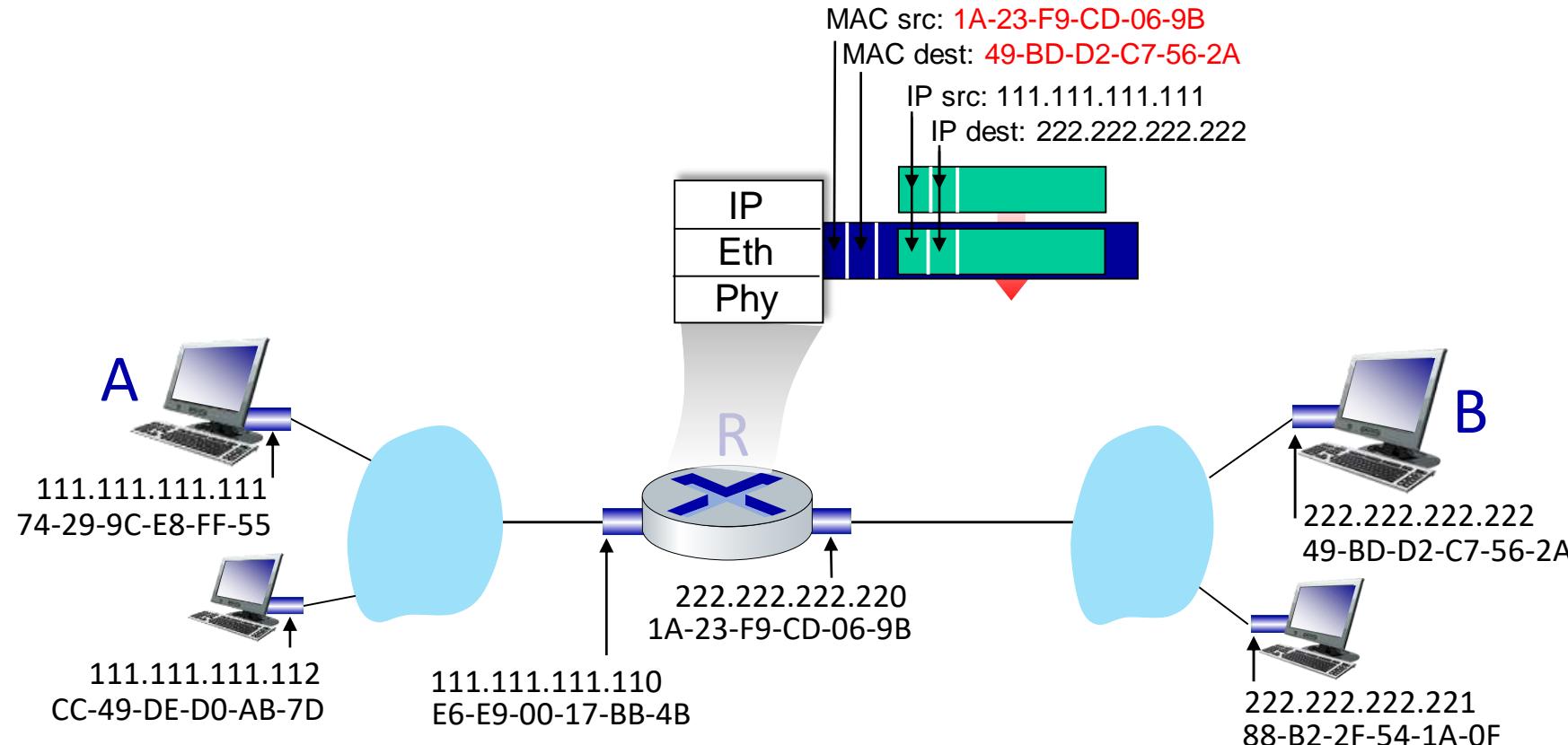
# Routing to another subnet: addressing

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



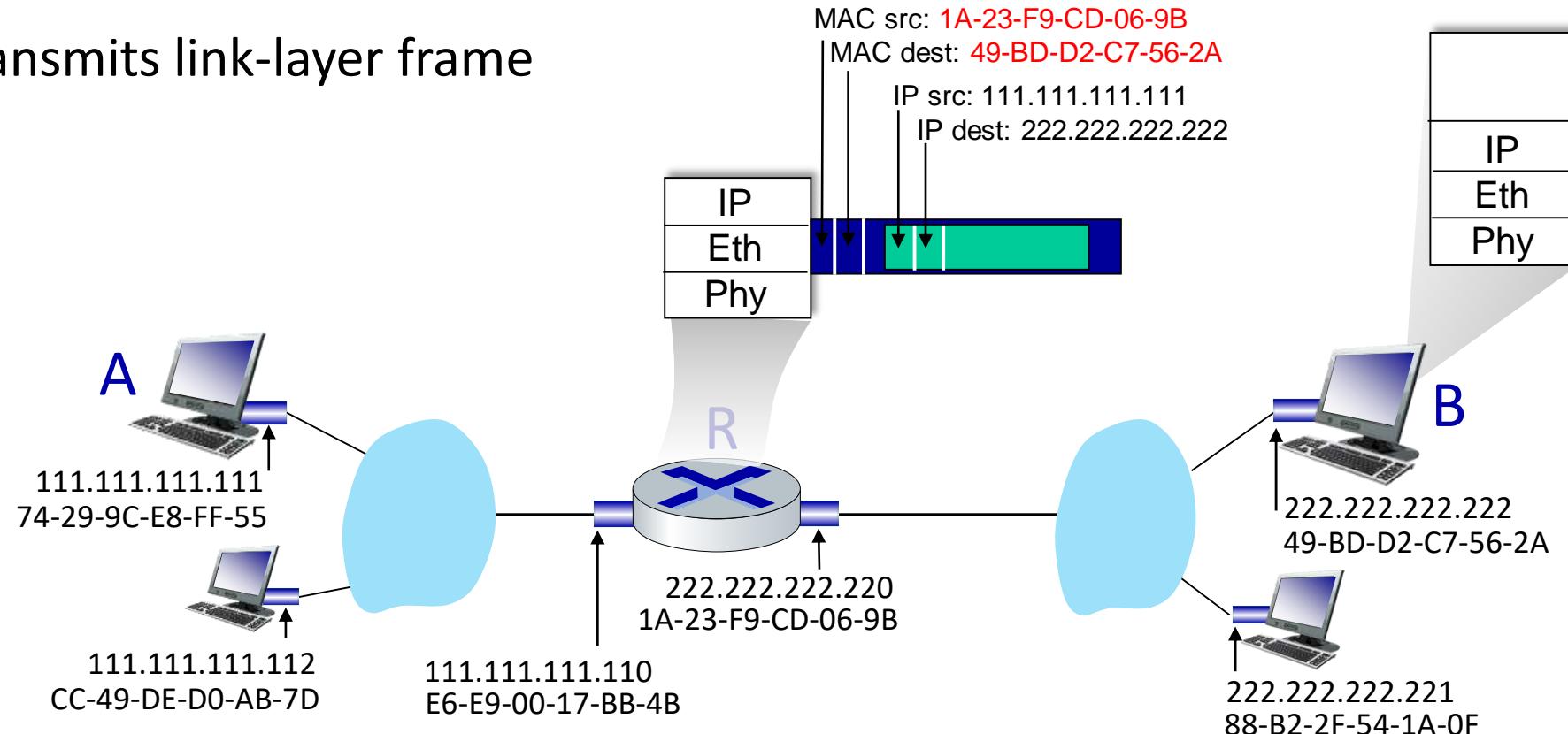
# Routing to another subnet: addressing

- R determines outgoing interface, passes datagram with IP source A, destination B to link layer
- R creates link-layer frame containing A-to-B IP datagram. Frame destination address: B's MAC address



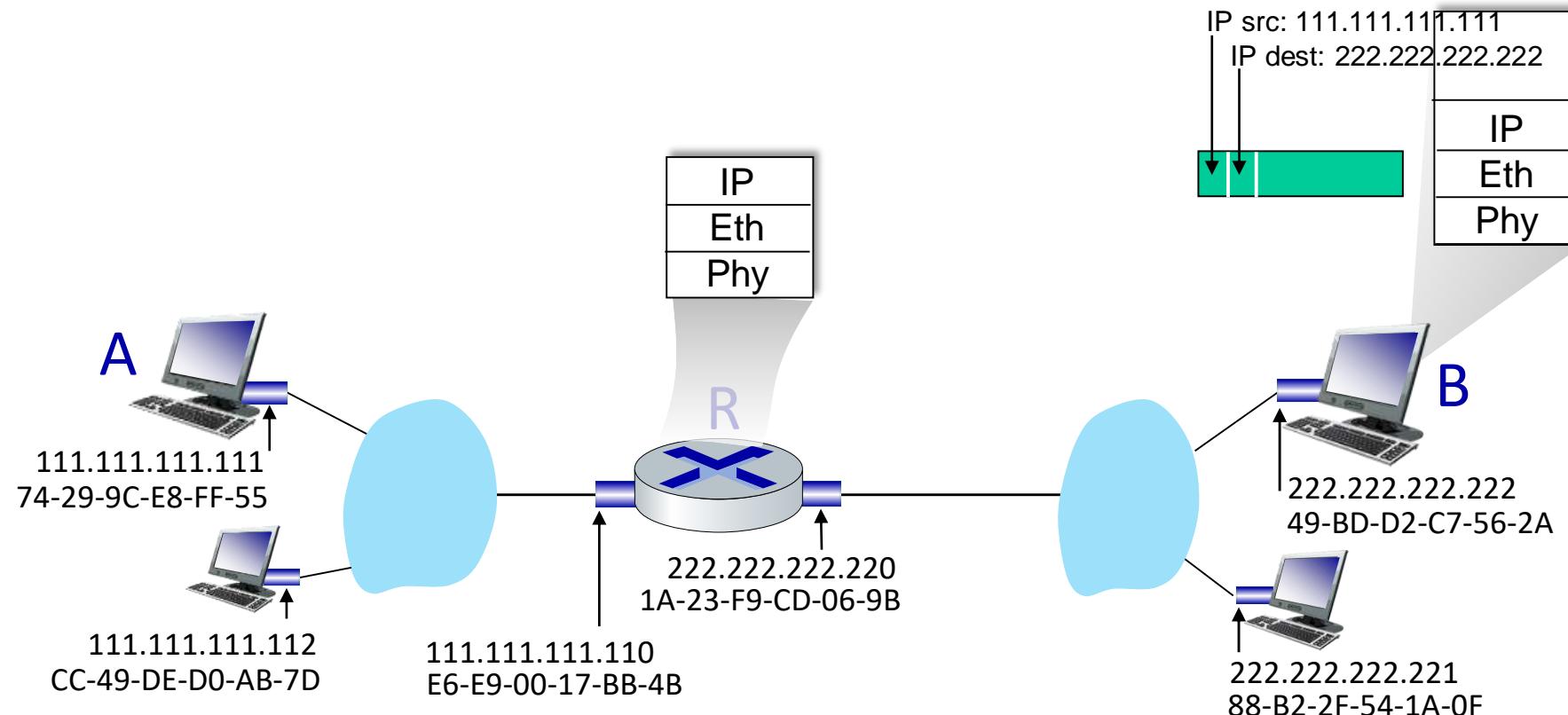
# Routing to another subnet: addressing

- R determines outgoing interface, passes datagram with IP source A, destination B to link layer
- R creates link-layer frame containing A-to-B IP datagram. Frame destination address: B's MAC address
- transmits link-layer frame



# Routing to another subnet: addressing

- B receives frame, extracts IP datagram destination B
- B passes datagram up protocol stack to IP



# Link layer, LANs: roadmap

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- **LANs**
  - addressing, ARP
  - **Ethernet**
  - switches
  - VLANs
- link virtualization: MPLS
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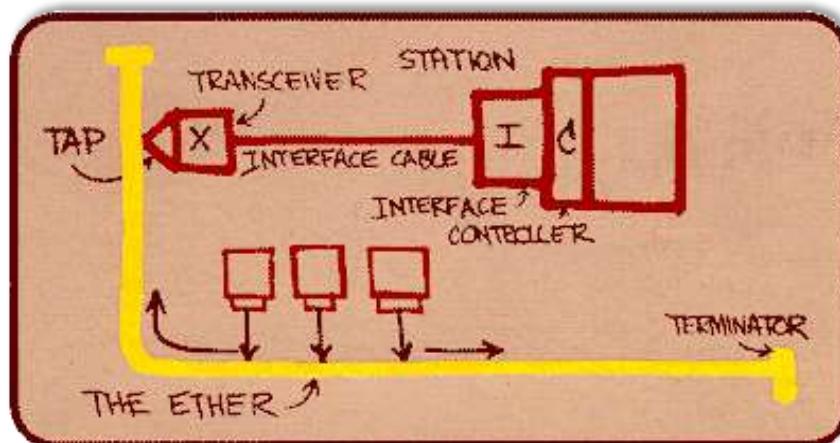


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# Ethernet

“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)

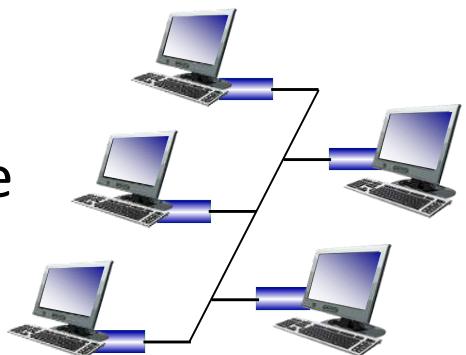


*Metcalfe's Ethernet  
sketch*

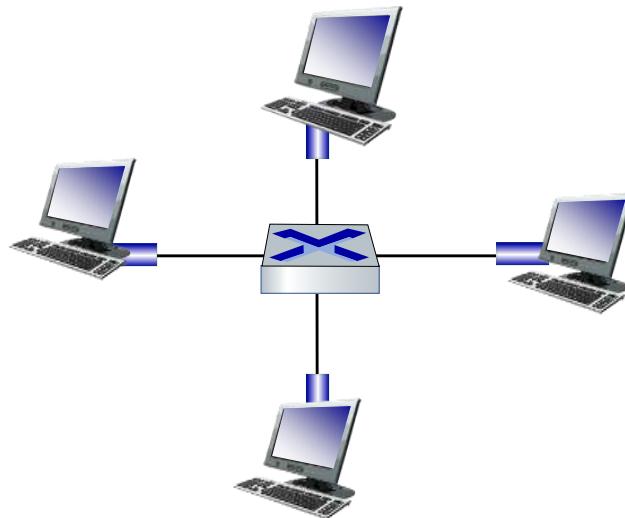
# Ethernet: physical topology

- **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 frame structure

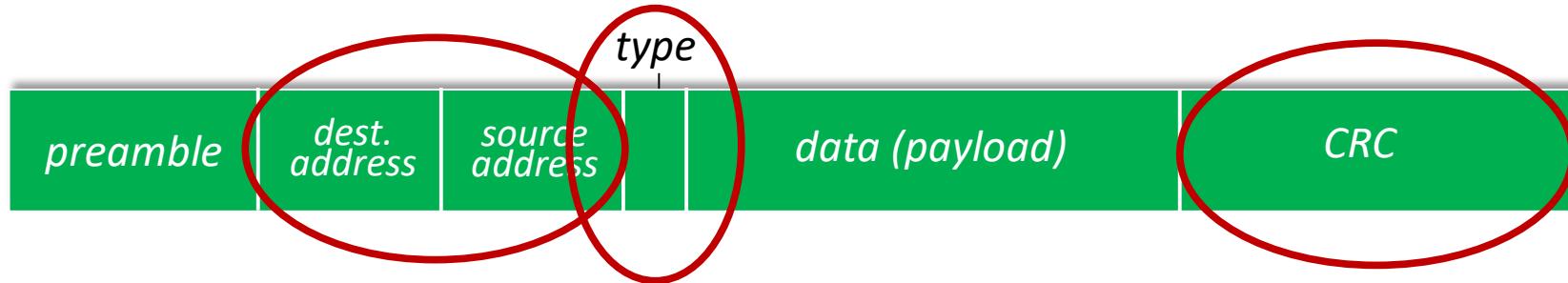
sending interface encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frame**



*preamble:*

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

# Ethernet frame structure (more)



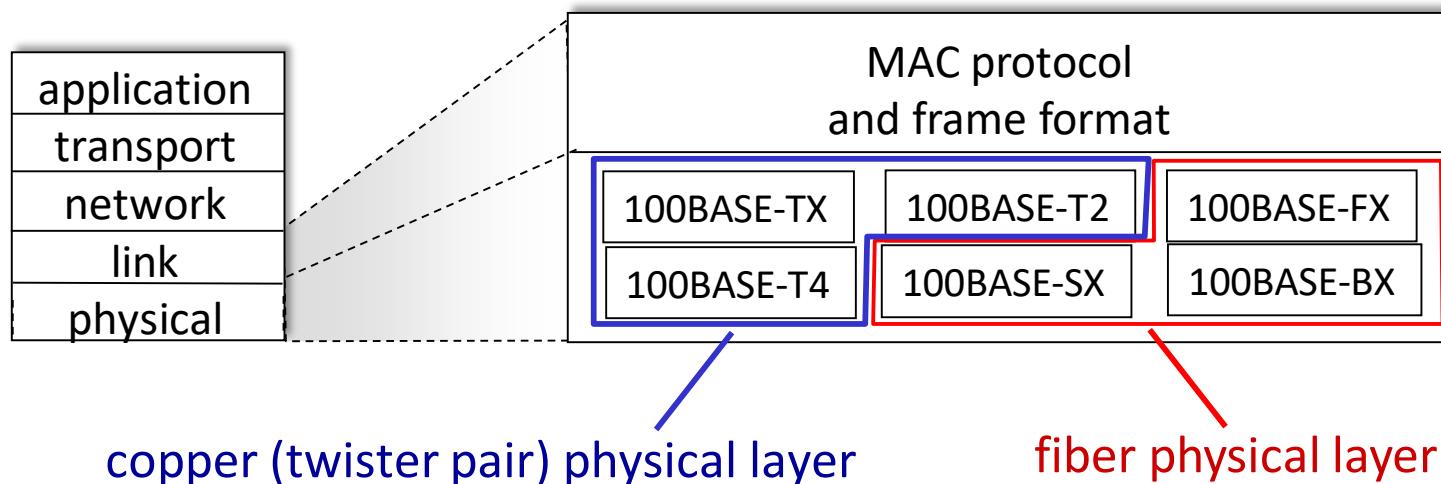
- **addresses**: 6 byte source, destination MAC addresses
  - if adapter receives frame with matching destination address, or with broadcast address (e.g., ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- **type**: indicates higher layer protocol
  - mostly IP but others possible, e.g., Novell IPX, AppleTalk
  - used to demultiplex up at receiver
- **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 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



# Link layer, LANs: roadmap

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- multiple access protocols
- **LANs**
  - addressing, ARP
  - Ethernet
  - **switches**
  - VLANs
- link virtualization: MPLS
- data center networking



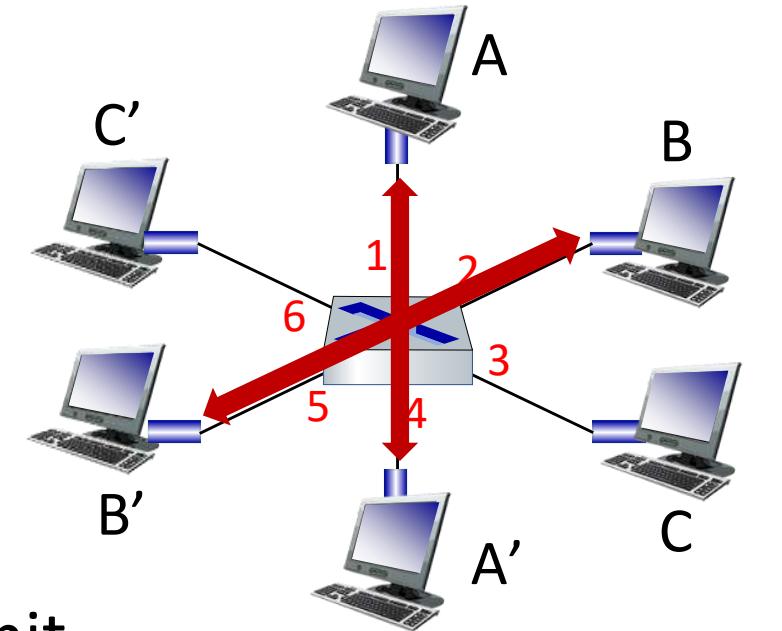
- a day in the life of a web request

# 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

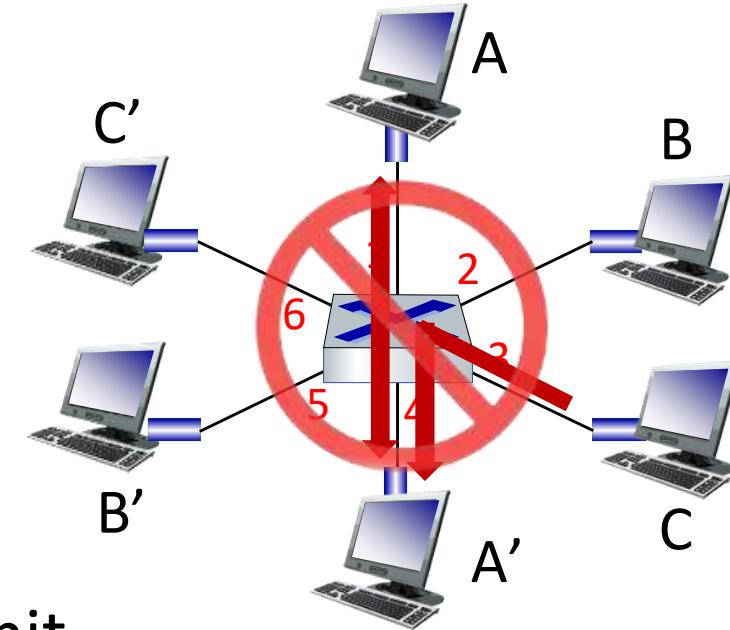
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, so:
  - no collisions; full duplex
  - each link is its own collision domain
- **switching:** A-to-A' and B-to-B' can transmit simultaneously, without collisions



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

# Switch: multiple simultaneous transmissions

- hosts have dedicated, direct connection to switch
- 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
  - 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

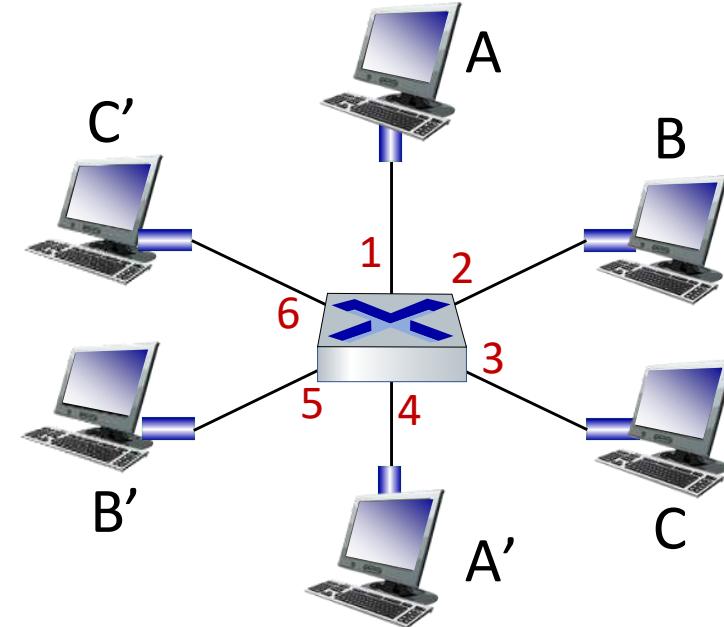
**Q:** how does switch know A' reachable via interface 4, B' reachable via interface 5?

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

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

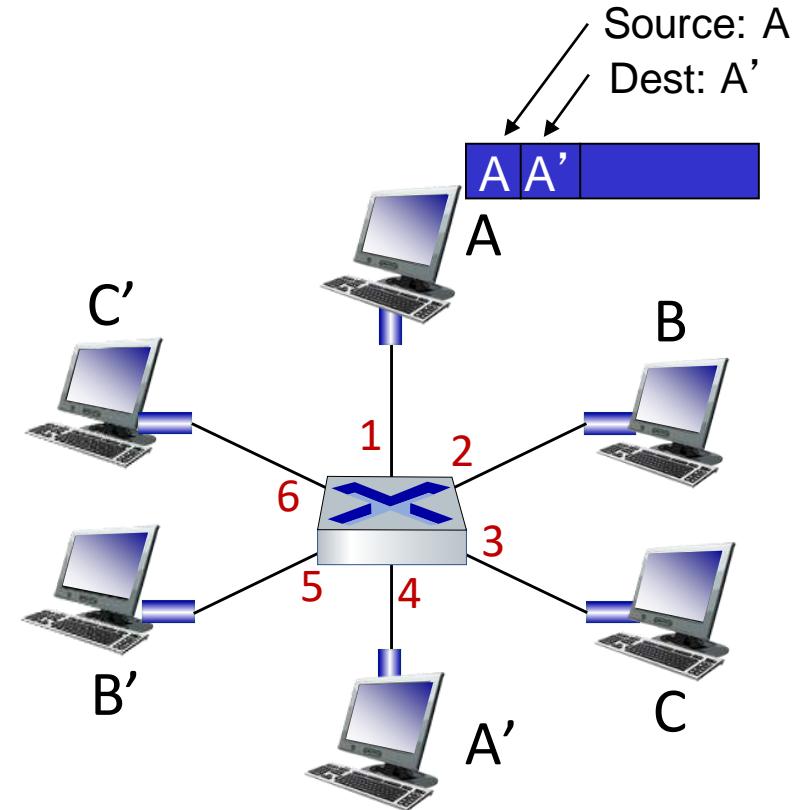
**Q:** how are entries created, maintained in switch table?

- 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)*

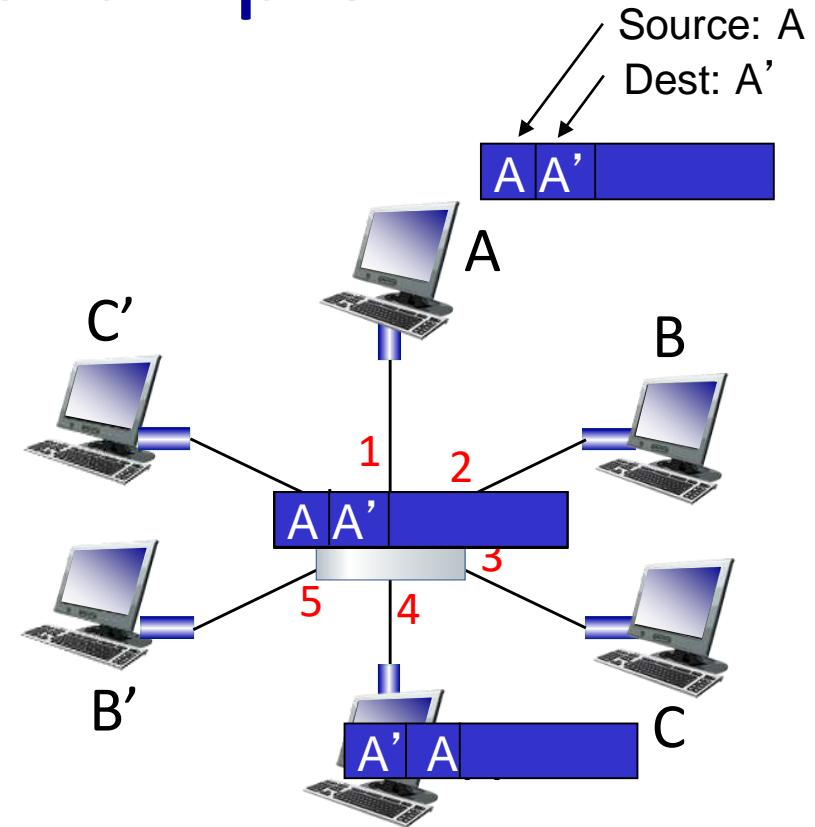
# Switch: frame filtering/forwarding

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**

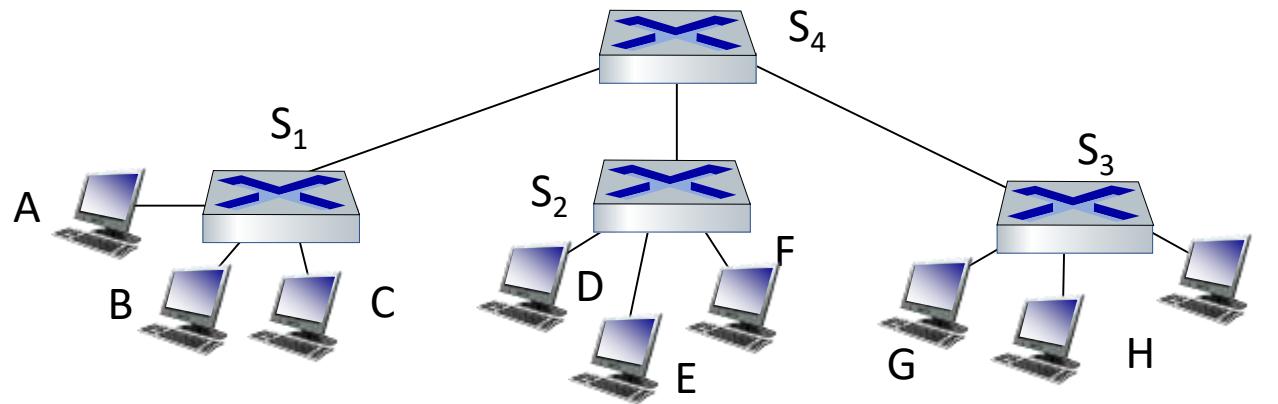


MAC addr	interface	TTL
A	1	60
A'	4	60

*switch table  
(initially empty)*

# Interconnecting switches

self-learning switches can be connected together:

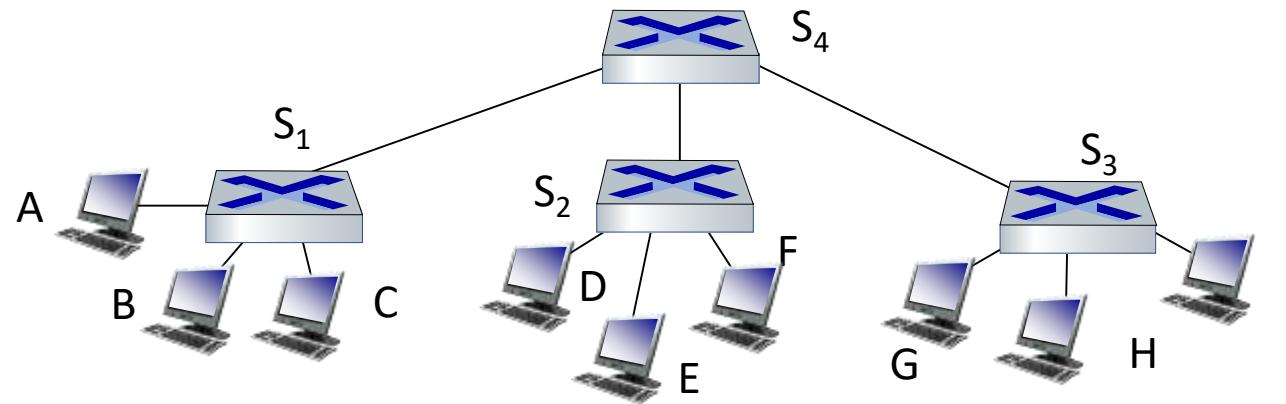


Q: sending from A to G - how does  $S_1$  know to forward frame destined to G via  $S_4$  and  $S_3$ ?

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

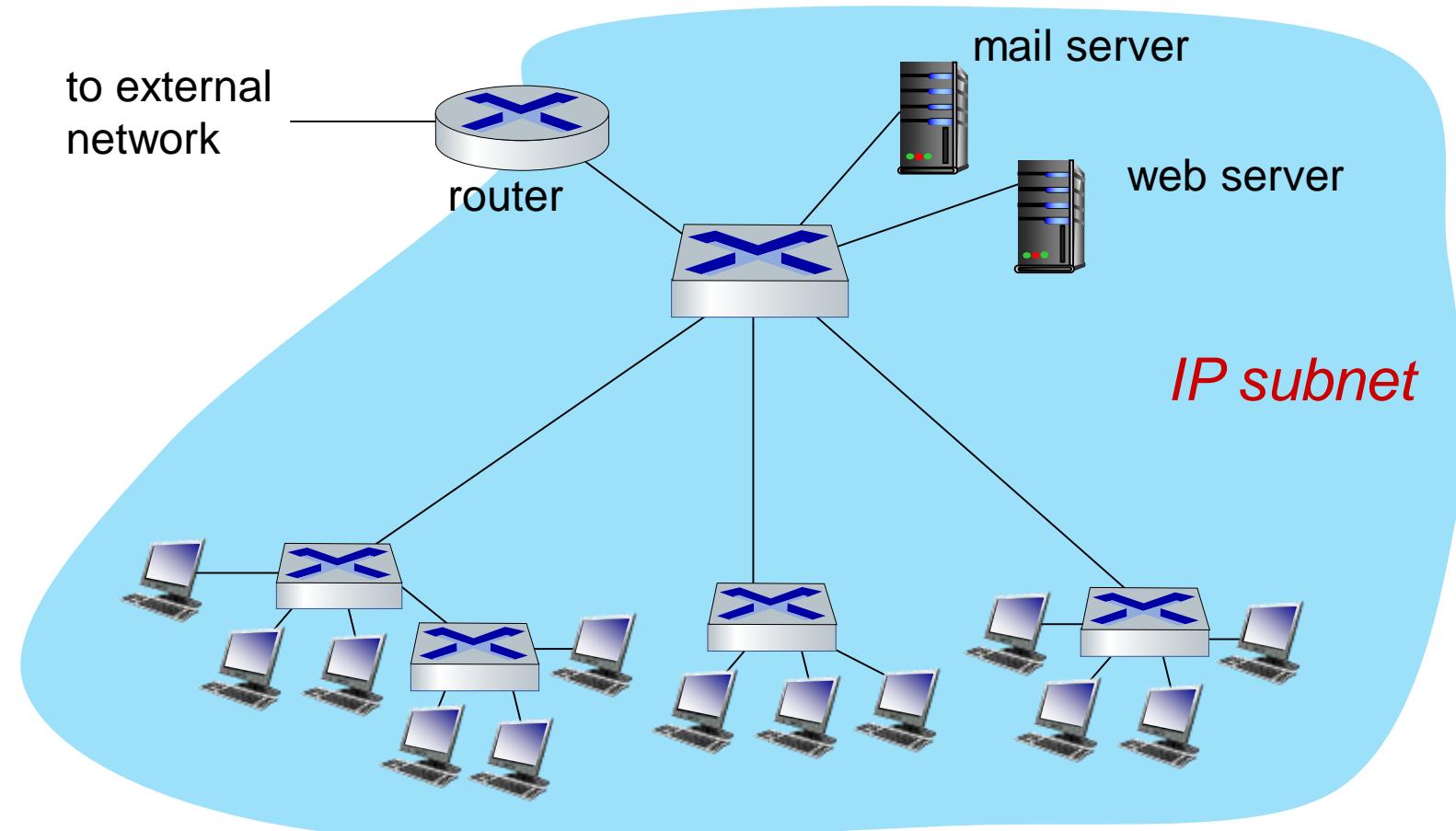
# Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



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

# Small institutional network



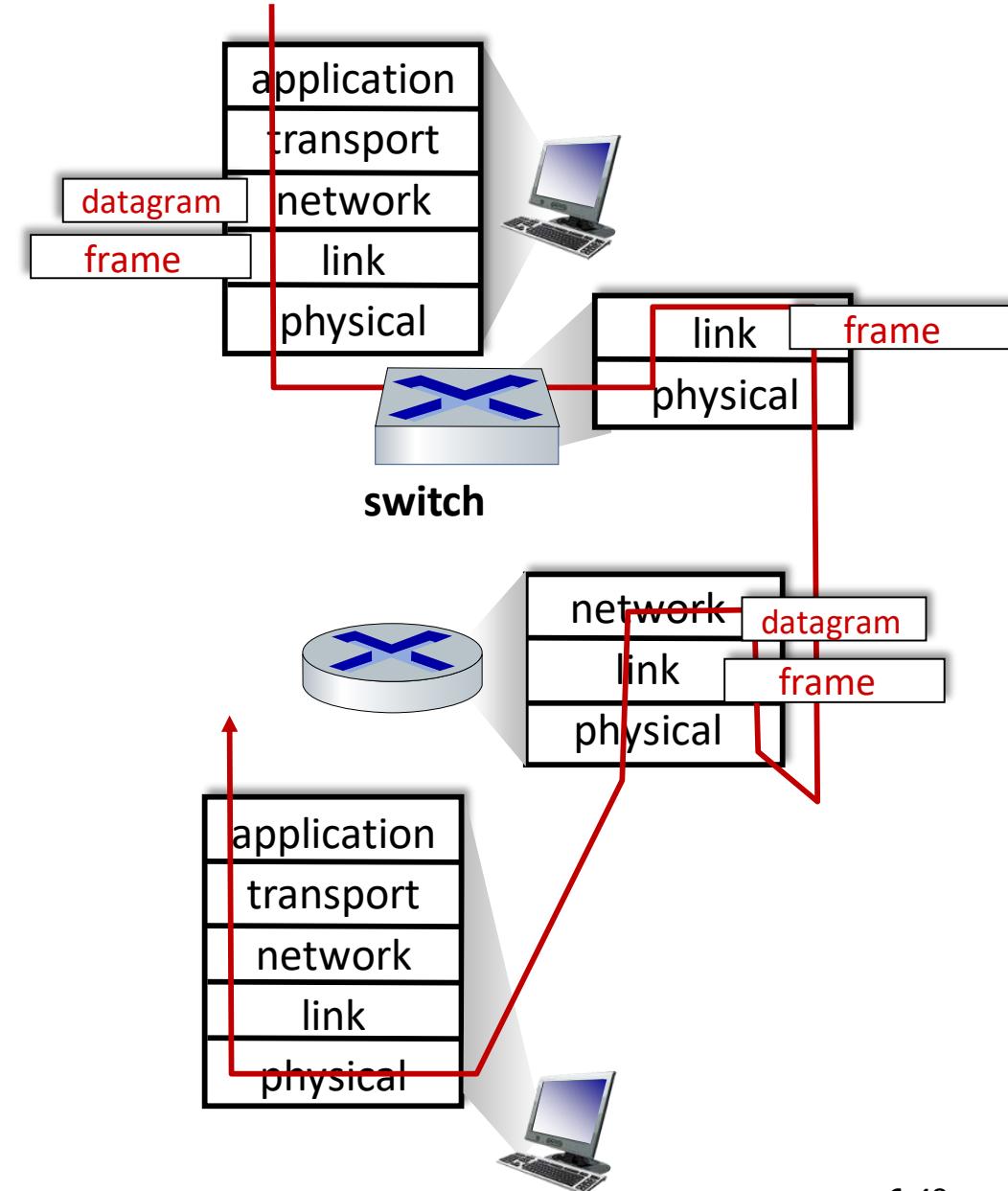
# Switches vs. routers

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

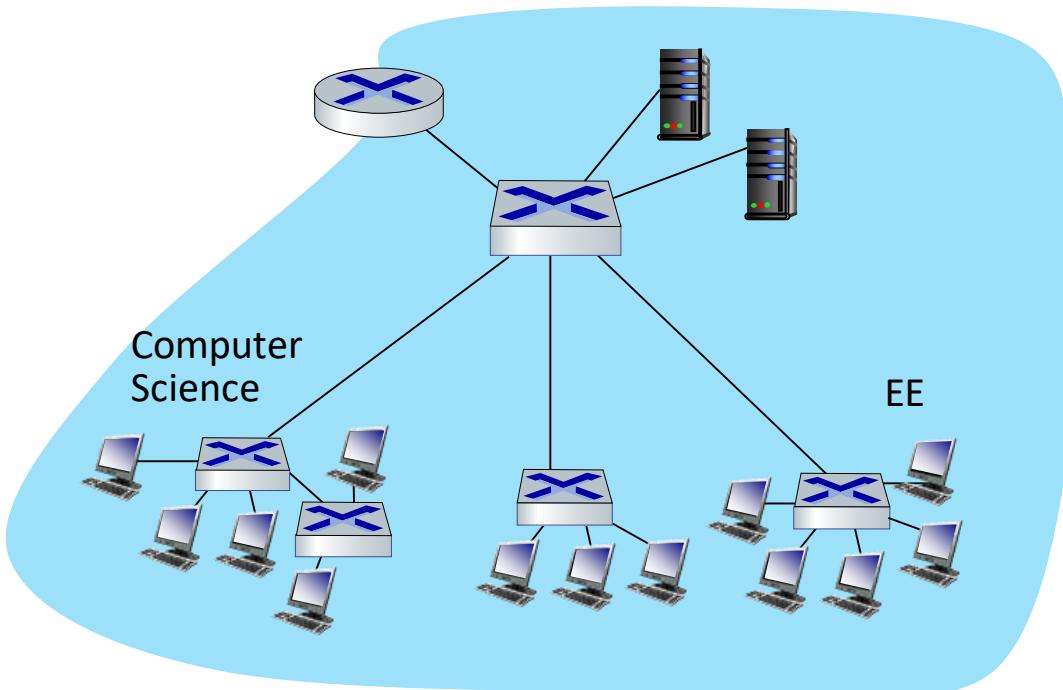
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# Virtual LANs (VLANs): motivation

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

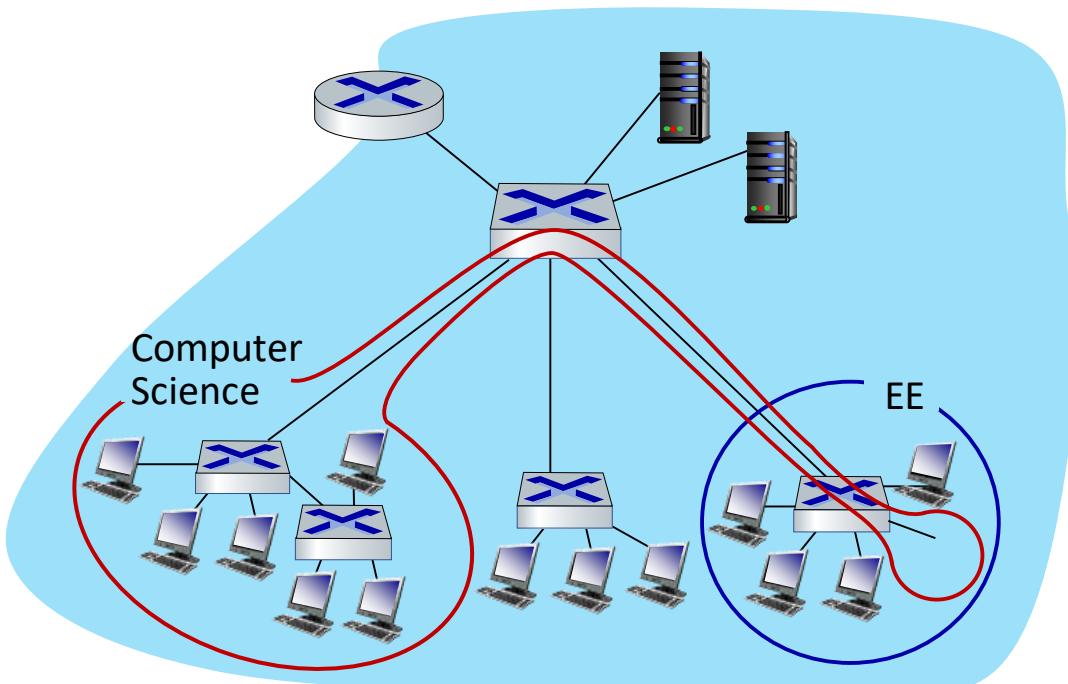


single broadcast domain:

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

# Virtual LANs (VLANs): motivation

*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, efficiency issues

administrative issues:

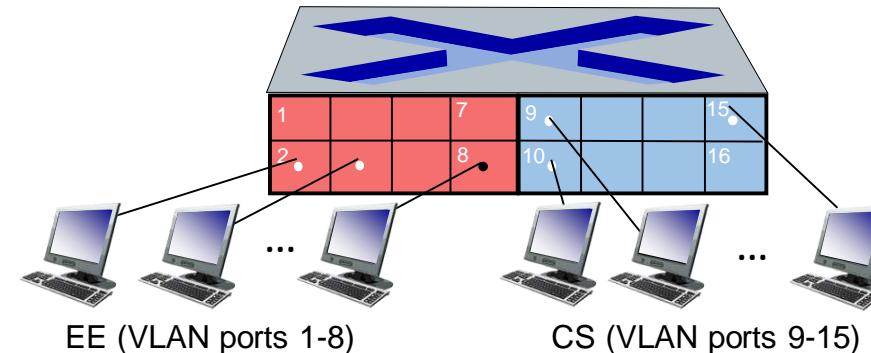
- CS user moves office to EE - *physically* attached to EE switch, but wants to remain *logically* attached to CS switch

# Port-based VLANs

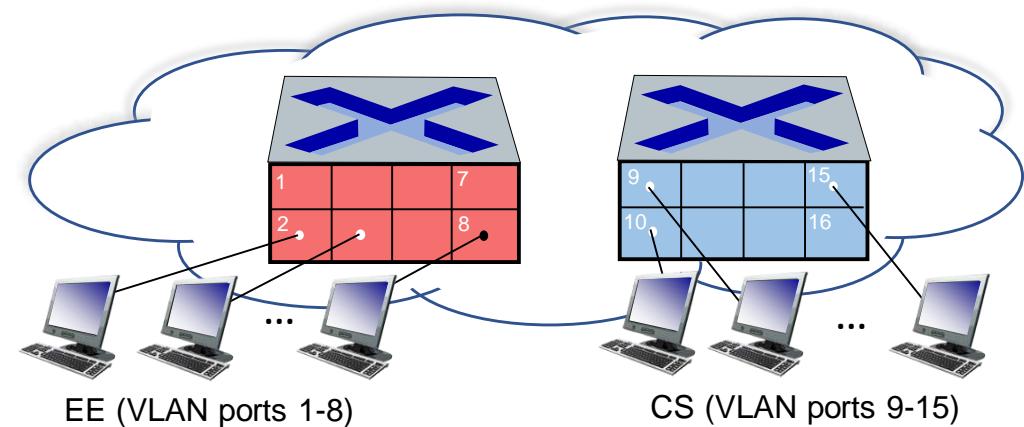
## Virtual Local Area Network (VLAN)

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 .....

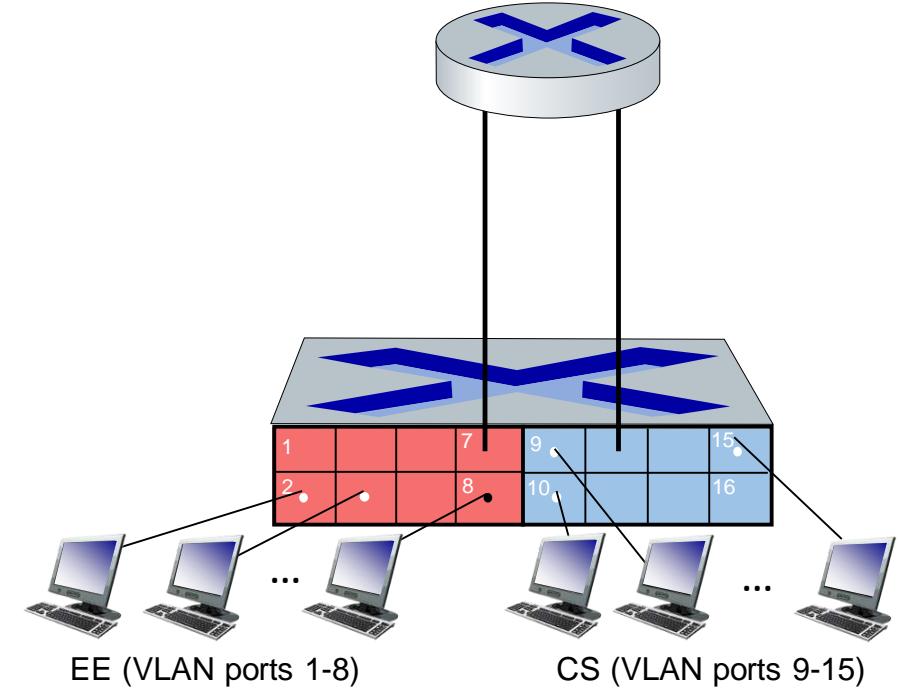


... operates as **multiple virtual switches**

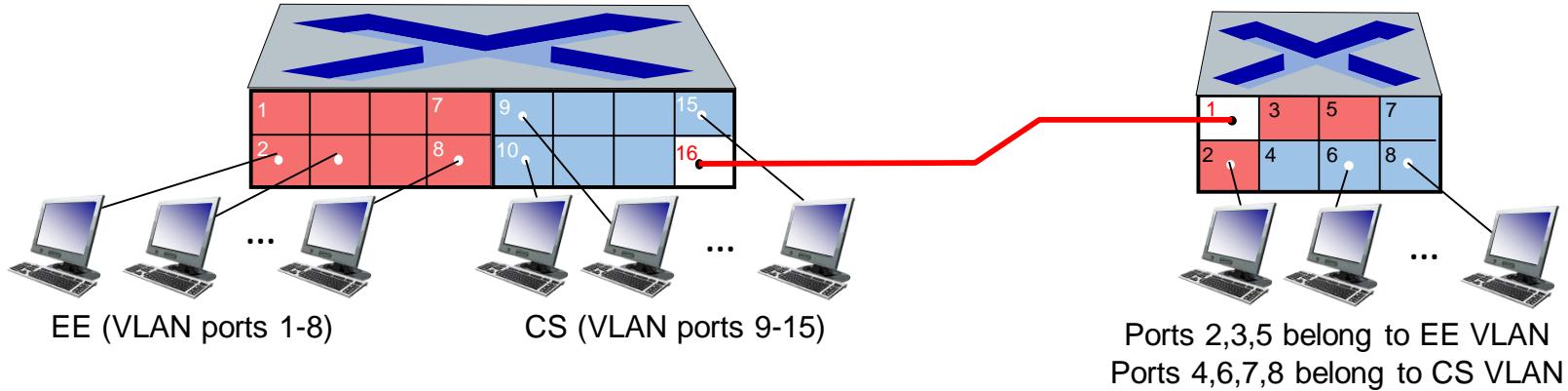


# Port-based VLANs

- **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



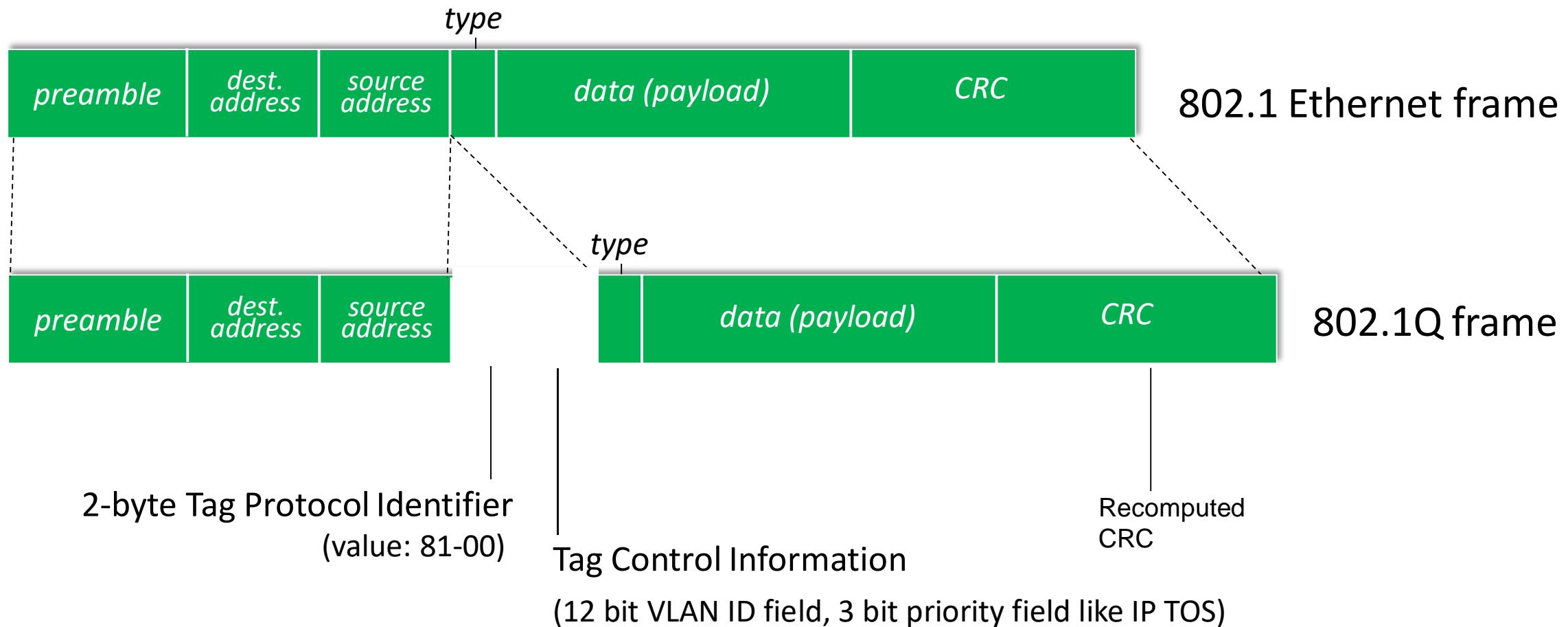
# VLANs spanning multiple switches



**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



# Link layer, LANs: roadmap

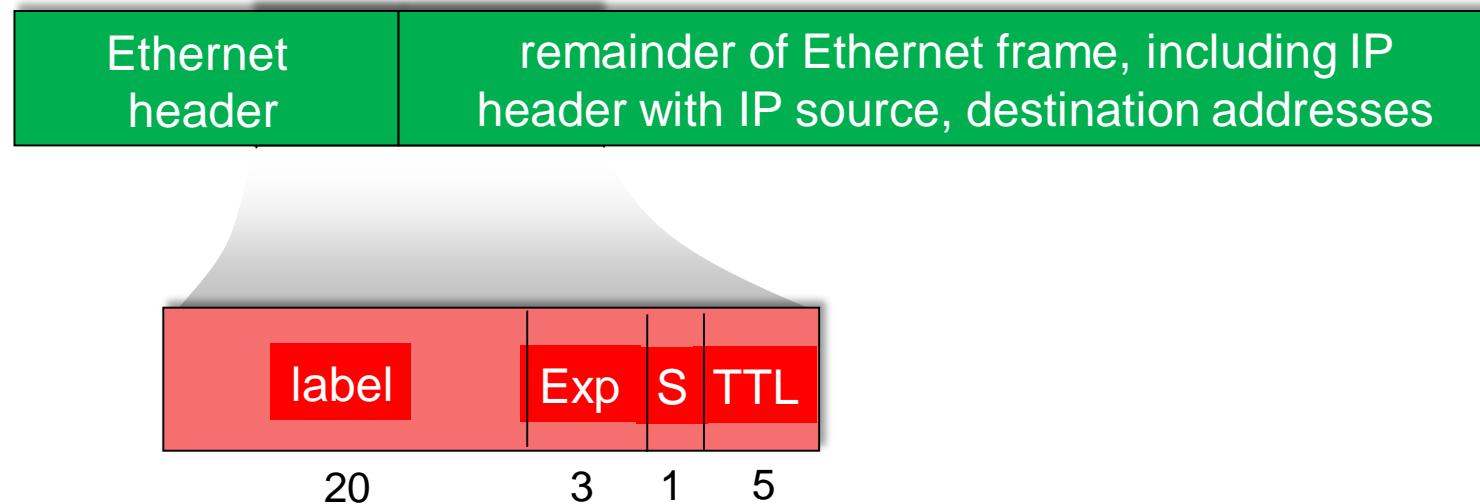
- introduction
- error detection, correction
- multiple access protocols
- LANs
  - addressing, ARP
  - Ethernet
  - switches
  - VLANs
- link virtualization: MPLS
- data center networking



- a day in the life of a web request

# Multiprotocol label switching (MPLS)

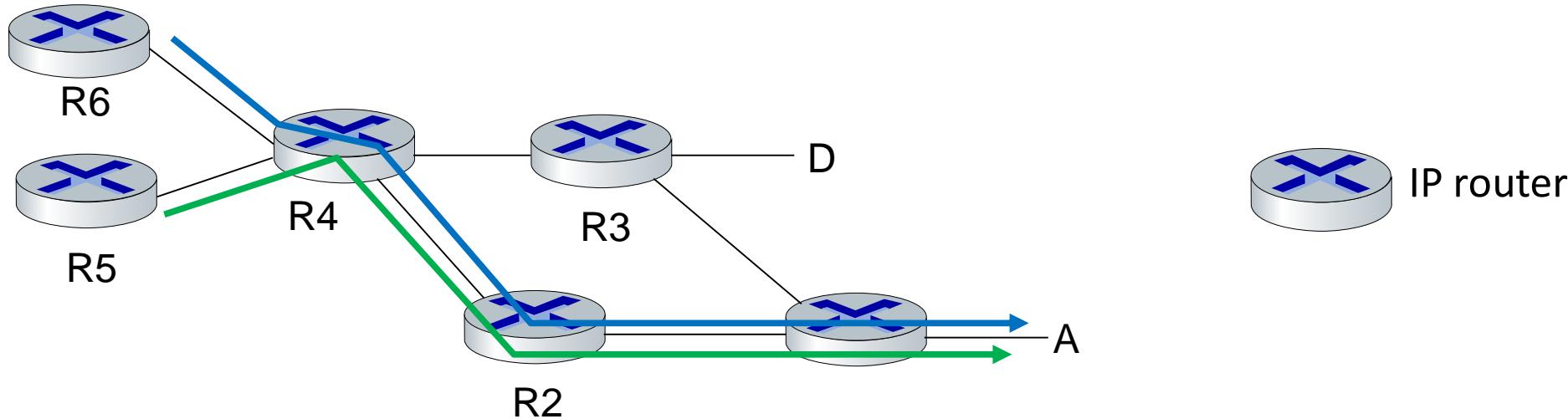
- goal: high-speed IP forwarding among network of MPLS-capable routers, using fixed length label (instead of shortest prefix matching)
  - faster lookup using fixed length identifier
  - borrowing ideas from Virtual Circuit (VC) approach
  - but IP datagram still keeps IP address!



# MPLS capable routers

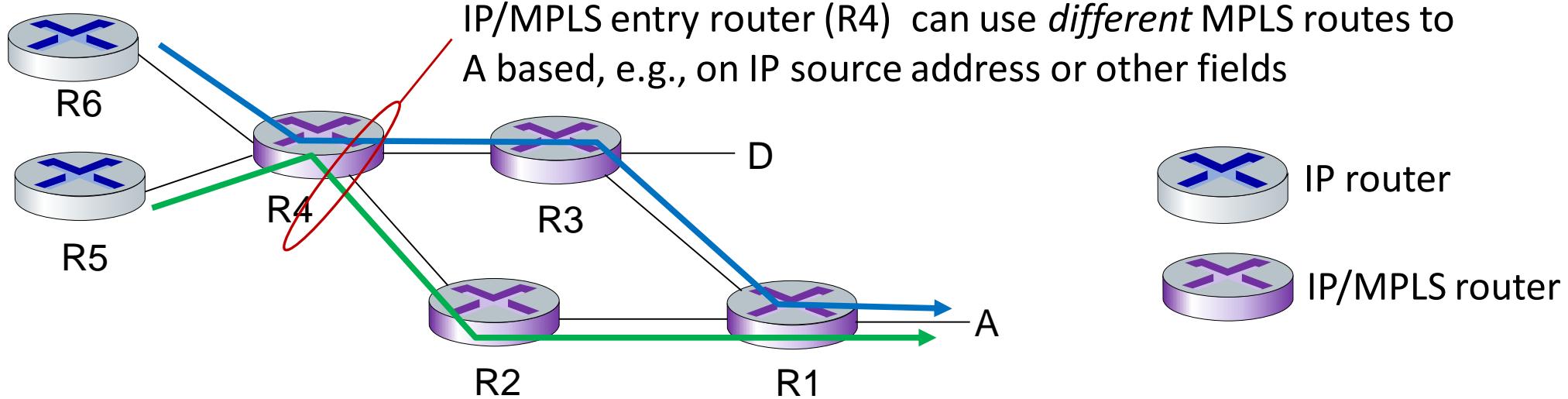
- a.k.a. label-switched router
- forward packets to outgoing interface based only on label value (*don't inspect IP address*)
  - MPLS forwarding table distinct from IP forwarding tables
- *flexibility*: MPLS forwarding decisions can *differ* from those of IP
  - use destination *and* source addresses to route flows to same destination differently (traffic engineering)
  - re-route flows quickly if link fails: pre-computed backup paths

# MPLS versus IP paths



- **IP routing:** path to destination determined by destination address alone

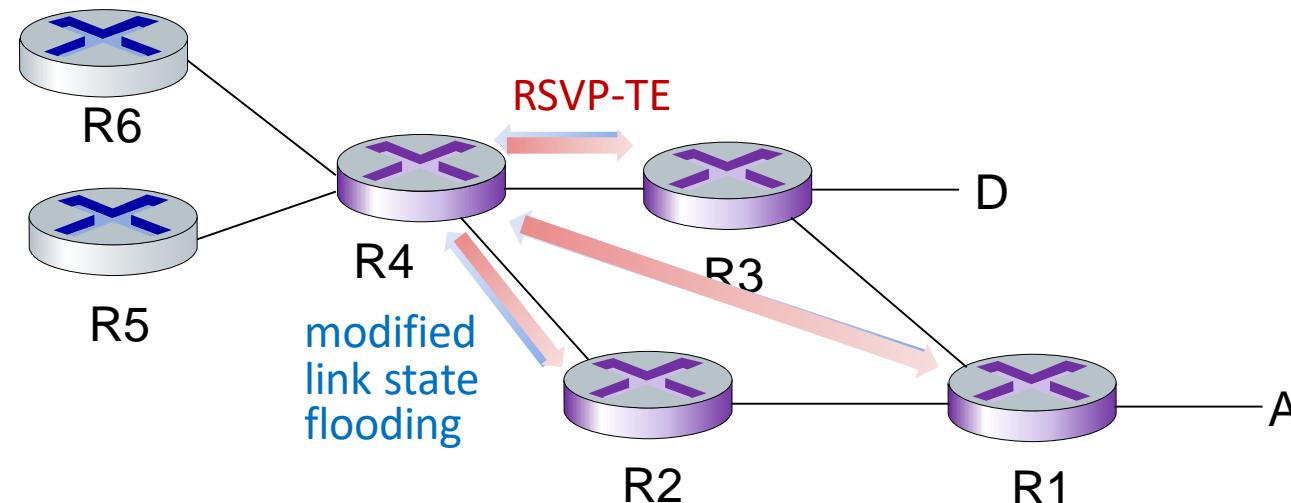
# MPLS versus IP paths



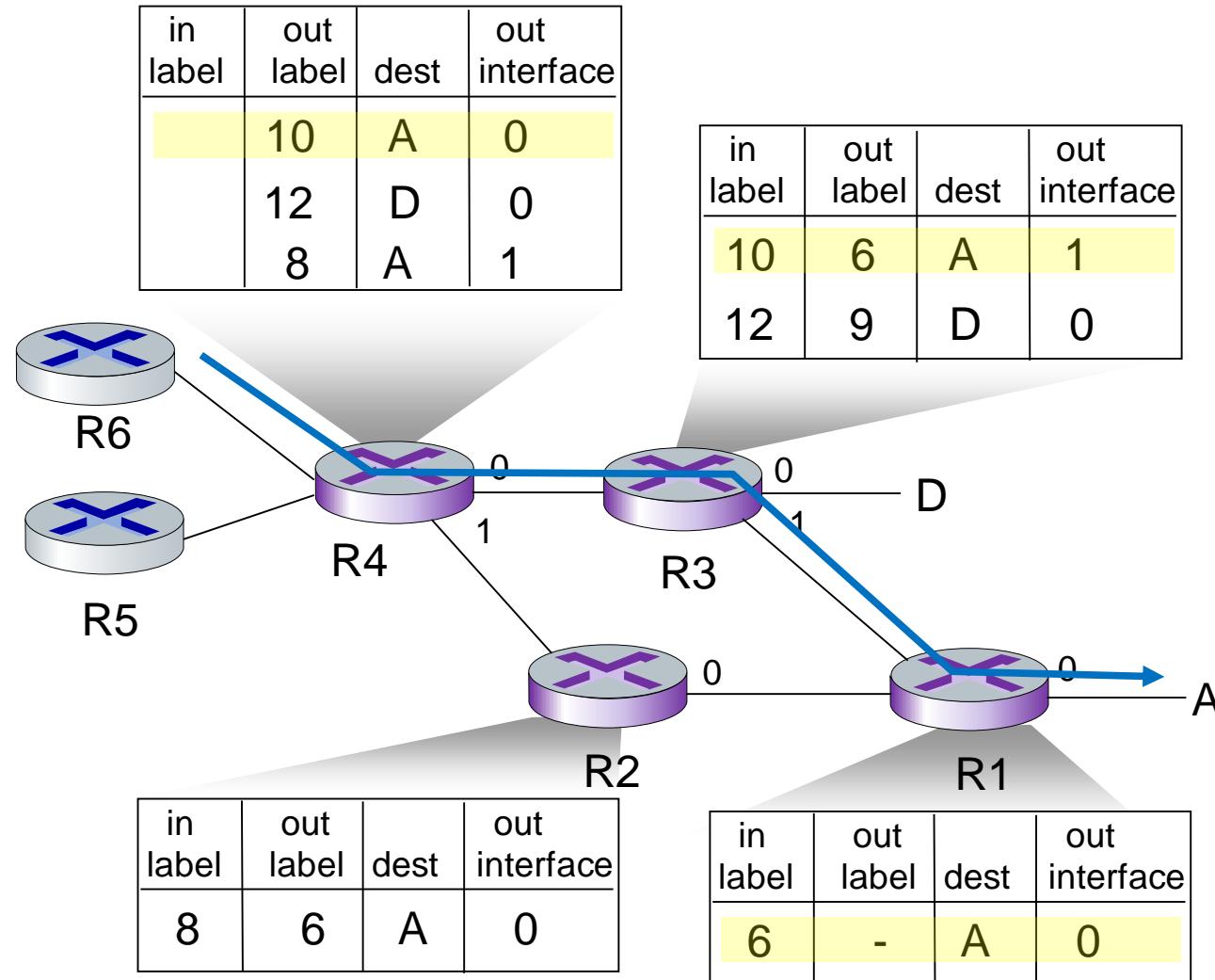
- **IP routing:** path to destination determined by destination address alone
- **MPLS routing:** path to destination can be based on source *and* destination address
  - flavor of generalized forwarding (MPLS 10 years earlier)
  - *fast reroute:* precompute backup routes in case of link failure

# MPLS signaling

- modify OSPF, IS-IS link-state flooding protocols to carry info used by MPLS routing:
  - e.g., link bandwidth, amount of “reserved” link bandwidth
- entry MPLS router uses RSVP-TE signaling protocol to set up MPLS forwarding at downstream routers



# MPLS forwarding tables



# Link layer, LANs: roadmap

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# Datacenter networks

10's to 100's of thousands of hosts, often closely coupled, in close proximity:

- e-business (e.g. Amazon)
- content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
- search engines, data mining (e.g., Google)

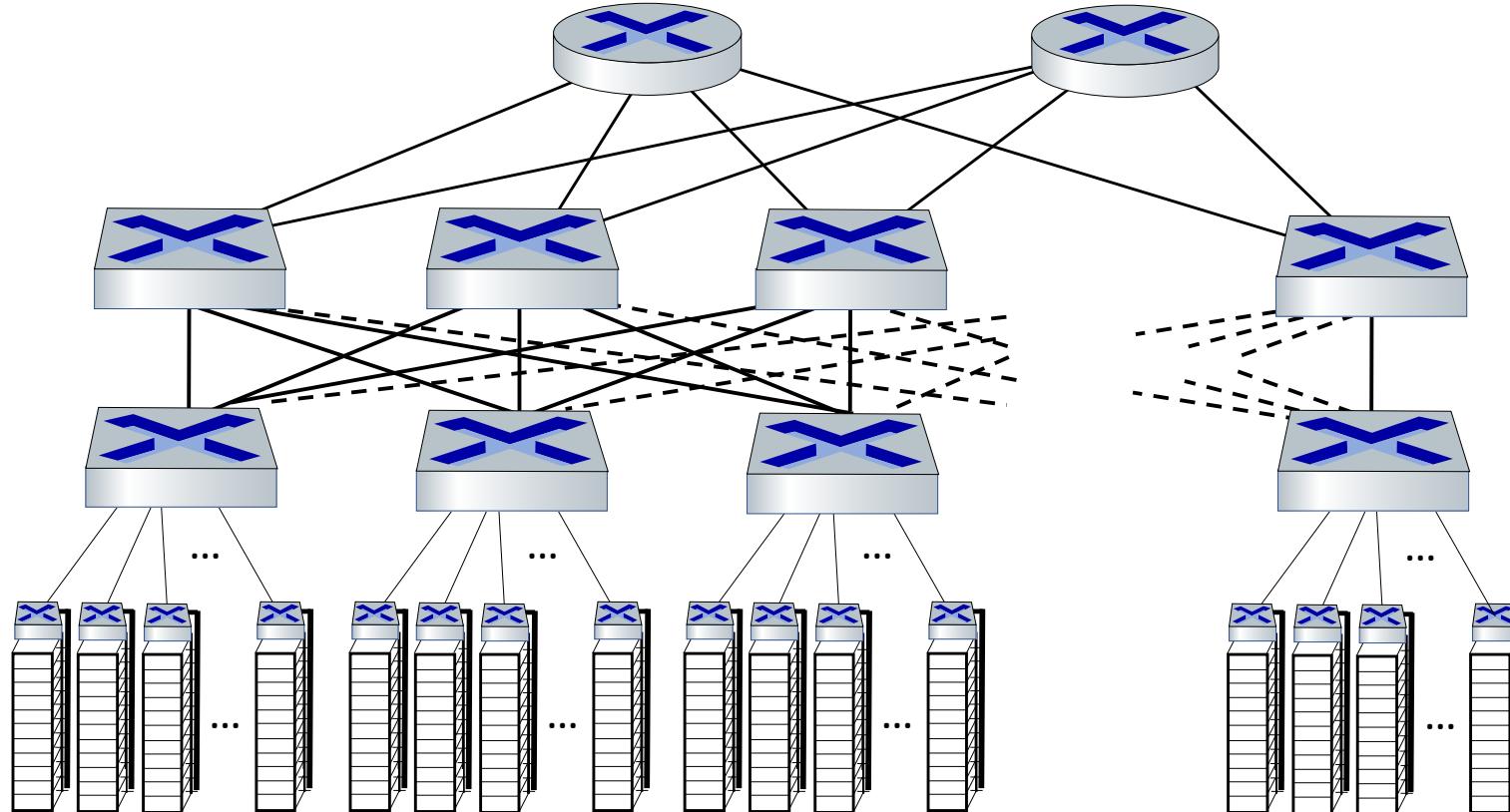
challenges:

- multiple applications, each serving massive numbers of clients
- reliability
- managing/balancing load, avoiding processing, networking, data bottlenecks



Inside a 40-ft Microsoft container, Chicago data center

# Datacenter networks: network elements



## Border routers

- connections outside datacenter

## Tier-1 switches

- connecting to ~16 T-2s below

## Tier-2 switches

- connecting to ~16 TORs below

## Top of Rack (TOR) switch

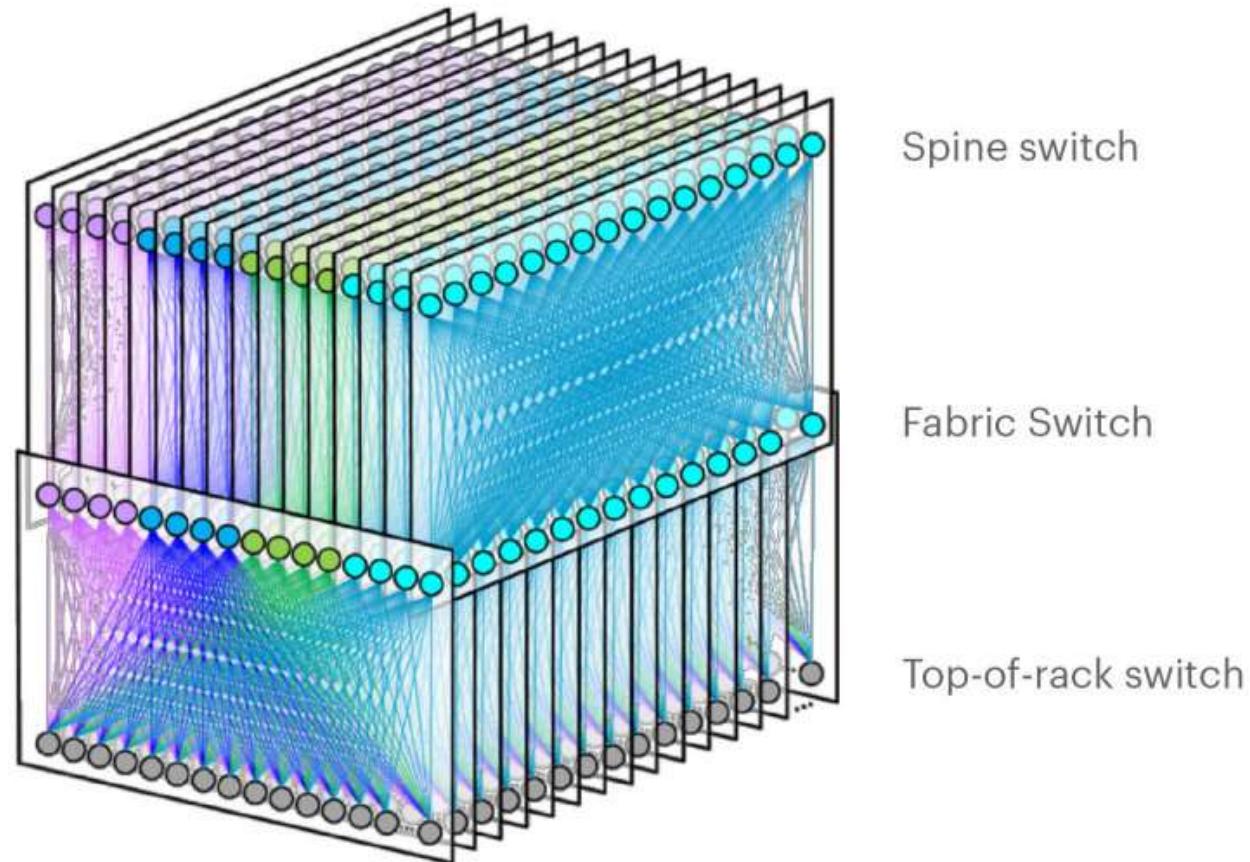
- one per rack
- 40-100Gbps Ethernet to blades

## Server racks

- 20- 40 server blades: hosts

# Datacenter networks: network elements

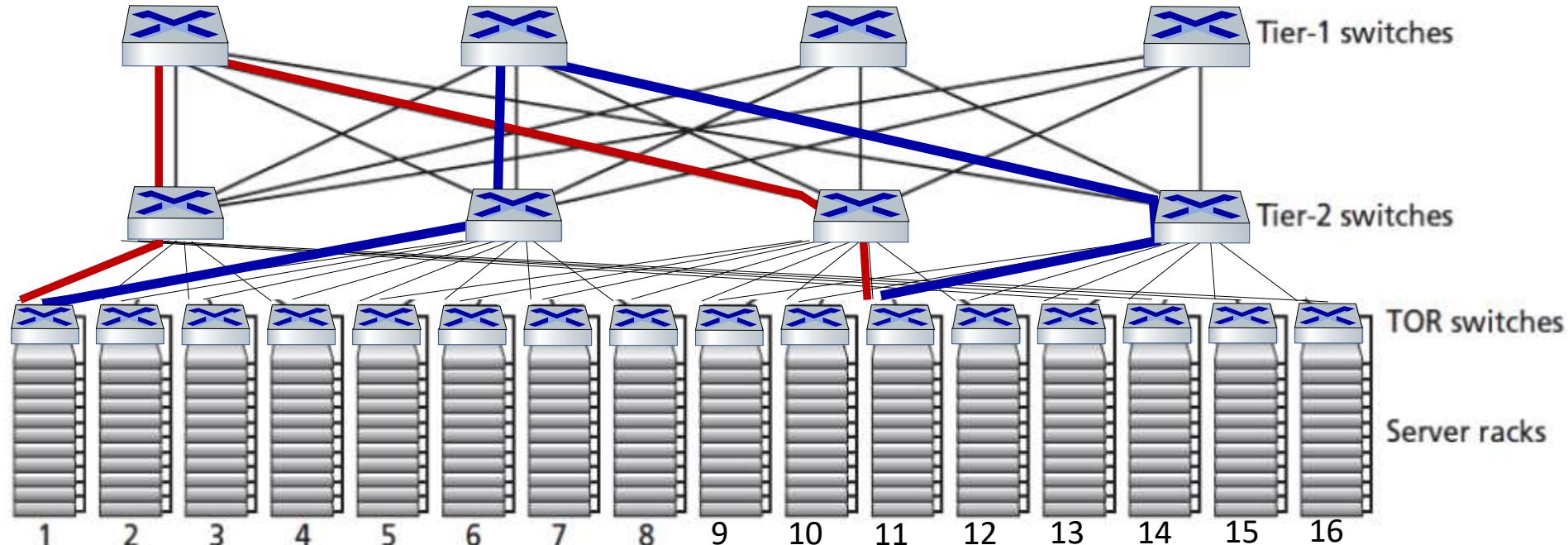
Facebook F16 data center network topology:



<https://engineering.fb.com/data-center-engineering/f16-minipack/> (posted 3/2019)

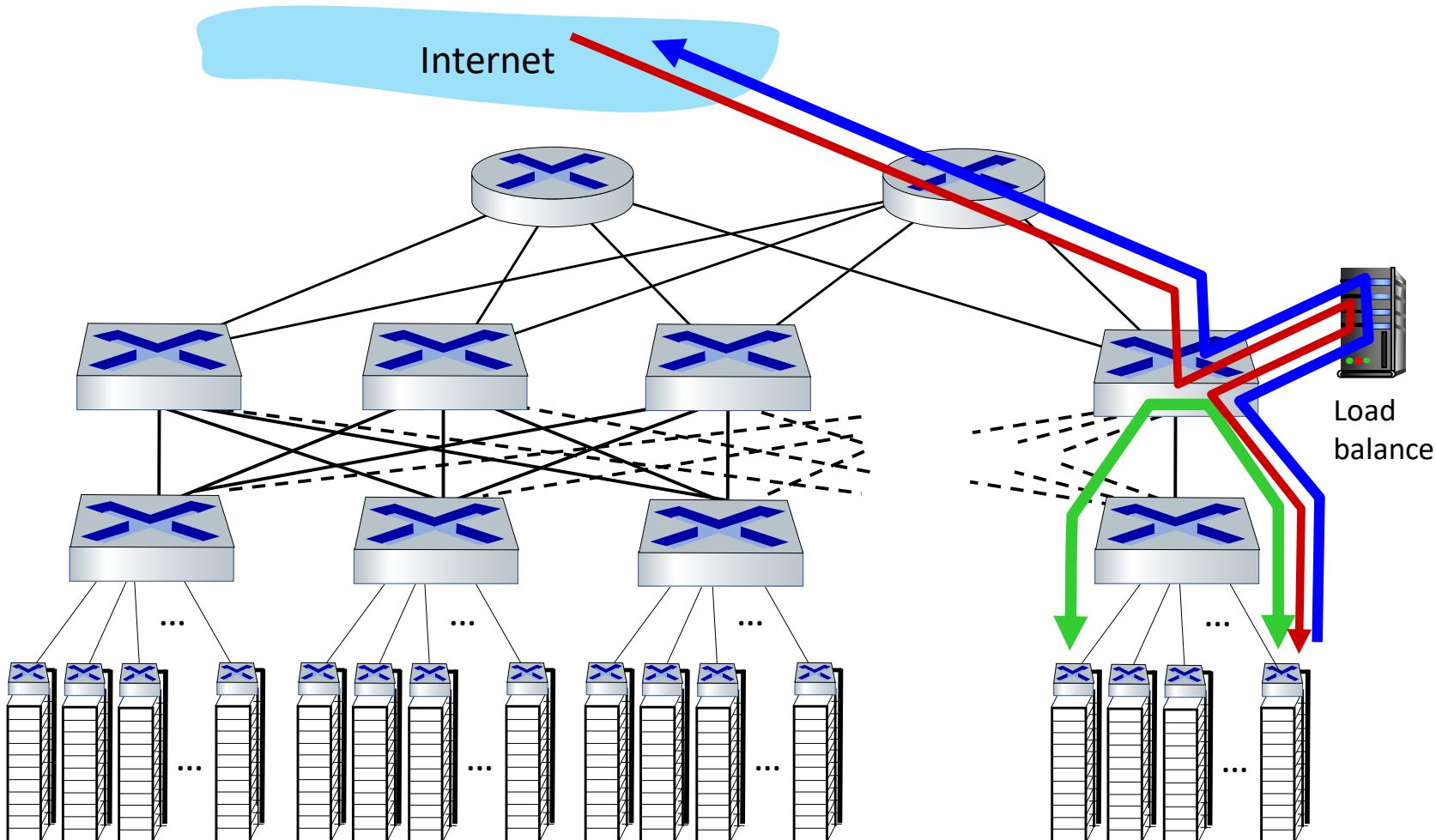
# Datacenter networks: multipath

- rich interconnection among switches, racks:
  - increased throughput between racks (multiple routing paths possible)
  - increased reliability via redundancy



two **disjoint** paths highlighted between racks 1 and 11

# Datacenter networks: application-layer routing



load balancer:  
application-layer  
routing

- receives external client requests
- directs workload within data center
- returns results to external client (hiding data center internals from client)

# Datacenter networks: protocol innovations

- link layer:
  - RoCE: remote DMA (RDMA) over Converged Ethernet
- transport layer:
  - ECN (explicit congestion notification) used in transport-layer congestion control (DCTCP, DCQCN)
  - experimentation with hop-by-hop (backpressure) congestion control
- routing, management:
  - SDN widely used within/among organizations' datacenters
  - place related services, data as close as possible (e.g., in same rack or nearby rack) to minimize tier-2, tier-1 communication

# Link layer, LANs: roadmap

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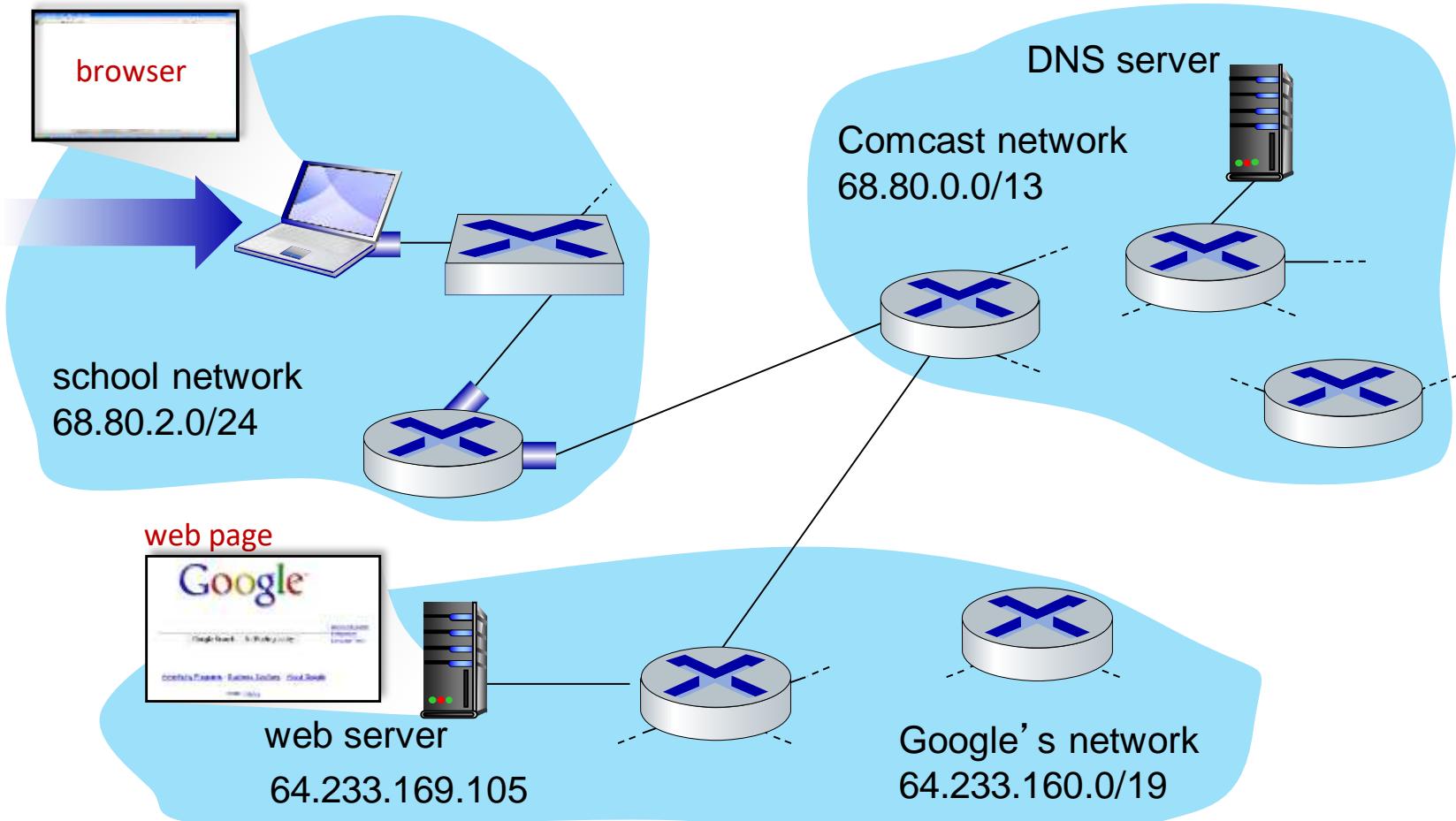


- a day in the life of a web request

# 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](http://www.google.com)

# A day in the life: scenario

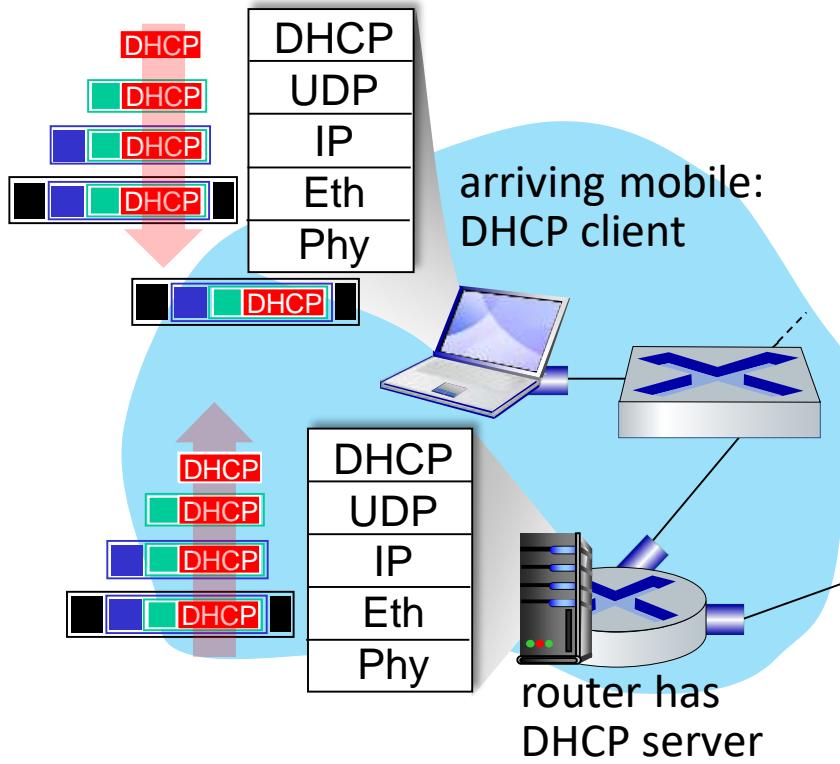


scenario:

- arriving mobile client attaches to network ...
- requests web page:  
[www.google.com](http://www.google.com)

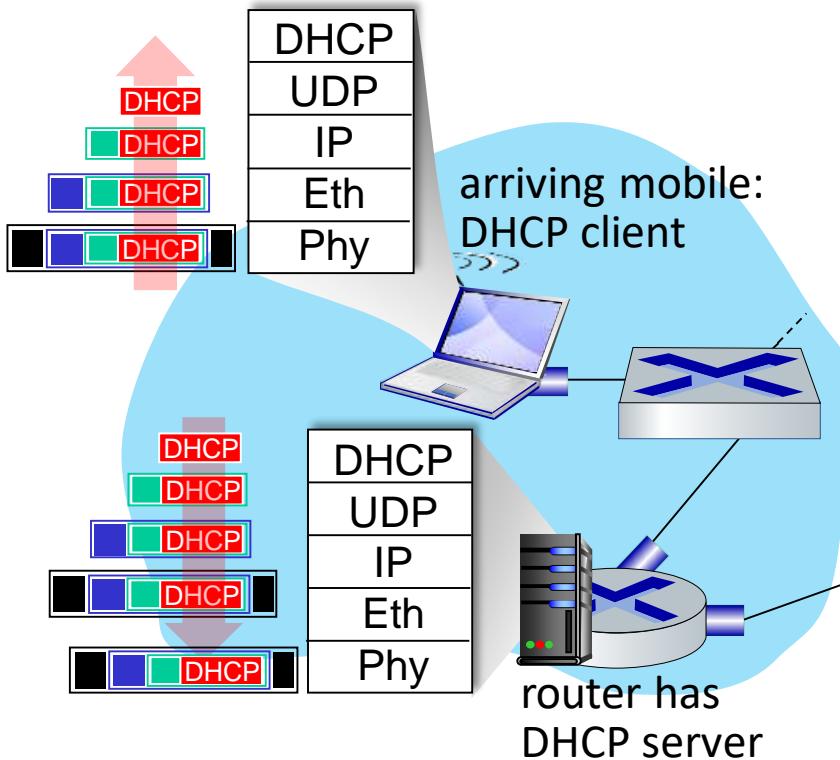
*Sounds simple!* !

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

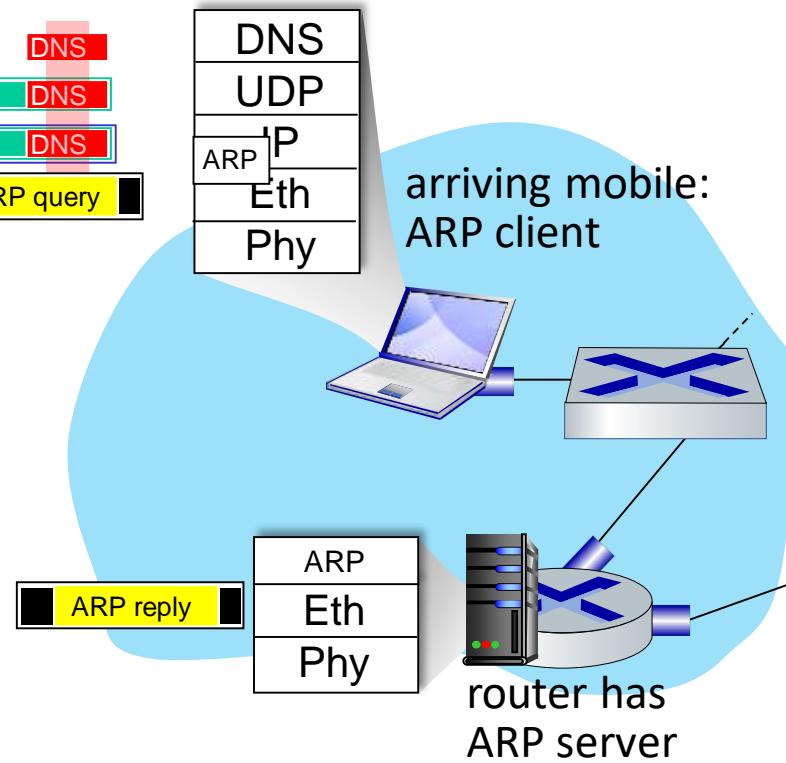
# A day in the life: connecting to the Internet



- 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

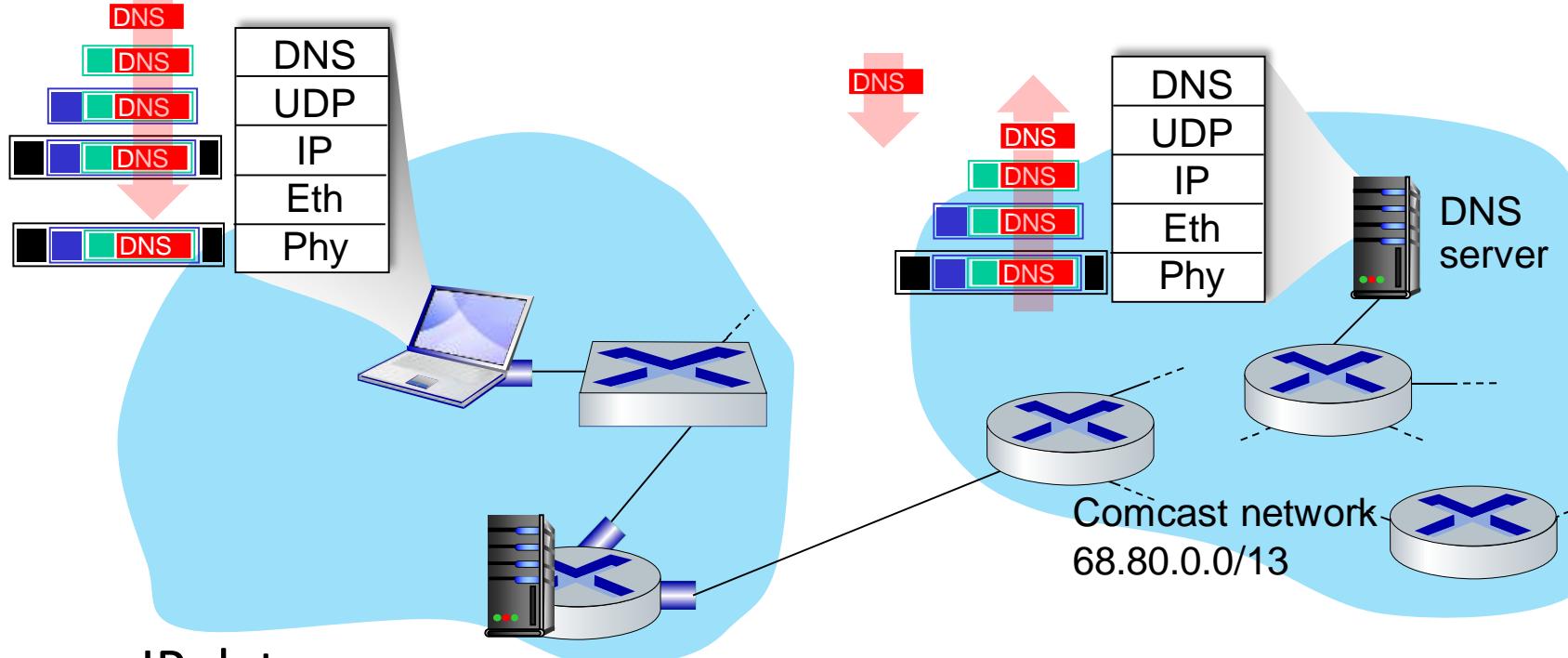
*Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router*

# 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

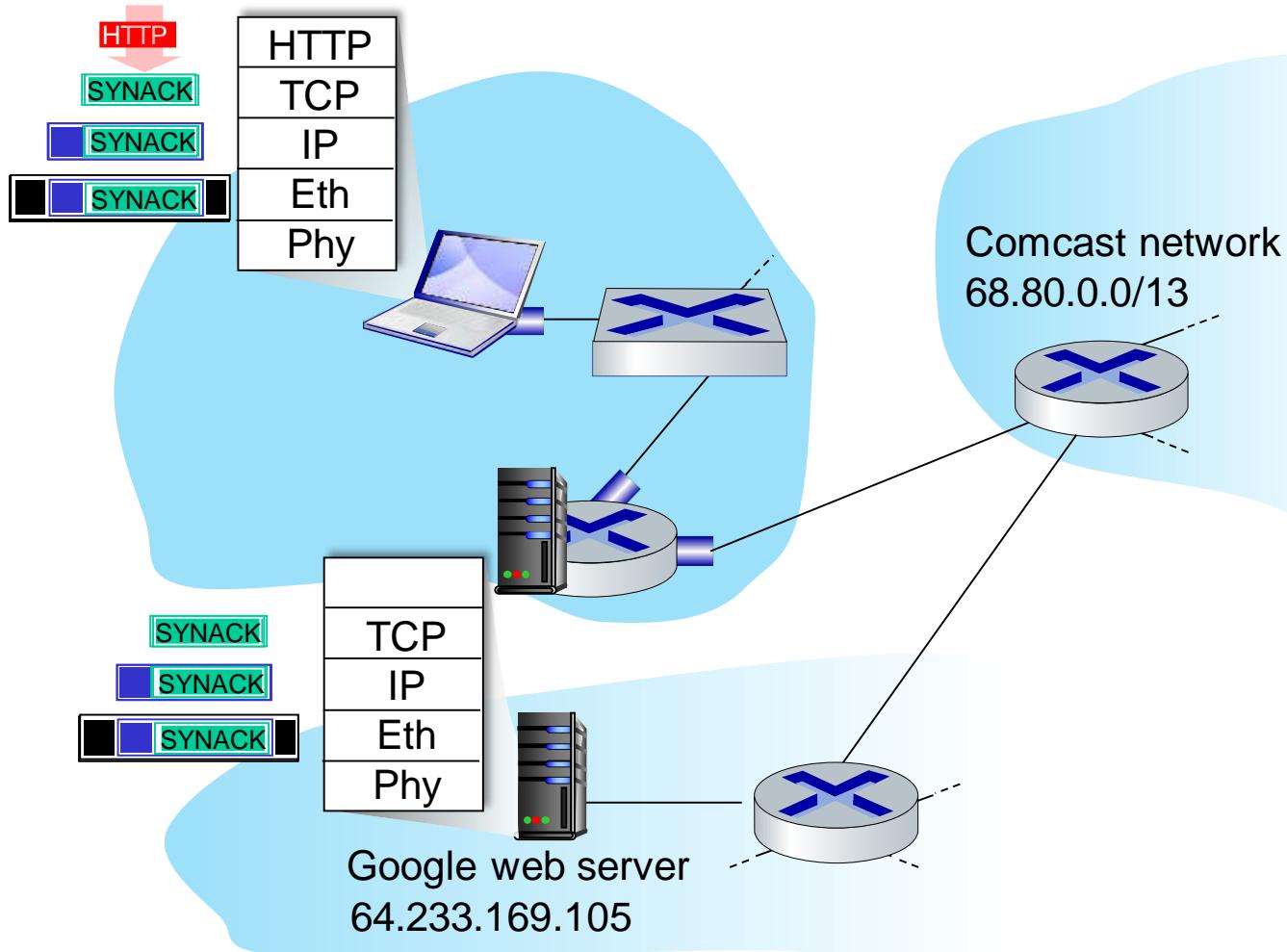
# A day in the life... using DNS



- IP datagram containing DNS query forwarded via LAN switch from client to 1<sup>st</sup> 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

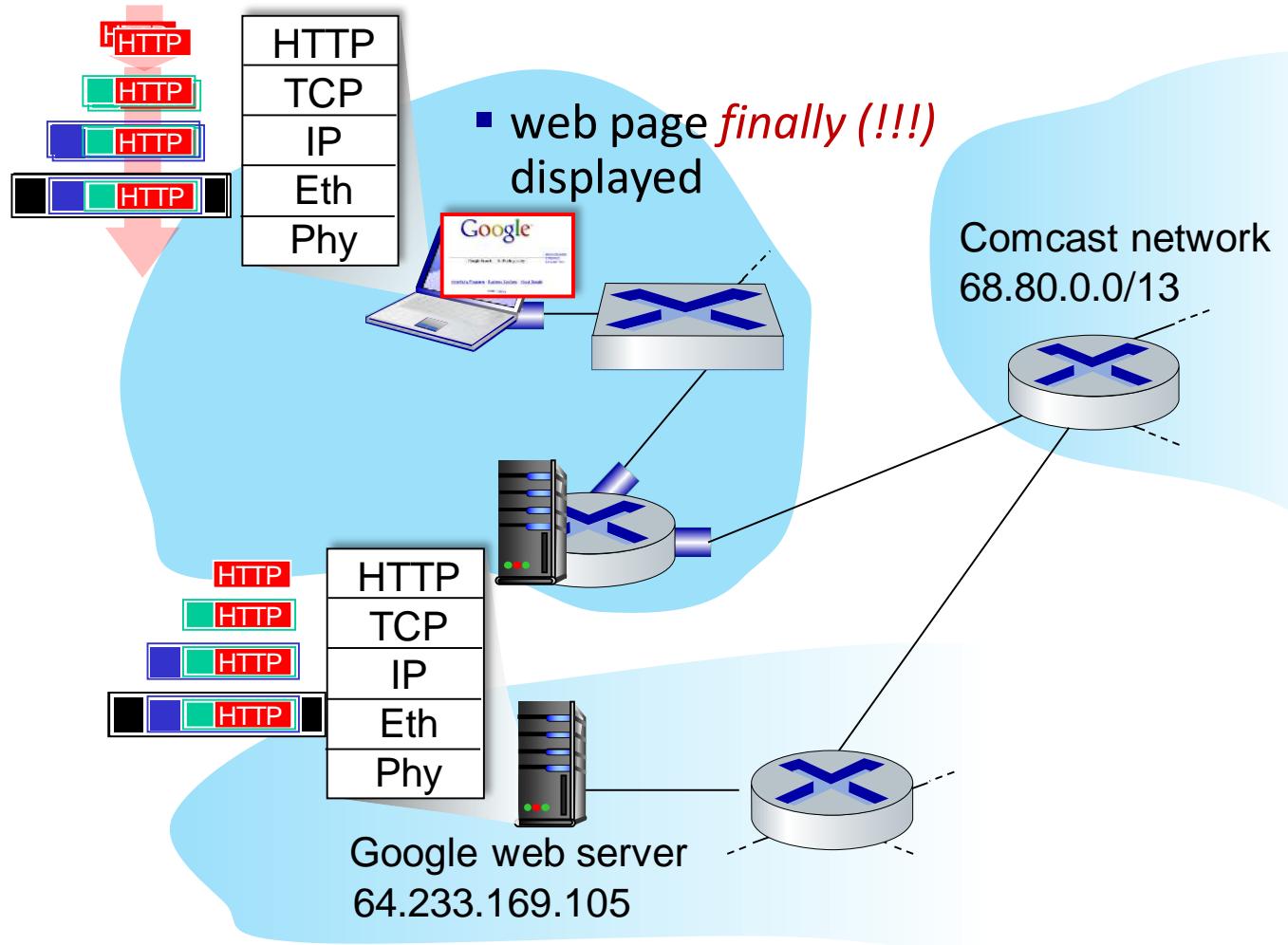
- demuxed to DNS
- DNS replies to client with IP address of [www.google.com](http://www.google.com)

# 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](http://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
  - virtualized networks as a link layer: MPLS
- synthesis: a day in the life of a web request

# Chapter 6: let's take a breath

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