COMP 3331/9331: Computer Networks and Applications

Week 9
Data Link Layer

Reading Guide: Chapter 6, Sections 6.1 – 6.4, 6.7

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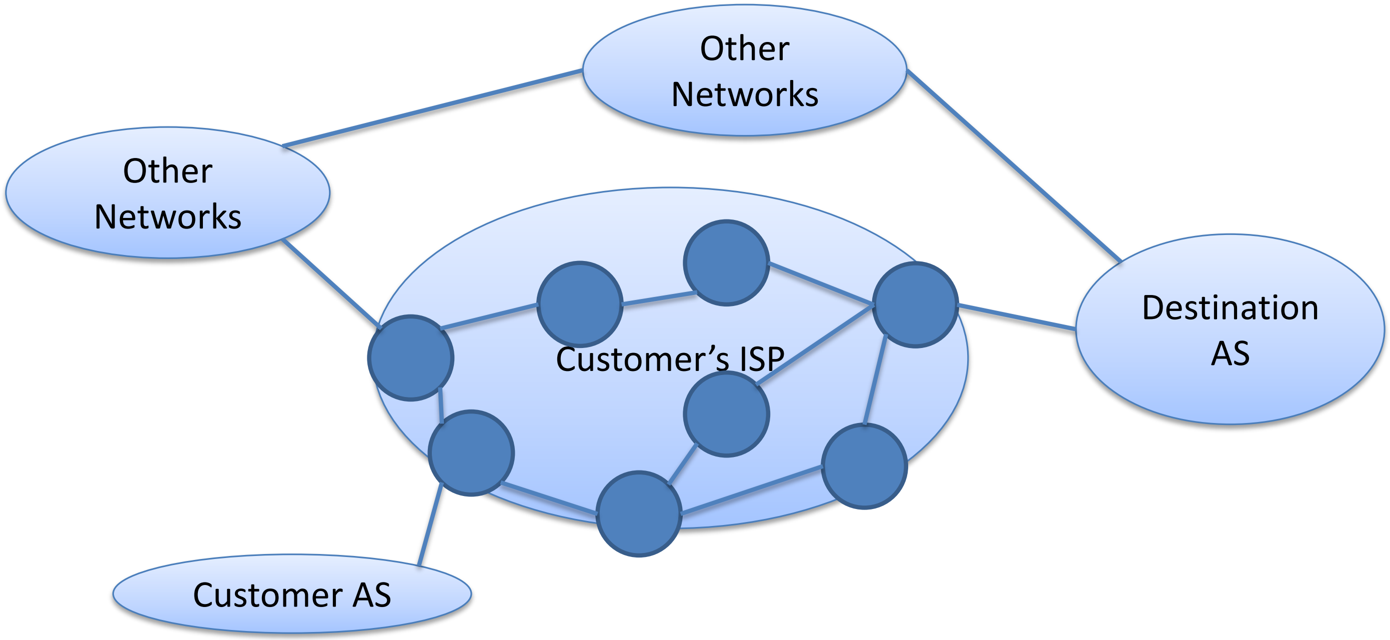
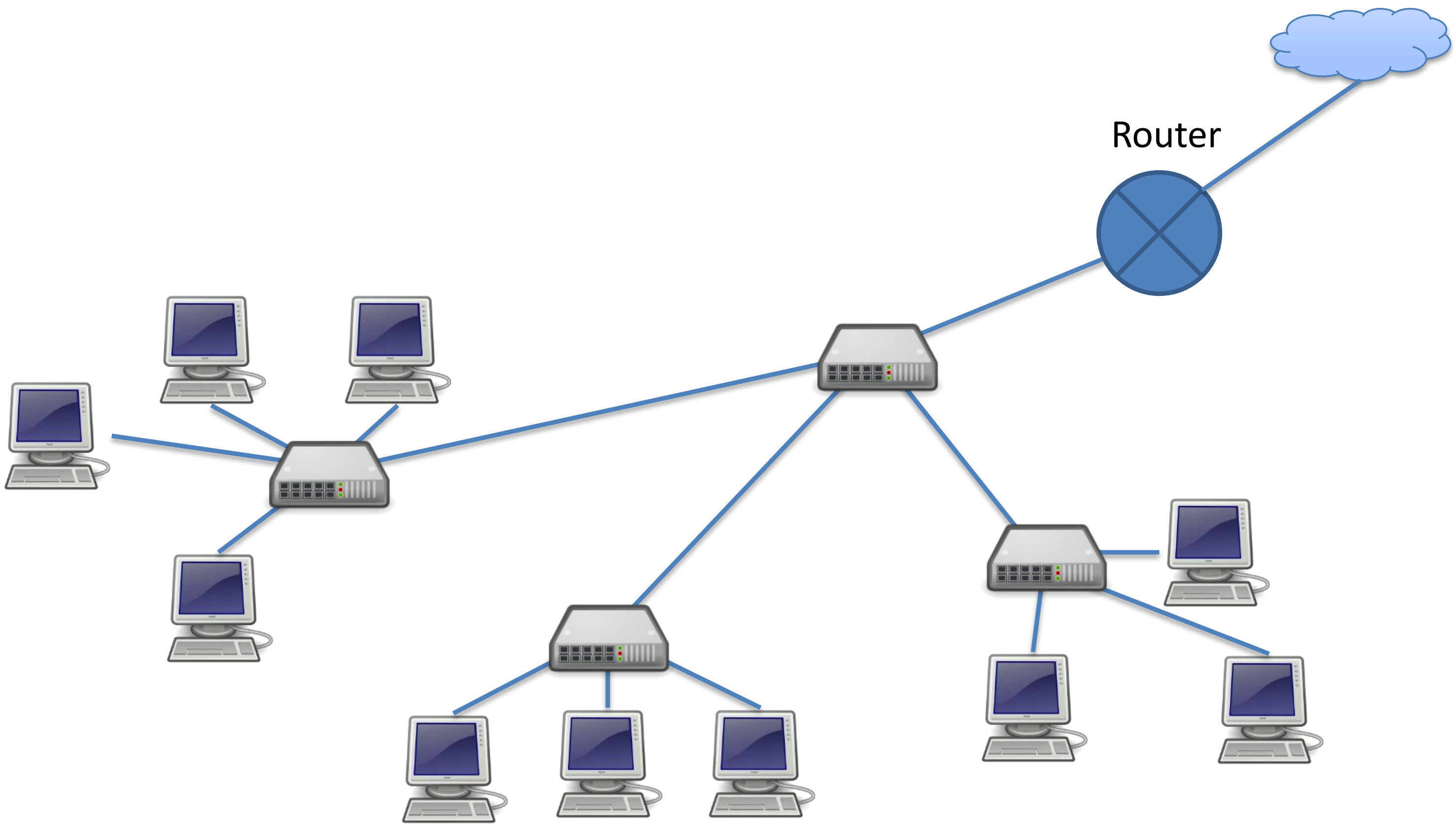
From Macro- to Micro-

- Previously, we looked at Internet scale…



Link layer focus: Within a Subnet



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

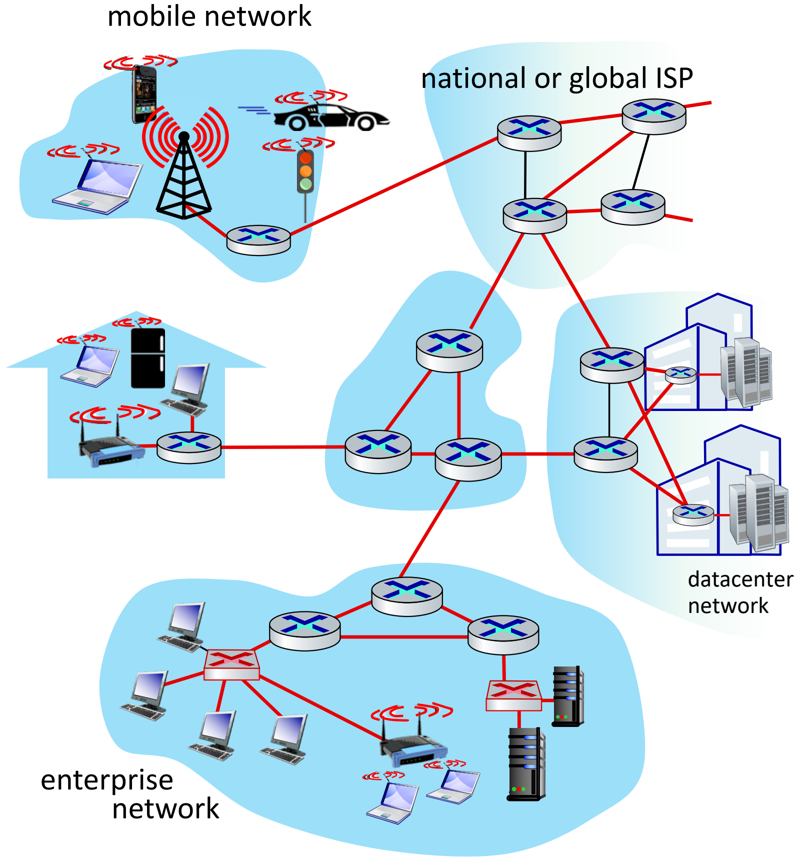
Link layer, LANs: roadmap

- *introduction*
- *error detection, correction*
- *multiple access protocols*
- *LANs*
  - *addressing, ARP*
  - *Ethernet*
  - *switches*
  - *VLANs (NOT COVERED)*
- *link virtualization: MPLS (NOT COVERED)*
- *data center networking (NOT COVERED)*
- *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

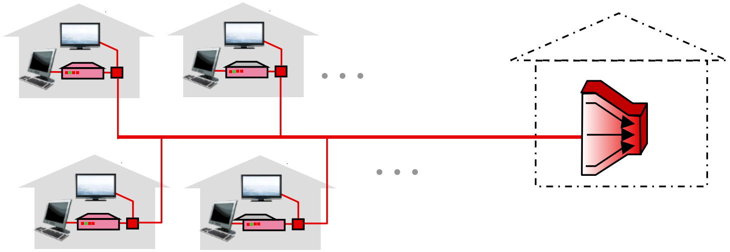
- *datagram transferred by different link protocols over different links:*
  - *e.g., WiFi on first link, Ethernet on next link*
- *each link protocol provides different services*
  - *e.g., may or may not provide reliable data transfer over link*

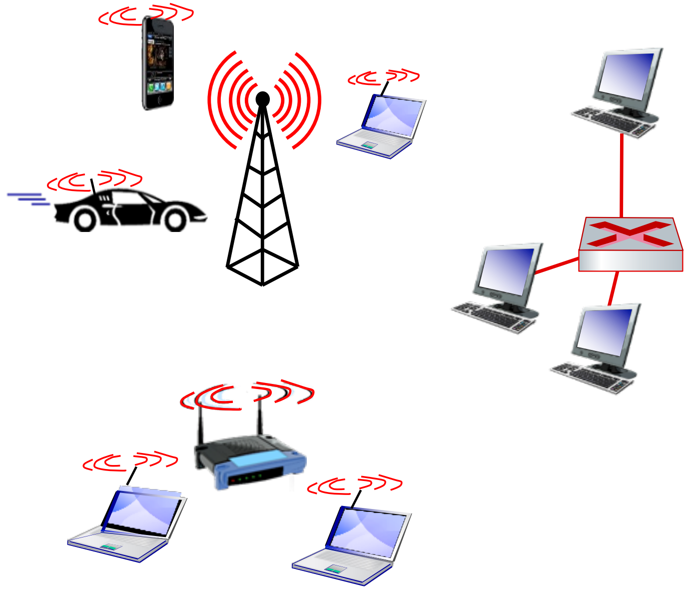
transportation analogy:

- *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

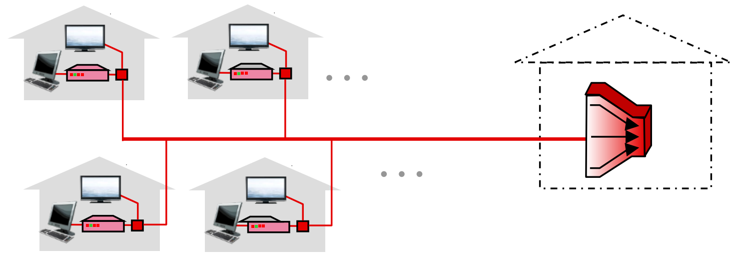
- *framing, link access:*
  - *encapsulate datagram into frame, adding header, trailer*
  - *channel access if shared medium*
  - *"MAC" addresses in frame headers identify source, destination (different from IP address!)*
- *reliable delivery between adjacent nodes*
  - *we already know how to do this!*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





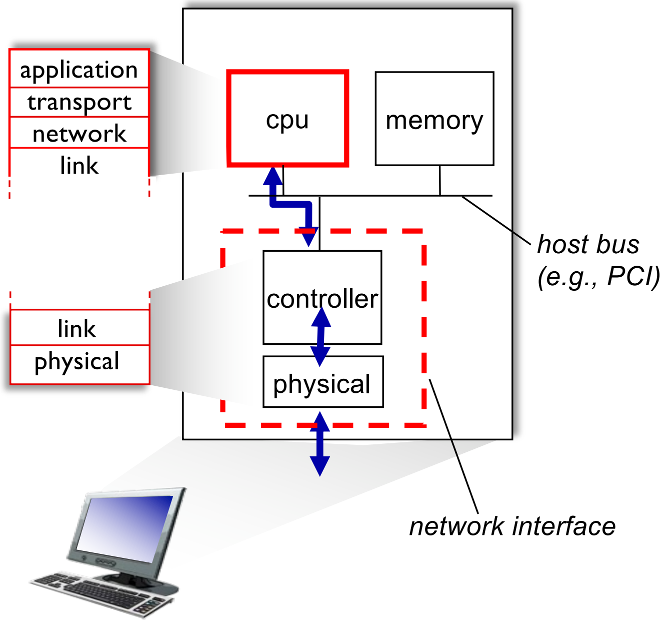
Link layer: services (more)

- *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*

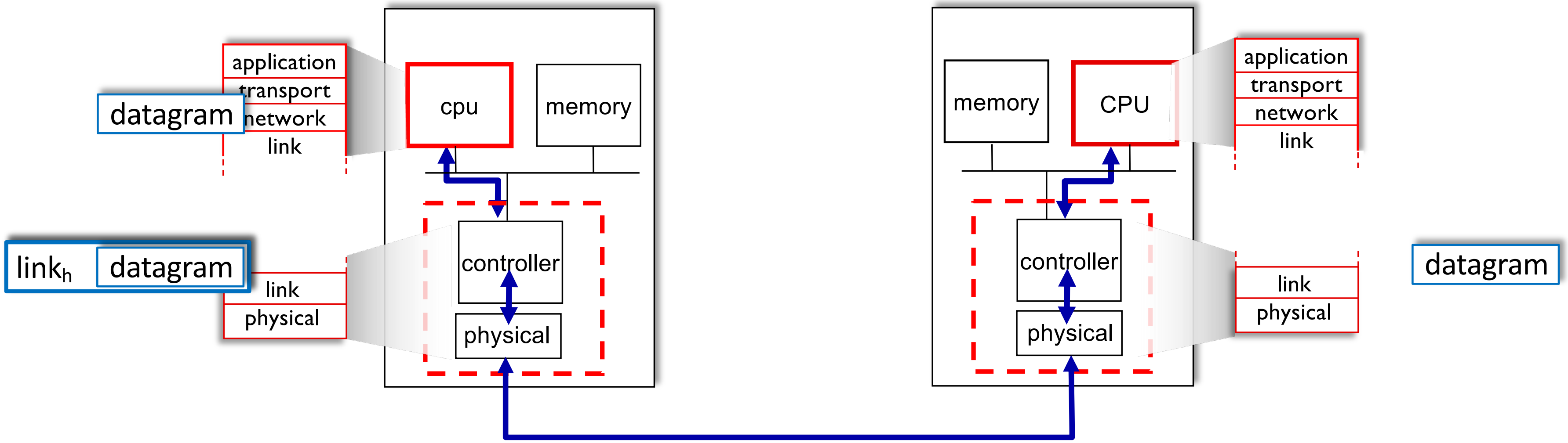


Where is the link layer implemented?

- *in each-and-every host*
- *link layer implemented in network interface card (NIC) or on a chip*
  - *Ethernet, WiFi card or chip*
  - *Often referred as network adapter*
  - *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:

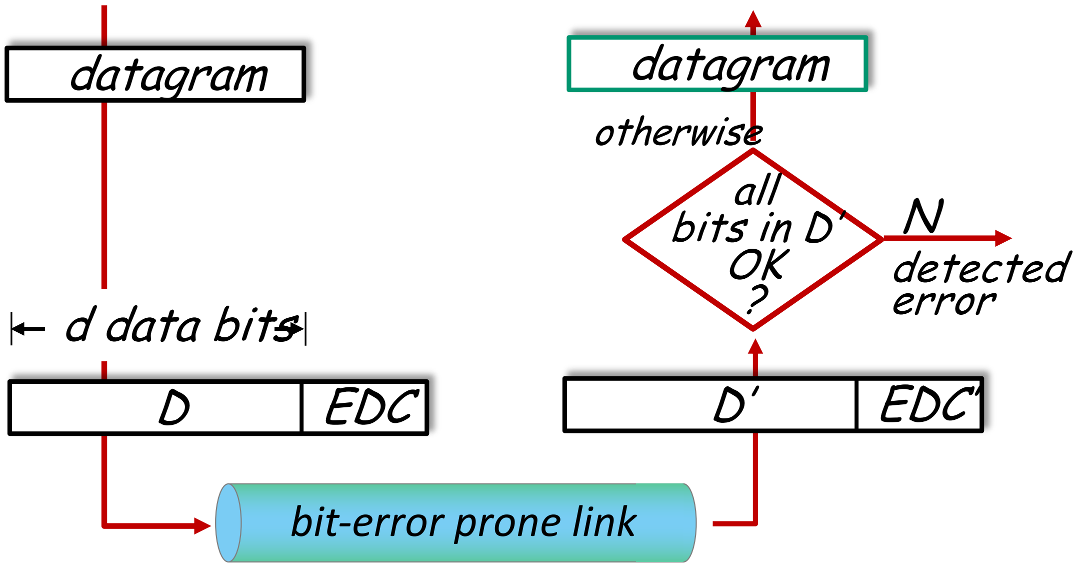
- *looks for errors, reliable data transfer, flow control, etc.*
- *extracts datagram, passes to upper layer at receiving side*

Link layer, LANs: roadmap

- *introduction*
- ***error detection, correction***
- *multiple access protocols*
- *LANs*
  - *addressing, ARP*
  - *Ethernet*
  - *switches*
  - *VLANs (NOT COVERED)*
- *link virtualization: MPLS (NOT COVERED)*
- *data center networking (NOT COVERED)*
- *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



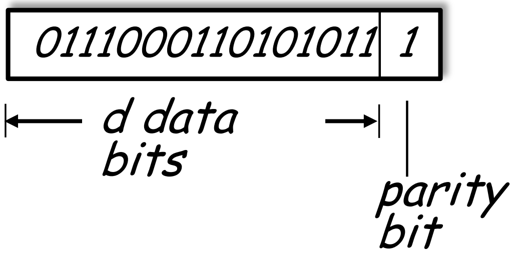
Error detection not 100% reliable!

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

Parity checking

single bit parity:

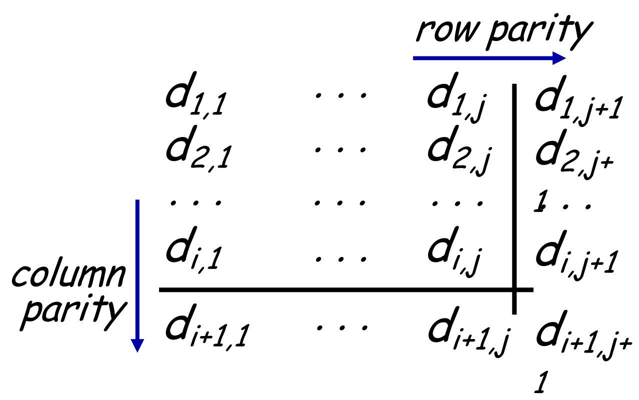
- detect single bit errors

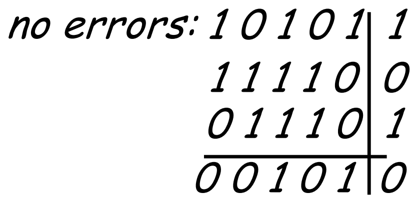


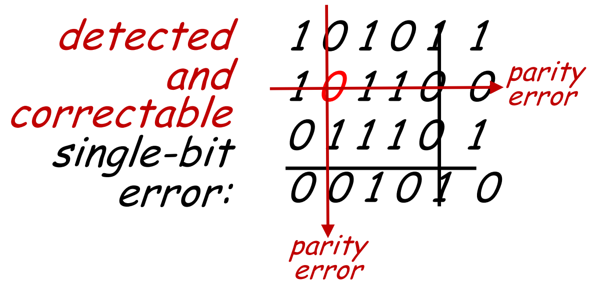
Even parity: set parity bit so there is an even number of 1's

two-dimensional bit parity:

- detect *and correct* single bit errors







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 ….

In practice

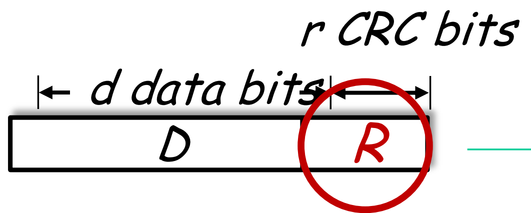
- Bit errors occur in bursts.

- We’re willing to trade computational complexity for space efficiency.
  - Make the detection routine more complex, to detect error bursts, without tons of extra data

- Insight: We need hardware to interface with the network, do the computation there!

Cyclic Redundancy Check (CRC)

- *more powerful error-detection coding*
- *D: data bits (given, think of these as a binary number)*
- *G: bit pattern (generator), of r+1 bits (given)*



bit pattern

$\langle D,R\rangle = D \cdot 2^r \text{ XOR } R$ *formula for bit pattern*

goal: choose r CRC bits, R, such that <D,R> exactly divisible by G (mod 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)*
  - *For example, CRC-32 which uses the following generator* $G_{\text{CRC-32}} = 100000100110000010001110110110111$

A Note on Modulo-2 Arithmetic

- All calculations are modulo-2 arithmetic
- No carries or borrows in subtraction
- Addition and subtraction are identical and both are equivalent to XOR
  - 1011 XOR 0101 = 1110
  - 1011 - 0101 = 1110
  - 1011 + 0101 = 1110
- Multiplication by 2^k is essentially a left shift by *k* bits
  - 1011 x 2^2 = 101100

XOR

A	B	Output
0	0	0
1	0	1
0	1	1
1	1	0

CRC example

want:

$D \cdot 2^r$ XOR R = nG

equivalently:

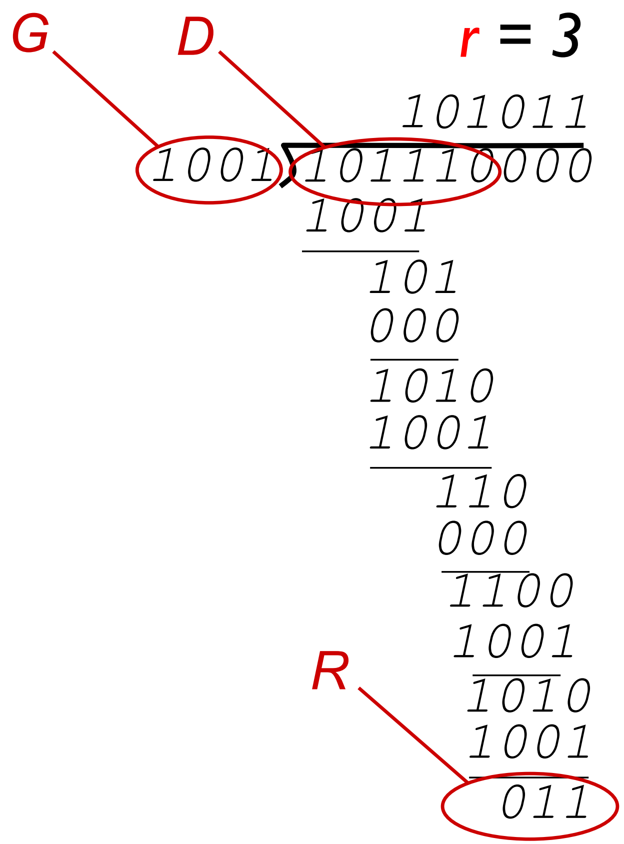
$D \cdot 2^r$ = nG XOR R

equivalently:

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

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

At the sender



Sender sends <D, R> into the channel

CRC example (contd)

At the receiver

Receiver divides the received frame and divides by G and checks if the remainder is zero.

In this example, there are no errors, so the receiver receives <D, R> (from previous slide)

G　　D　　r = 3　　R

```
            101011
     1001 ) 101110011
            1001
             101
             000
             1010
             1001
               110
               000
               1101
               1001
                1001
                1001
                 000
```

Remainder is zero, so no errors

Quiz: Error Detection/Correction

- Can these schemes respectively correct any bit errors: Internet checksums, two-dimensional parity, cyclic redundancy check (CRC)

a) Yes, No, No
b) No, Yes, Yes
c) No, Yes, No
d) No, No, Yes
e) No, No, No

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Answer: C

Link layer, LANs: roadmap

- *introduction*
- *error detection, correction*
- ***multiple access protocols***
- *LANs*
  - *addressing, ARP*
  - *Ethernet*
  - *switches*
  - *VLANs*
- *link virtualization: MPLS (NOT COVERED)*
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Multiple access links, protocols

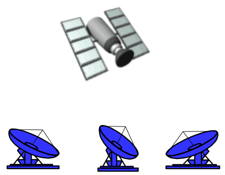
two types of "links":

- *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)

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: multiple access channel (MAC) of rate R bps

desired properties:

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

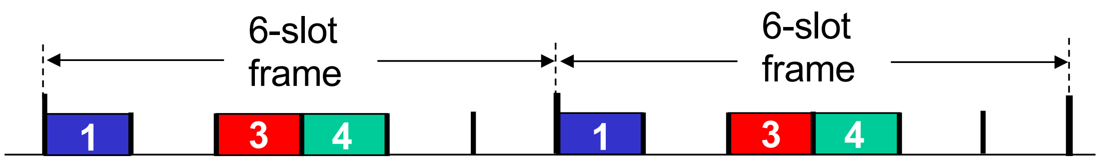
three broad classes:

- *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

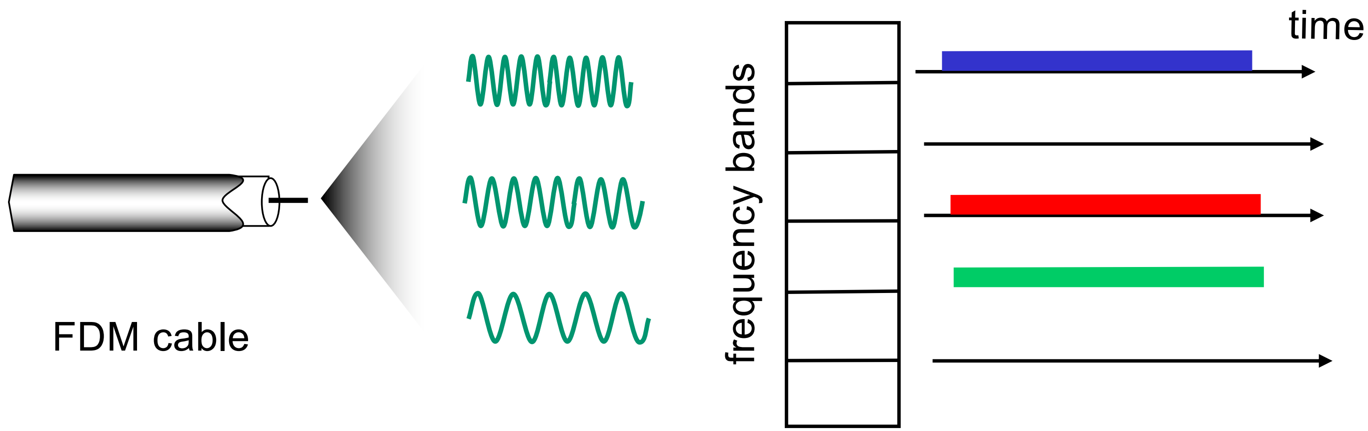
- *access to channel in "rounds"*
- *each node gets fixed length slot (length = packet transmission time) in each round*
- *unused slots go idle*
- *example: 6-node LAN, 1,3,4 have packets to send, slots 2,5,6 idle*



Channel partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

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



Quiz: Does channel partitioning satisfy ideal properties ?

1. if only 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 (fairness)
3. fully decentralized:
   - no synchronization of clocks, slots
   - no special node to coordinate transmissions
4. simple

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A. 0
B. 1
C. 2
D. 3
E. 4

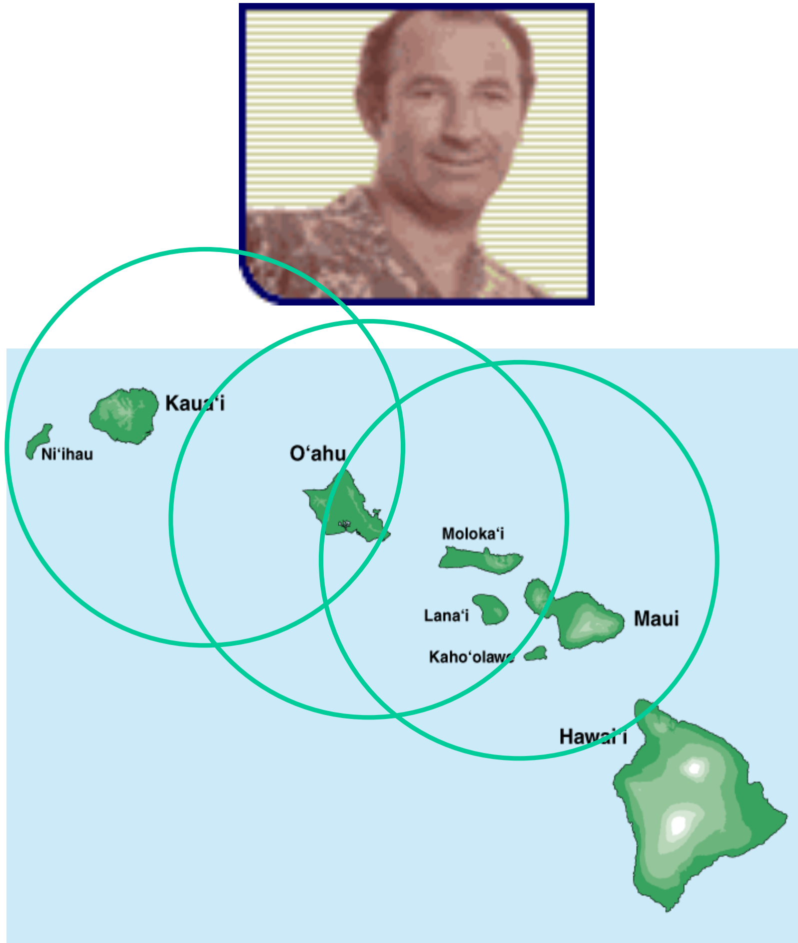
(Which ones?)

ANSWER: B
Only 4 is satisfied
Note that 2 is satisfied if M=N (no of nodes on the network)
However, more generally for $M < N$, 2 is not satisfied

Random access protocols

- *when node has packet to send*
  - *transmit at full channel data rate R.*
  - *no a priori coordination among nodes*
- *two or more transmitting nodes: "collision"*
- *random access MAC protocol specifies:*
  - *how to detect collisions*
  - *how to recover from collisions (e.g., via delayed retransmissions)*
- *examples of random-access MAC protocols:*
  - *ALOHA, slotted ALOHA*
  - *CSMA, CSMA/CD, CSMA/CA*

Where it all Started: AlohaNet



- Norm Abramson left Stanford in 1970 (***so he could surf!)***
- Set up first data communication system for Hawaiian islands
- Central hub at U. Hawaii, Oahu

Slotted ALOHA

assumptions:

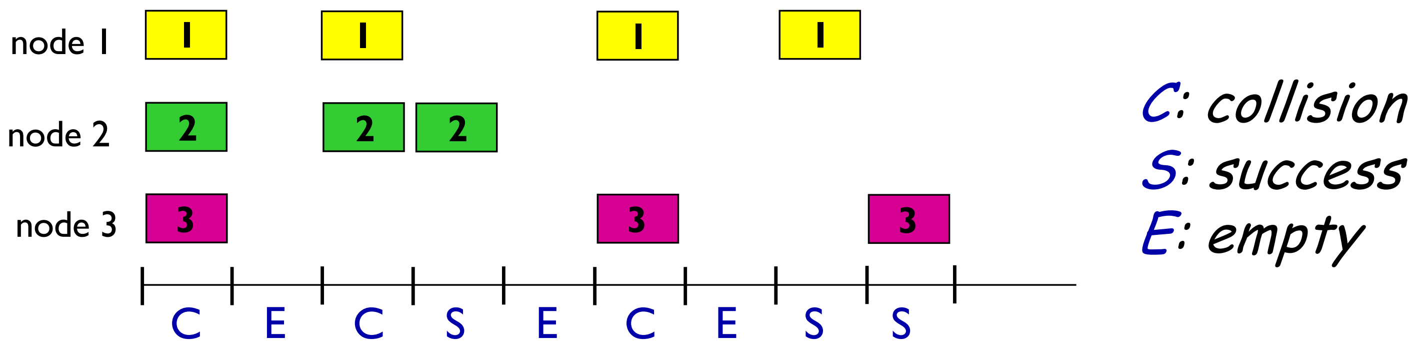
- *all frames same size*
- *time divided into equal size slots (time to transmit 1 frame)*
- *nodes start to transmit only slot beginning*
- *nodes are synchronized*
- *if 2 or more nodes transmit in slot, all nodes detect collision*

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 probability p until success*

randomization – why?

Slotted ALOHA



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)

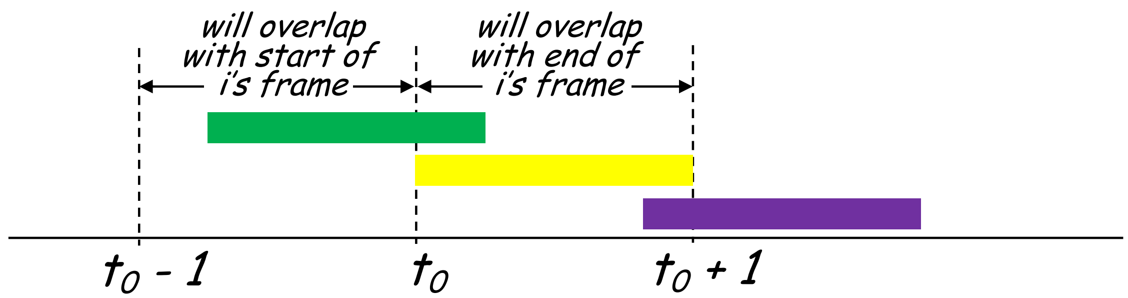
- *suppose:* N nodes with many frames to send, each transmits in slot with probability p
  - prob that given node has success in a slot = $p(1-p)^{N-1}$
  - prob that *any* node has a success = $Np(1-p)^{N-1}$
  - max efficiency: find p^* that maximizes $Np(1-p)^{N-1}$
  - for many nodes, take limit 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 ALOHA

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



- *pure Aloha efficiency: 18% !*

CSMA (carrier sense multiple access)

simple CSMA: listen before transmit:

- *if channel sensed idle: transmit entire frame*
- *if channel sensed busy: defer transmission*

- *human analogy: don't interrupt others!*

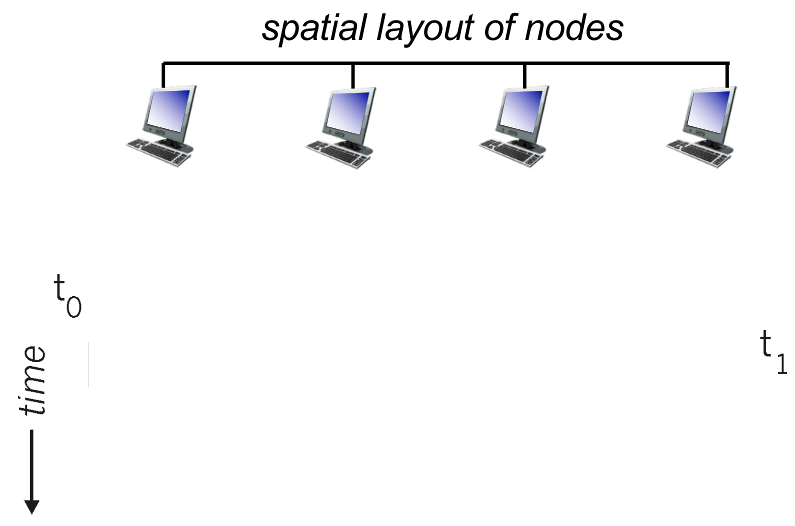
CSMA/CD: CSMA with collision detection

- *collisions detected within short time*
- *colliding transmissions aborted, reducing channel wastage*
- *collision detection easy in wired, difficult with wireless*

- *human analogy: the polite conversationalist*

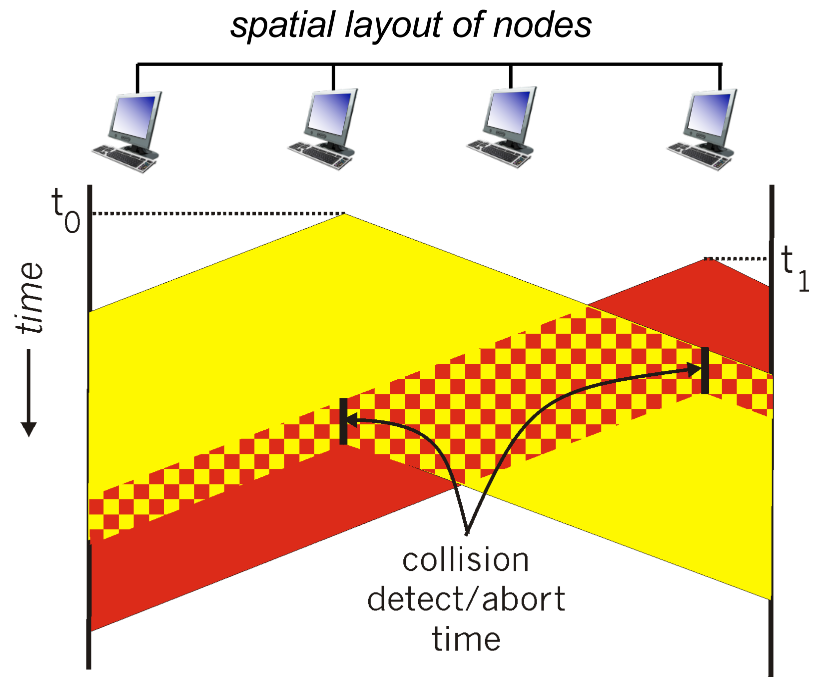
CSMA: collisions

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



CSMA/CD:

- *CSMA/CD reduces the amount of time wasted in collisions*
  - *transmission aborted on collision detection*



http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/csmacd/csmacd.html

Ethernet CSMA/CD algorithm

1. *NIC receives datagram from network layer, creates frame*
2. *If NIC senses channel:*

   if idle: start frame transmission.

   if busy: wait until channel idle, then transmit
3. *If NIC transmits entire frame without collision, NIC is done with frame !*
4. *If NIC detects another transmission while sending: abort, send jam signal*
5. *After aborting, NIC enters binary (exponential) backoff:*
   - *after mth collision, NIC chooses K at random from $\{0,1,2, \ldots, 2^m-1\}$. NIC waits $K \cdot 512$ bit times, returns to Step 2*
   - *more collisions: longer backoff interval*

NIC = Network Interface Card

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} becomes very large*
- *better performance than ALOHA: and simple, cheap, decentralized!*

Quiz: Does CSMA/CD satisfy ideal properties ?

1. if only 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 (fairness)
3. fully decentralized:
   - no synchronization of clocks, slots
   - no special node to coordinate transmissions
4. simple

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A. 0
B. 1
C. 2
D. 3
E. 4

(Which ones?)

Answer: D
1, 3 and 4 are satisfied
2 is not satisfied as bandwidth is wasted due to collisions when multiple nodes are transmitting (neglect the overheads for channel sensing)

“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*

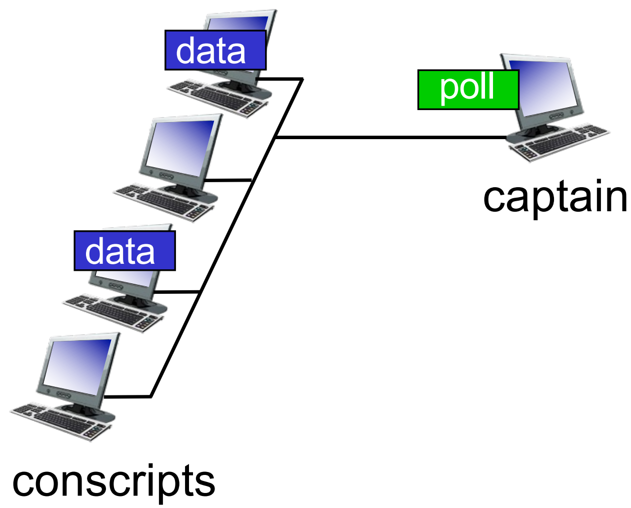
“taking turns” protocols

- *look for best of both worlds!*

“Taking turns” MAC protocols

polling:

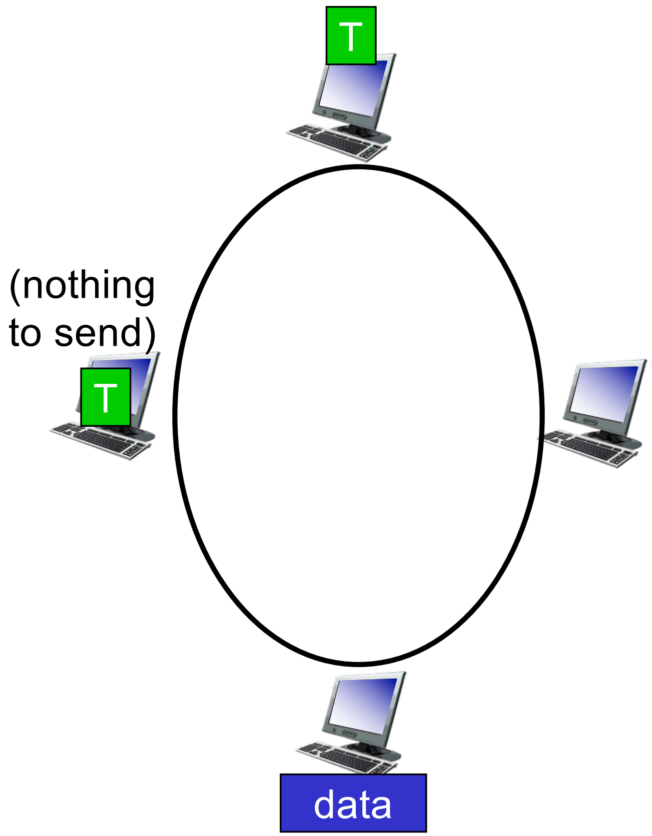
- *captain node “invites” other nodes to transmit in turn*
- *typically used with “dumb” devices*
- *concerns:*
  - *polling overhead*
  - *latency*
  - *single point of failure (captain)*



"Taking turns" MAC protocols

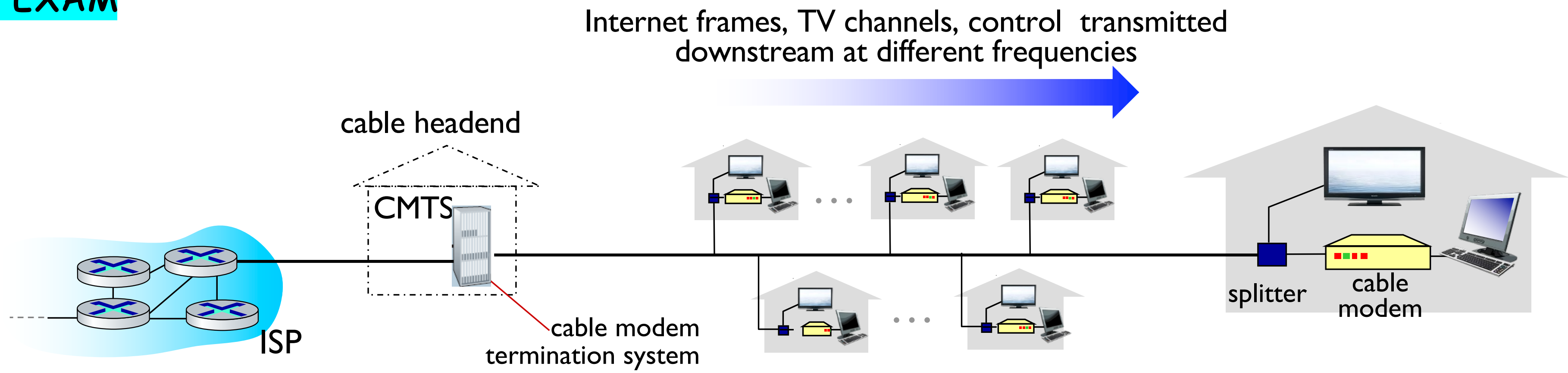
token passing:

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



Cable access network: FDMA, TDMA *and* random access!

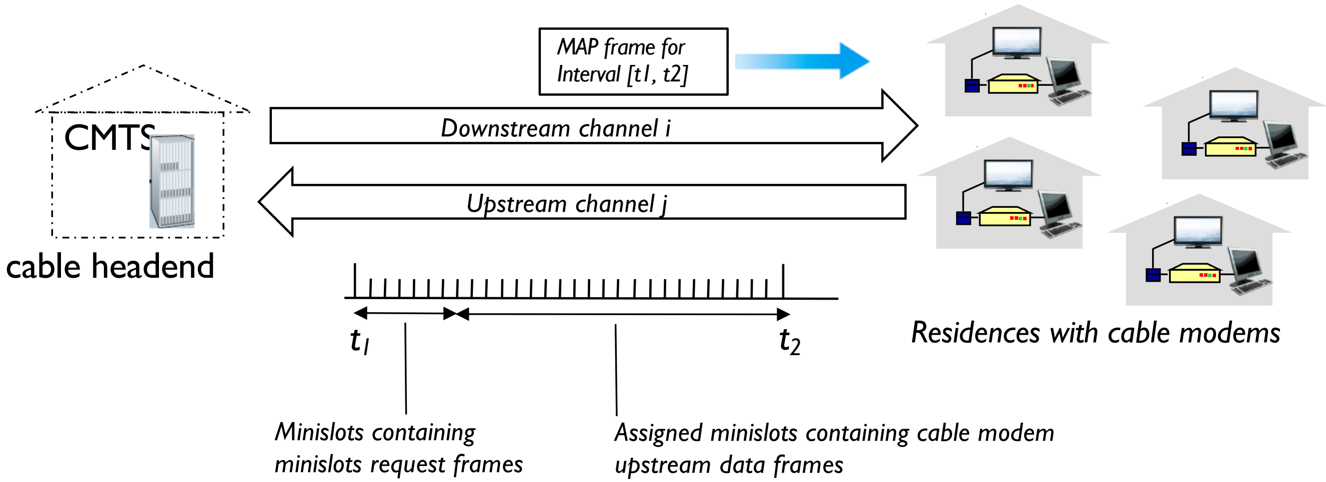
NOT ON EXAM



- *multiple* downstream (broadcast) *FDMA 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 using TDMA

Cable access network:

NOT ON EXAM



DOCSIS: data over cable service interface specificaiton

- *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*

Quiz: Does taking turns satisfy ideal properties ?

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Answer: D
1, 2 and 4 are satisfied
(neglect the overheads for polling and token passing)

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: roadmap

- *introduction*
- *error detection, correction*
- *multiple access protocols*
- ***LANs***
  - ***addressing, ARP***
  - *Ethernet*
  - *switches*
  - *VLANs*
- *link virtualization: MPLS (NOT COVERED)*
- *data center networking (NOT COVERED)*
- *a day in the life of a web request*

MAC addresses

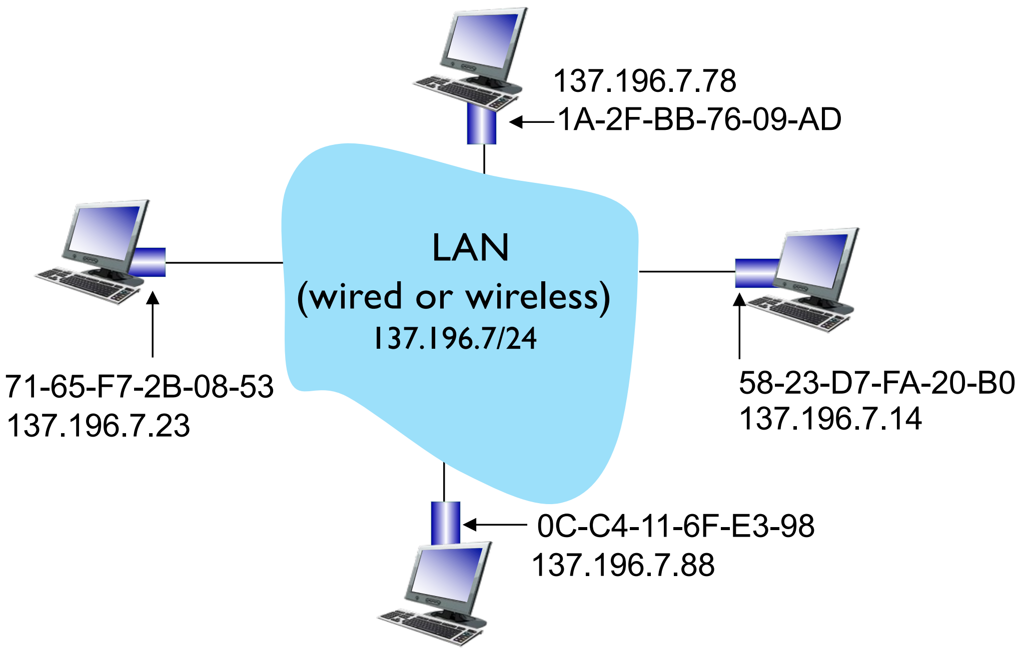
- *32-bit IP address:*
  - *network-layer address for interface*
  - *used for layer 3 (network layer) forwarding*
  - e.g.: *128.119.40.136*
- *MAC (or LAN or physical or Ethernet) address:*
  - *function: used "locally" to get frame from one interface to another physically-connected interface (same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

MAC Address vs. IP Address

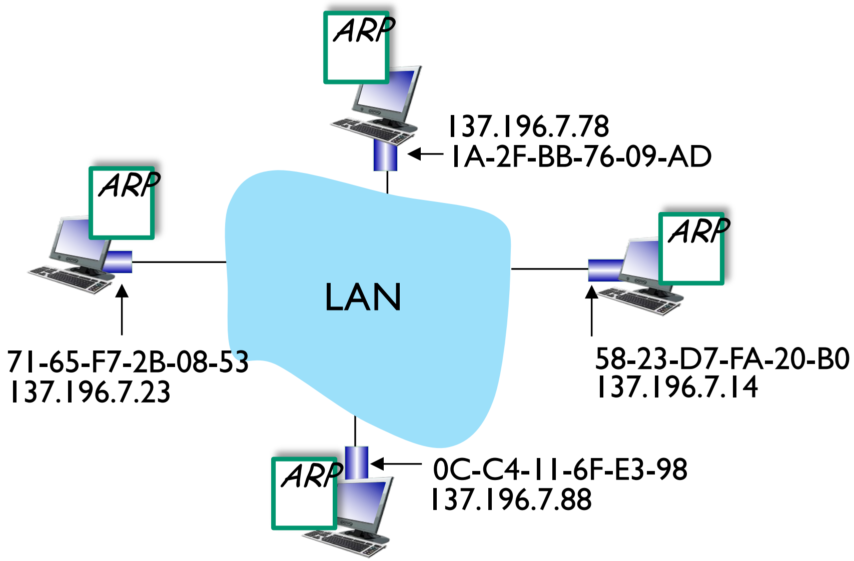
- MAC addresses (used in link-layer)
  - Hard-coded in read-only memory when adapter is built
  - Flat name space of 48 bits (e.g., 00-0E-9B-6E-49-76)
  - Portable, and can stay the same as the host moves
  - Used to get packet between interfaces on same network
- IP addresses
  - learned dynamically
  - Hierarchical name space of 32 bits (e.g., 12.178.66.9)
  - Not portable, and depends on where the host is attached
  - Used to get a packet to destination IP subnet

Taking Stock: Naming

Layer	Examples	Structure	Configuration	Resolution Service
App. Layer	www.cse.unsw.edu.au	organizational hierarchy	~ manual	DNS
Network Layer	129.94.242.51	topological hierarchy	DHCP	ARP
Link layer	45-CC-4E-12-F0-97	vendor (flat)	hard-coded	

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:*

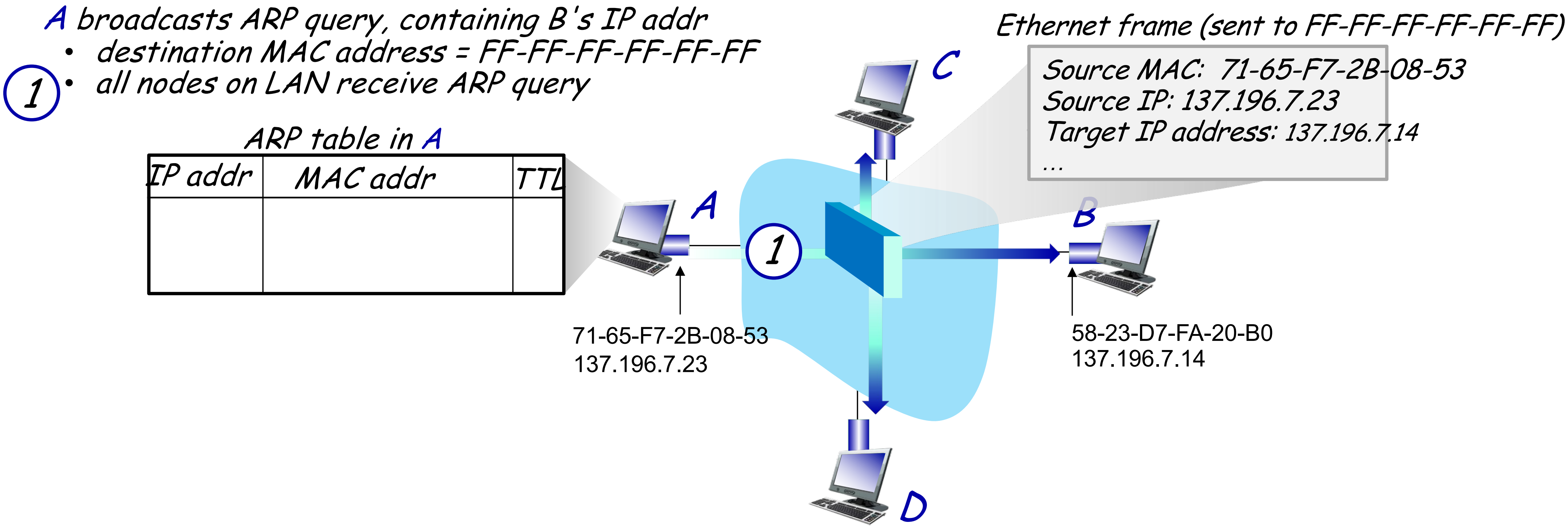
  < IP address; MAC address;TTL>

- *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*



ARP protocol in action

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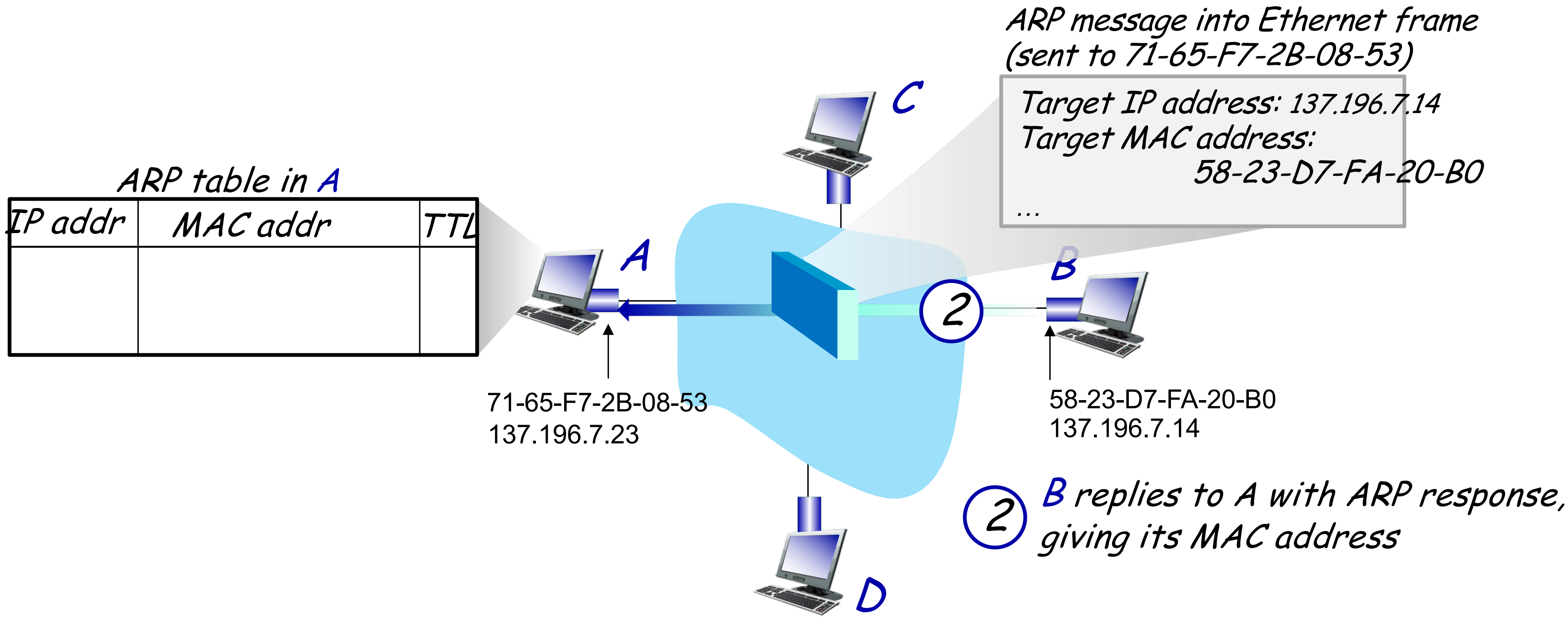


ARP protocol in action

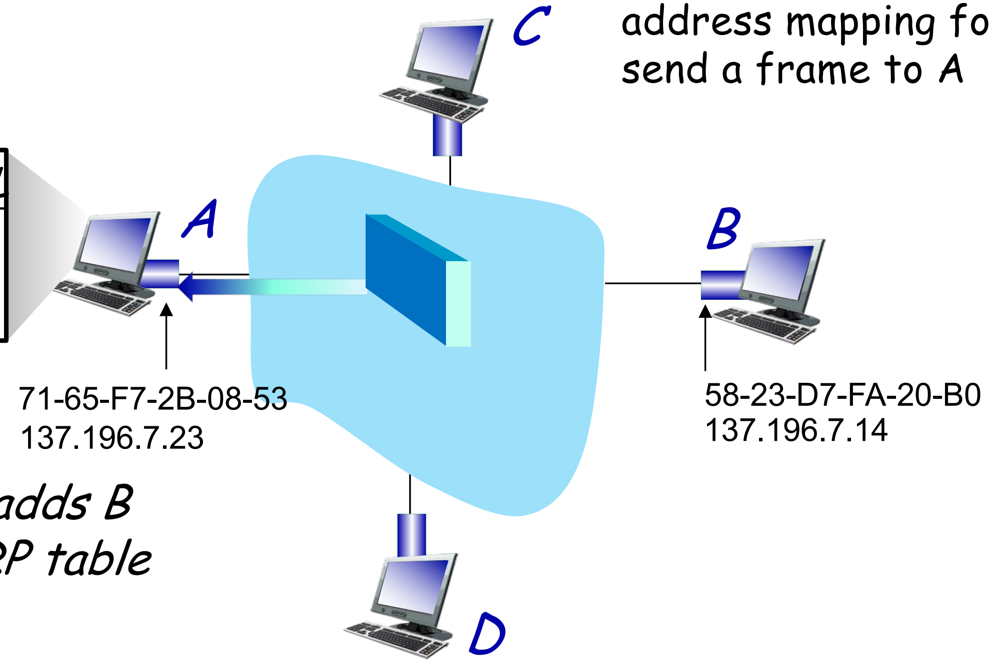
example: A wants to send datagram to B

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

B would store the IP address-MAC address mapping for A as B is likely to send a frame to A

ARP table in A

IP addr	*MAC addr*	*TTL*
137.196.7.14	58-23-D7-FA-20-B0	500

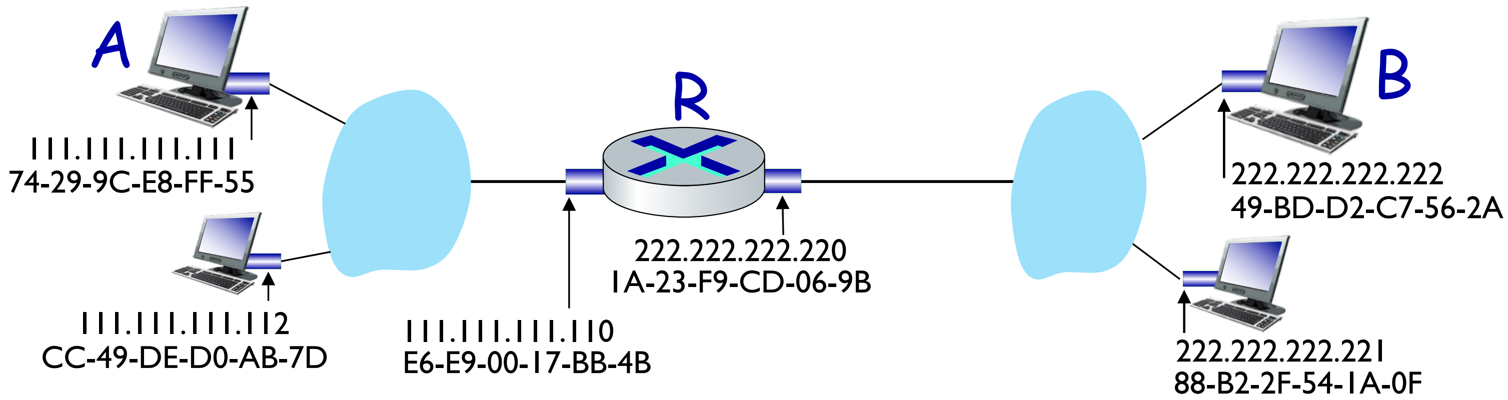


③ *A receives B's reply, adds B entry into its local ARP table*

Routing to another subnet: addressing

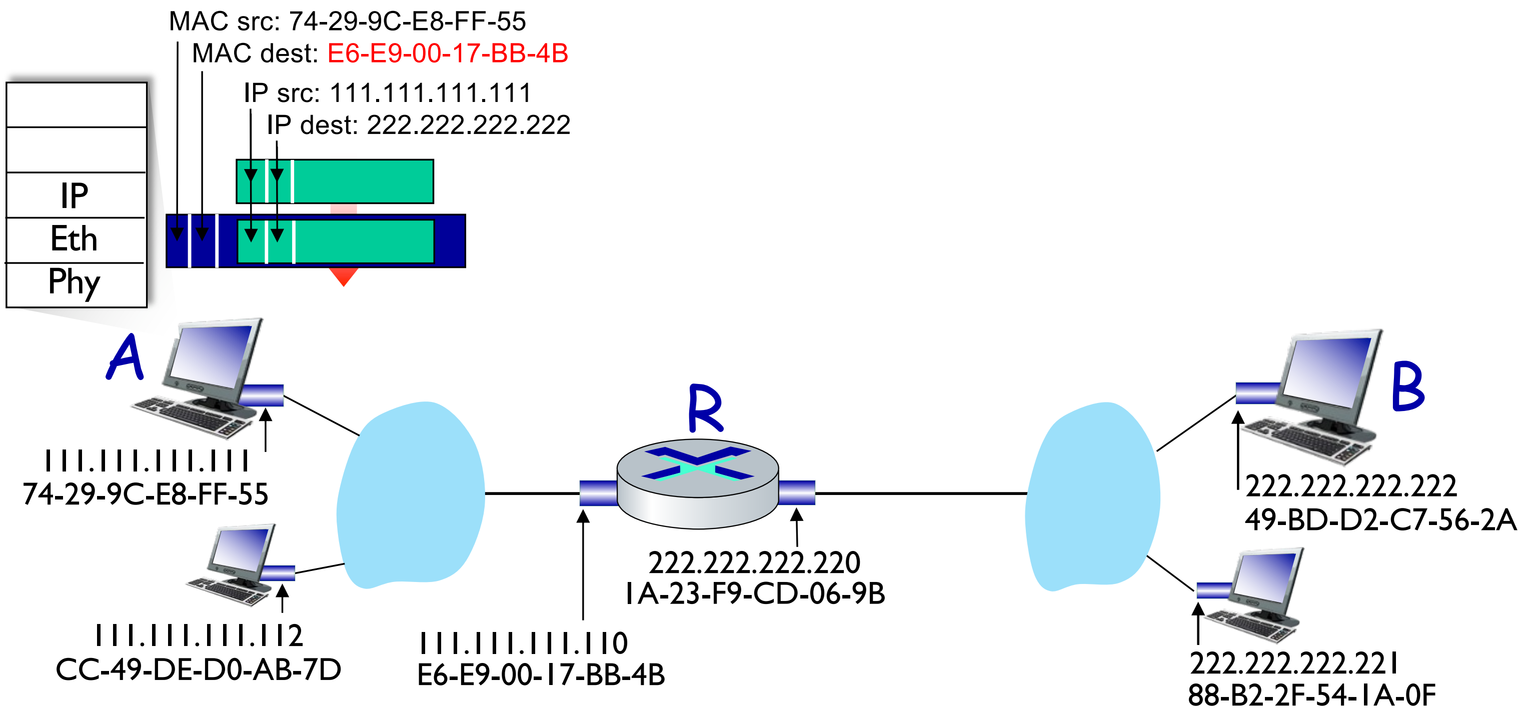
walkthrough: sending a datagram from A to B via R

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



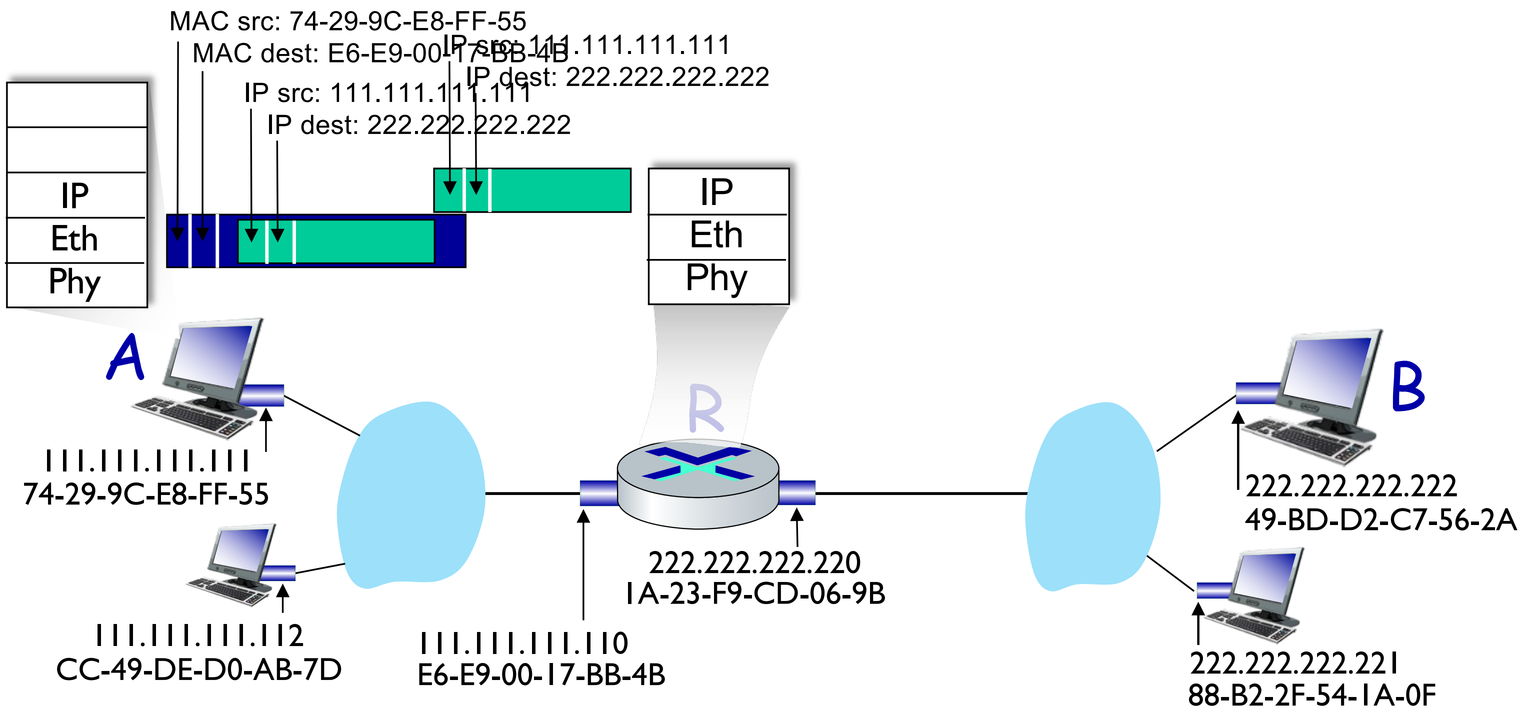
Routing to another subnet: addressing

- *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*



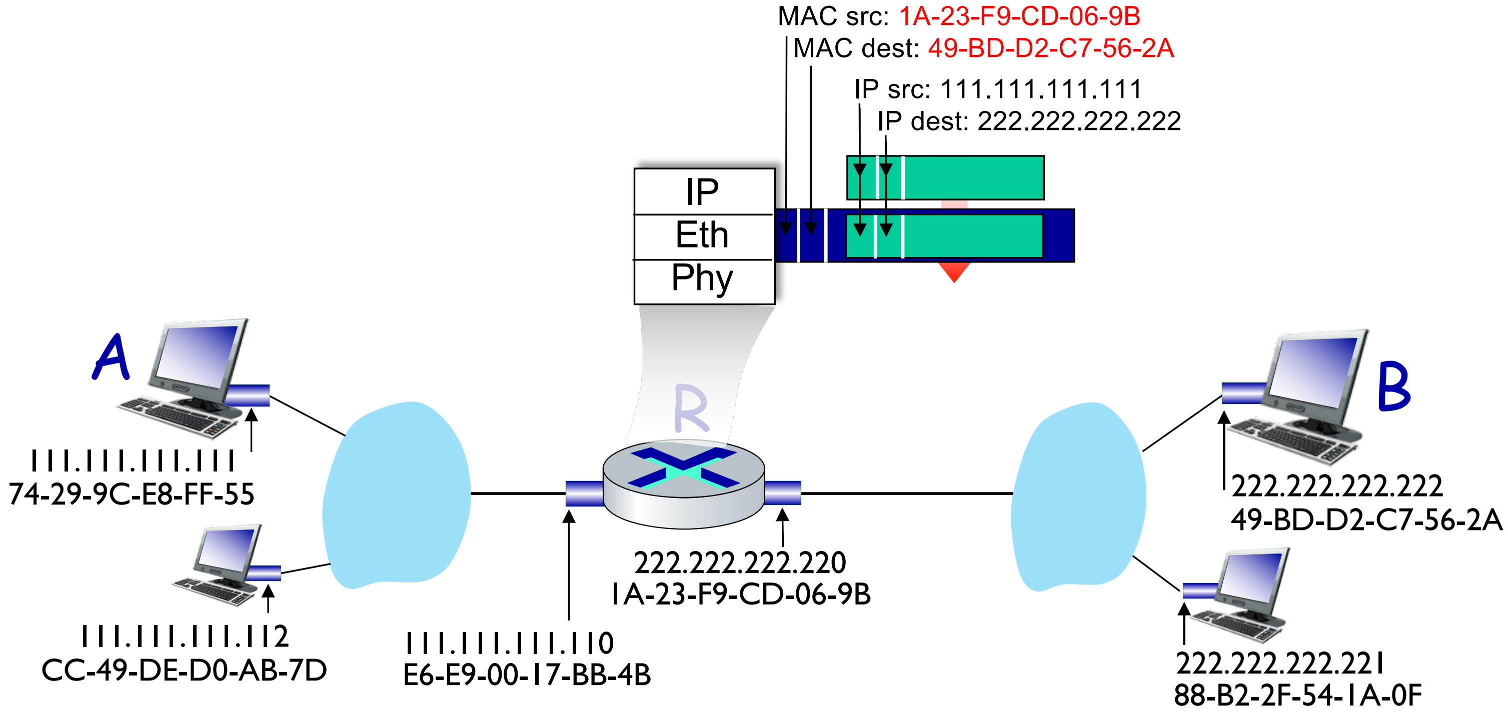
Routing to another subnet: addressing

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



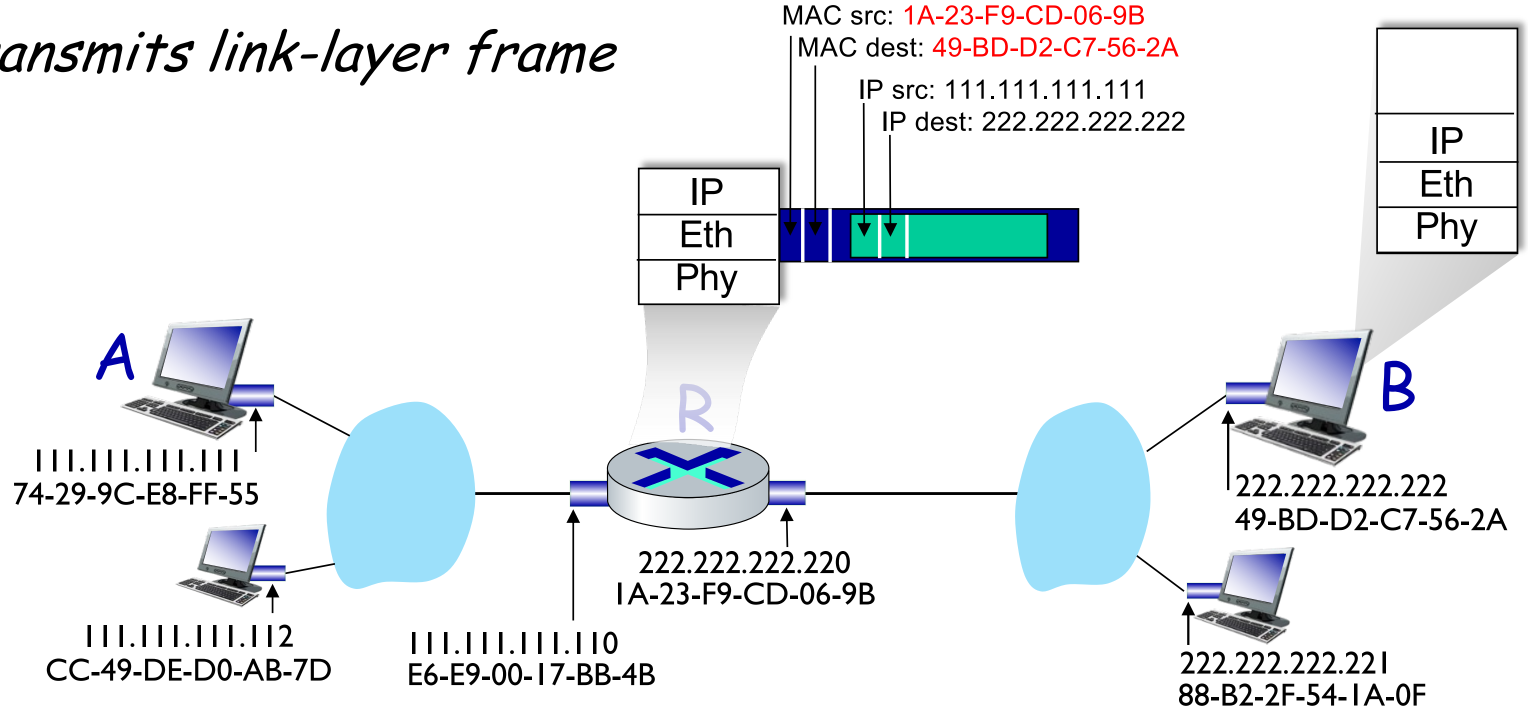
Routing to another subnet: addressing

- *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



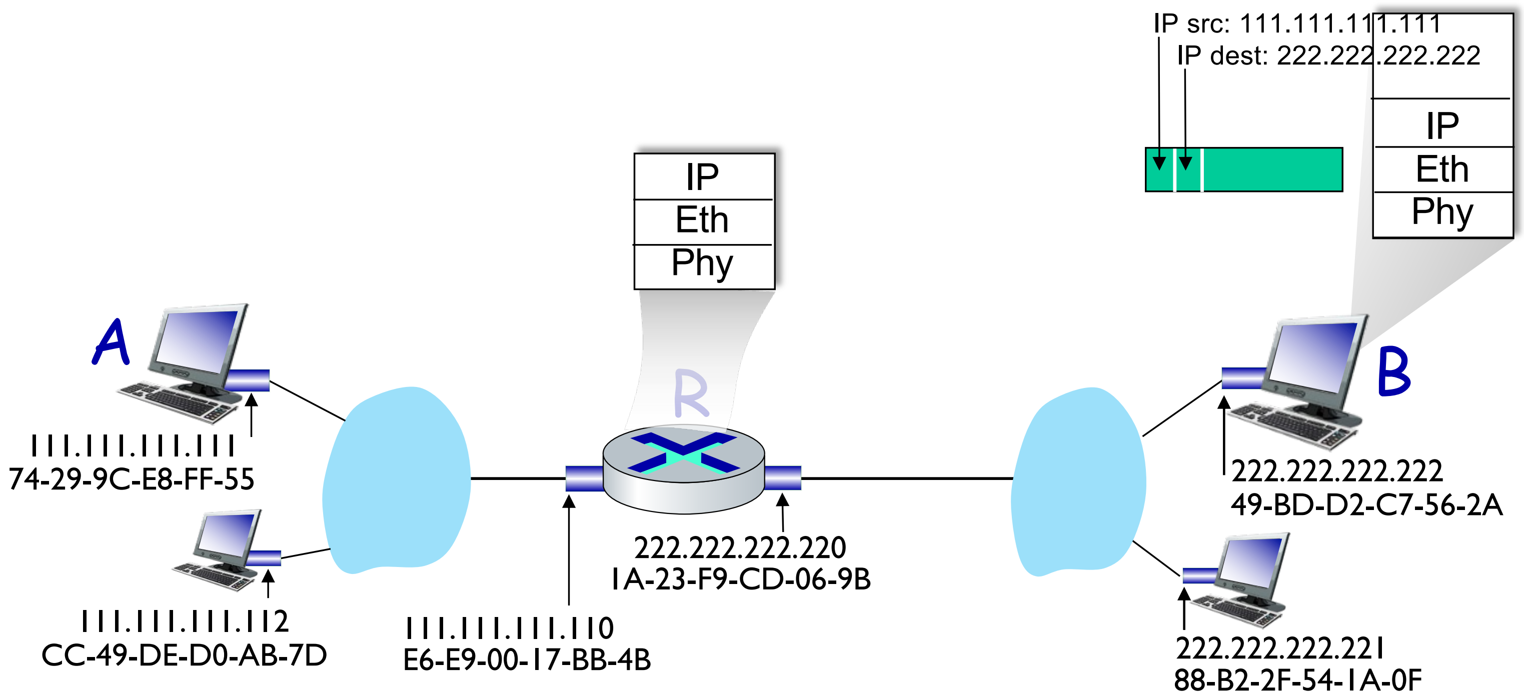
Routing to another subnet: addressing

- *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 passes datagram up protocol stack to IP

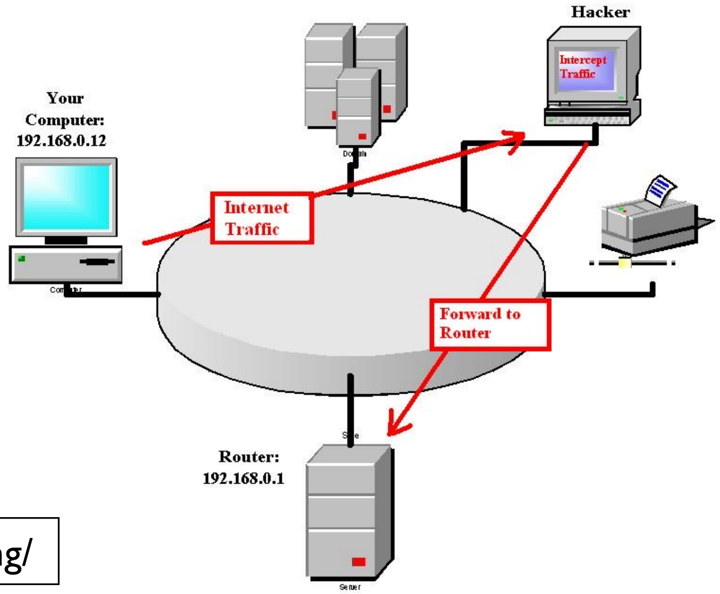


Security Issues: ARP Cache Poisoning

- Denial of Service - Hacker replies back to an ARP query for the router inferface with a fake MAC address
- Man-in-the-middle attack - Hacker can insert his/her machine along the path between victim machine and gateway router
- Such attacks are generally hard to launch as hacker needs physical access to the network

Solutions -
• Use Switched Ethernet with port security enabled (i.e., one host MAC address per switch port)
• Adopt static ARP configuration for small size networks
• Use ARP monitoring tools such as ARPWatch

https://www.okta.com/au/identity-101/arp-poisoning/



Link layer, LANs: roadmap

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- *error detection, correction*
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- *LANs*
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  - ***Ethernet***
  - *switches*
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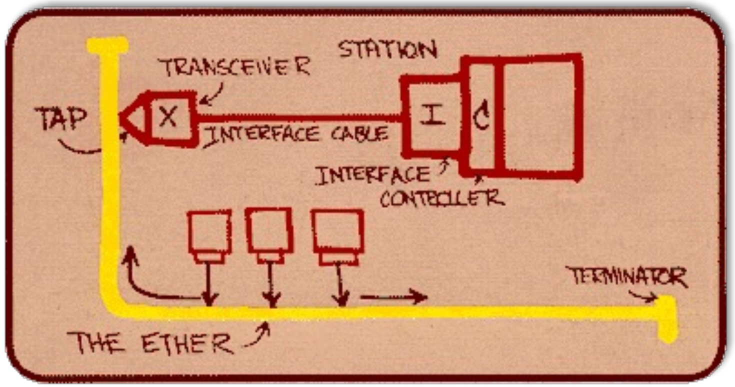
- *a day in the life of a web request*

Ethernet

Awarded ACM Turing Award in 2023 !!

"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)*



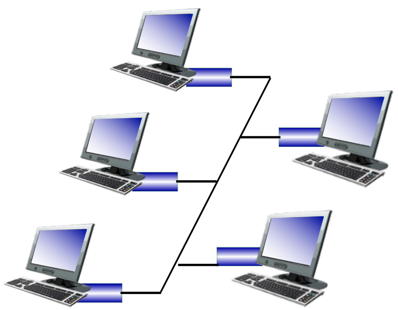
Metcalfe's Ethernet sketch

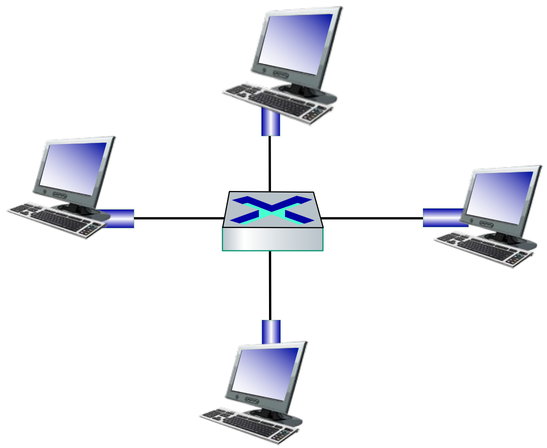
https://www.uspto.gov/learning-and-resources/journeys-innovation/audio-stories/defying-doubters

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

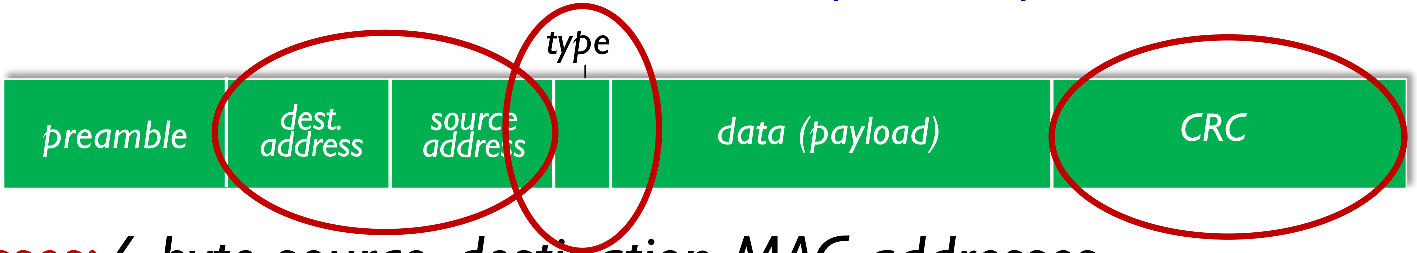
Ethernet frame structure

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
- Data: typically IP datagram. 46 to 1500 bytes, smaller datagrams will need padding

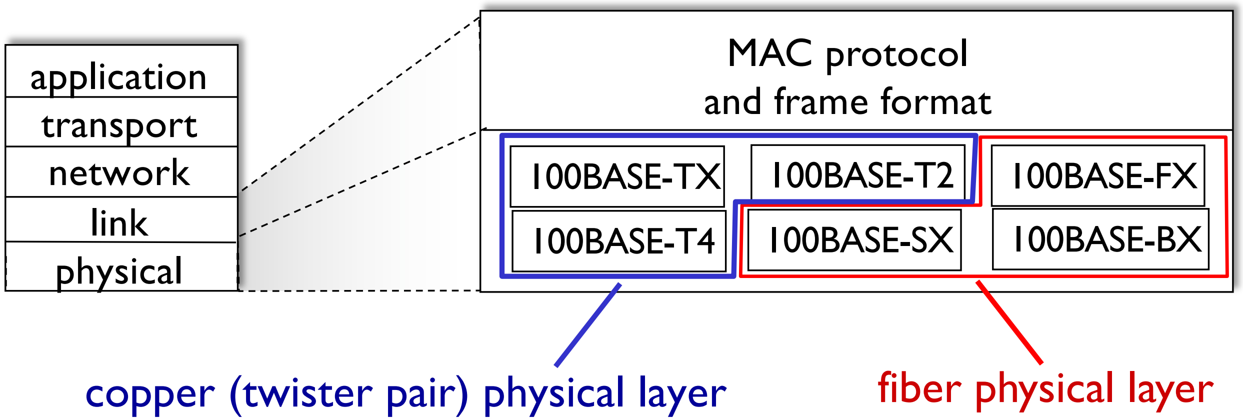
Ethernet: unreliable, connectionless

- *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

NOT ON EXAM

- *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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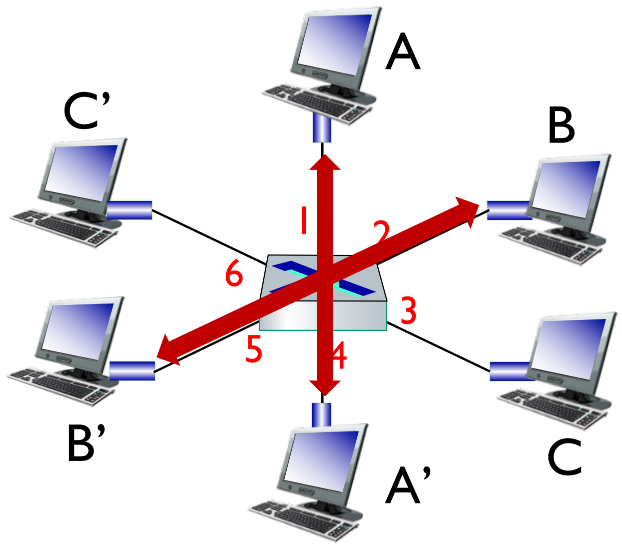
- *link virtualization: MPLS (NOT COVERED)*
- *data center networking (NOT COVERED)*
- *a day in the life of a web request*

Ethernet switch

- *Switch is a link-layer device: it 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, may use 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

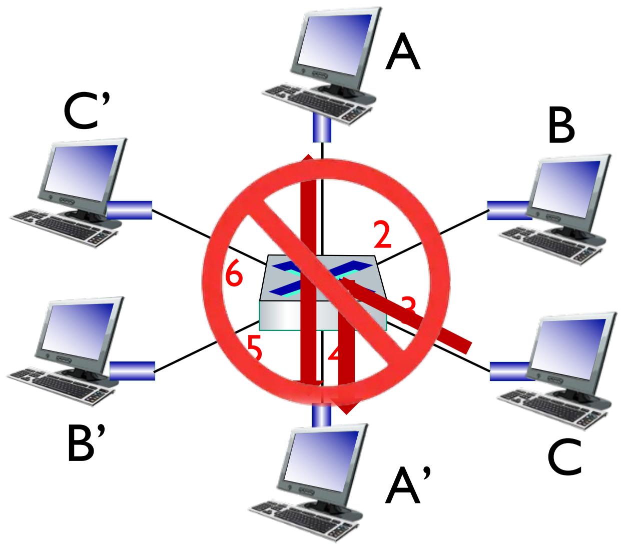
- *hosts have dedicated, direct connection to switch*
- *switches buffer packets*
- *Ethernet protocol used on each incoming link, so:*
  - *no collisions; full duplex*
  - *each link is its own collision domain*
- *switching: A-to-A' and B-to-B' can transmit simultaneously, without collisions*



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*



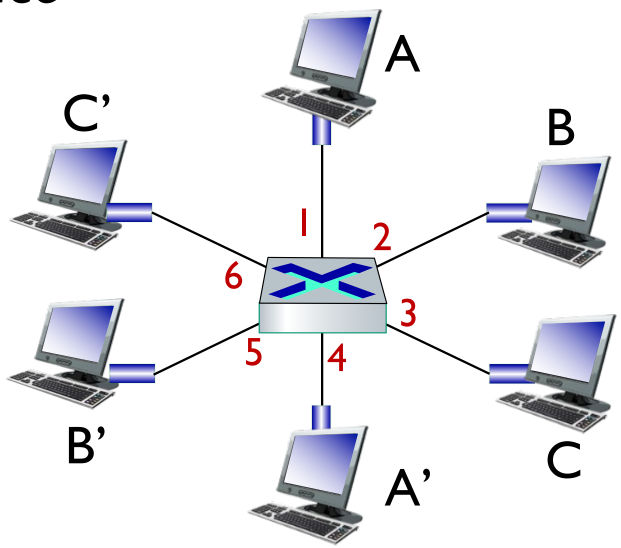
switch with six interfaces (1,2,3,4,5,6)

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!*

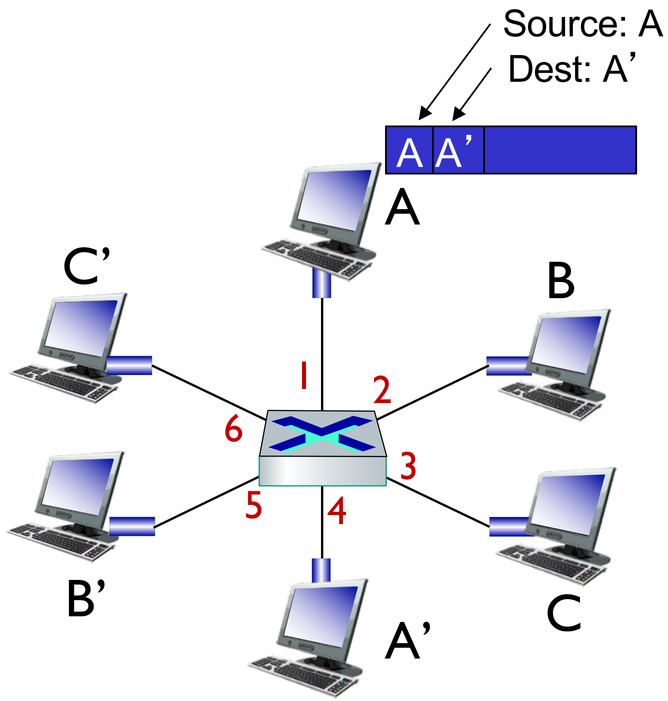


Q: how are entries created, maintained in switch table?

- *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)

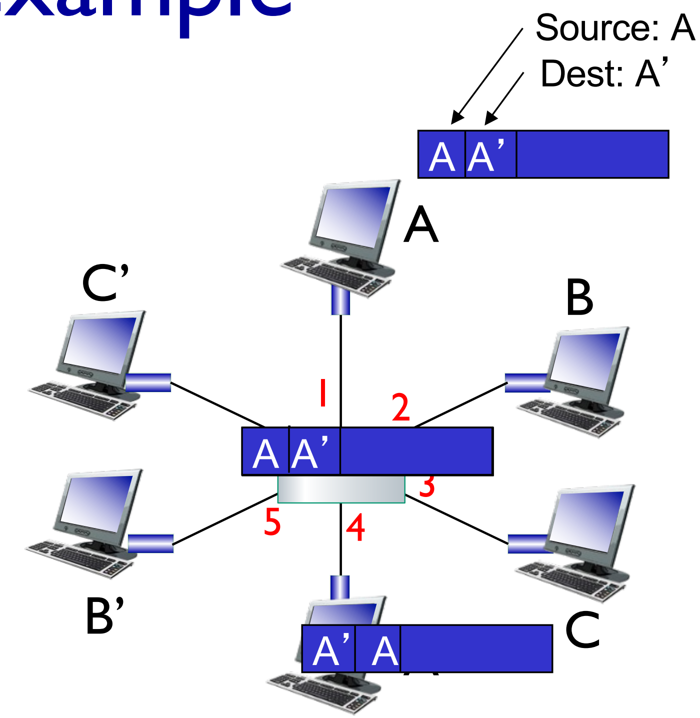
Switch: frame filtering/forwarding

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*

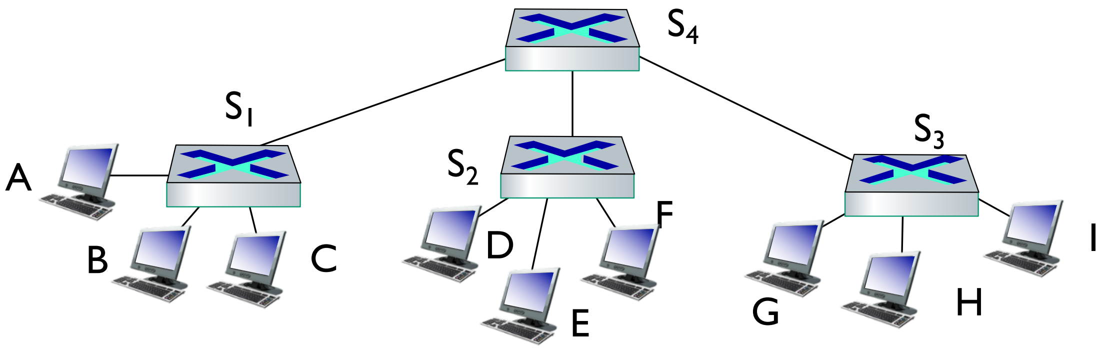


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

switch table (initially empty)

Interconnecting switches

self-learning switches can be connected together:

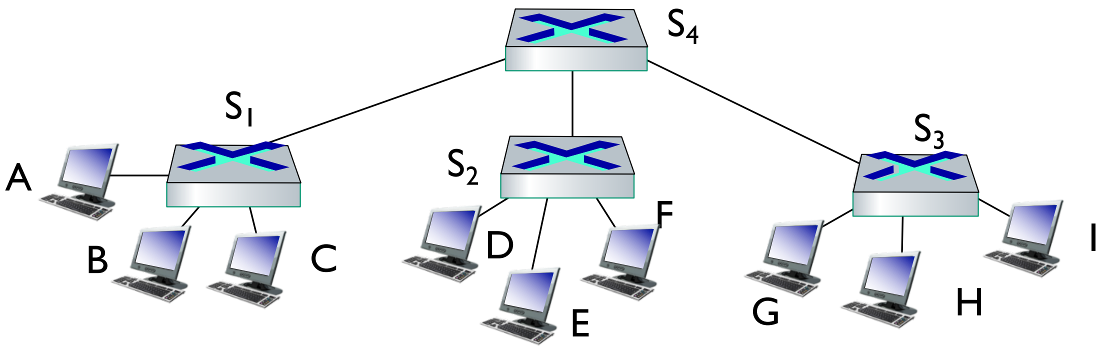


Q: sending from A to G - how does S_1 know to forward frame destined to G via S_4 and S_3?

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

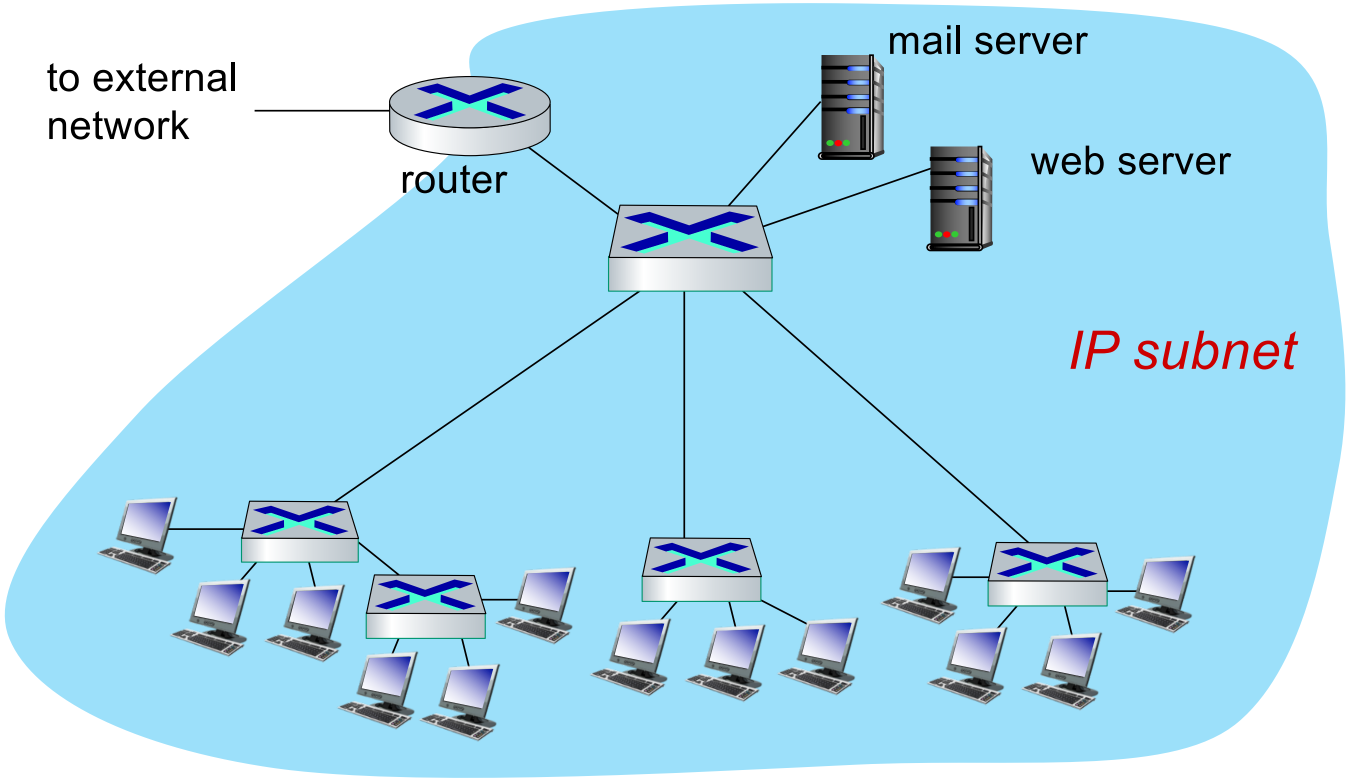
Self-learning multi-switch example

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



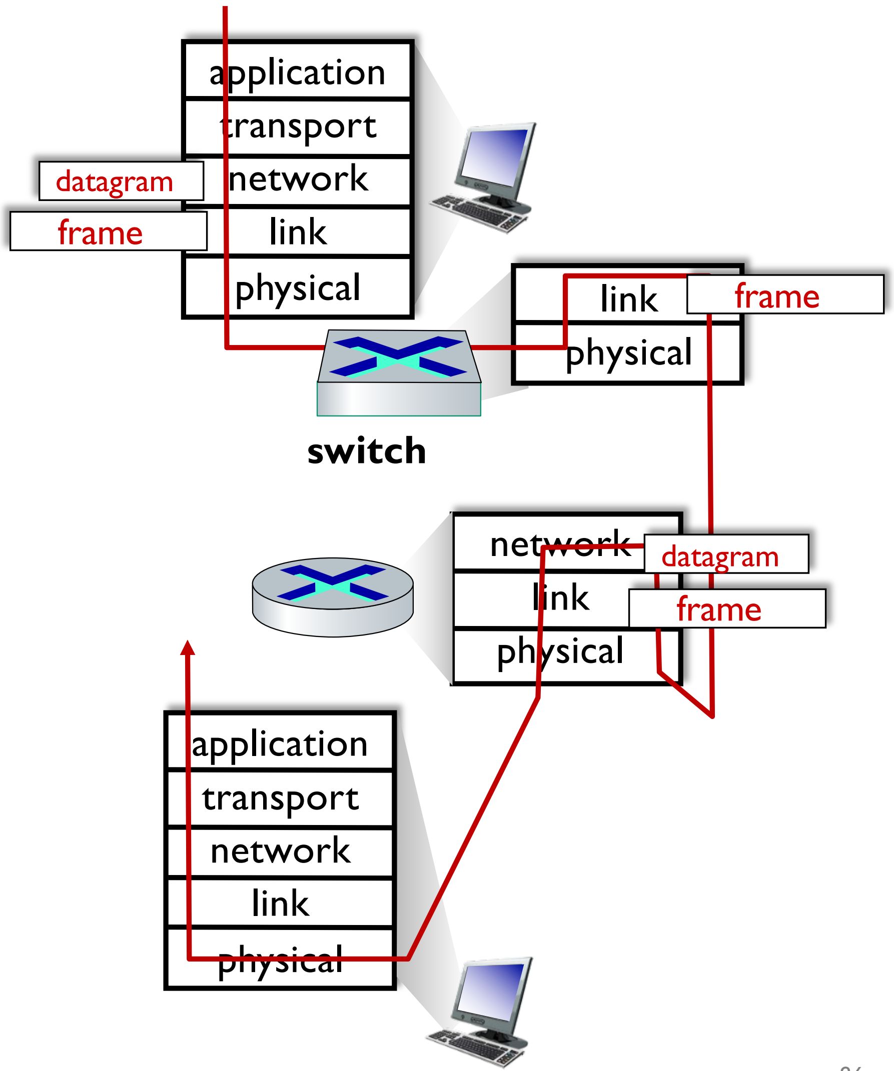
Switches vs. routers

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*



Security Issues

- In a switched LAN once the switch table entries are established frames are not broadcast
  - Sniffing frames is harder than pure broadcast LANs
  - Note: attacker can still sniff broadcast frames and frames for which there are no entries (as they are broadcast)
- Switch Poisoning: Attacker fills up switch table with bogus entries by sending large # of frames with bogus source MAC addresses
- Since switch table is full, genuine packets frequently need to be broadcast as previous entries have been wiped out

Quiz

www.pollev.com/salil

- A switch can

  A. Filter a frame

  B. Forward a frame

  C. Extend a LAN

  D. All of the above

Answer: D

Quiz

- The ________ will typically change from link to link, but the ____________ will typically remain the same

www.pollev.com/salil

A. Source MAC address, destination MAC address

B. Source IP address, destination IP address

C. Source & destination IP addresses, source & destination MAC addresses

D. Source & destination MAC addresses, source & destination IP addresses

ANSWER: D (Slides 62-66)

Link layer, LANs: roadmap

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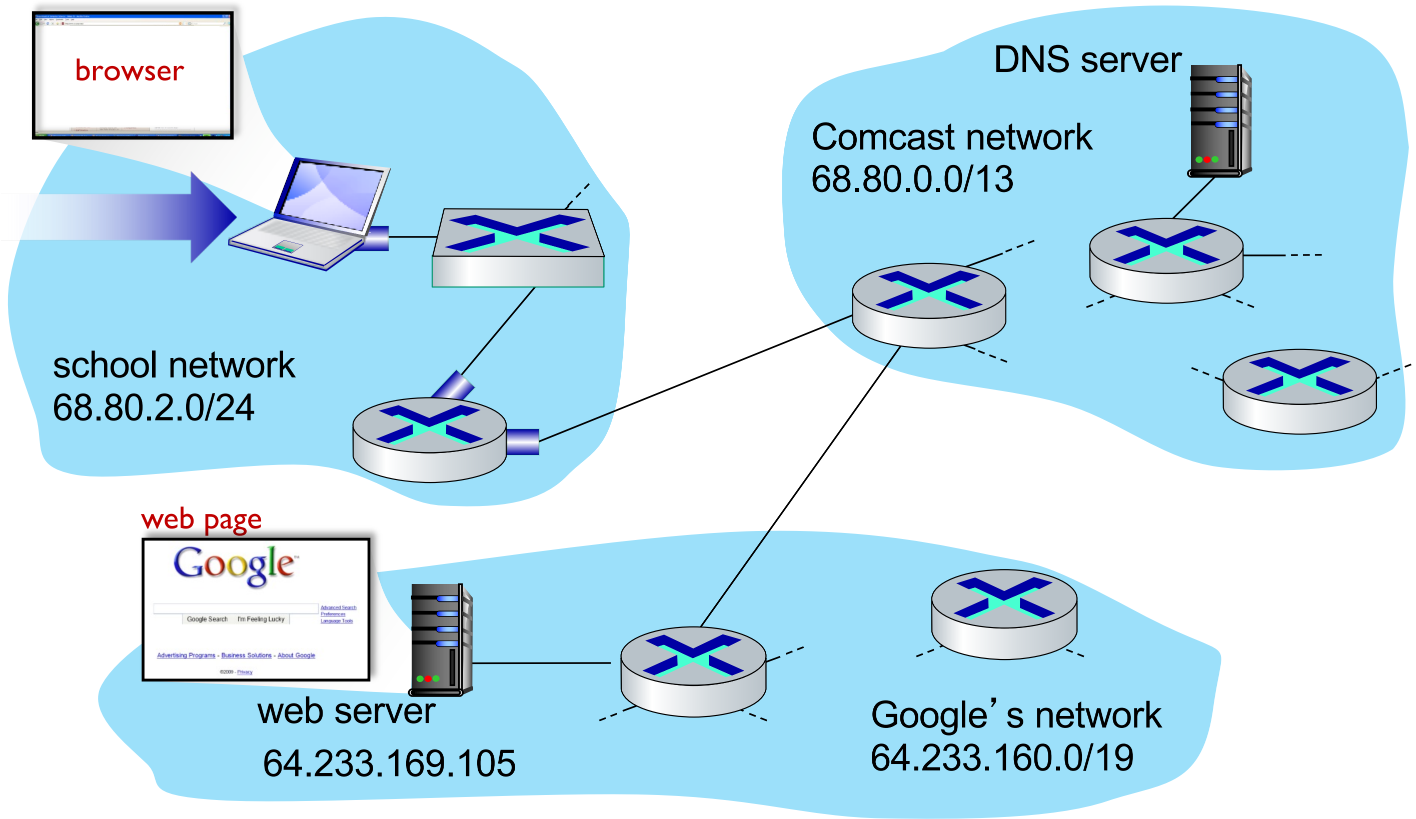
Synthesis: a day in the life of a web request

- *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

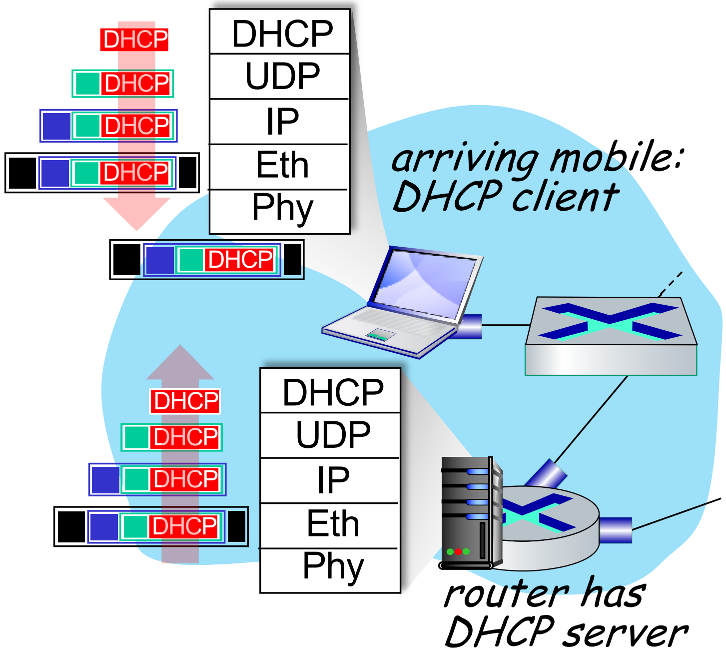


scenario:

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

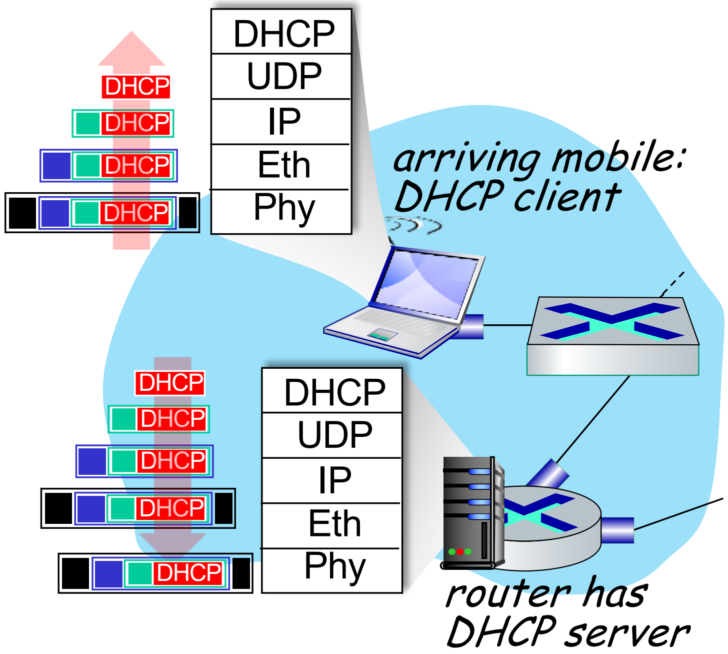
Sounds simple!

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

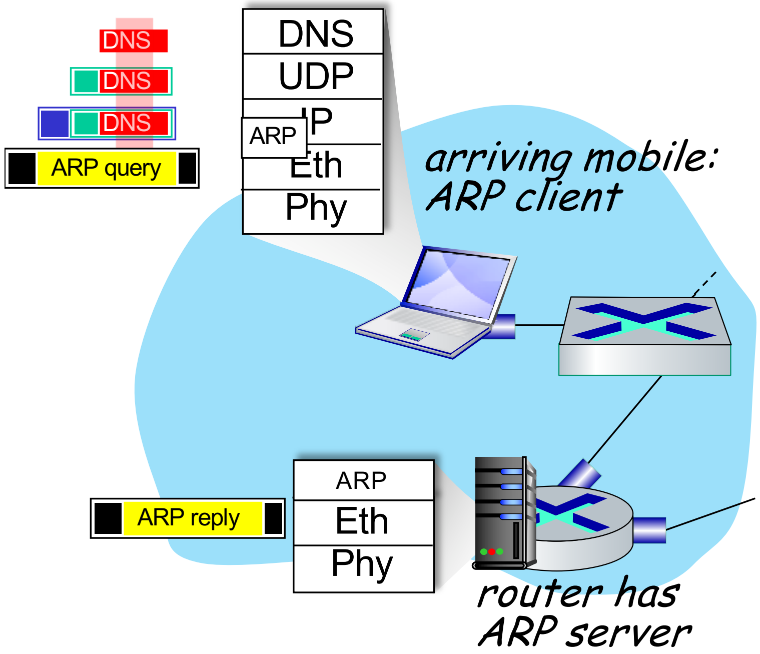
A day in the life: connecting to the Internet



- 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

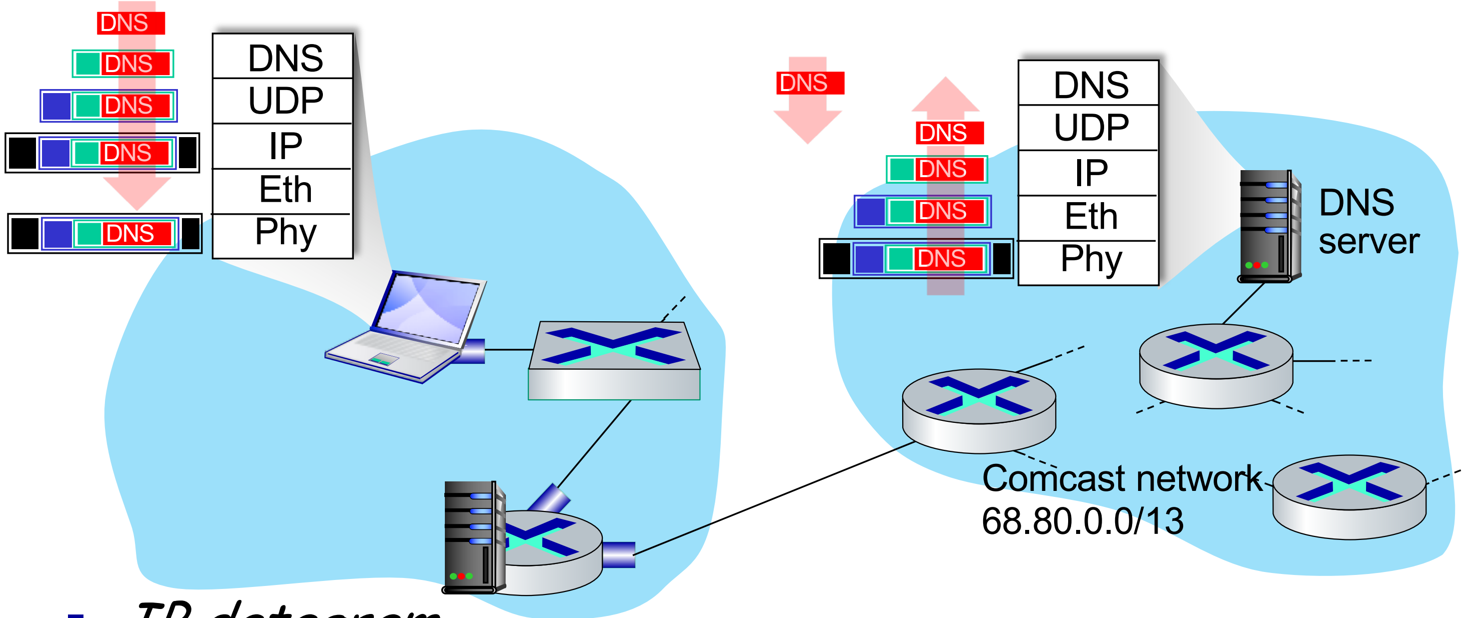
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

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

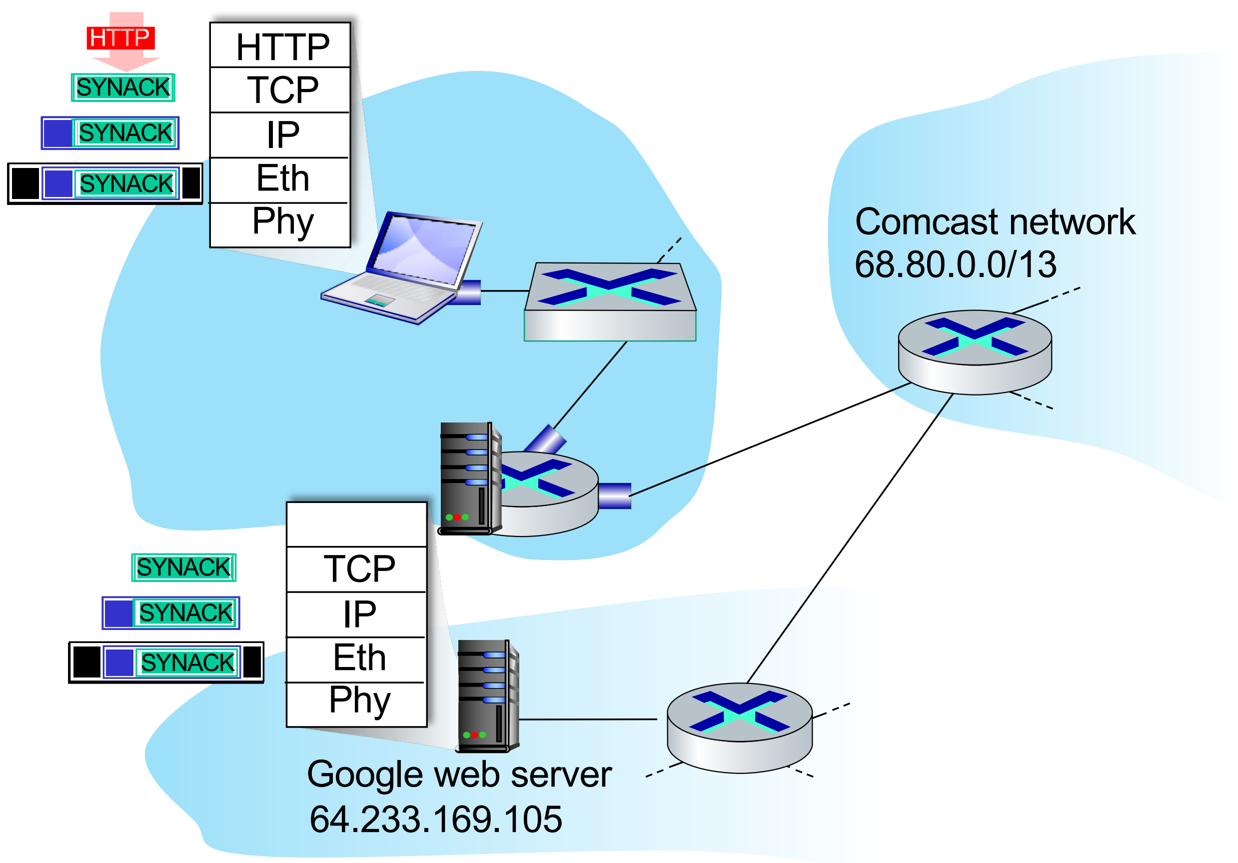


- *demuxed to DNS*
- *DNS replies to client with IP address of www.google.com*

- *IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router*

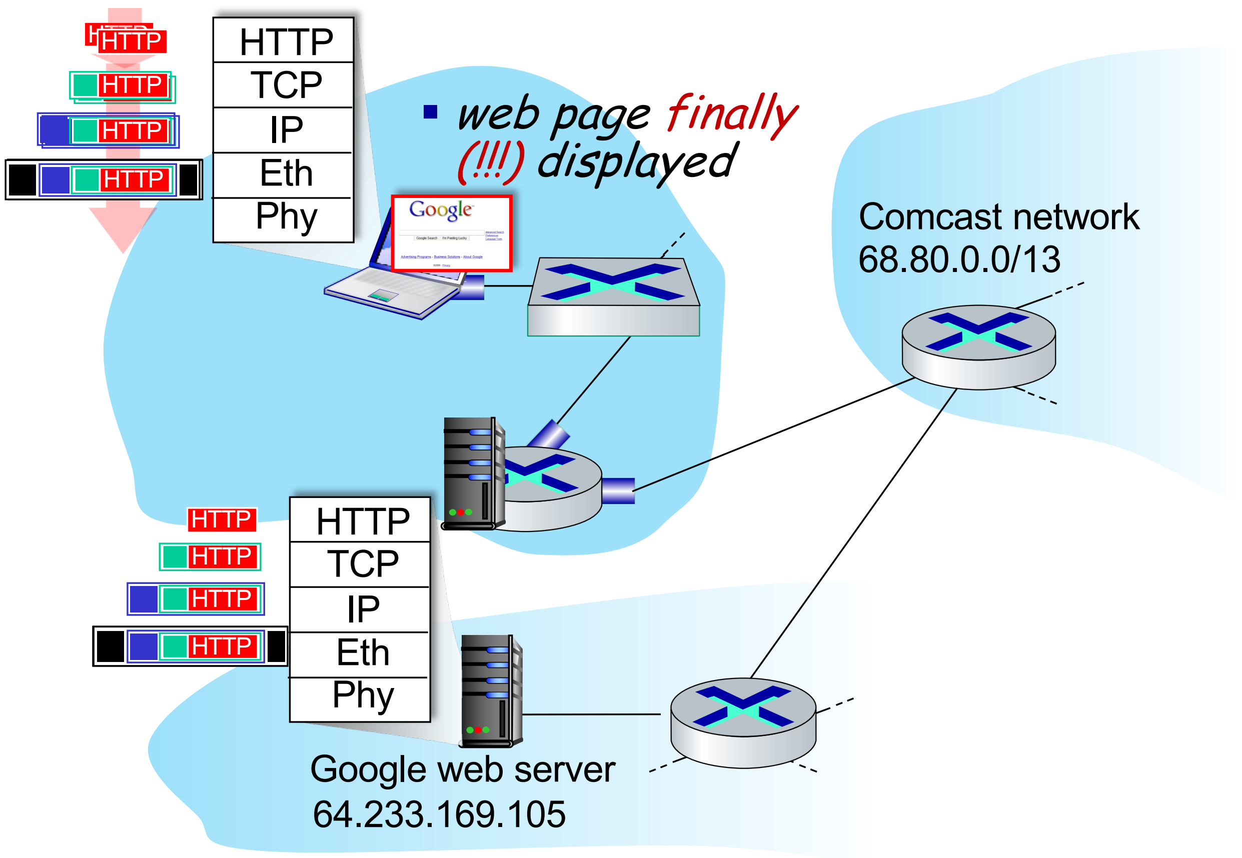
- *IP datagram forwarded from campus network into Comcast network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server*

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*

Link Layer: 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,*
- *synthesis: a day in the life of a web request*