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SAPIENZA
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Chapter 5
Data Link Layer

Reti di Elaboratori
Corso di Laurea in Informatica
Università degli Studi di Roma "La Sapienza"
Canale A-L
Prof.ssa Chiara Petrioli

Parte di queste slide sono state prese dal materiale associato al libro *Computer Networking: A Top Down Approach* , 5th edition.

Thanks also to Antonio Capone, Politecnico di Milano, Giuseppe Bianchi and Francesco LoPresti, Un. di Roma Tor Vergata

LAN Addresses and ARP

32-bit IP address:

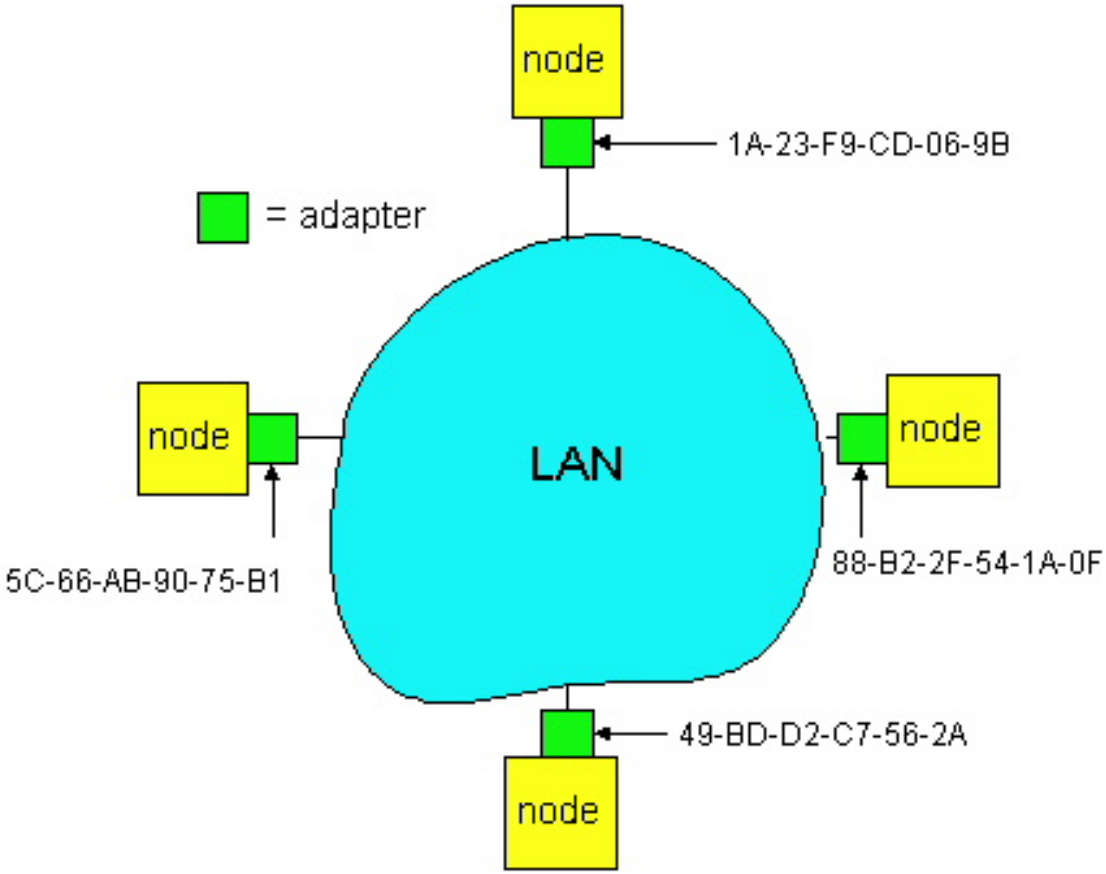
- *network-layer* address
- used to get datagram to destination IP network (recall IP network definition)

LAN (or MAC or physical or Ethernet) address:

- used to get datagram from one interface to another physically-connected interface (same network)
- 48 bit MAC address (for most LANs) burned in the adapter ROM

LAN Addresses and ARP

Each adapter on LAN has unique LAN address



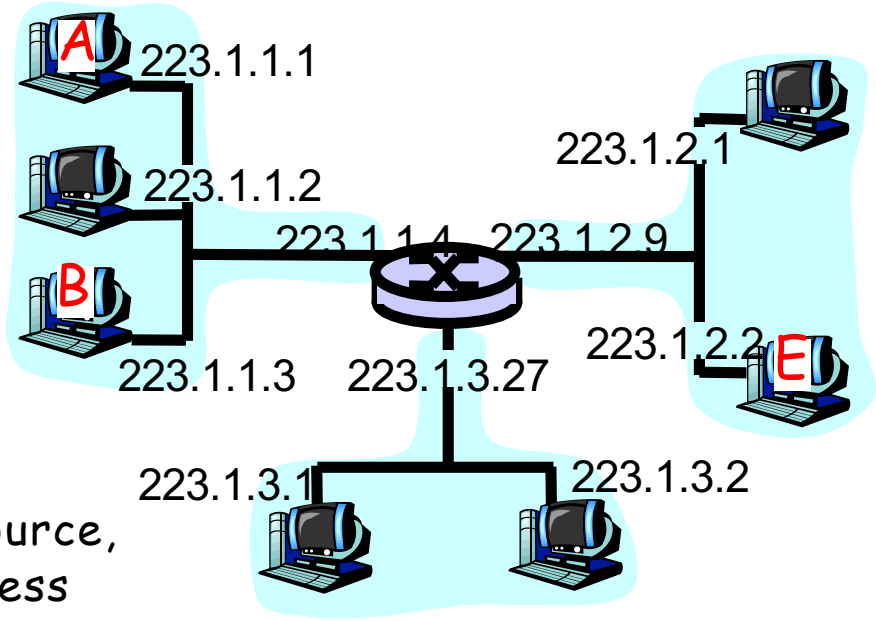
LAN Address (more)

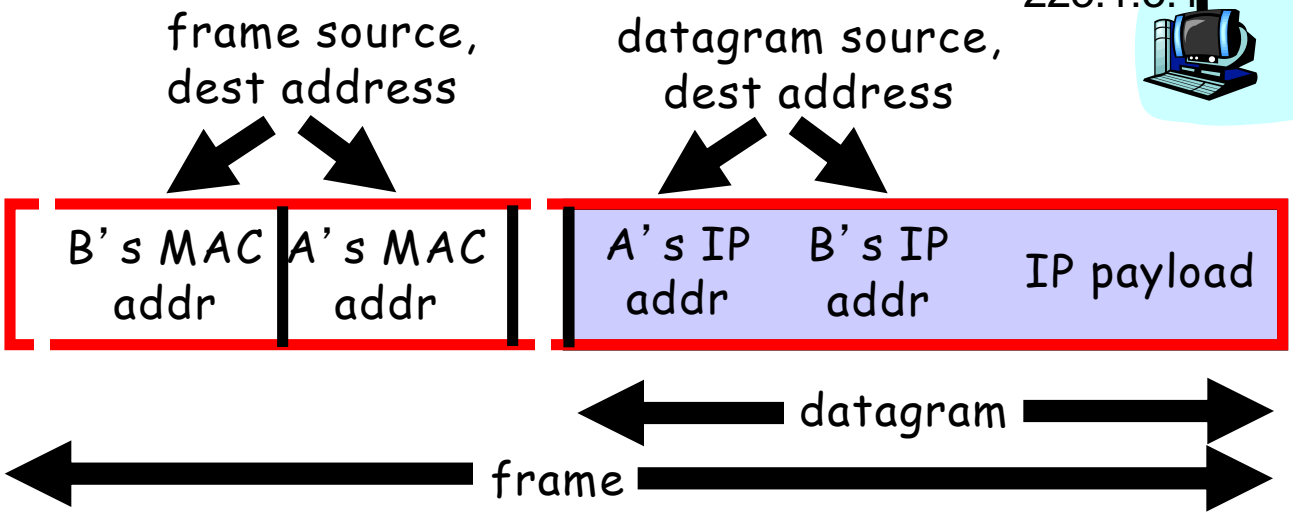
- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- Analogy:
  - (a) MAC address: like Social Security Number
  - (b) IP address: like postal address
- MAC flat address => portability
  - can move LAN card from one LAN to another
- IP hierarchical address NOT portable
  - depends on IP network to which node is attached

Recall earlier routing discussion

Starting at A, given IP datagram addressed to B:

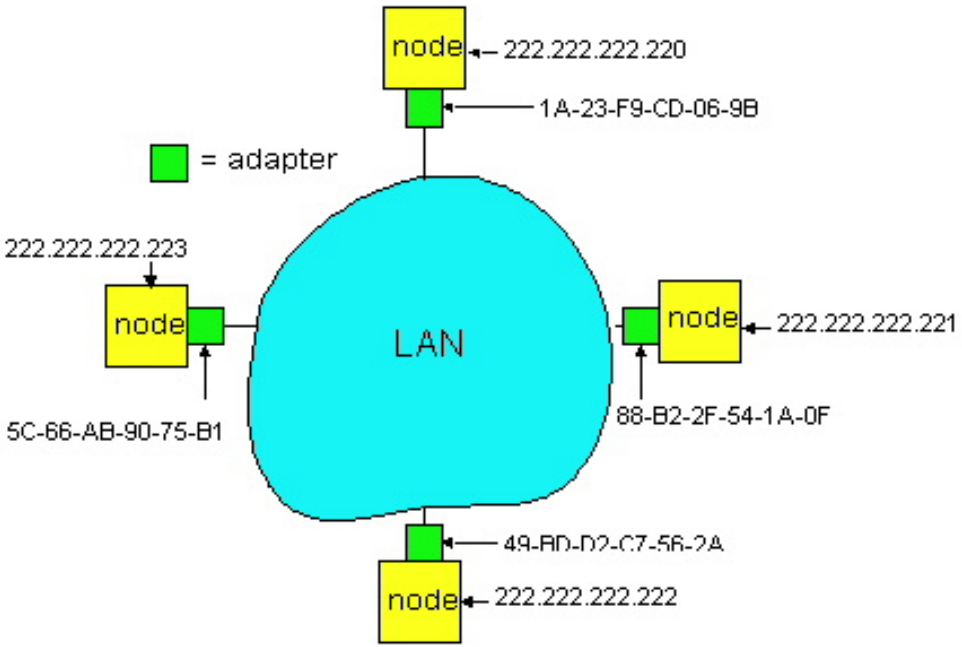
- look up net. address of B, find B on same net. as A
- link layer send datagram to B inside link-layer frame





ARP: Address Resolution Protocol

Question: how to determine MAC address of B knowing B's IP address?



- Each IP node (Host, Router) on LAN has ARP table
- ARP 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)

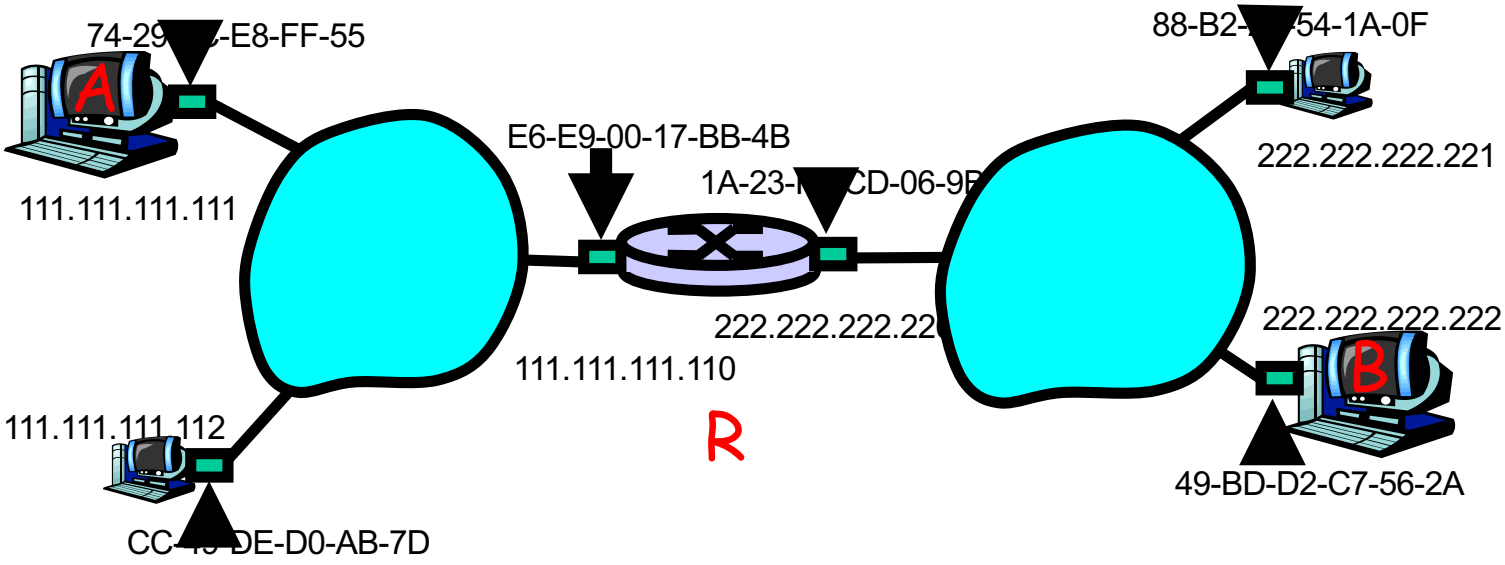
ARP protocol

- A wants to send datagram to B, and A knows B's IP address.
- Suppose B's MAC address is not in A's ARP table.
- A broadcasts ARP query packet, containing B's IP address
  - all machines on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's MAC address (unicast)
- A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed
  - USED to save ARP messages: if a receive an ARP message I cache all the informations associated to it
- ARP is "plug-and-play":
  - nodes create their ARP tables without intervention from net administrator

Addressing: routing to another LAN

walkthrough: send datagram from A to B via R

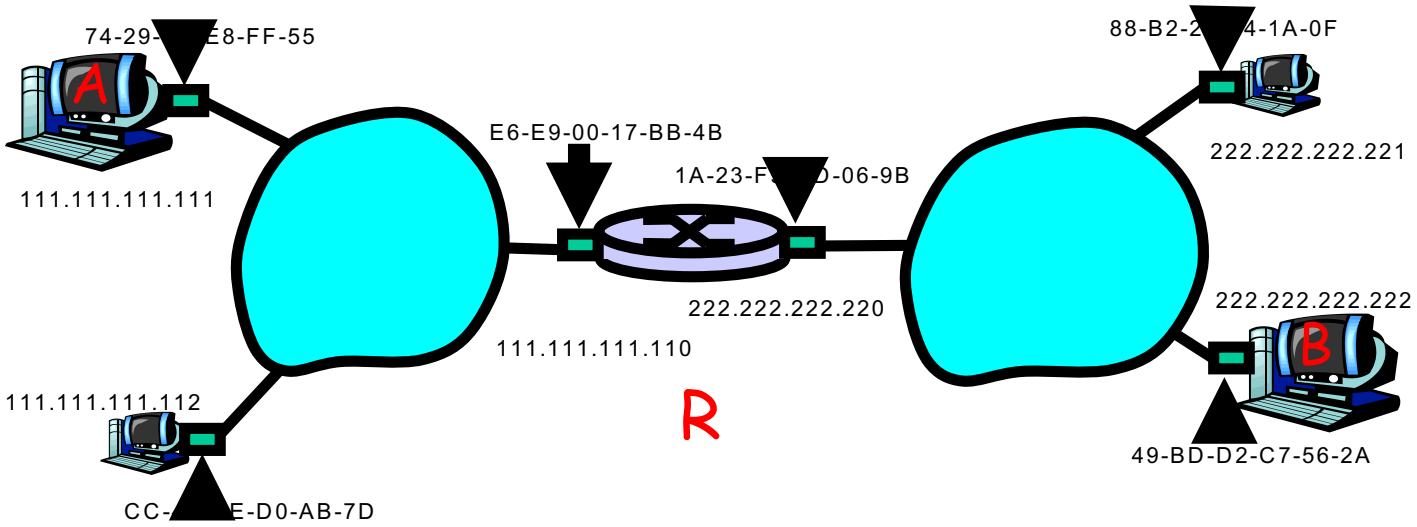
assume A knows B's IP address



- two ARP tables in router R, one for each IP network (LAN)

- A creates IP datagram with source A, destination B
- A uses ARP to get R's MAC address for 111.111.111.110
- A creates link-layer frame with R's MAC address as dest, frame contains A-to-B IP datagram
- A's NIC sends frame
- R's NIC receives frame
- R removes IP datagram from Ethernet frame, sees its destined to B
- R uses ARP to get B's MAC address
- R creates frame containing A-to-B IP datagram sends to B

This is a really important example – make sure you understand!



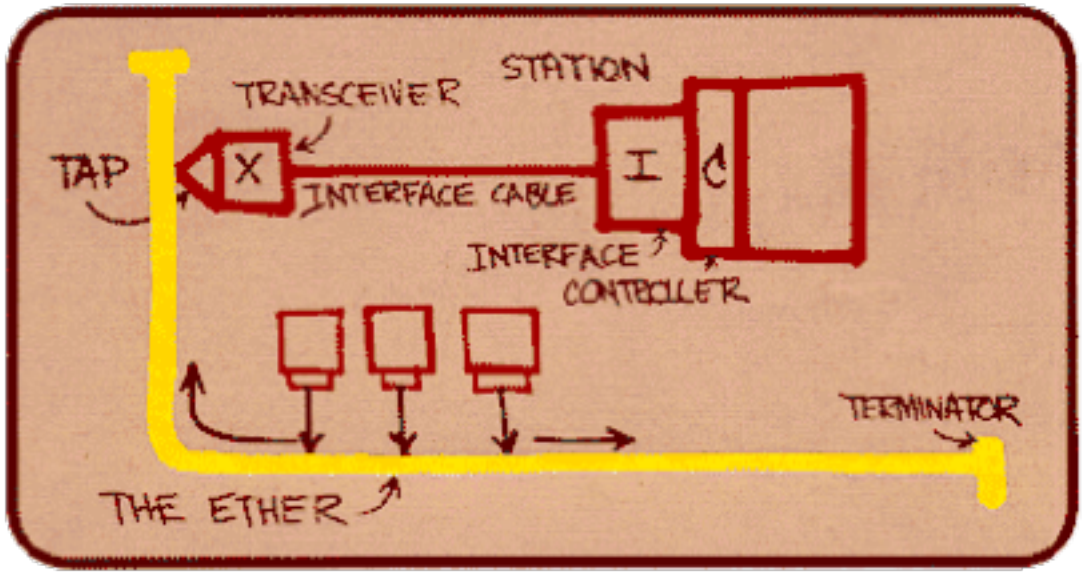
Link Layer

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3Multiple access protocols
- 5.4 Link-Layer Addressing
- 5.5 Ethernet
- 5.6 Link-layer switches
- 5.7 PPP
- 5.8 Link virtualization: MPLS
- 5.9 A day in the life of a web request

Ethernet

"dominant" wired LAN technology:

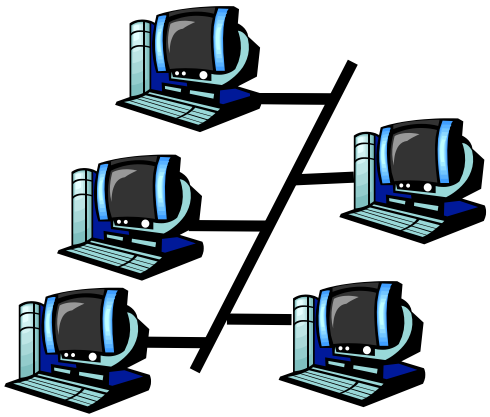
- cheap $20 for NIC
- first widely used LAN technology
- simpler, cheaper than token LANs and ATM
- kept up with speed race: 10 Mbps – 10 Gbps



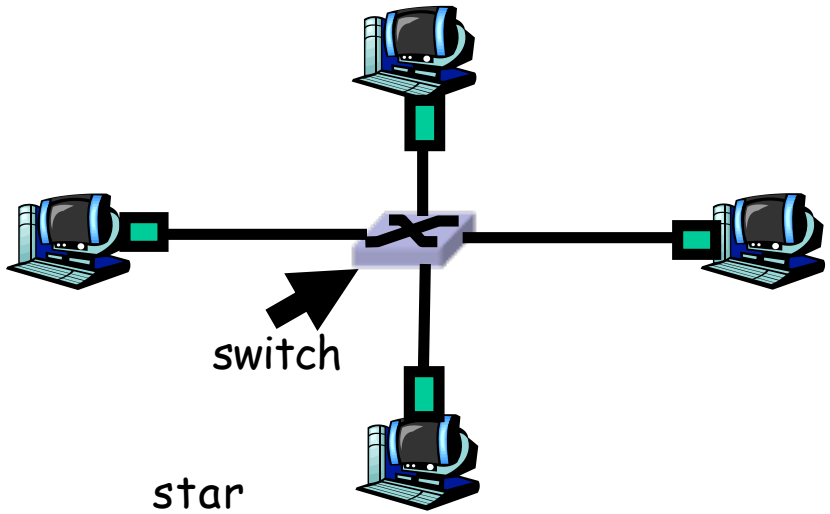
Metcalfe's Ethernet sketch

Star topology

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



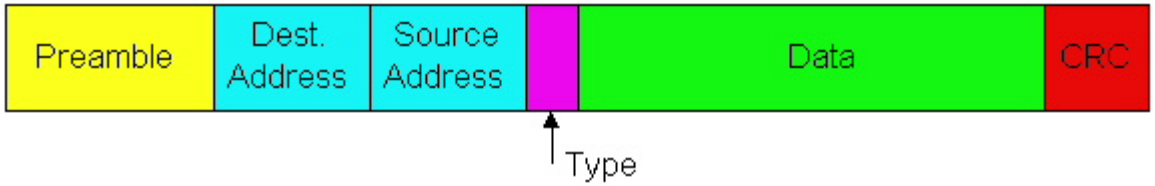
bus: coaxial cable



star

Ethernet Frame Structure

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

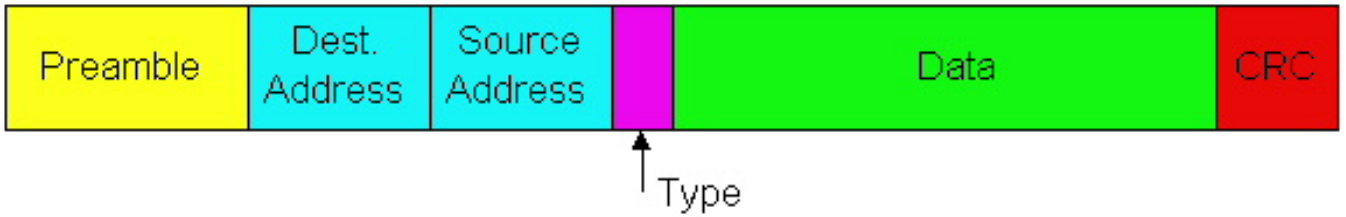


Preamble:

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

Ethernet Frame Structure (more)

- Addresses: 6 bytes
  - if adapter receives frame with matching destination address, or with broadcast address (eg ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- Type: indicates higher layer protocol (mostly IP but others possible, e.g., Novell IPX, AppleTalk)
- CRC: checked at receiver, if error is detected, frame is dropped



Ethernet: Unreliable, connectionless

- connectionless: No handshaking between sending and receiving NICs
- unreliable: receiving NIC doesn't send acks or nacks to sending NIC
  - stream of datagrams passed to network layer can have gaps (missing datagrams)
  - gaps will be filled if app is using TCP
  - otherwise, app will see gaps
- Ethernet's MAC protocol: unslotted CSMA/CD

Ethernet CSMA/CD algorithm

1. NIC receives datagram from network layer, creates frame
2. If NIC senses channel idle, starts frame transmission If NIC senses channel busy, waits until channel idle, then transmits
3. If NIC transmits entire frame without detecting another transmission, NIC is done with frame !
4. If NIC detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, NIC enters **exponential backoff**: after *m*th 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

Ethernet's CSMA/CD (more)

Jam Signal: make sure all other transmitters are aware of collision; 48 bits

Bit time: .1 microsec for 10 Mbps Ethernet ; for K=1023, wait time is about 50 msec

Exponential Backoff:

- *Goal*: adapt retransmission attempts to estimated current load
  - heavy load: random wait will be longer
- first collision: choose K from {0,1}; delay is K· 512 bit transmission times
- after second collision: choose K from {0,1,2,3}…
- after ten collisions, choose K from {0,1,2,3,4,…,1023}

CSMA/CD efficiency

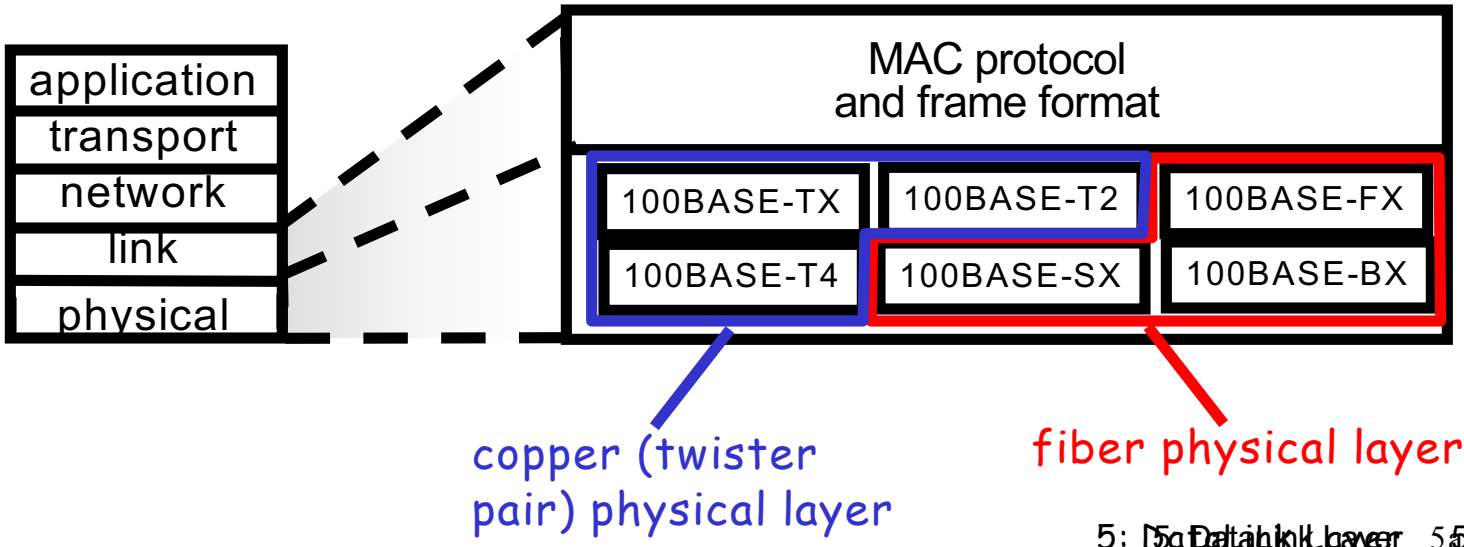
- T_{prop} = max prop delay between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame

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

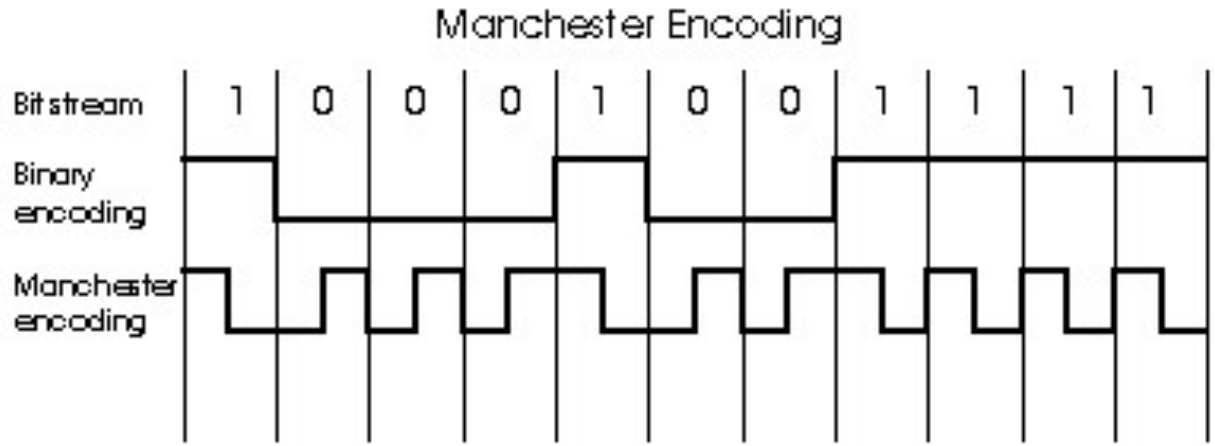
- efficiency goes to 1
  - as t_{prop} goes to 0
  - as t_{trans} goes to infinity
- better performance than ALOHA: and simple, cheap, decentralized!

802.3 Ethernet Standards: Link & Physical Layers

- *many* different Ethernet standards
  - common MAC protocol and frame format
  - different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10G bps
  - different physical layer media: fiber, cable



Manchester encoding



- used in 10BaseT
- each bit has a transition
- allows clocks in sending and receiving nodes to synchronize to each other
  - no need for a centralized, global clock among nodes!
- Hey, this is physical-layer stuff!

Ethernet: some numbers..

- Slot time 512 bit times (di riferimento, la tras missione NON e' slottizzata!!)
- Interframegap 9.6 micros
- Number of times max for retransmitting a frame 16
- Backoff limit (2 $^{\text{backoff limit}}$ indicates max length of the backoff interval): 10
- Jam size: 48 bits
- Max frame size: 1518 bytes
- Min frame size 64 bytes (512 bits)
- Address size: 48 bits

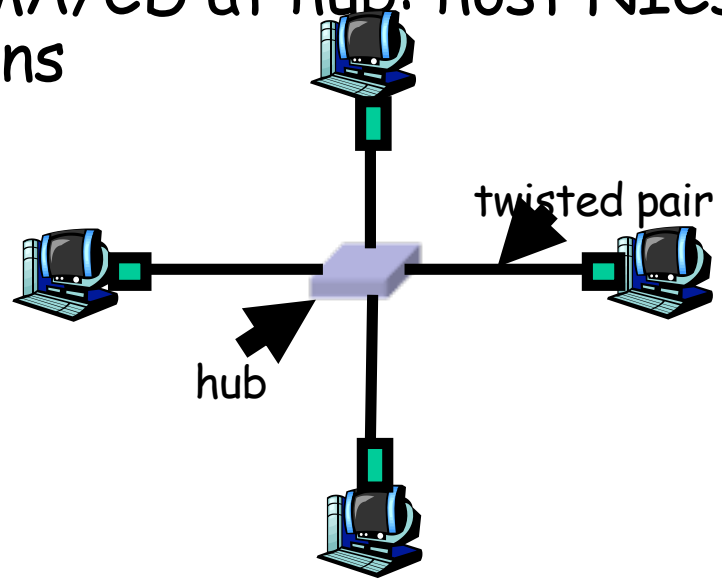
Link Layer

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3 Multiple access protocols
- 5.4 Link-layer Addressing
- 5.5 Ethernet
- 5.6 Link-layer switches, LANs, VLANs
- 5.7 PPP
- 5.8 Link virtualization: MPLS
- 5.9 A day in the life of a web request

Hubs

… physical-layer ("dumb") repeaters:

- bits coming in one link go out *all* other links at same rate
- all nodes connected to hub can collide with one another
- no frame buffering
- no CSMA/CD at hub: host NICs detect collisions

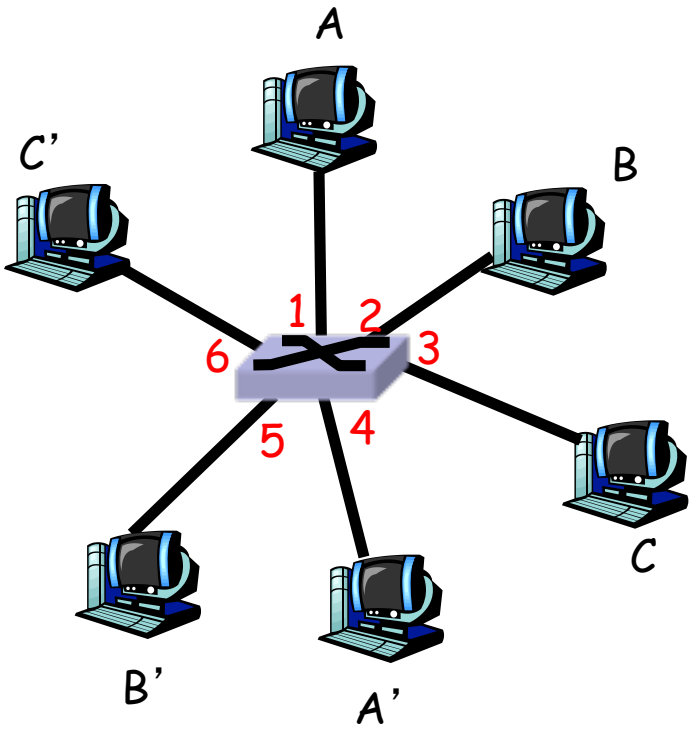


Switch

- link-layer device: smarter than hubs, take *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, selectively forward frame to one-or-more outgoing links
- *transparent*
  - hosts are unaware of presence of switches
- *plug-and-play, self-learning*
  - switches do not need to be configured

Switch: allows *multiple* simultaneous transmissions

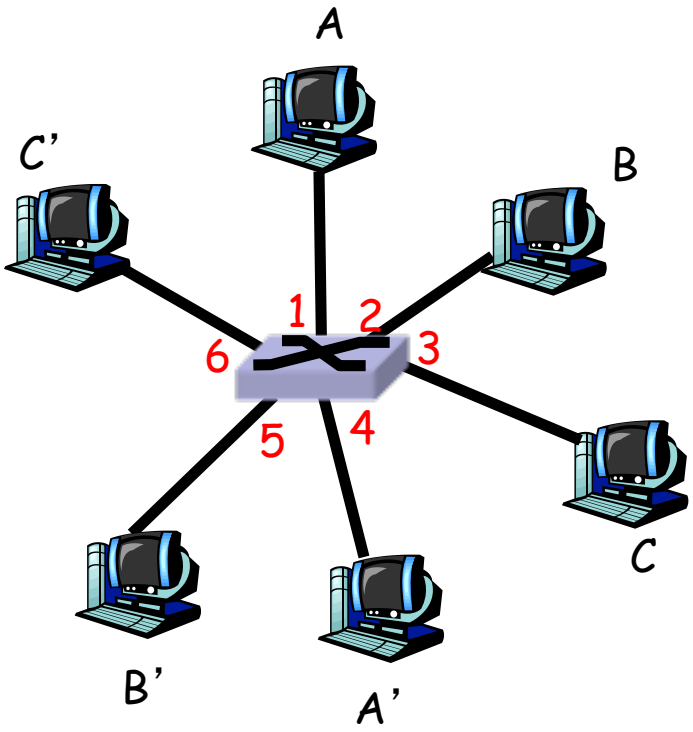
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, but no collisions; full duplex
  - each link is its own collision domain
- *switching:* A-to-A' and B-to-B' simultaneously, without collisions
  - not possible with dumb hub



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

Switch Table

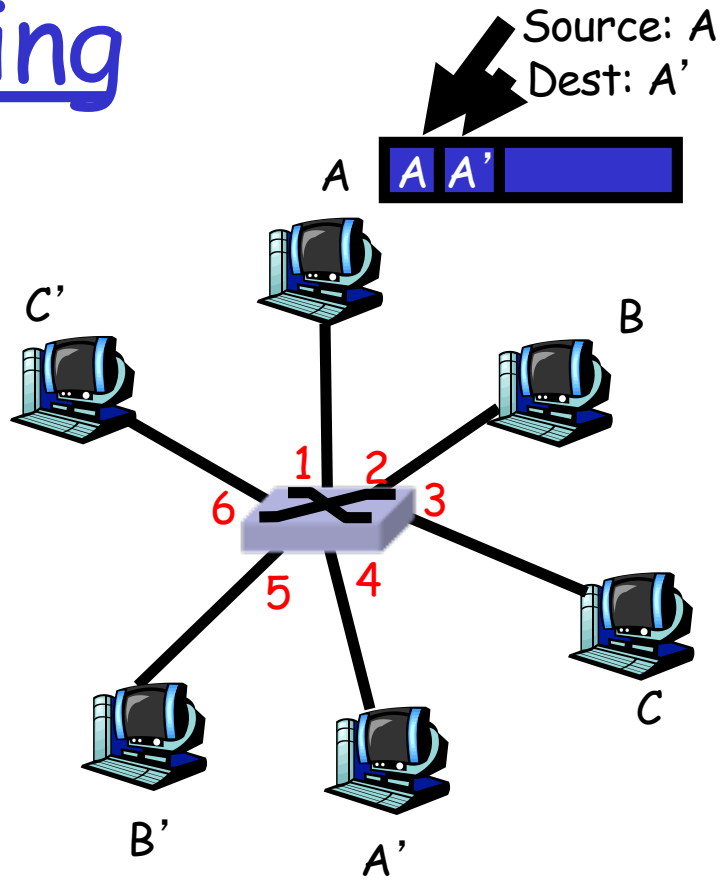
- *Q:* how does switch know that A' reachable via interface 4, B' reachable via interface 5?
- *A:* each switch has a switch table, each entry:
  - (MAC address of host, interface to reach host, time stamp)
- looks like a routing table!
- *Q:* how are entries created, maintained in switch table?
  - something like a routing protocol?



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

Switch: self-learning

- 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

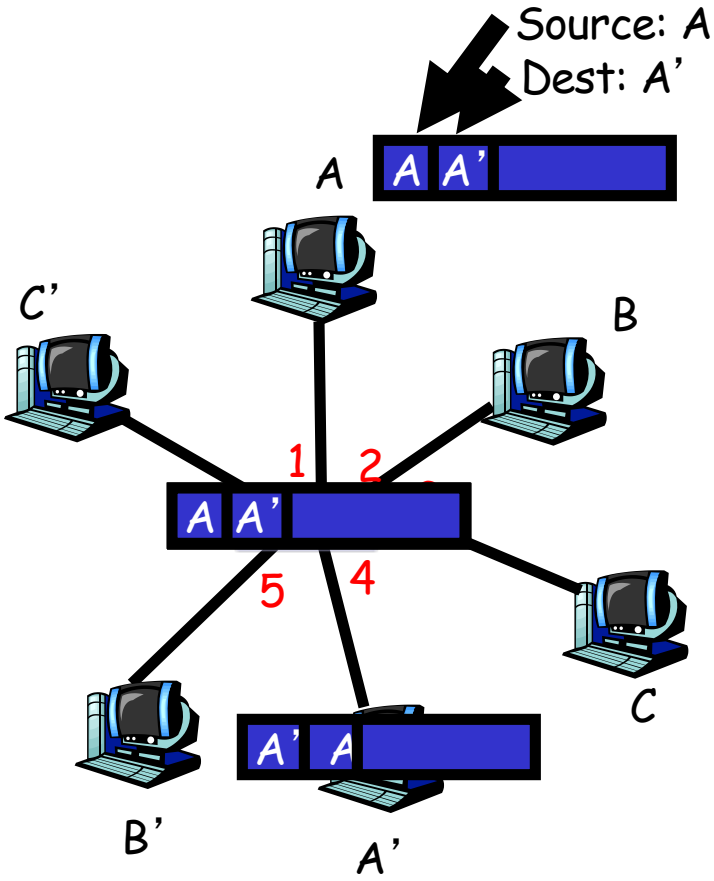
When frame received:

1. record link associated with sending host
2. index switch table using MAC dest address
3. **if** entry found for destination
   then {
   if dest on segment from which frame arrived
   then drop the frame
   else forward the frame on interface indicated
   }
   else flood

forward on all but the interface on which the frame arrived

Self-learning, forwarding: example

- frame destination unknown: *flood*
- destination A location known: *selective send*

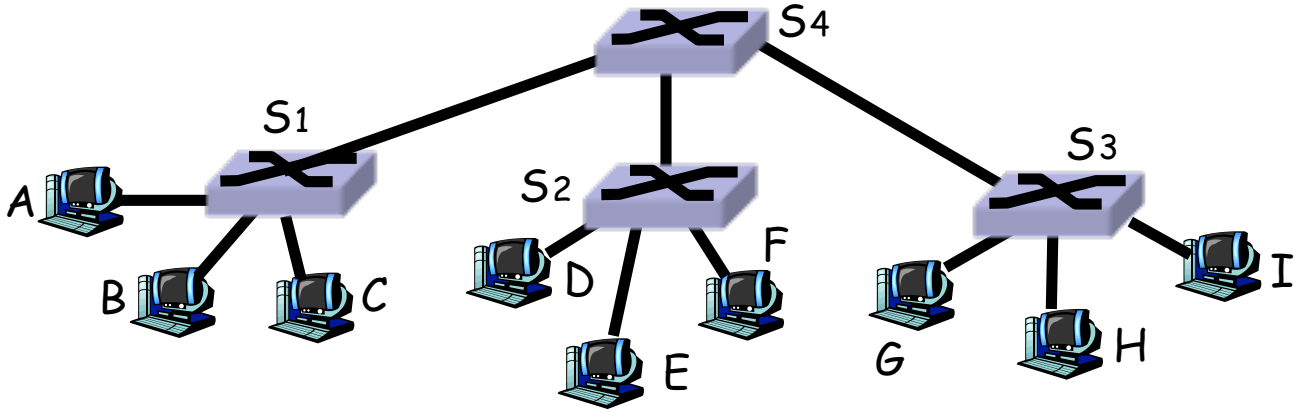


MAC addr	interface	TTL
A	1	60
A'	4	60

Switch table (initially empty)

Interconnecting switches

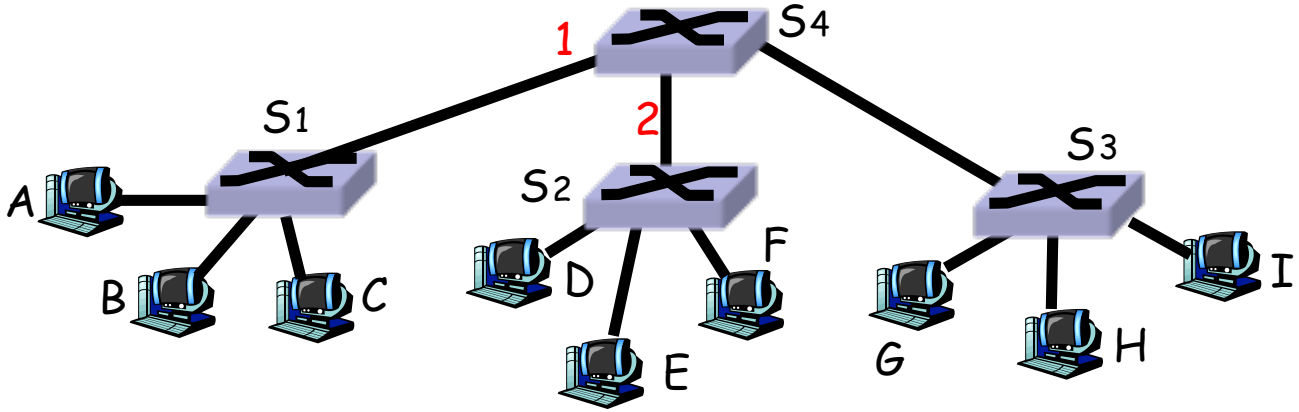
- switches can be connected together



- *Q:* sending from A to G - how does S_1 know to forward frame destined to F via S_4 and S_3?
- *A:* self learning! (works exactly the same as in single-switch case!)

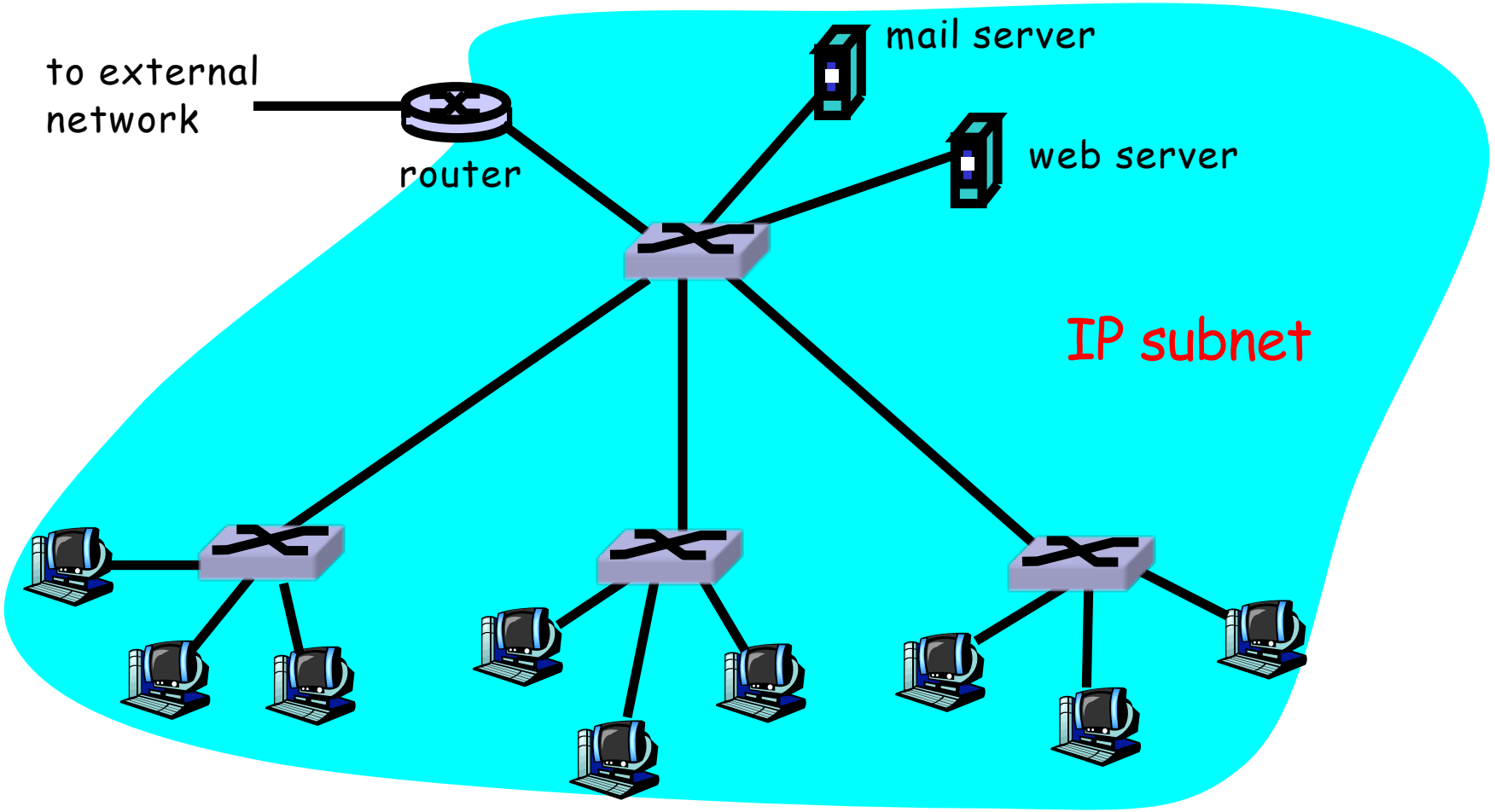
Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



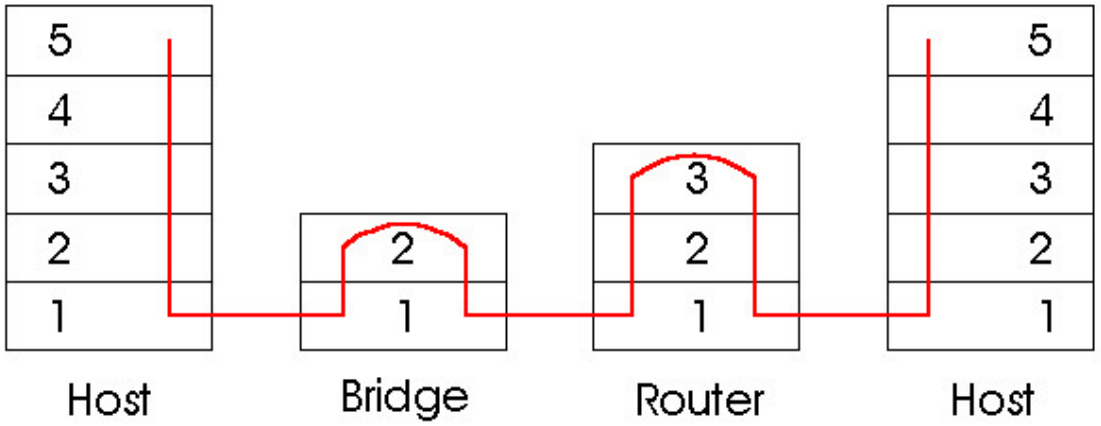
- *Q:* show switch tables and packet forwarding in S_1, S_2, S_3, S_4

Institutional network



Switches vs. Routers

- both store-and-forward devices
  - routers: network layer devices (examine network layer headers)
  - switches are link layer devices
- routers maintain routing tables, implement routing algorithms
- switches maintain switch tables, implement filtering, learning algorithms



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Virtualization of networks

Virtualization of resources: powerful abstraction in systems engineering:

- computing examples: virtual memory, virtual devices
  - Virtual machines: e.g., java
  - IBM VM os from 1960's/70's
- layering of abstractions: don't sweat the details of the lower layer, only deal with lower layers abstractly

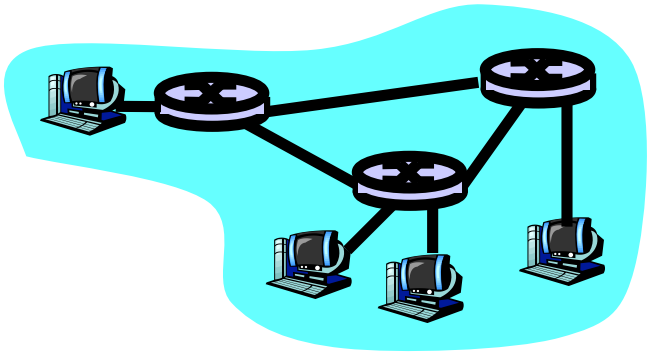
The Internet: virtualizing networks

1974: multiple unconnected nets

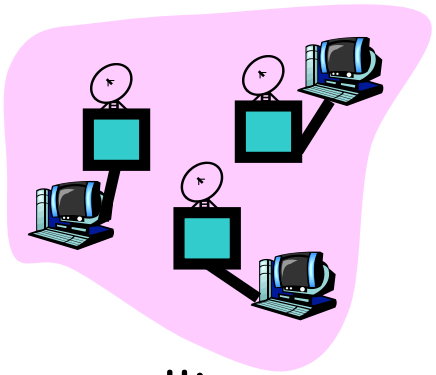
- ARPAnet
- data-over-cable networks
- packet satellite network (Aloha)
- packet radio network

... differing in:

- addressing conventions
- packet formats
- error recovery
- routing



ARPAnet



satellite net

"A Protocol for Packet Network Intercommunication", V. Cerf, R. Kahn, IEEE Transactions on Communications, May, 1974, pp. 637-648.

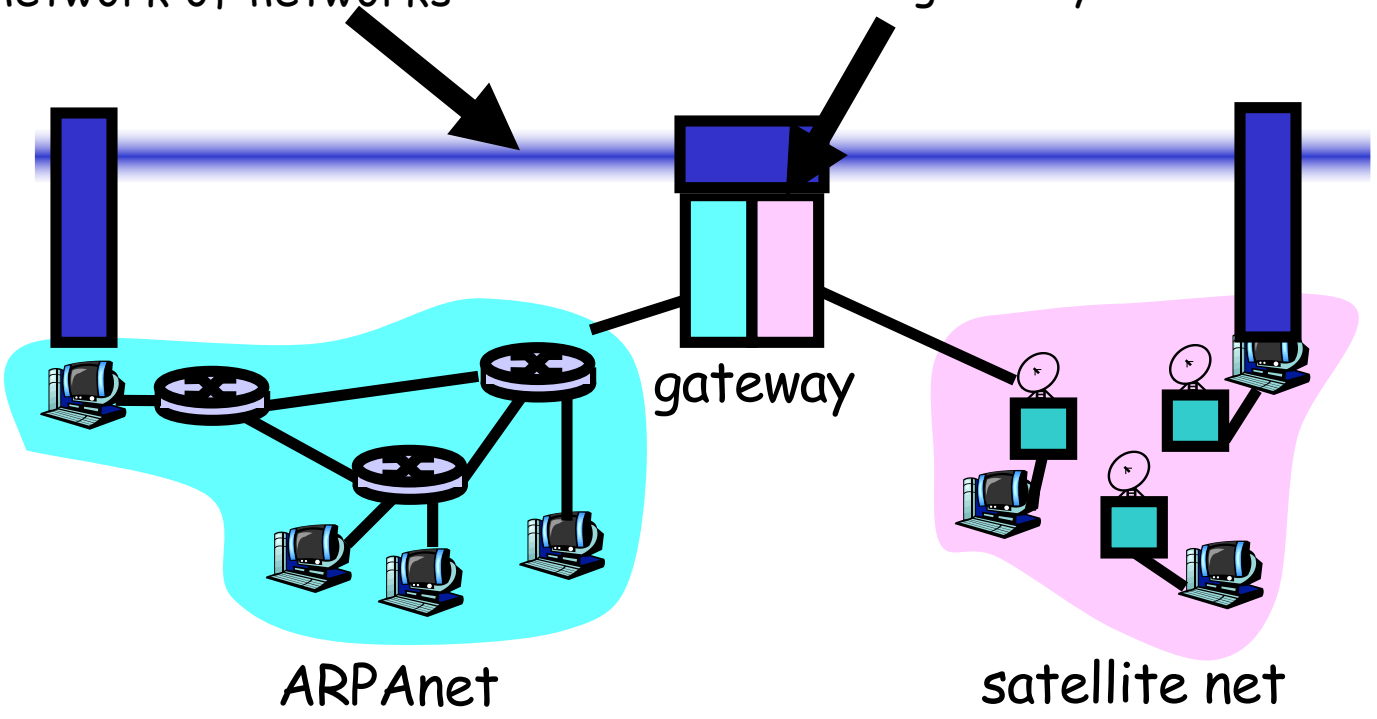
The Internet: virtualizing networks

Internetwork layer (IP):

- addressing: internetwork appears as single, uniform entity, despite underlying local network heterogeneity
- network of networks

Gateway:

- "embed internetwork packets in local packet format or extract them"
- route (at internetwork level) to next gateway



Cerf & Kahn's Internetwork Architecture

What is virtualized?

- two layers of addressing: internetwork and local network
- new layer (IP) makes everything homogeneous at internetwork layer
- underlying local network technology
  - cable
  - satellite
  - 56K telephone modem
  - today: ATM, MPLS

... "invisible" at internetwork layer. Looks like a link layer technology to IP!

ATM and MPLS

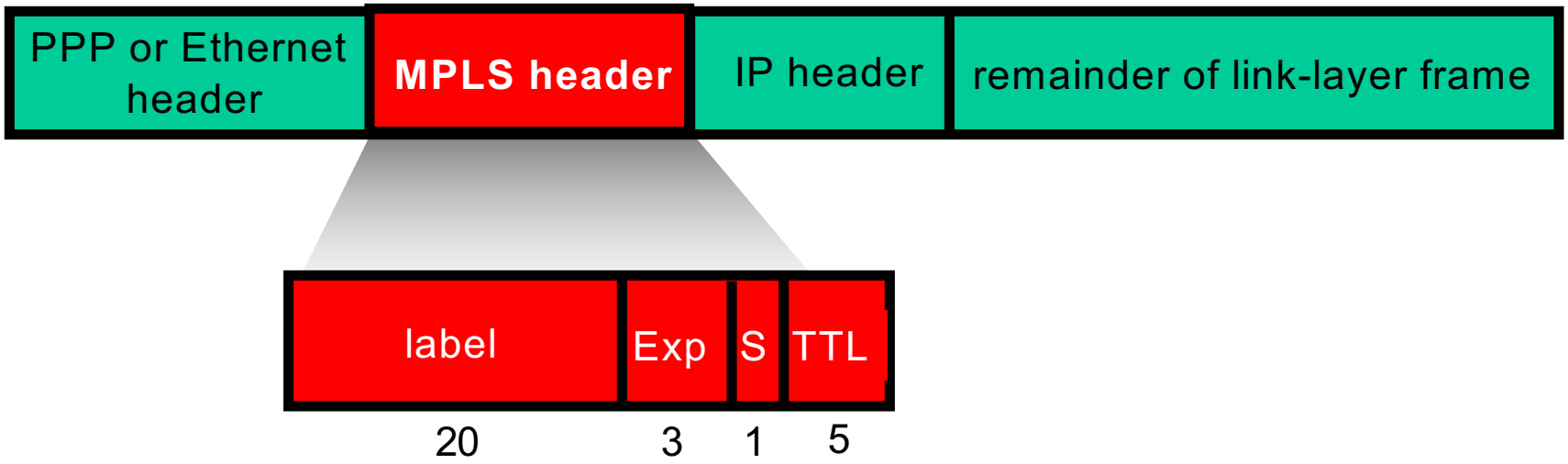
- ATM, MPLS separate networks in their own right
  - different service models, addressing, routing from Internet
- viewed by Internet as logical link connecting IP routers
  - just like dialup link is really part of separate network (telephone network)
- ATM, MPLS: of technical interest in their own right

Asynchronous Transfer Mode: ATM

- **1990's/00 standard for high-speed** (155Mbps to 622 Mbps and higher) *Broadband Integrated Service Digital Network* architecture
- Goal: *integrated, end-end transport of carry voice, video, data*
  - meeting timing/QoS requirements of voice, video (versus Internet best-effort model)
  - "next generation" telephony: technical roots in telephone world
  - packet-switching (fixed length packets, called "cells") using virtual circuits

Multiprotocol label switching (MPLS)

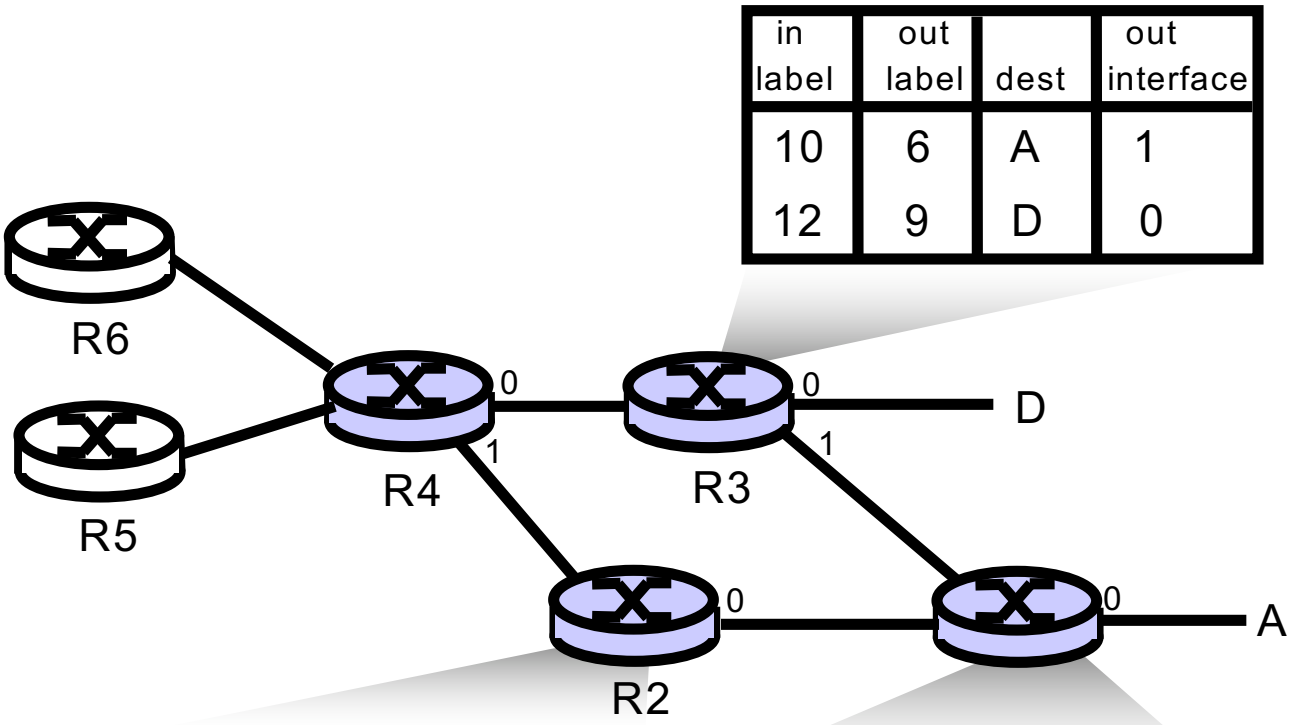
- initial goal: speed up IP forwarding by using fixed length label (instead of IP address) to do forwarding
  - borrowing ideas from Virtual Circuit (VC) approach
  - but IP datagram still keeps IP address!



MPLS capable routers

- a.k.a. label-switched router
- forwards packets to outgoing interface based only on label value (don't inspect IP address)
  - MPLS forwarding table distinct from IP forwarding tables
- signaling protocol needed to set up forwarding
  - RSVP-TE
  - forwarding possible along paths that IP alone would not allow (e.g., source-specific routing) !!
  - use MPLS for traffic engineering
- must co-exist with IP-only routers

MPLS forwarding tables



in label	out label	dest	out interface
10	6	A	1
12	9	D	0

in label	out label	dest	out interface
8	6	A	0

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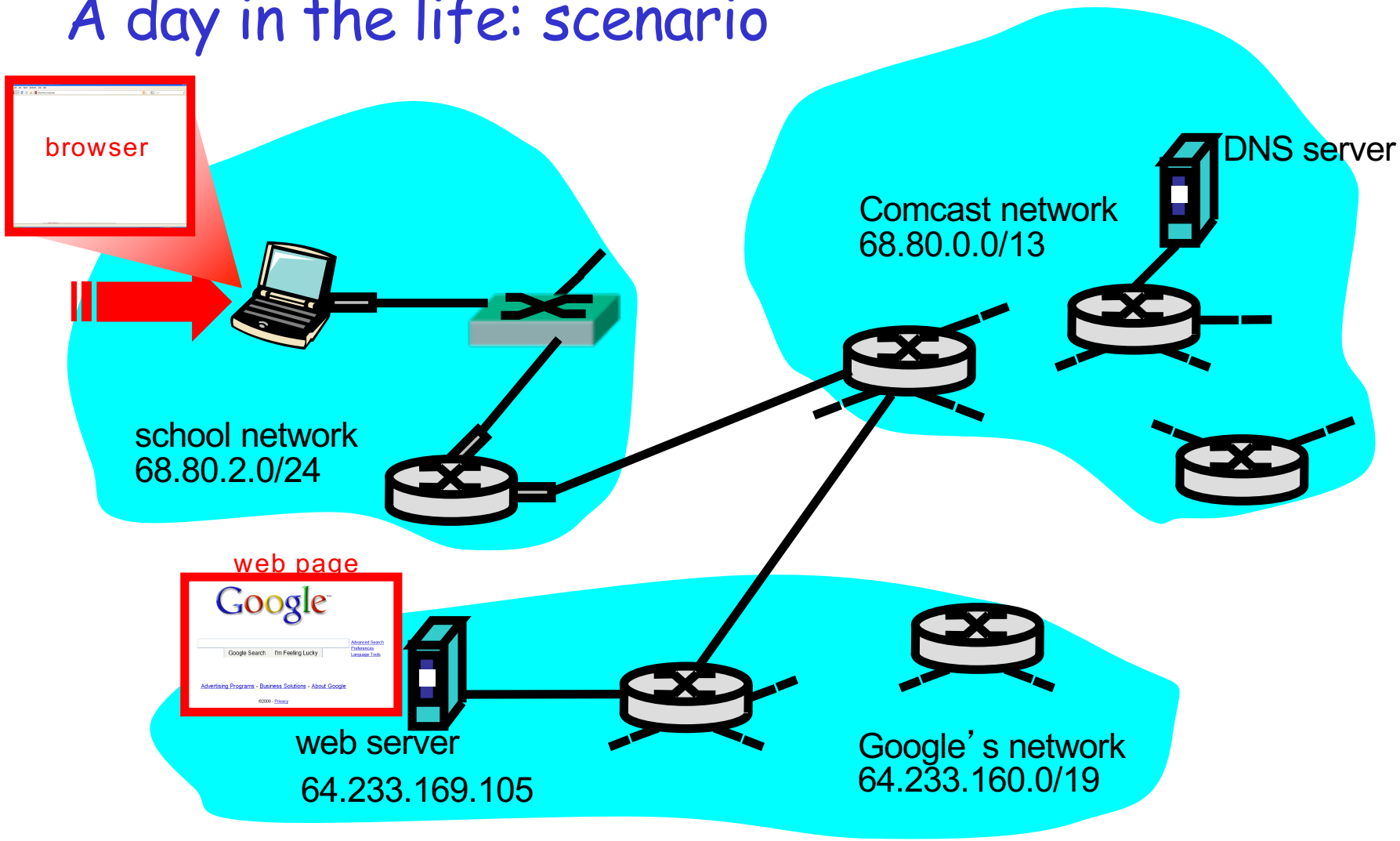
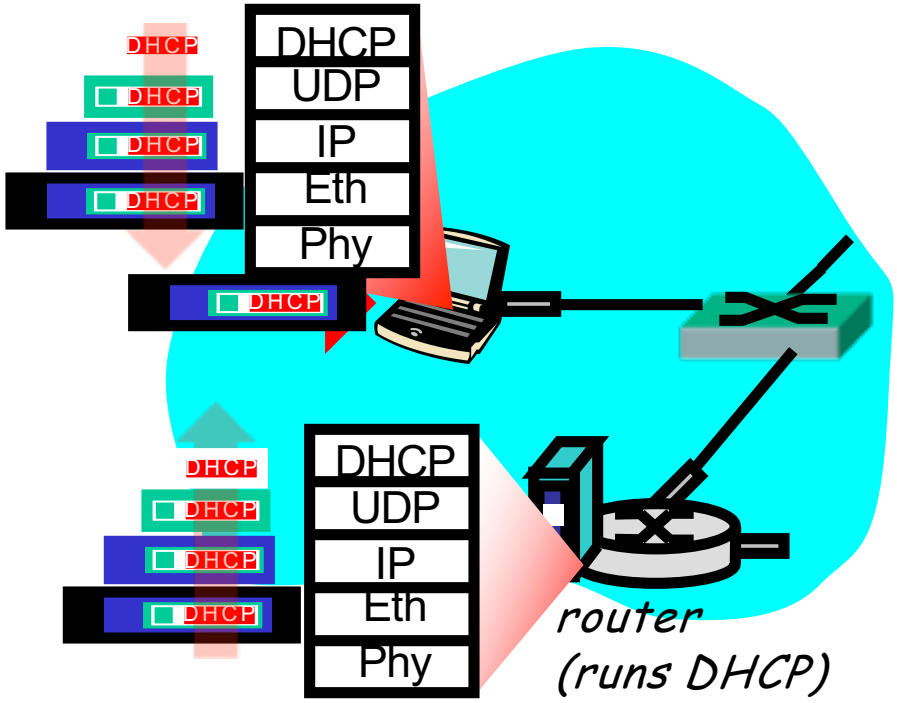
Synthesis: a day in the life of a web request

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

A day in the life: scenario

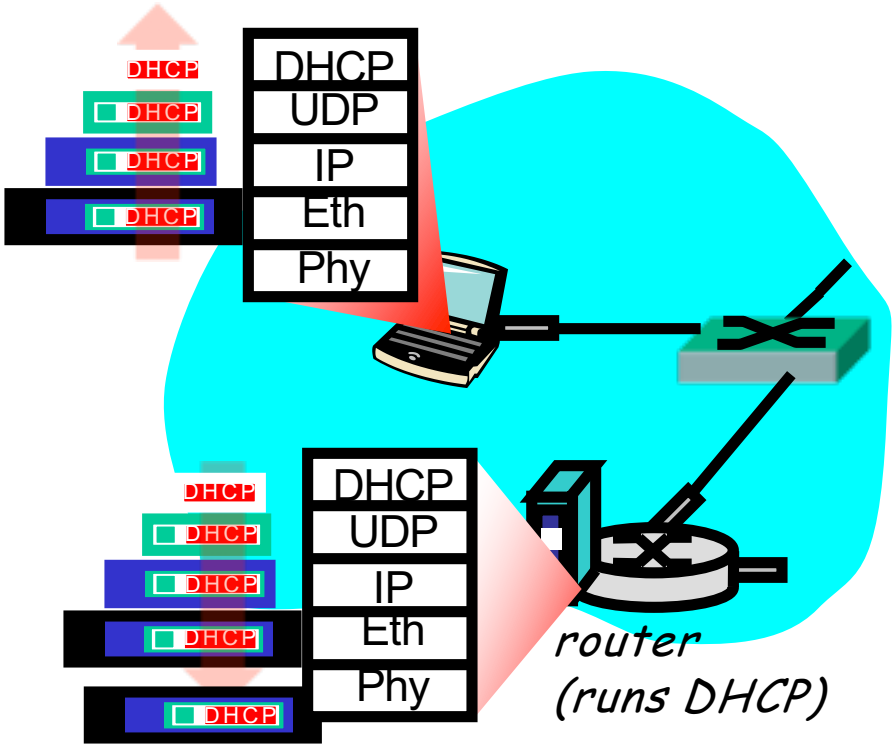


A day in the life… connecting to the Internet



- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use *DHCP*
- DHCP request *encapsulated* in *UDP*, encapsulated in *IP*, encapsulated in *802.1* Ethernet
- Ethernet frame *broadcast* (dest: FFFFFFFFFFFF) on LAN, received at router running *DHCP* server
- Ethernet *demux'ed* to IP demux'ed, UDP demux'ed to DHCP

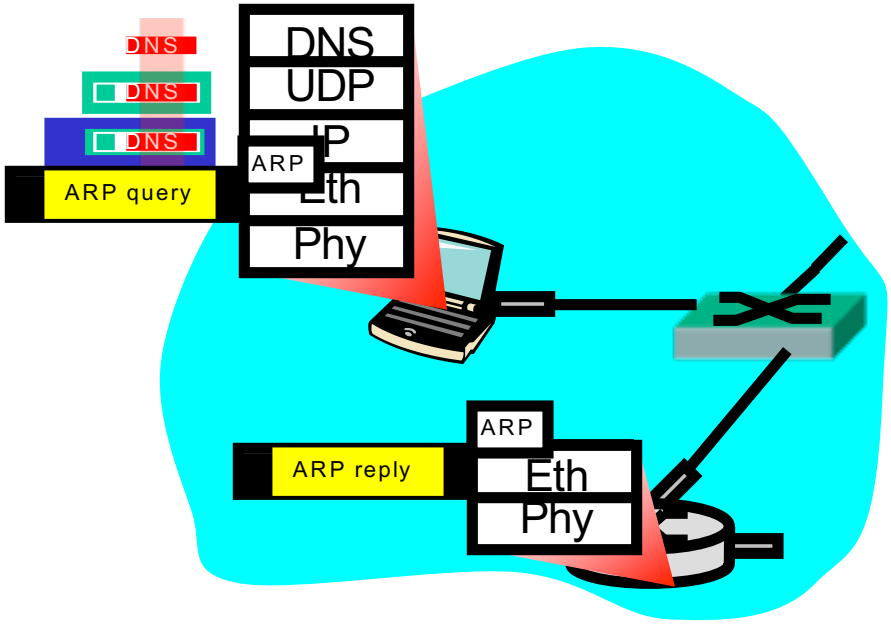
A day in the life… connecting to the Internet



- 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

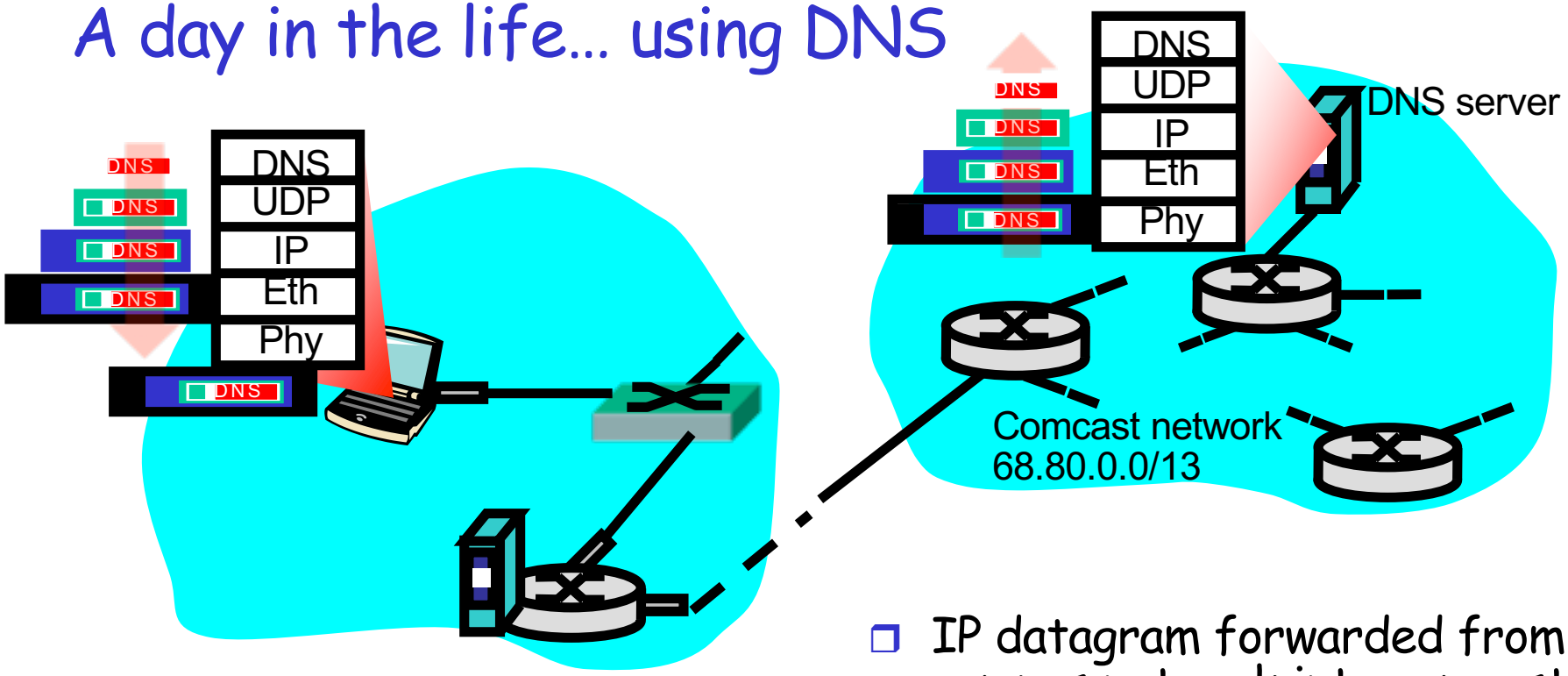
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

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



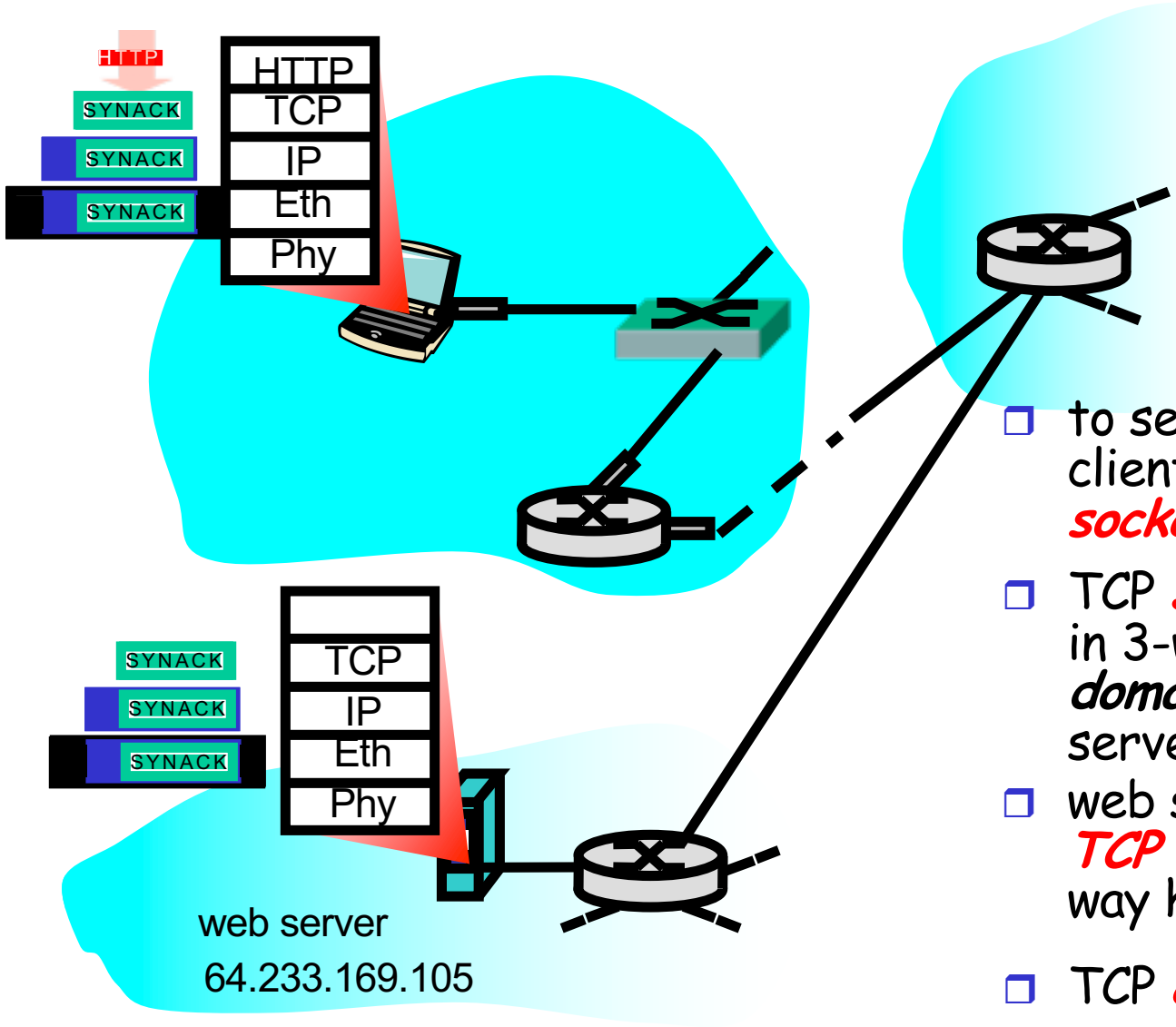
- before sending *HTTP* request, need IP address of www.google.com: *DNS*
- DNS query created, encapsulated in UDP, encapsulated in IP, encasulated in Eth. In order to send frame to router, need MAC address of router interface: *ARP*
- *ARP query* broadcast, received by router, which replies with *ARP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

A day in the life… using DNS



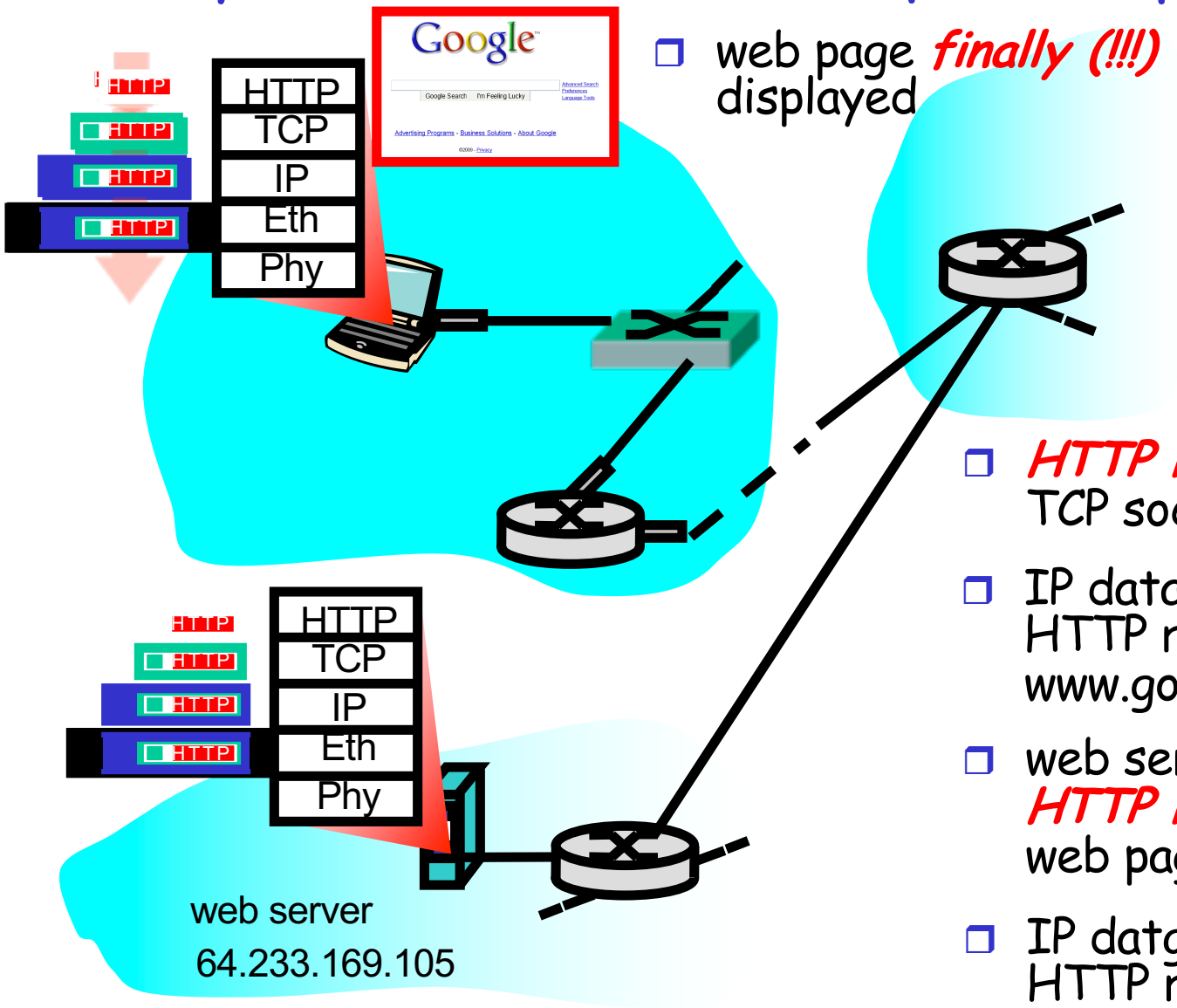
- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router
- IP datagram forwarded from campus network into comcast network, routed (tables created by ***RIP, OSPF, IS-IS*** and/or ***BGP*** routing protocols) to DNS server
- demux'ed to DNS server
- DNS server replies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

A day in the life… TCP connection carrying HTTP



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

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



- web page *finally (!!!)* displayed

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

Chapter 5 outline

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3Multiple access protocols
- 5.4 LAN addresses and ARP
- 5.5 Ethernet
- 5.6 Hubs, bridges, and switches
- 5.7 Wireless links and LANs
- 5.8 PPP
- 5.9 ATM
- 5.10 Frame Relay

IEEE 802.11 Wireless LAN

802.11b

- 2.4-5 GHz unlicensed radio spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
  - all hosts use same chipping code
- widely deployed, using base stations

802.11a

- 5-6 GHz range
- up to 54 Mbps

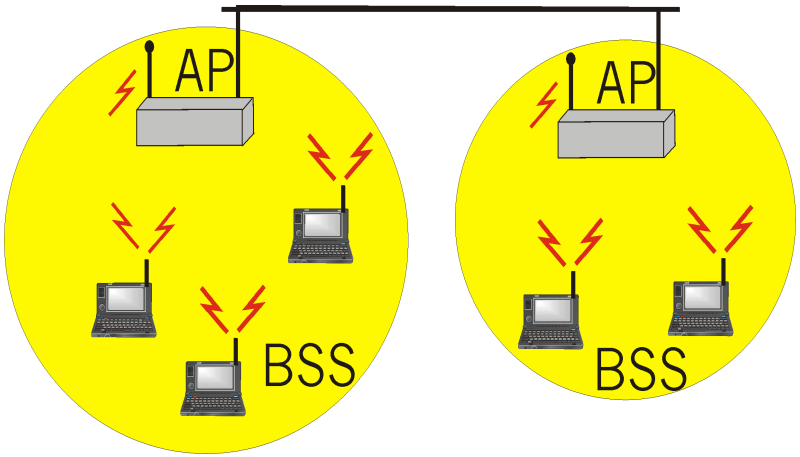
802.11g

- 2.4-5 GHz range
- up to 54 Mbps

- All use CSMA/CA for multiple access
- All have base-station and ad-hoc network versions

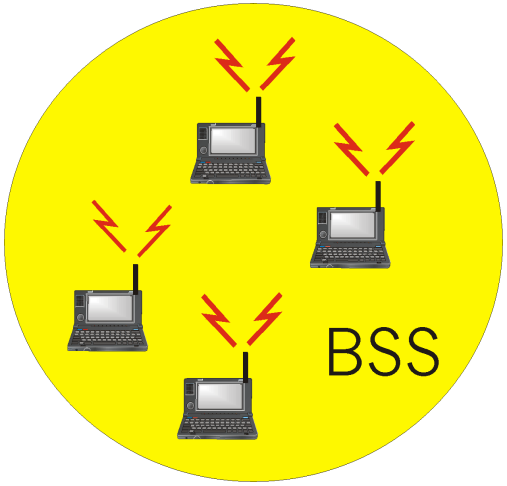
Base station approch

- Wireless host communicates with a base station
  - base station = access point (AP)
- Basic Service Set (BSS) (a.k.a. "cell") contains:
  - wireless hosts
  - access point (AP): base station
- BSS's combined to form distribution system (DS)



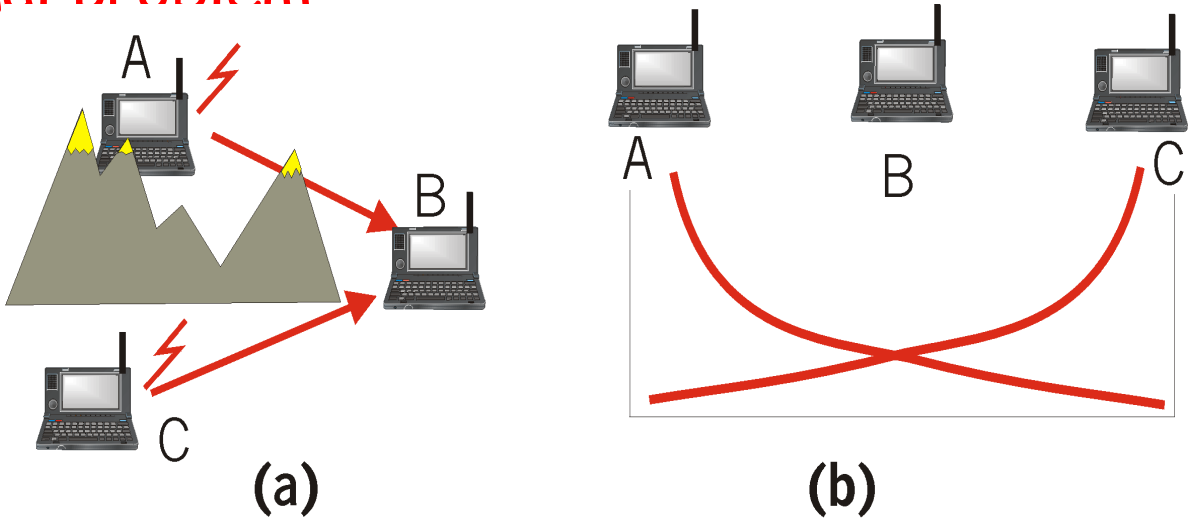
Ad Hoc Network approach

- No AP (i.e., base station):IBSS (independent Basic Service Set)
- wireless hosts communicate with each other
  - to get packet from wireless host A to B may need to route through wireless hosts X,Y,Z
- Applications:
  - "laptop" meeting in conference room, car
  - interconnection of "personal" devices
  - battlefield
- IETF MANET (Mobile Ad hoc Networks) working group



IEEE 802.11: multiple access

- Collision if 2 or more nodes within transmission range transmit at same time
- CSMA makes sense:
  - get all the bandwidth if you're the only one transmitting
  - shouldn't cause a collision if you sense another transmission
- Collision detection has problems (send and receive simoultaneously not allowed) and doesn't work: hidden terminal problem



IEEE 802.11 MAC Protocol: CSMA/CA

802.11 CSMA: sender

- if sense channel idle for **DISF** (Distributed Interframe Space) sec. then transmit entire frame (no collision detection)

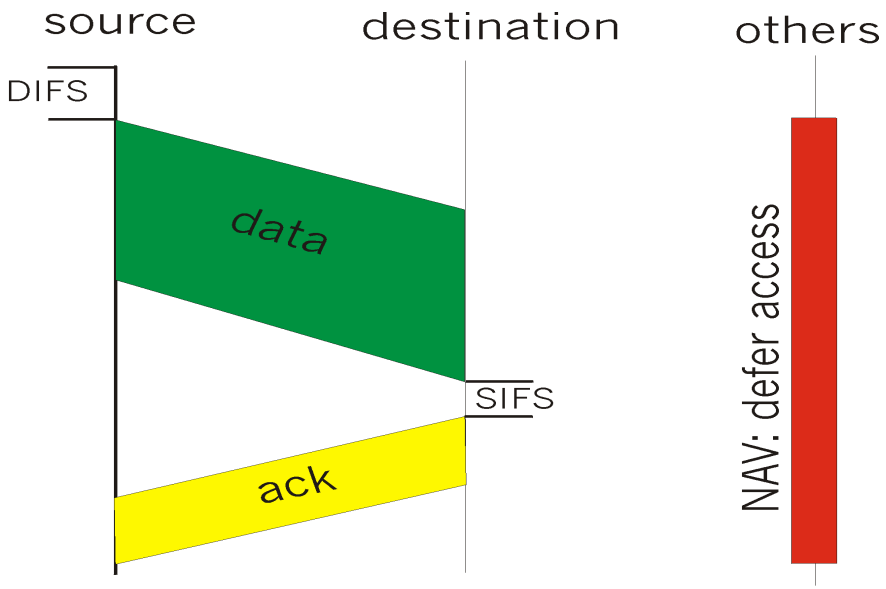
-if sense channel busy then binary backoff (waits until channel sensed idle + random interval selected according to binary backoff rules)

802.11 CSMA receiver

- if received OK

return ACK after **SIFS(Short InterFrame Spacing)**

(ACK is needed due to hidden terminal problem)

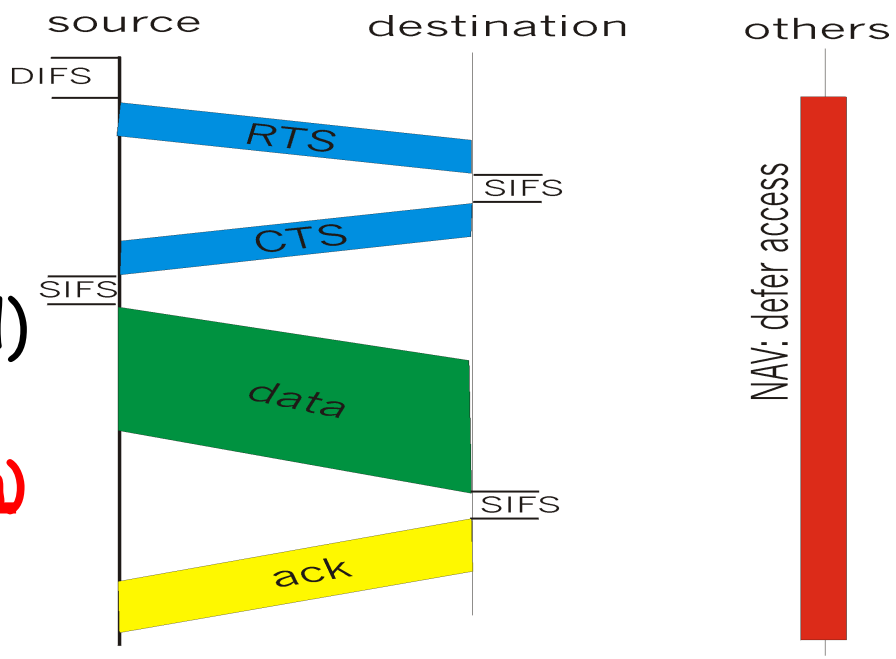


Collision avoidance mechanisms

- Problem:
  - two nodes, hidden from each other, transmit complete frames to base station
  - wasted bandwidth for long duration !
- Solution:
  - small reservation packets
  - nodes track reservation interval with internal "network allocation vector" (NAV)

Collision Avoidance: RTS-CTS exchange

- sender transmits short RTS (request to send) packet: indicates duration of transmission
- receiver replies with short CTS (clear to send) packet
  - notifying (possibly hidden) nodes
- hidden nodes will not transmit for specified duration: NAV



Collision Avoidance: RTS-CTS exchange

- RTS and CTS short:
  - collisions less likely, of shorter duration
  - end result similar to collision detection
- IEEE 802.11 allows:
  - CSMA
  - CSMA/CA: reservations
  - polling from AP