Computer Network

Link Layer

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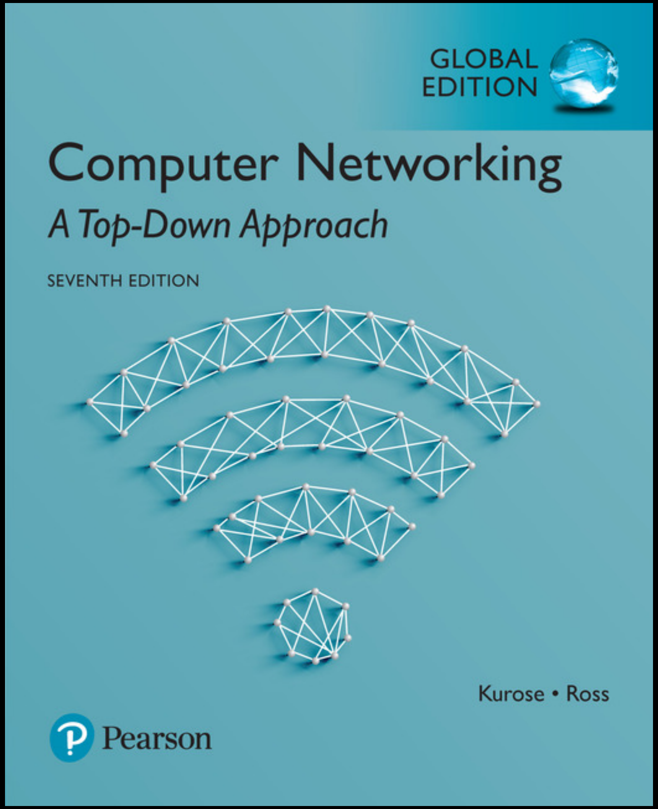
Textbook



Computer Networking

A Top–Down Approach

7th edition

Jim Kurose, Keith Ross

Pearson

April 2016

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Computer Network introduction

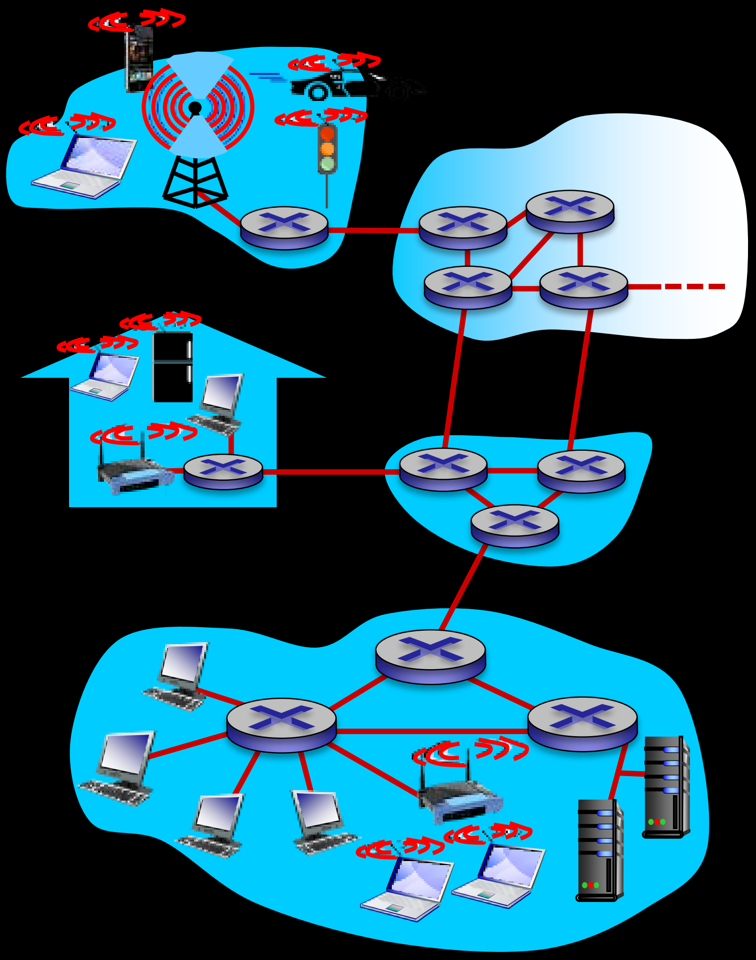
Contents

Computer Network introduction

01. Link Layer Basics

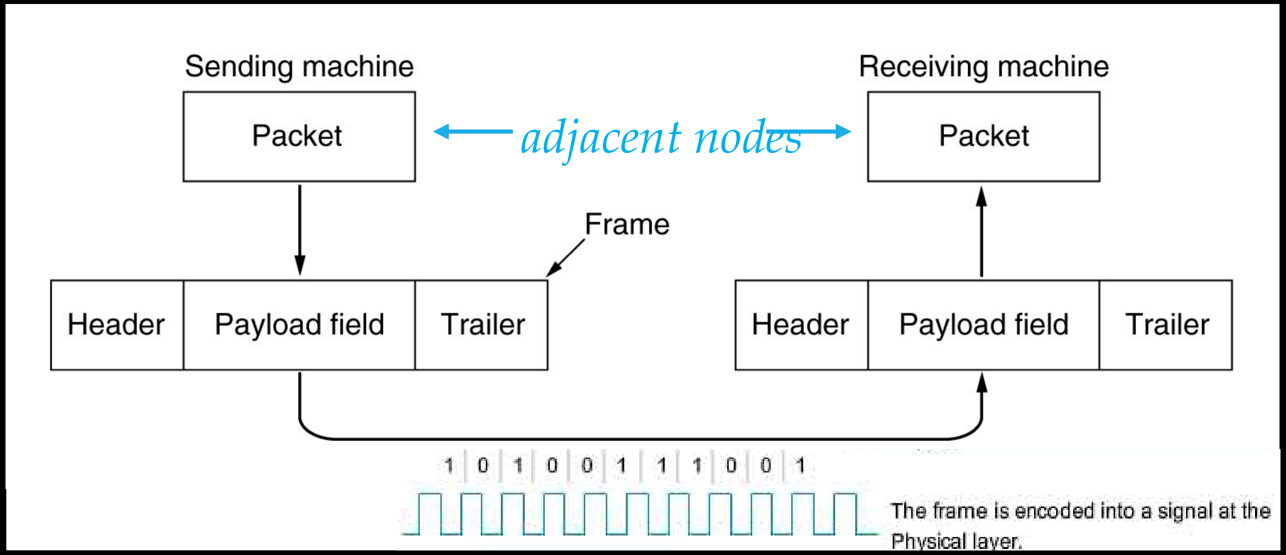
Link Layer Terminologies

- Node: host and router
- Link (or media): communication channel that connects adjacent nodes along communication path
  - wired
  - wireless
- Frame
  - layer-2 packet
  - encapsulates datagram



Link Layer Basic Functions

- Responsible for transferring datagram from one node to <u>physically adjacent</u> node over a link
  - bit error handling
  - packet collision handling



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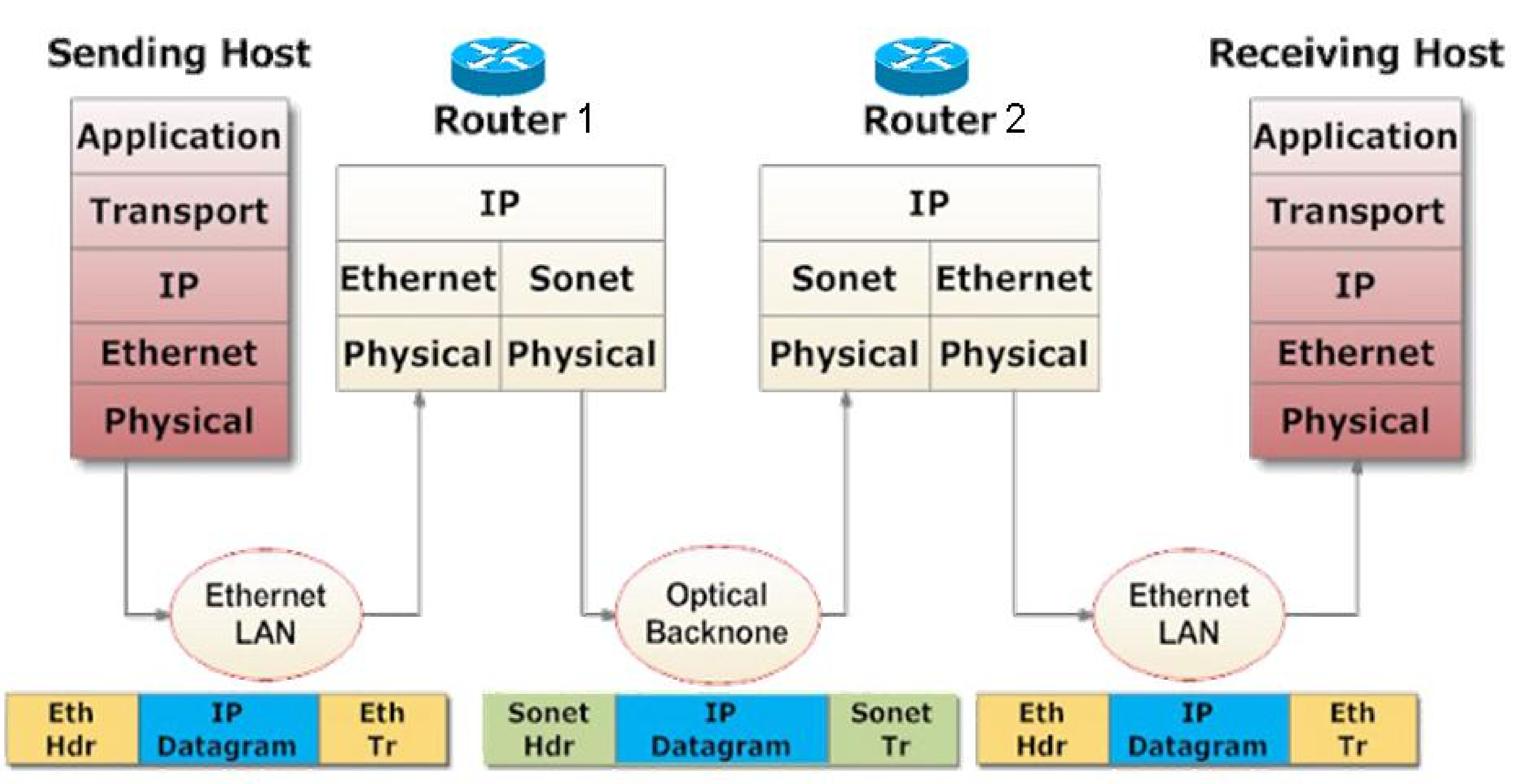
- Datagram transferred by different link protocols over different links



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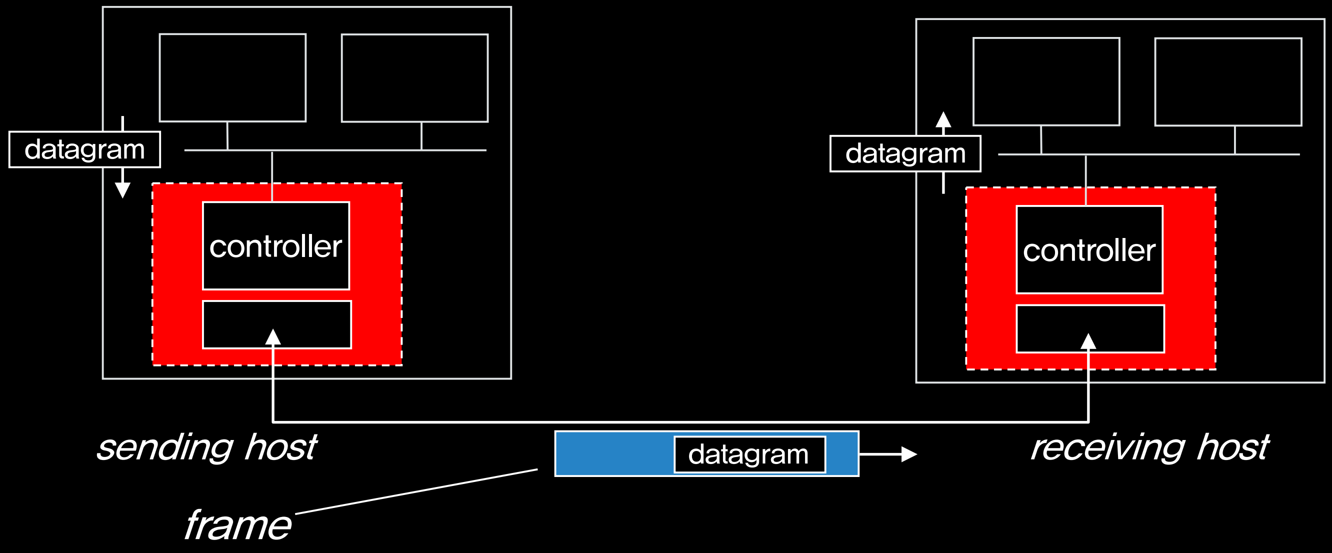
Link Layer Services

- Framing, link access
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - “MAC” addresses used in frame headers to identify source, destination
- Flow control
  - pacing between adjacent sending and receiving nodes
- Error detection
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors: signals sender for retransmission or drops frame
- Error correction
  - receiver identifies and corrects bit error(s) without resorting to retransmission

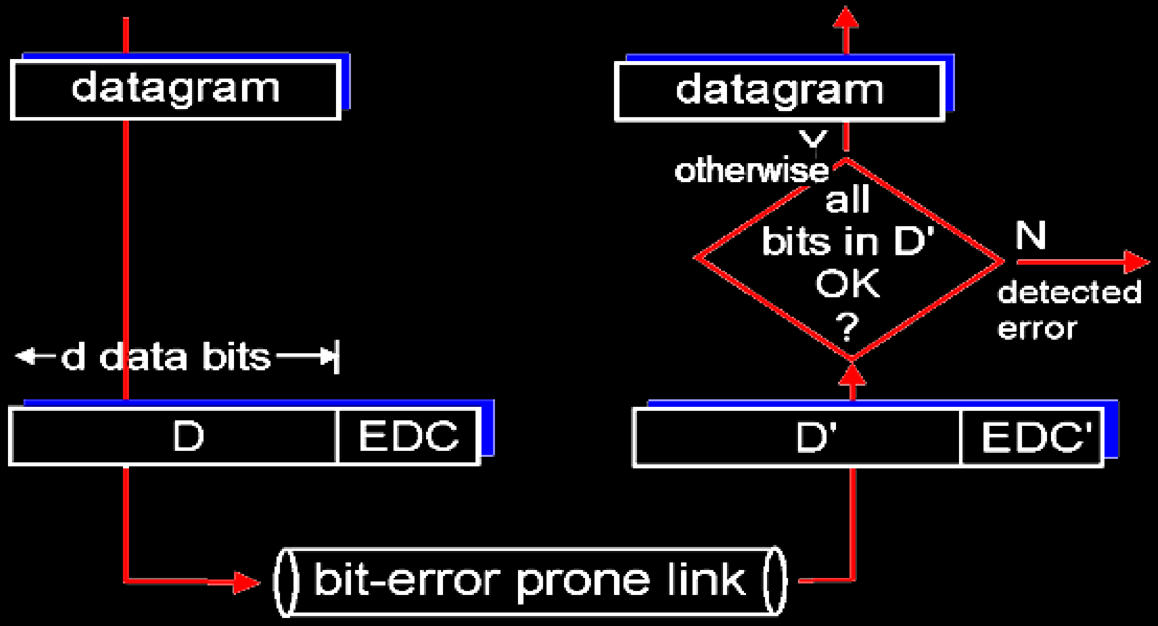
Link Communication



- Sending side
  - encapsulates datagram in frame
  - adds error checking bits, flow control, etc.
- Receiving side
  - looks for errors, flow control, etc.
  - extracts datagram, passes to upper layer at receiving side

02. Error Detection & Correction

Error Detection and Correction Principles



EDC= Error Detection and Correction bits (redundancy)

D = Data protected by error checking

- Error detection and correction is 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

D data bits	Parity bit
0111000110101011	0

two-dimensional bit parity: detect and correct single bit errors

row parity

$d_{1,1}$	. . .	$d_{1,1}$	$d_{1,j+1}$
$d_{2,1}$	. . .	$d_{1,1}$	$d_{2,j+1}$
. . .	. . .	. . .	. . .
$d_{i,1}$	. . .	$d_{1,1}$	$d_{i,j+1}$
$d_{i+1,1}$	. . .	$d_{i+1,j}$	$d_{i+1,j+1}$

Column parity

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

No errors

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

Parity error

Parity error

Correctable s
ingle bit error

Cyclic Redundancy Check (CRC)

← D bits →	← R bits →	
D:data bits to be sent	*R* :CRC bits	Bit pattern

$$D * 2^r \quad XOR \quad R$$ Mathematical formula

- More powerful error-detection coding, not for correction
- View data bits, D, as a binary number
- Choose r+1 bit pattern (generator), G
- Goal: choose r CRC bits, R, such that
  - ⟨D,R⟩ exactly divisible by G (modulo 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 Wi-Fi, ATM)

CRC Principle: Sender

want to find R such that:

$D \cdot 2^r \text{ XOR } R = nG$

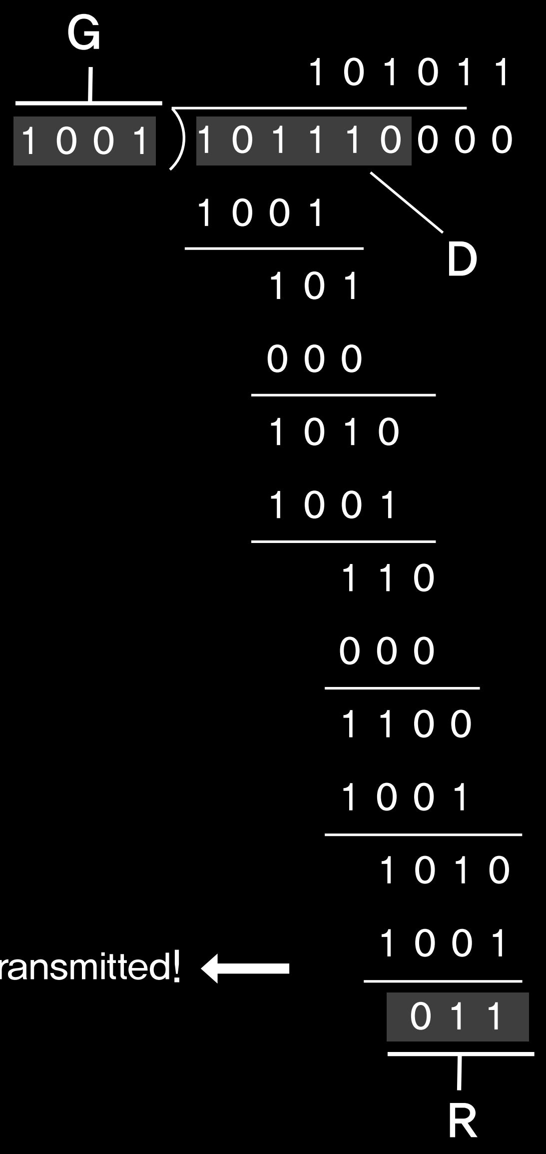
equivalently:

$D \cdot 2^r = nG \text{ XOR } R$

equivalently:

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

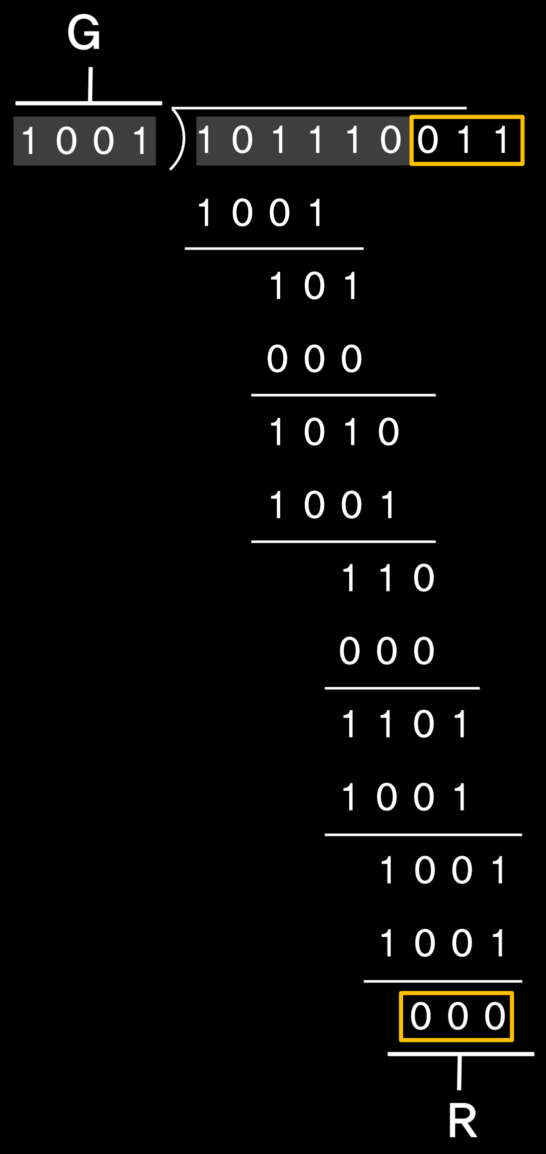
$$R = \textit{remainder}\left[\frac{D \cdot 2^r}{G}\right]$$



⟨D, R⟩ = 101110011 transmitted!

CRC Principle： Receiver

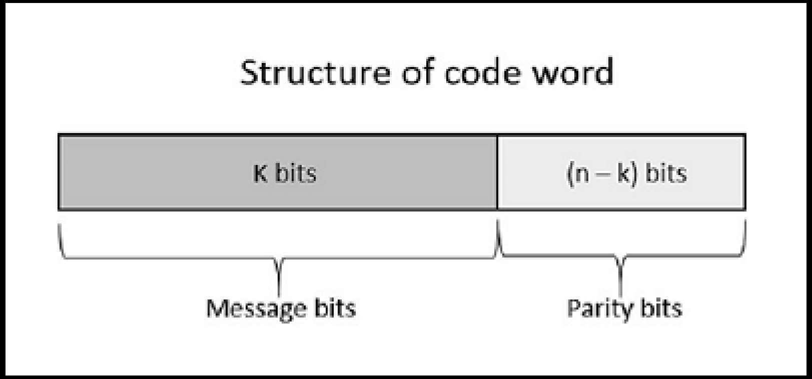
- Receiving host receives packet, and checks the CRC：
  - see if the remainder is 0 by dividing 〈D, R〉 with G



Error Correction

- Forward error correction (FEC) or channel coding
  - a technique used for controlling errors in data transmission over unreliable or noisy communication channels

- Block code principles
  - k: length of data
    n: length of codeword
  - redundancy = (n–k)/k
  - code rate = k/n
  - e.g., code rate of 1/2 requires double the transmission capacity of an uncoded system



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FEC: Hamming Code (1/2)

- k=2, n=5

Data Block	Codeword
00	00000
01	00111
10	11001
11	11110

- Codeword block received with bit pattern <u>00100</u>
  - d(00000, <u>00100</u>) = 1; d(00111, <u>00100</u>) = 2;
    d(11001, <u>00100</u>) = 4; d(11110, <u>00100</u>) = 3
  - the closet one: 00000
  - work if there is a unique valid codeword at a minimum distance from each invalid codeword

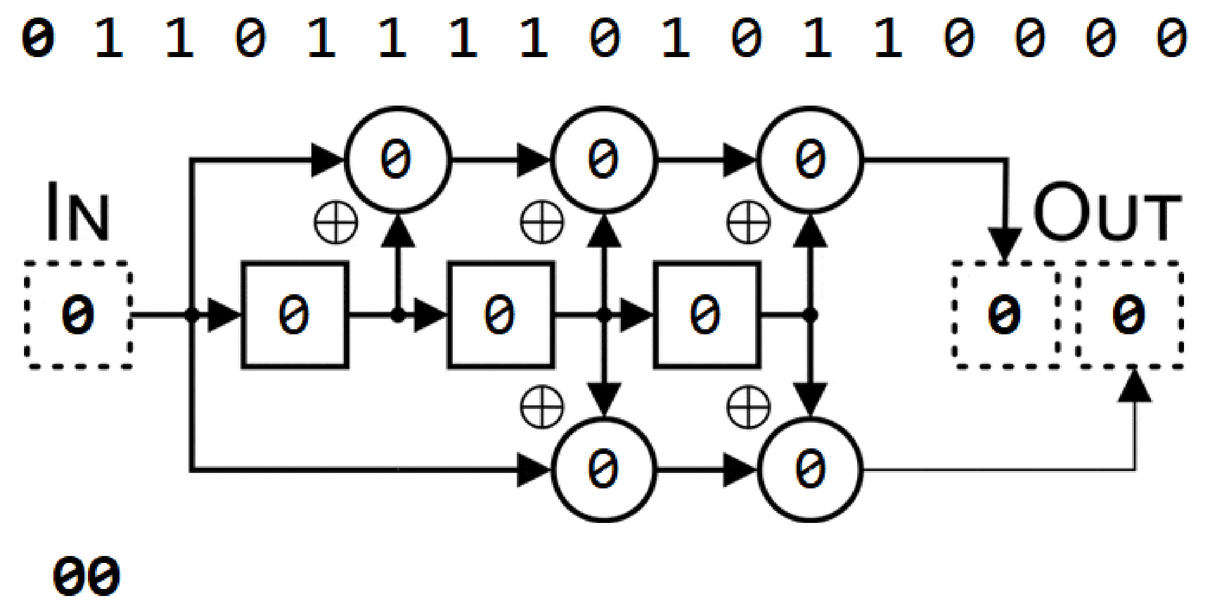
> • Hamming distance d(v1, v2): the number of bits in which v1 and v2 disagree

FEC: Hamming Code (2/2)

- Pairwise distances
  - d(00000, 00111) = 3; d(00000, 11001) = 3;
    d(00000, 11110) = 4; d(00111, 11001) = 4;
    d(00111, 11110) = 3; d(11000, 11110) = 3;
  - minimum distance = 3
  - a single-bit error results in an invalid codeword that is a distance 1 from the original valid codeword
  - always correct a single-bit error
  - always detect a double-bit error

Codeword
00000
00111
11001
11110

- Error-correcting code that generates parity symbols via the sliding application of a boolean polynomial function to a data stream
- 'Convolution' of the encoder over data
  - gives rise to the term 'convolutional coding'



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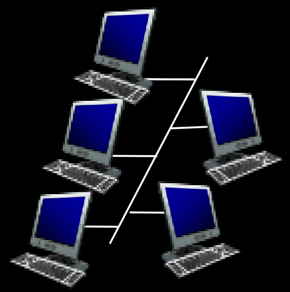
03. Multiple Access Protocols

Multiple Access Links

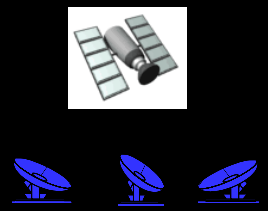
Two types of "links":

- Point–to–point
  - PPP for dial–up access
  - point–to–point link between Ethernet switch and host
- Broadcast (shared medium)
  - old–fashioned Ethernet
  - 802.11 wireless LAN
  - satellite communication



shared wire (e.g., cabled Ethernet)

shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

Multiple Access Protocols

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
  - collision occurs 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

humans at a
cocktail party
(shared air, acoustical)

Ideal Multiple Access Protocol

- Given broadcast channel of rate R bps,

Desiderata:

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

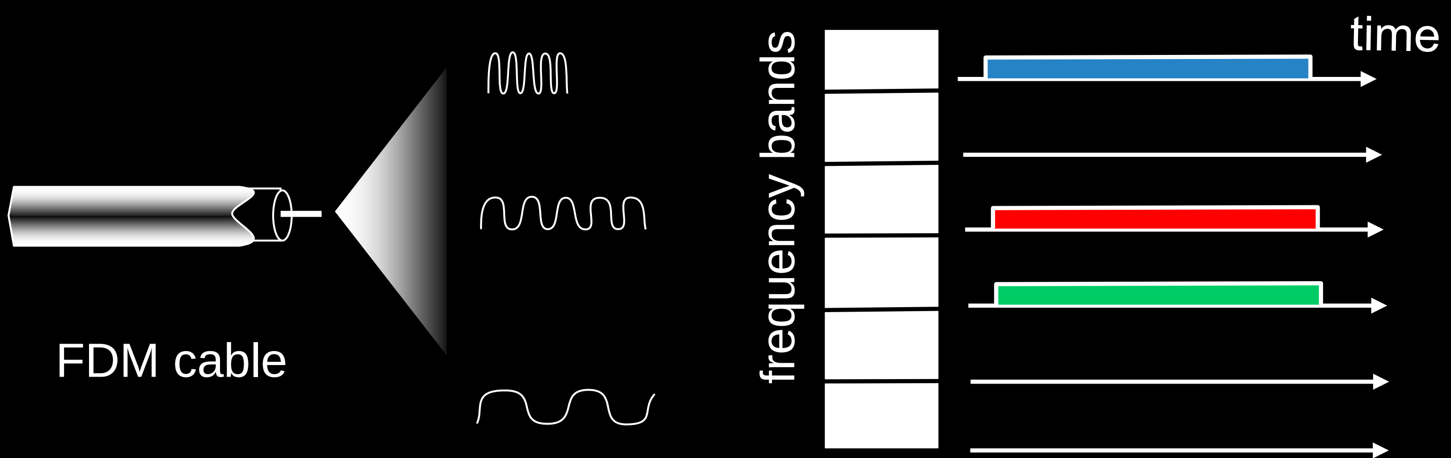
MAC Protocols Taxonomy

Types	Features	Remarks
Channel partitioning	• divide channel into smaller “pieces” (time slots, frequency, code) • allocate piece to node for exclusive use	No collision occurs
Taking turns	• nodes take turns, but nodes with more to send can take longer turns	
Random access	• channel not divided, allow collisions • “recover” from collisions	Collision occurs

04. MAC Protocols without Collision

FDMA: frequency division multiple access

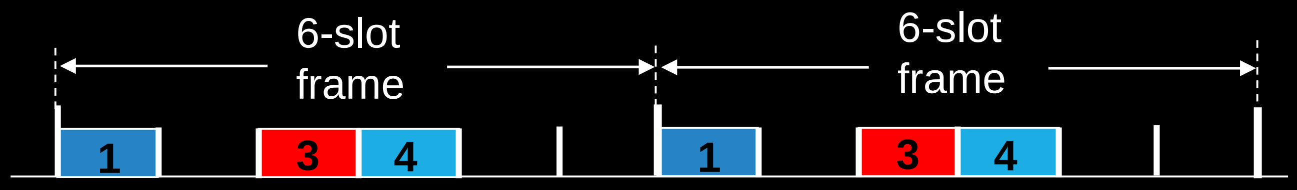
- Channel spectrum divided into frequency bands
- Each station assigned fixed frequency band
- Unused transmission time in frequency bands go idle
- Example: 6–station LAN, 1,3,4 have packet to send, frequency bands 2,5,6 idle



Channel Partitioning: TDMA

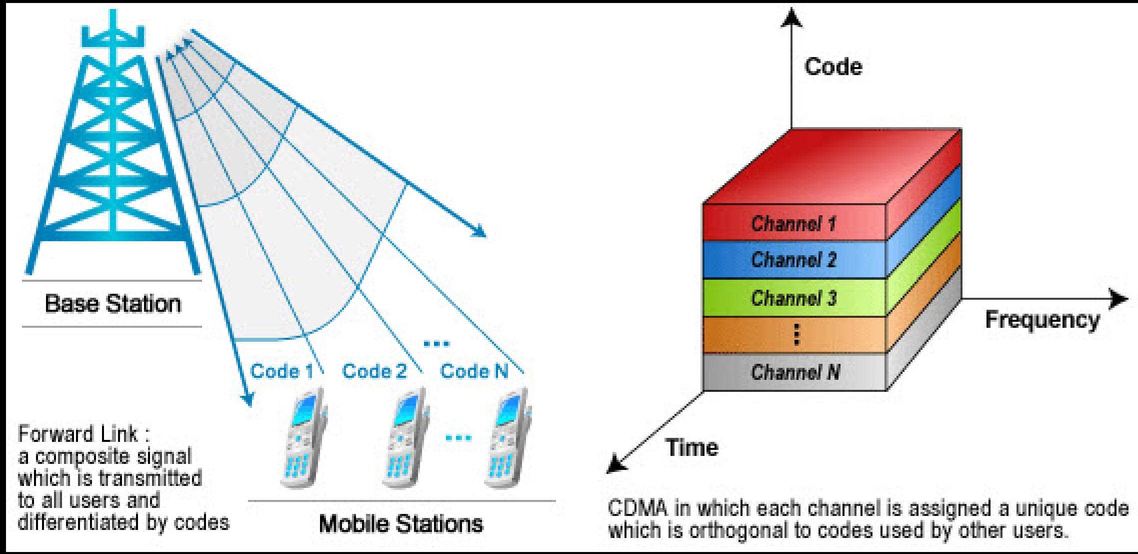
TDMA: time division multiple access

- Access to channel in "rounds"
- Each station gets fixed length slot (length = packet transmission time) in each round
- Unused slots go idle
- Example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle



CDMA: code division multiple access

- Each channel encoded with different code
- In order to decode the data, the receiver must know the code
- Frequency spectrum and access time need not be divided for each channel



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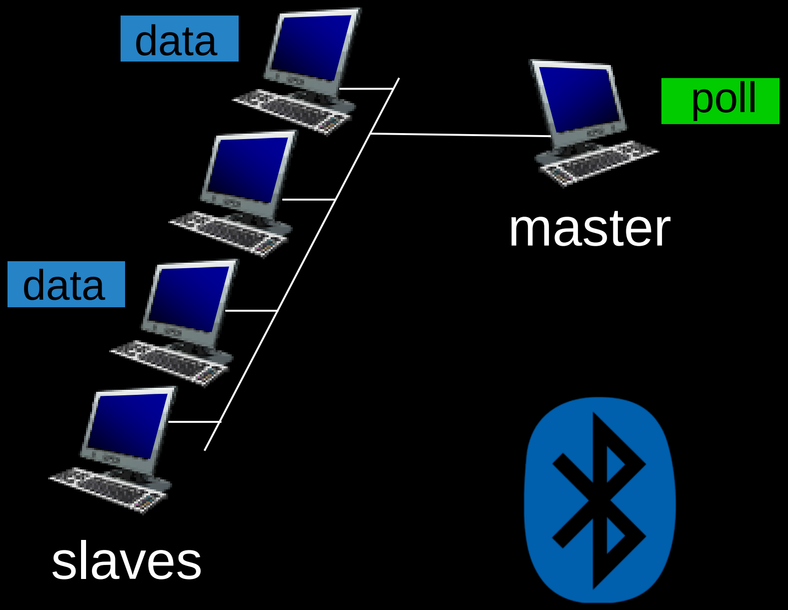
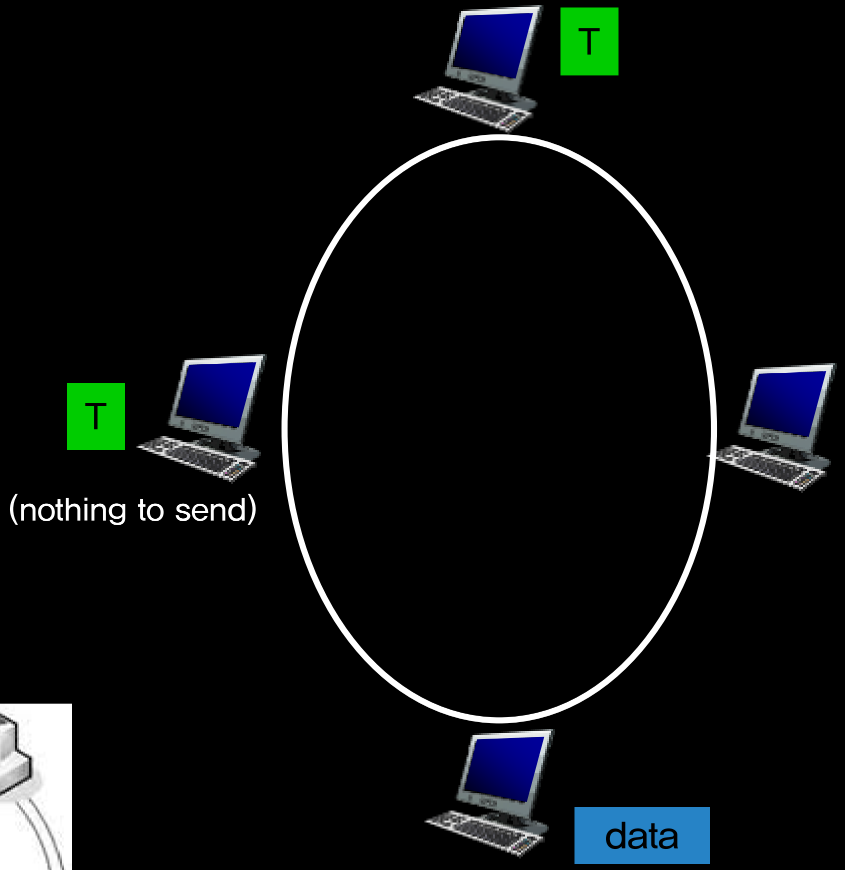
Taking Turns: Polling

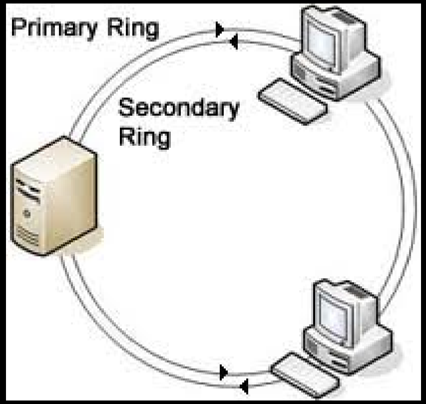
- Master node "invites" slave nodes to transmit in turn
- Typically used with "dumb" slave devices
- Concerns:
  - polling overhead
  - latency
  - single point of failure (master)



Taking Turns: Token Passing

- Control token passed from one node to next sequentially
- Only the node that has the token can send its message
- Concerns:
  - token overhead
  - latency
  - single point of failure (token)





* FDDI (Fiber Distributed Dual Interface)
: dual token ring

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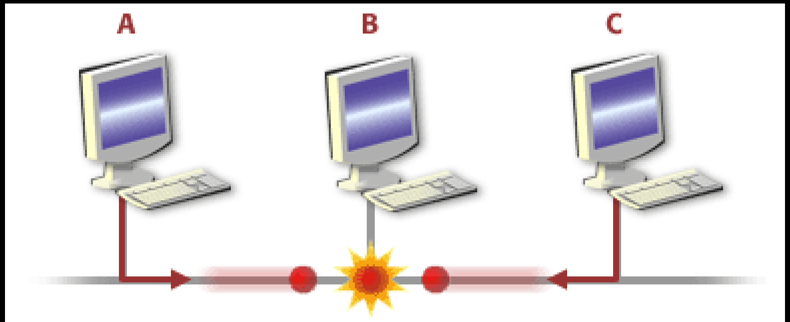
05. MAC Protocols with Collision

- 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



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ALOHAnet

- Developed at the University of Hawaii
- Operational in June 1971
- Originally stood for Additive Links Online Hawaii Area

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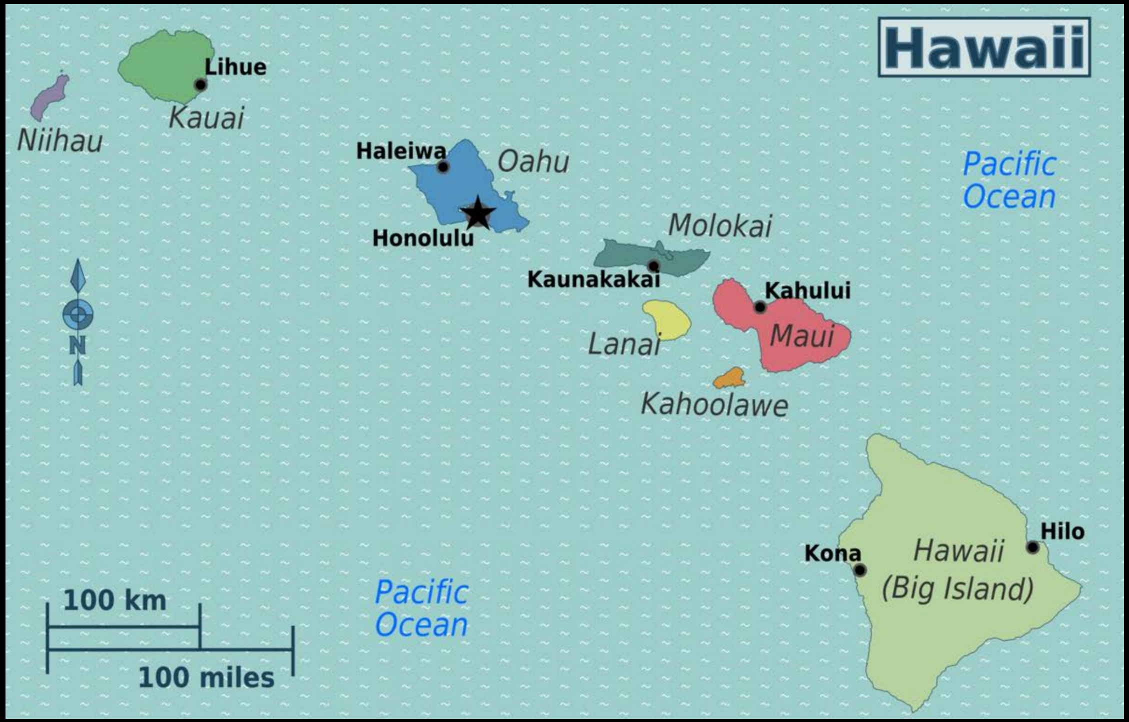

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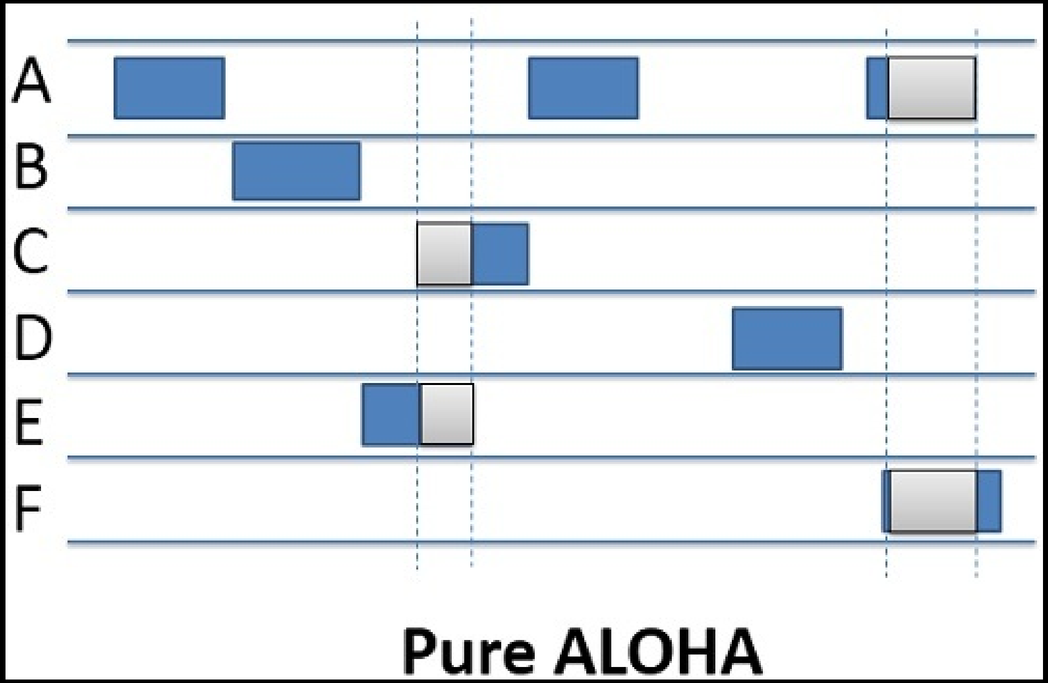
ALOHA Protocol

- All frames have the same length
  ➜ same air time for every frame
- When frame is ready, node transmits the frame immediately
- If collision occurs, node retransmits the frame after random delay until success



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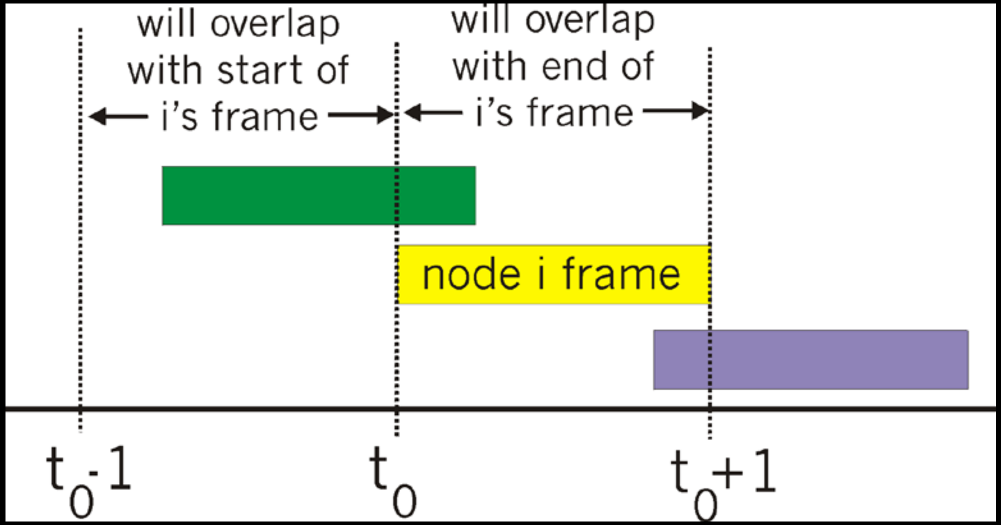
ALOHA Efficiency

- Collision analysis
  - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



Max. prob. of successful trans.: 0.184

- Assuming number of stations → ∞
  - G: average number of transmission-attempt nodes per timeslot

$$P(k \text{ nodes transmit in a timeslot}) = \frac{G^k e^{-G}}{k!}$$

$$P(k \text{ nodes transmit in 2 timeslots}) = \frac{(2G)^k e^{-2G}}{k!}$$

$$\therefore P(\text{no transmission in 2 timeslots}) = e^{-2G}$$

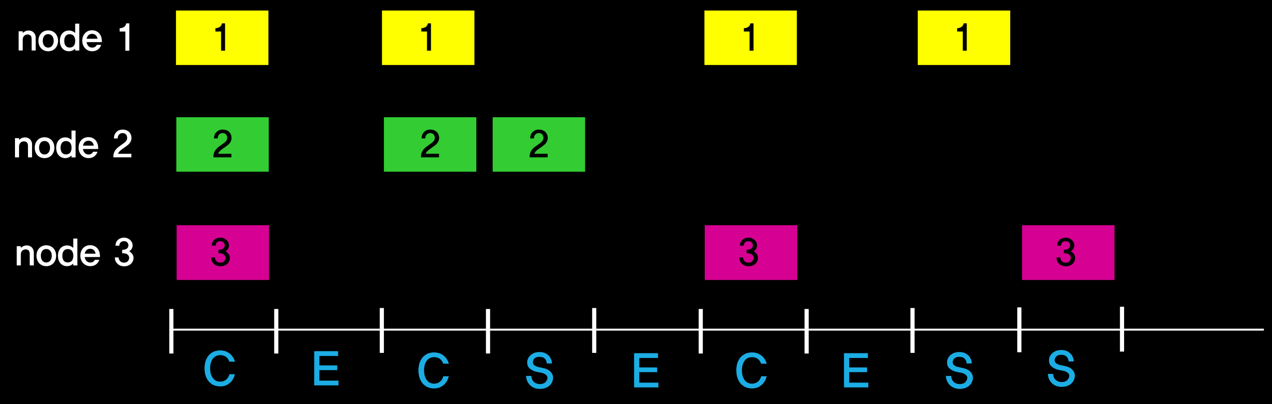
$$\text{Then, frame delivery prob. in a timeslot } S(G) = Ge^{-2G}$$

$$\text{If differentiated, } S'(G) = (1-2G)e^{-2G}$$

$$\therefore \text{When } G = 0.5,\ S(G) \text{ is the maximum} : S(0.5) \approx 0.184$$

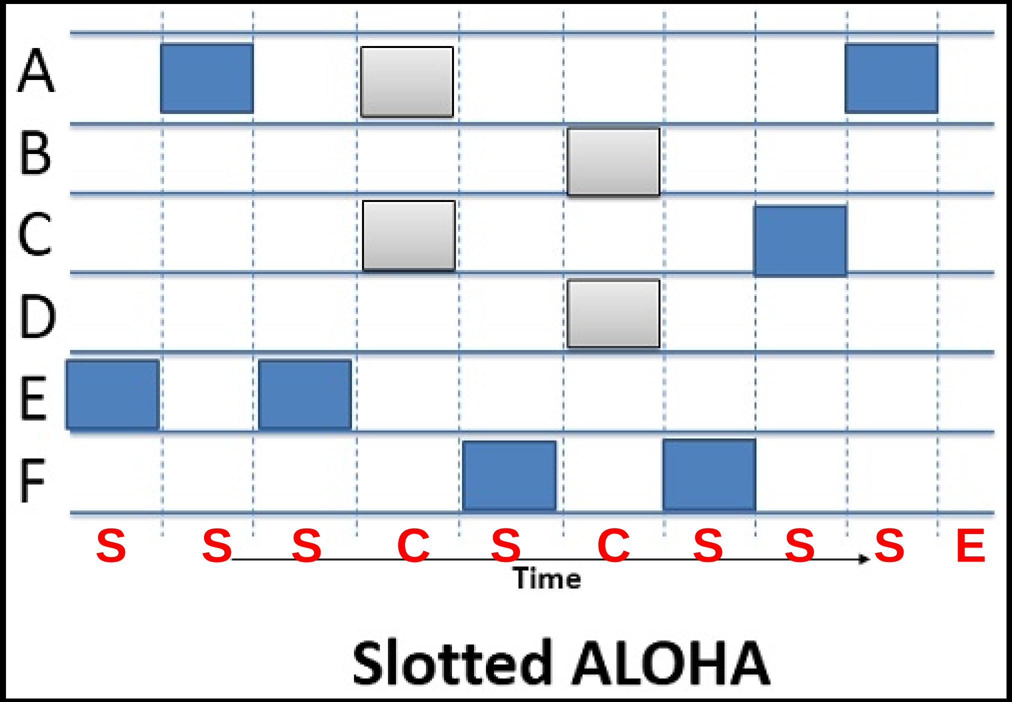
Slotted ALOHA

- Nodes are synchronized
- Time divided into equal size slots (time to transmit 1 frame)
- Nodes start to transmit only at slot beginning
  - if a node obtains a fresh frame in the middle of one timeslot, it can be transmitted in the next slot
- If collision, node retransmits frame in each subsequent slot with probability *p* until success



Slotted ALOHA Efficiency

- Collision occurs when only the transmitting timeslot is selected by others
- Compared to pure ALOHA
  - collision decreases to 1/2
  - efficiency improves two times: 37%



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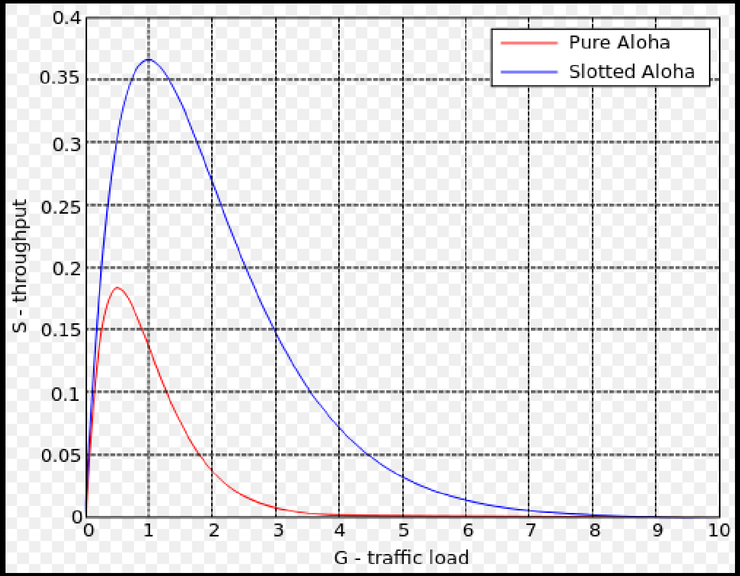
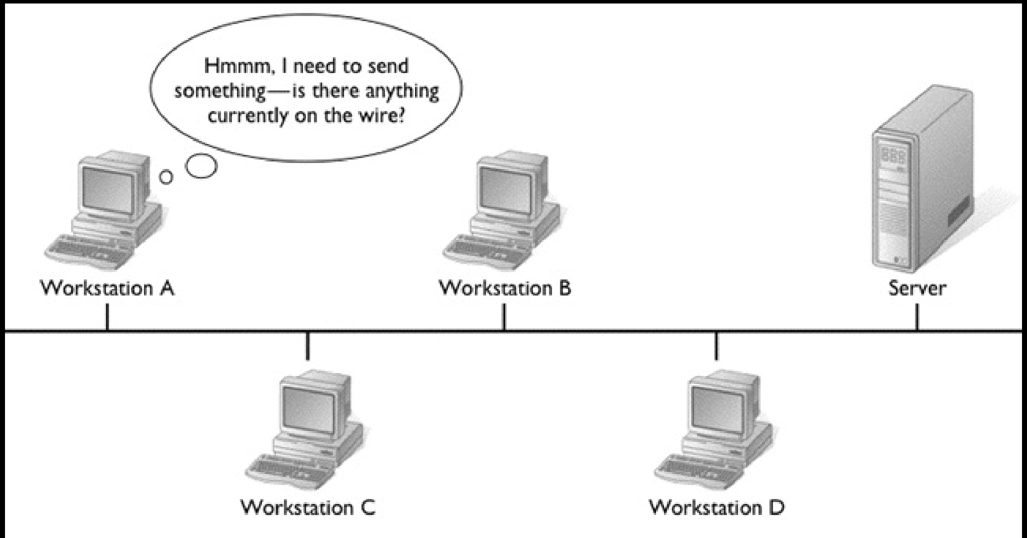


출처 – https://en.wikipedia.org/wiki/ALOHAnet#Pure_ALOHA

CSMA (Carrier Sense Multiple Access)

- Maximum channel efficiency of slotted ALOHA: at best 37%
  - due to too many collisions because each node does not care to interrupt others
- CSMA: listen before transmit
  - if channel sensed idle, transmit entire frame
  - if channel sensed busy, defer transmission



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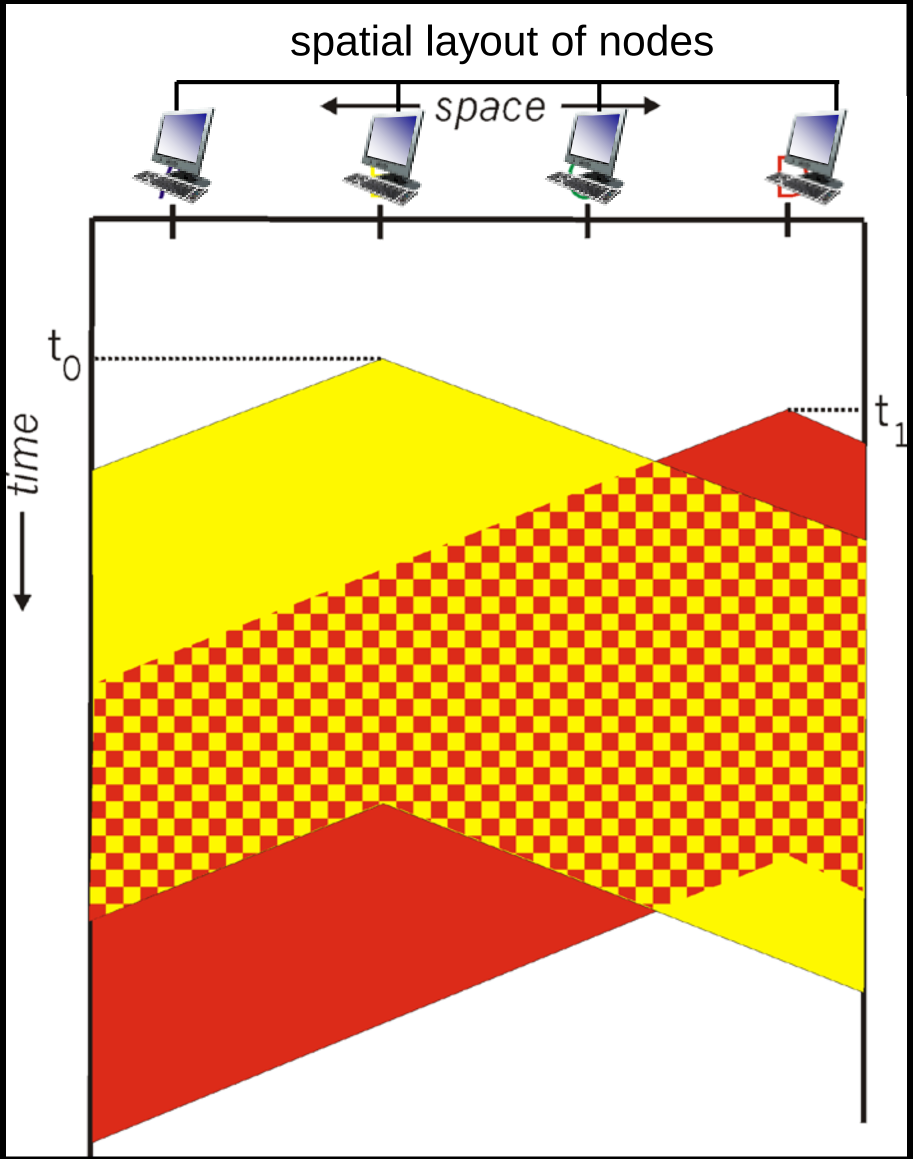
- Q: Does CSMA resolve the collision problem completely?

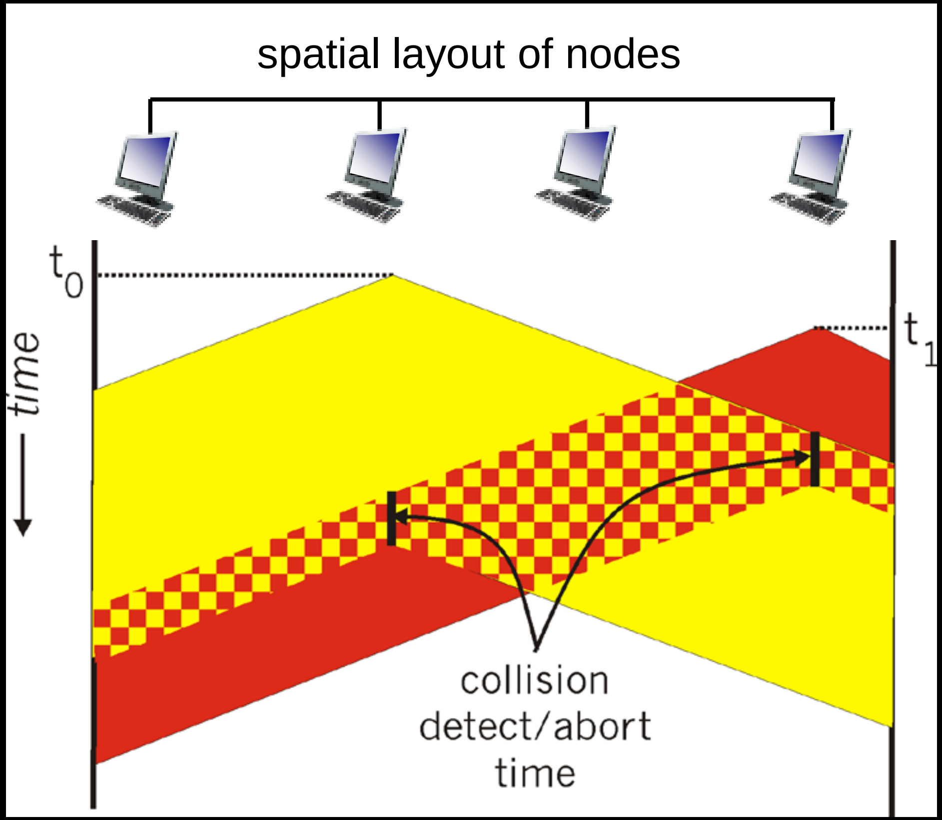
CSMA Collisions

- Collisions can still occur
  - two nodes may not hear each other's transmission before they send packets due to propagation delay
- If collision, entire packet transmission time is wasted



CSMA/CD (Collision Detection)

- Collisions detected within short time
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: received signal strength overwhelmed by local transmission strength
- Colliding transmissions aborted and jam signal broadcast, reducing channel wastage
- e.g, Ethernet



Summary of MAC Protocols

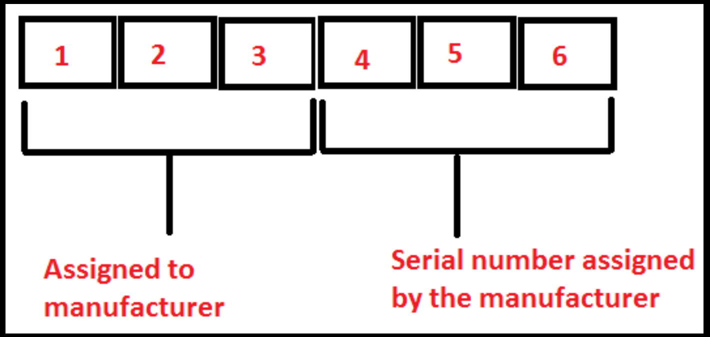
Types	Pros and Cons
Channel partitioning	• share channel efficiently and fairly at high load • inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!
Random access	• efficient at low load: single node can fully utilize channel • high load: collision overhead
Taking turns	• look for best of both worlds! • control overhead, single point of failure

06. Address Resolution Protocol

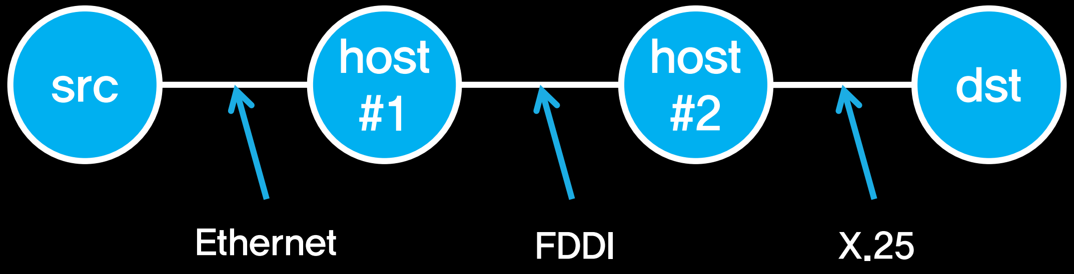
MAC Address

- IP address (32–bits or 128–bits)
  - logical address at network layer (like postal address)
- MAC address (48–bits)
  - physical address at link layer (like resident registration number)
  - burned in NIC ROM
  - e.g.: 1A–2F–BB–76–09–AD

    hexadecimal (base 16) notation
    (each “numeral” represents 4 bits)
  - globally unique
  - portable from one LAN to another (cf. IP not portable)



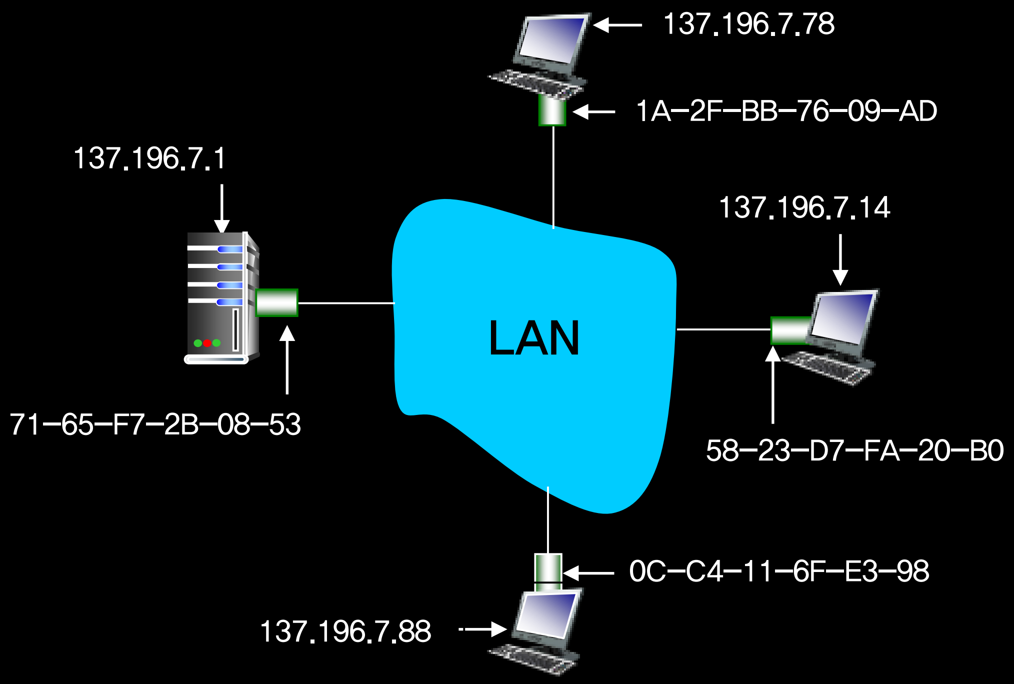
- Function: used 'locally" to get frame from one interface to another physically-connected interface (same network, in IP-addressing sense)



- MAC address is needed to reach the final host, while IP routing is used until datagram gets to the destination network

ARP (Address Resolution Protocol)

- Q: How to determine interface's MAC address, knowing its IP address?



ARP table: each IP node (host, router) on LAN has table

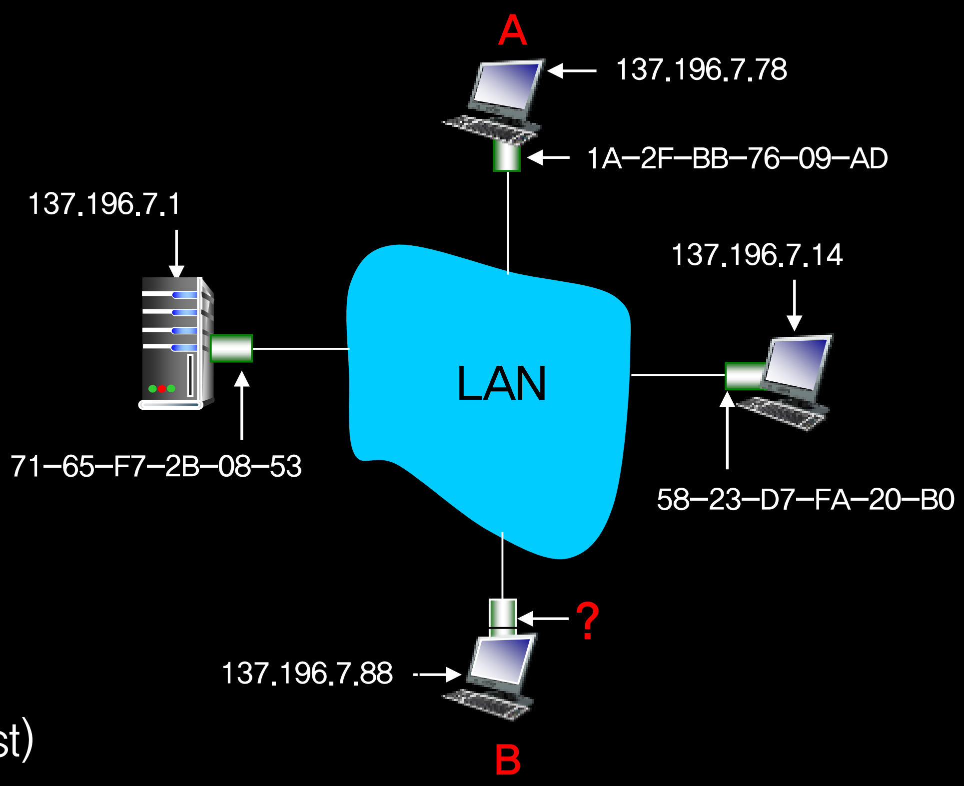
- IP/MAC address mappings for some LAN nodes:

  〈 IP address; MAC address; TTL〉

- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

ARP in Same LAN

- Scenario
  - A wants to send datagram to B
  - B’s MAC address not in A’s ARP table



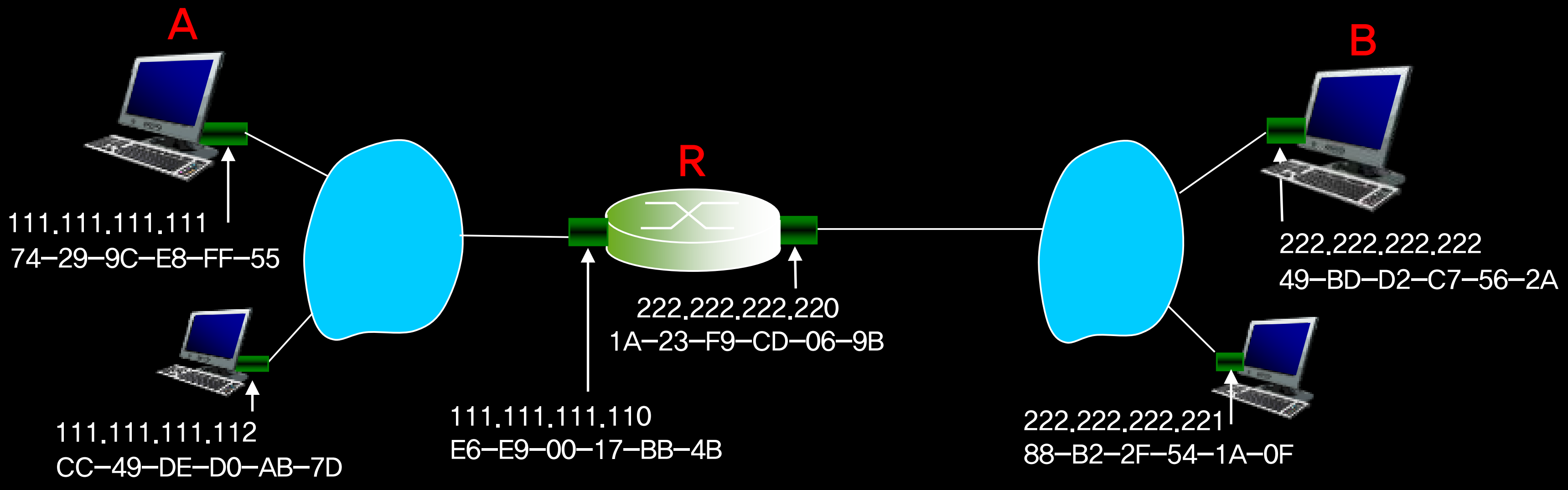
ARP steps:

1. A broadcasts ARP query packet, containing B's IP address
   - destination MAC address = FF-FF-FF-FF-FF-FF (bcast)
   - all nodes on LAN receive ARP query
2. B receives ARP packet, replies to A with its (B's) MAC address
   - frame sent to A’s MAC address (unicast)
3. A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
   - soft state: information that times out (goes away) unless refreshed

ARP: Routing to Another LAN

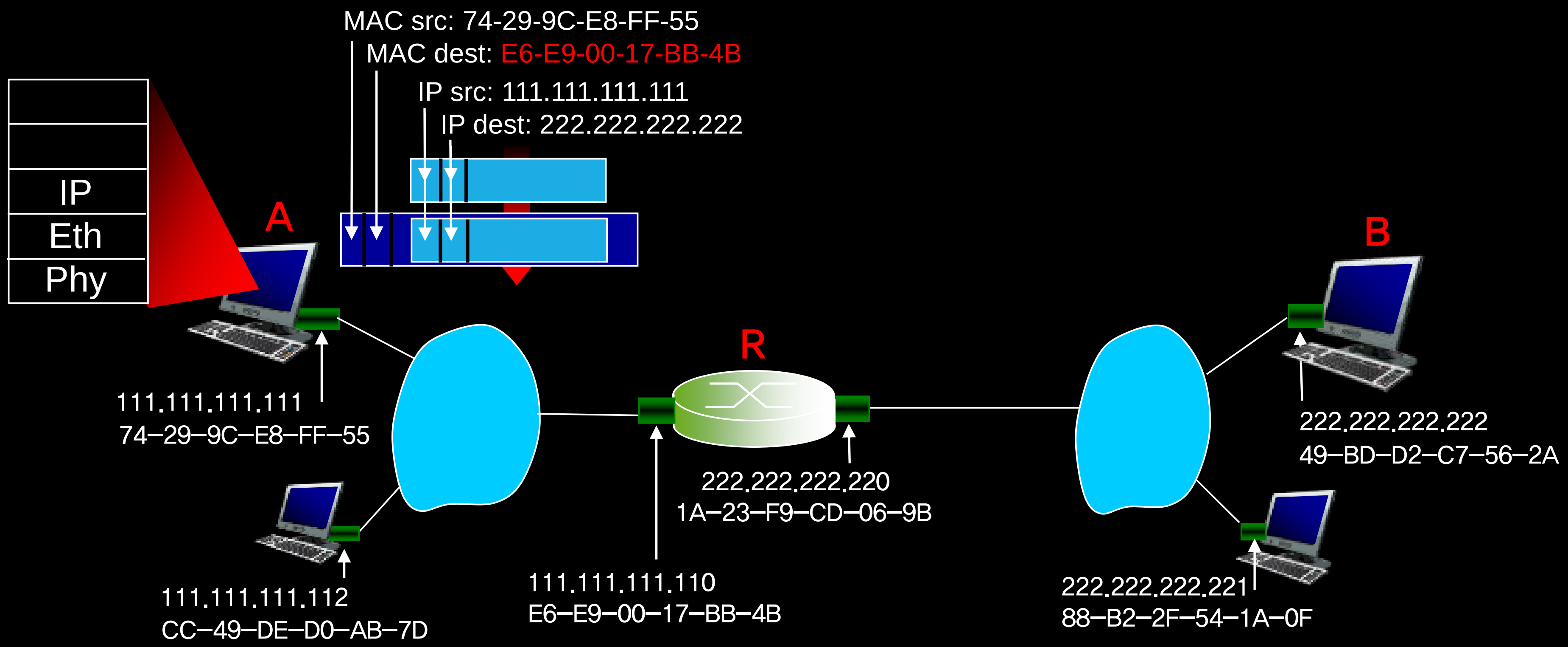
Walkthrough: send datagram from A to B via R

- Focus on addressing – at IP (datagram) and MAC layer (frame)
- Assume A knows b's IP address
- Assume A knows IP address of first hop router, R (how?)
- Assume a knows r's mac address (how?)



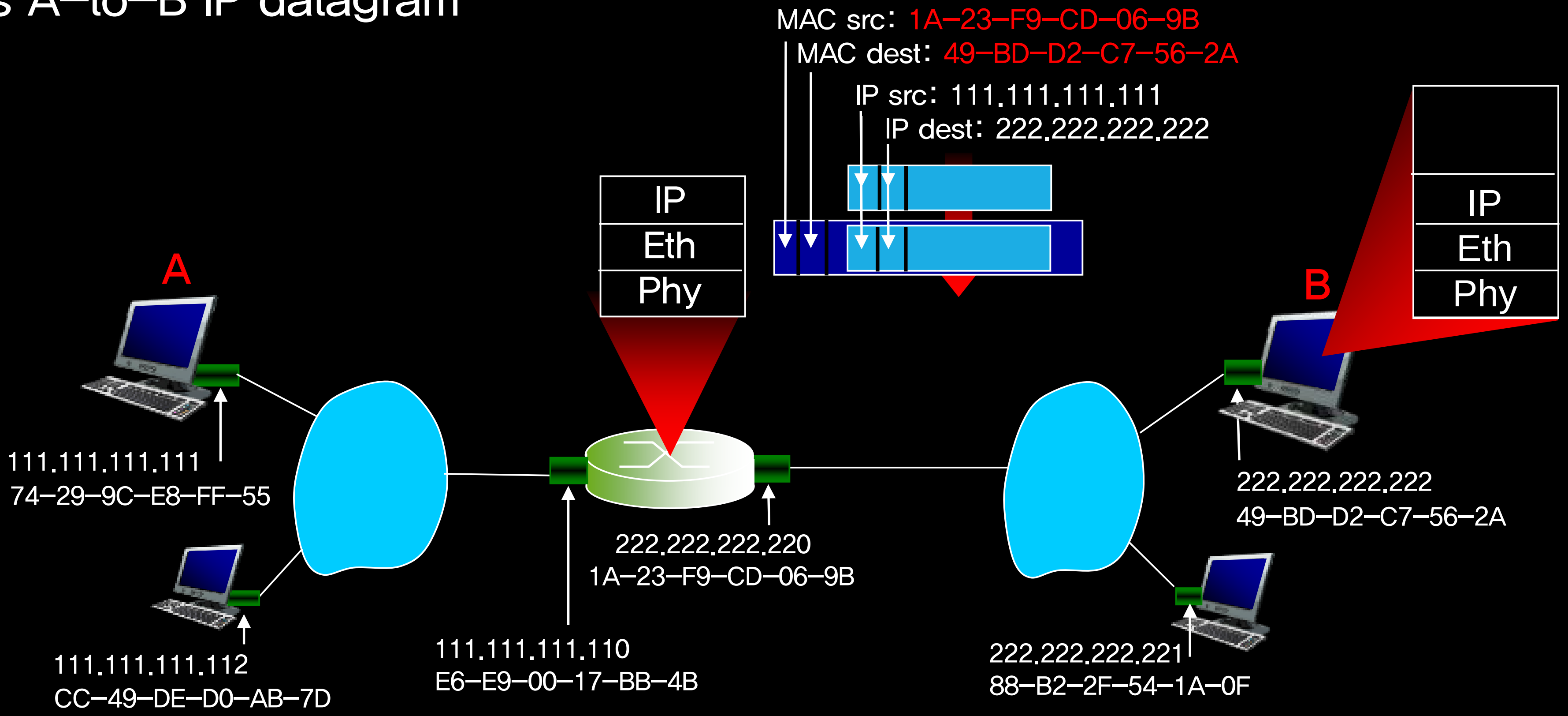
ARP: Routing to Another LAN

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



ARP: Routing to Another LAN

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



ARP: Routing to Another LAN

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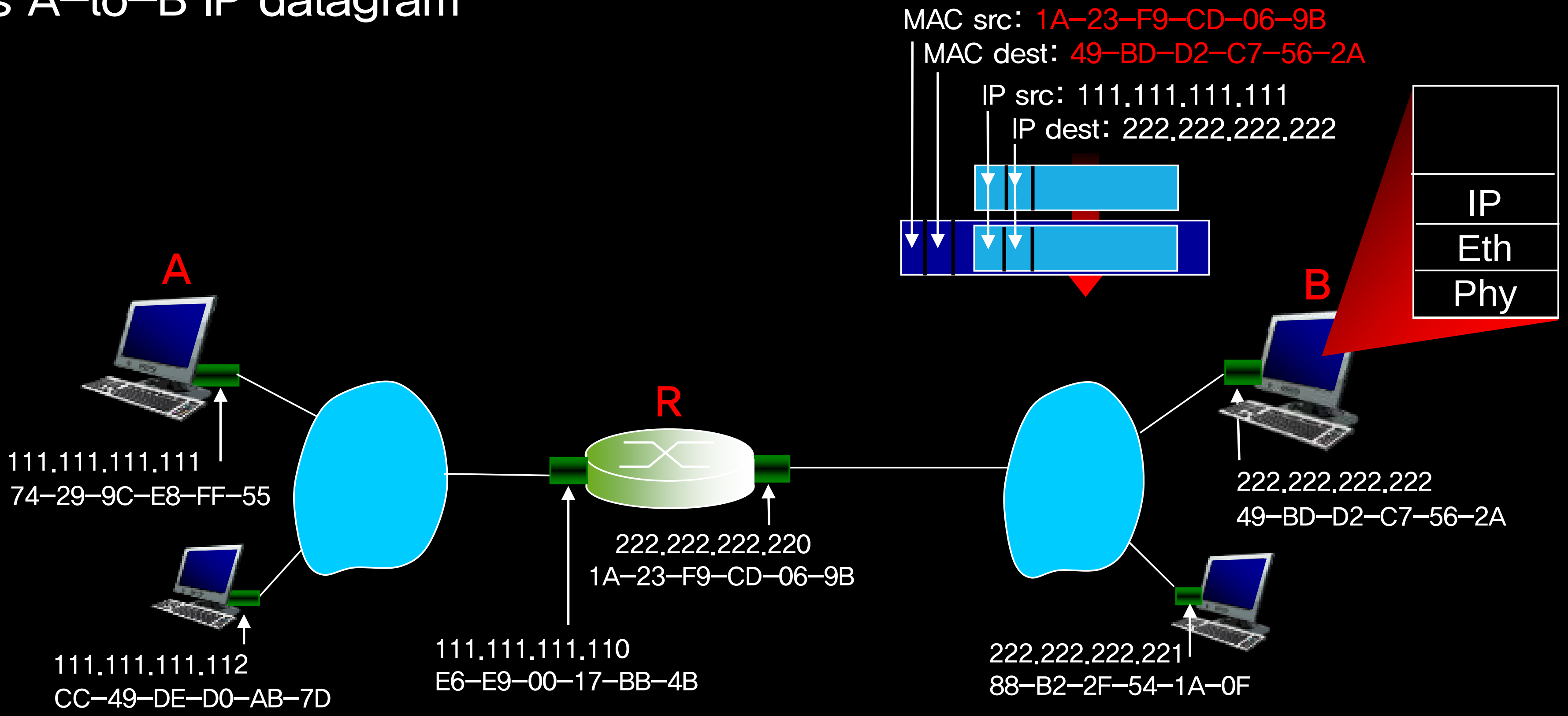
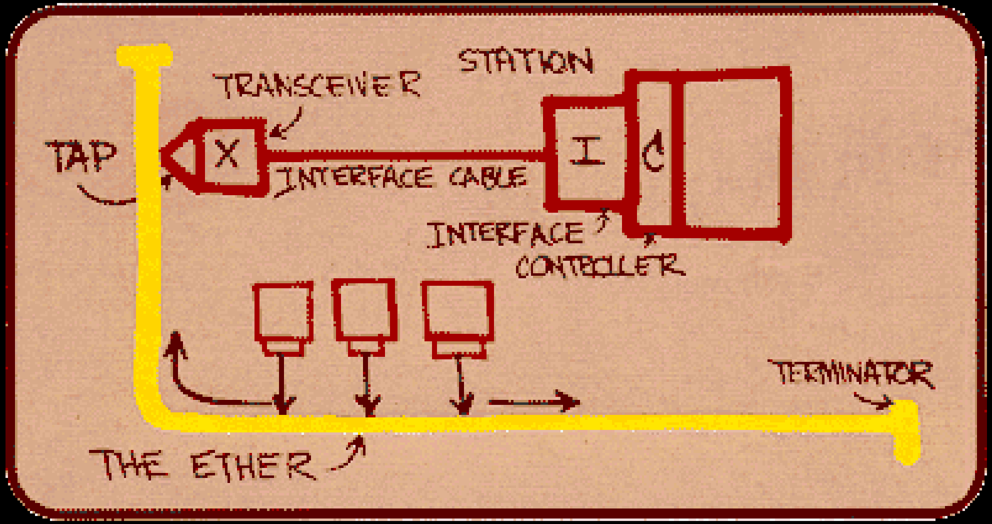


07. Ethernet

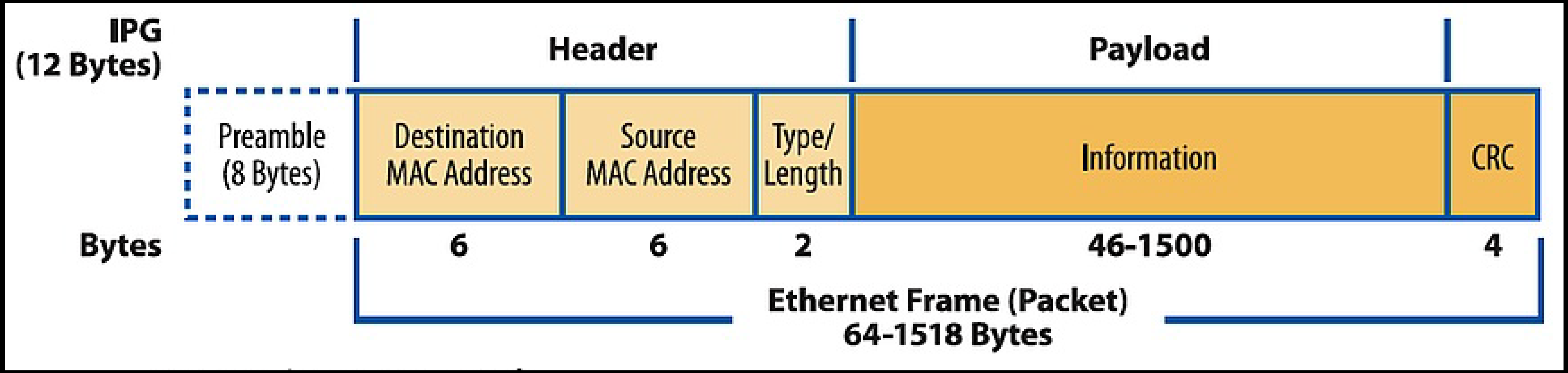
Ethernet

- First widely used LAN technology
- “Dominant” wired LAN technology
- Simpler, cheap
- Kept up with speed race: 10 mbps – 10 gbps



Metcalfe's Ethernet sketch

Ethernet Frame



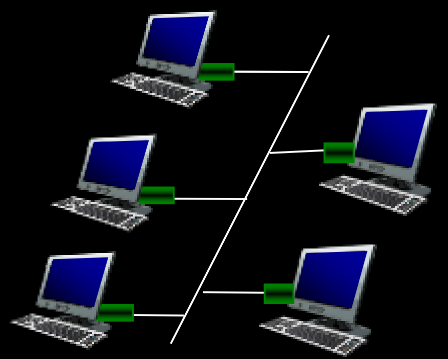
출처 – https://www.google.com/url?sa=i&source=images&cd=&cad=rja&uact=8&ved=2ahUKEwiliMP2p8ncAhWRZt4KHT9hDOYQjRx6BAgBEAU&url=http%3A%2F%2Fwww.embedded–computing.com%2Fembedded–computing–design%2Fmanaging–network–traffic–flow–for–multicore–x86–processors–at–40–100g–part–1–of–2&psig=AOvVaw2_PTRCHDFXTf7F5pEQuldE&ust=1533124329138872

- Preamble: used for synchronization
  - 7 octets with pattern 10101010 and 1 octet with pattern 10101011
- Addresses: 6 bytes each for sender and receiver
- Type/Length: higher layer protocol or data length
- FCS: CRC code
  - if error detected, frame is dropped
  - ACK is not used for reliable transfer

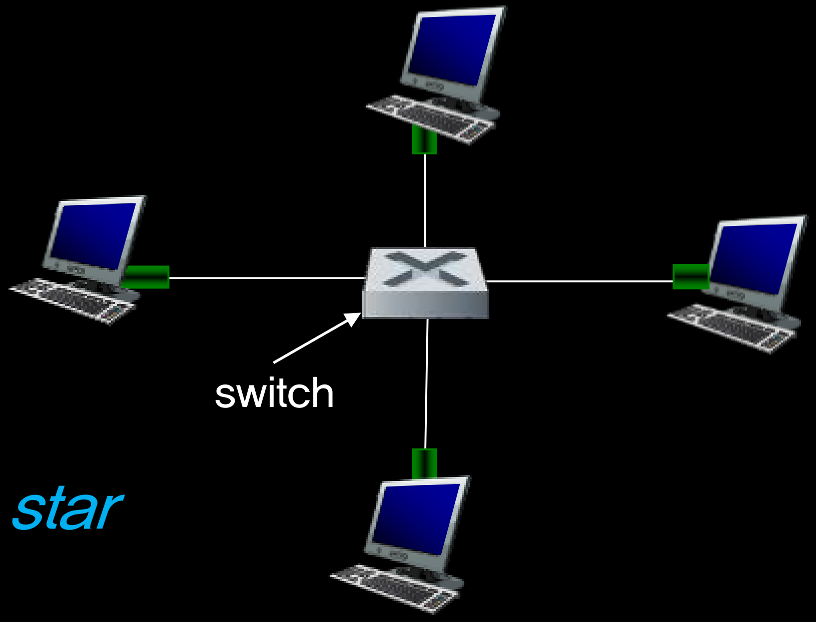
➡ **Unreliable service**

Physical Topology

- Bus: popular through mid 90s
  - all nodes in same collision domain (can collide with each other)
- Star: prevails today
  - active switch in center
  - each "spoke" runs a (separate) Ethernet protocol



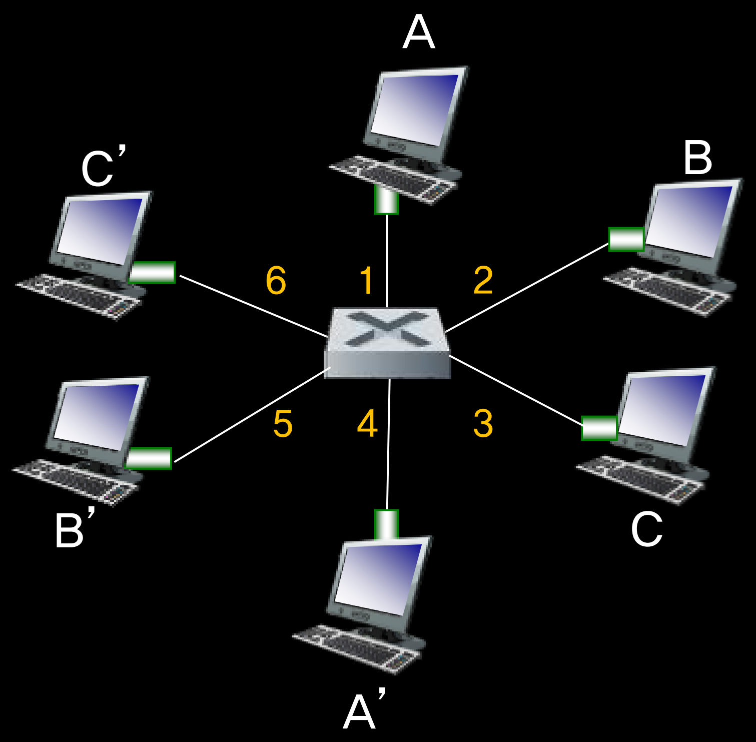
bus: coaxial cable



star

Switch: Enable Multiple Simultaneous Transmissions

- Hosts have dedicated, direct connection to switch
- Switches
  1) buffer packets
  2) examine incoming frame's MAC address
  3) selectively forward frame to one-or-more outgoing links
- Ethernet protocol used on each incoming link, but no collisions
- Switching: A-to-A' and B-to-B' can transmit simultaneously without collisions

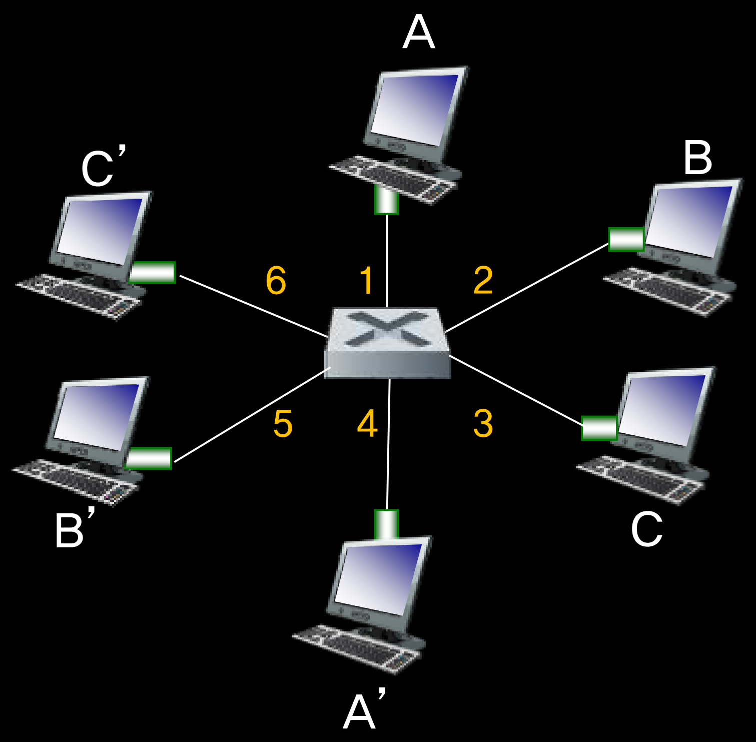


switch with six interfaces (1,2,3,4,5,6)

Switch Forwarding Table

- Q: How does switch know A' reachable via interface 4, B' reachable via interface 5?
- A: Each switch has a switch table with each entry form
  - (MAC address of host, interface to reach host, time stamp)
  - looks like a routing table!

MAC addr	Interface	TTL
A	1	60
A'	4	60



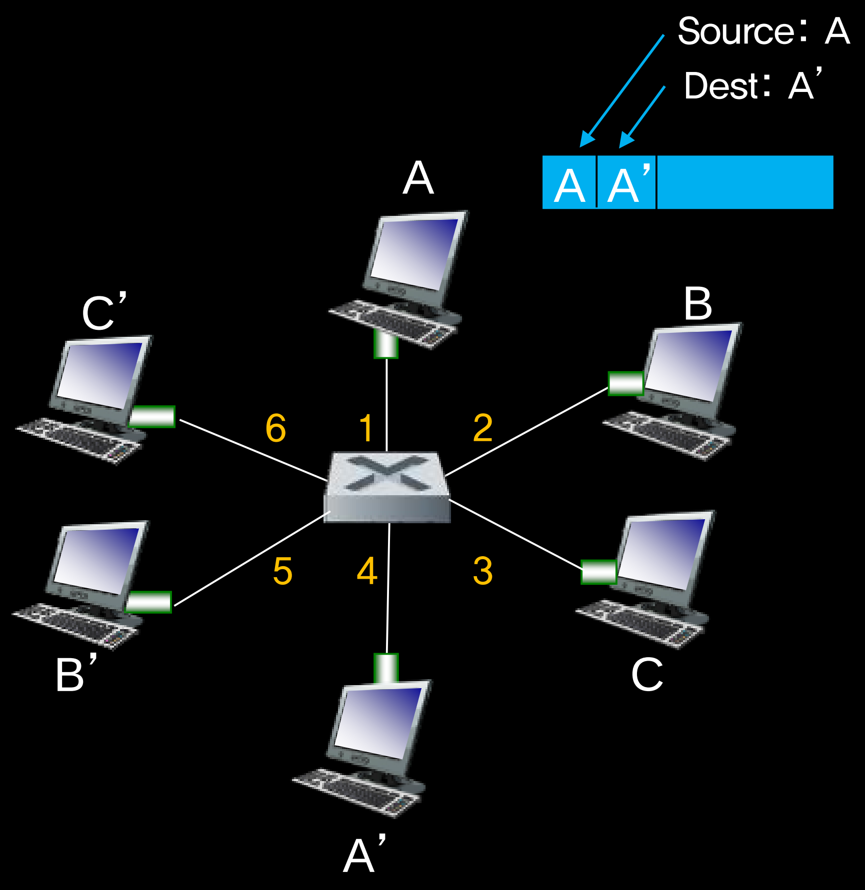
switch with six interfaces (1,2,3,4,5,6)

Plug-and-Play, Self-Learning

- Q: How are entries created, maintained in switch table?
- 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
- Self-learning: need not to be configured

MAC addr	interface	TTL
A	*1*	*60*

Switch table (initially empty)



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

Self-Learning and Forwarding Example

- Frame destination, A', location unknown:

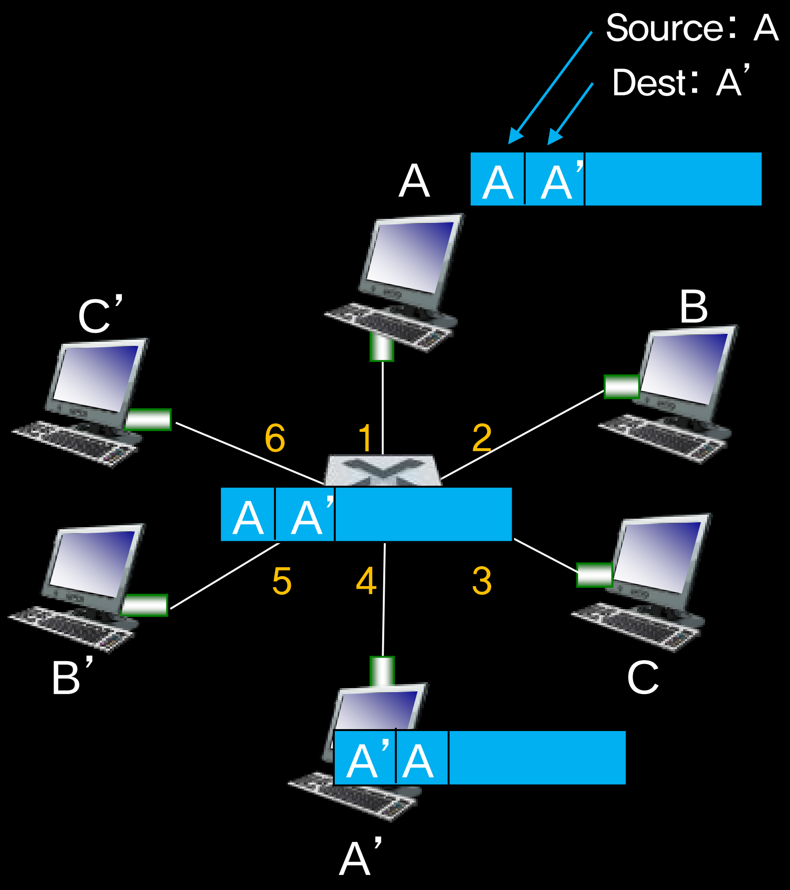
  flooding

- destination A location known:

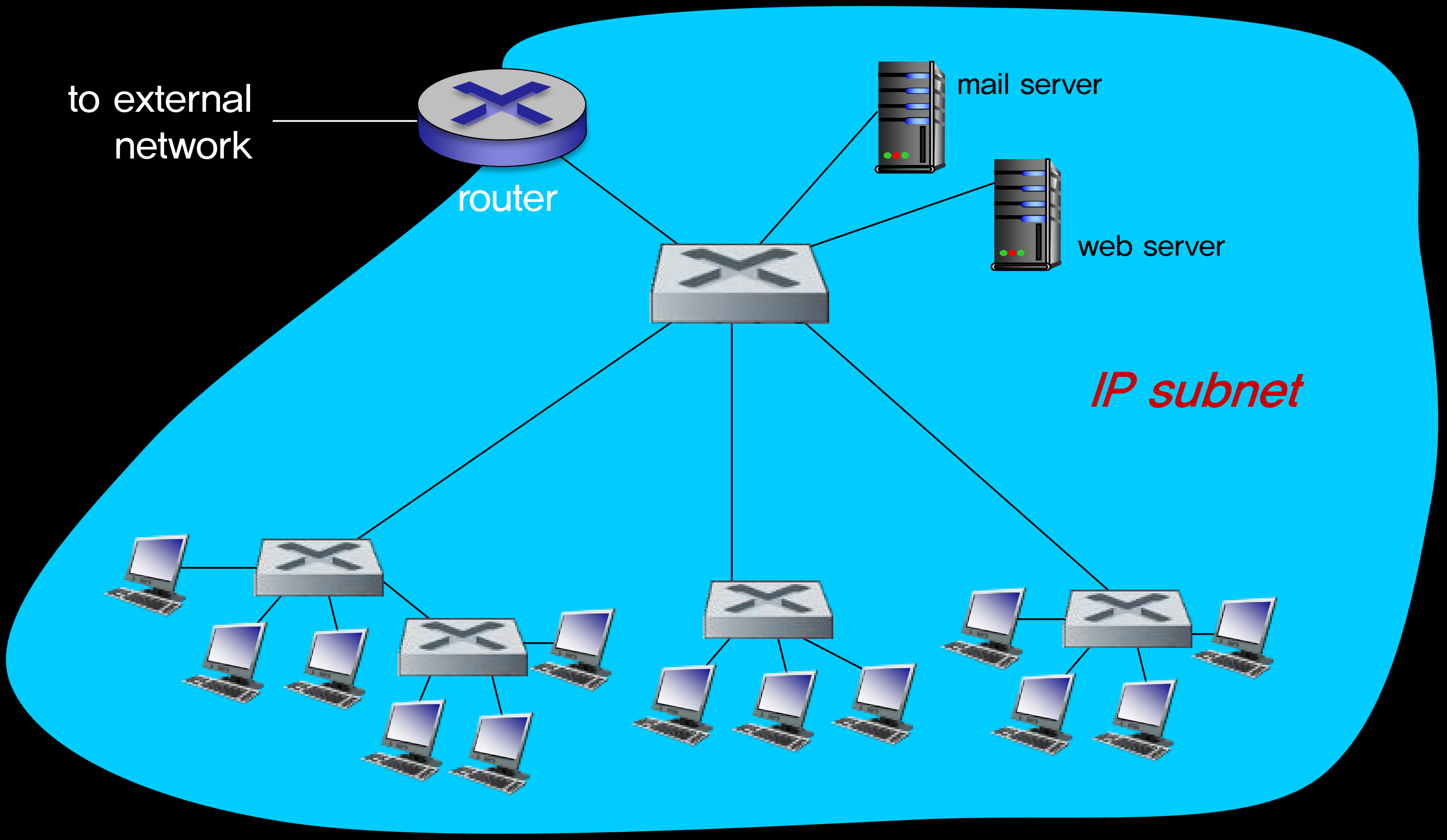
  selectively send on just one link

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

switch table (initially empty)

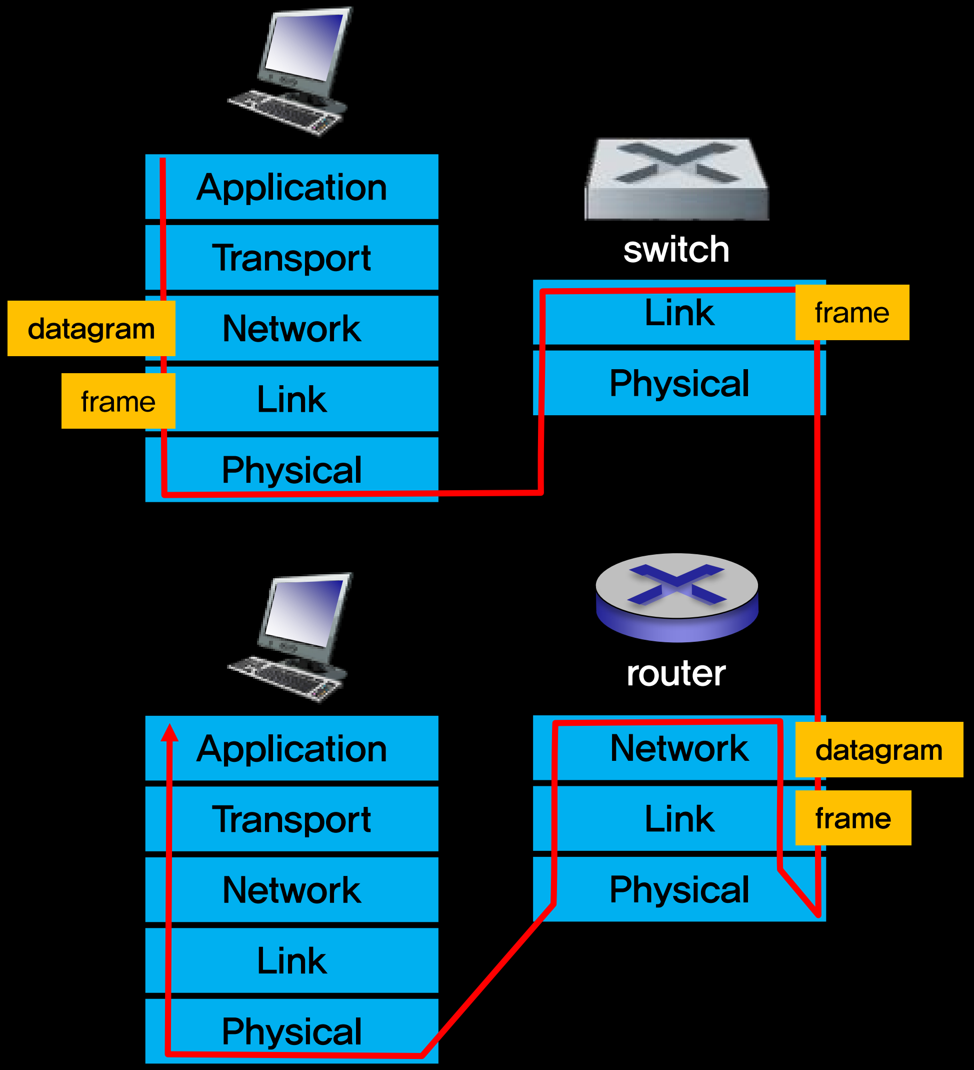


Institutional Network



Switches vs. Routers

- 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

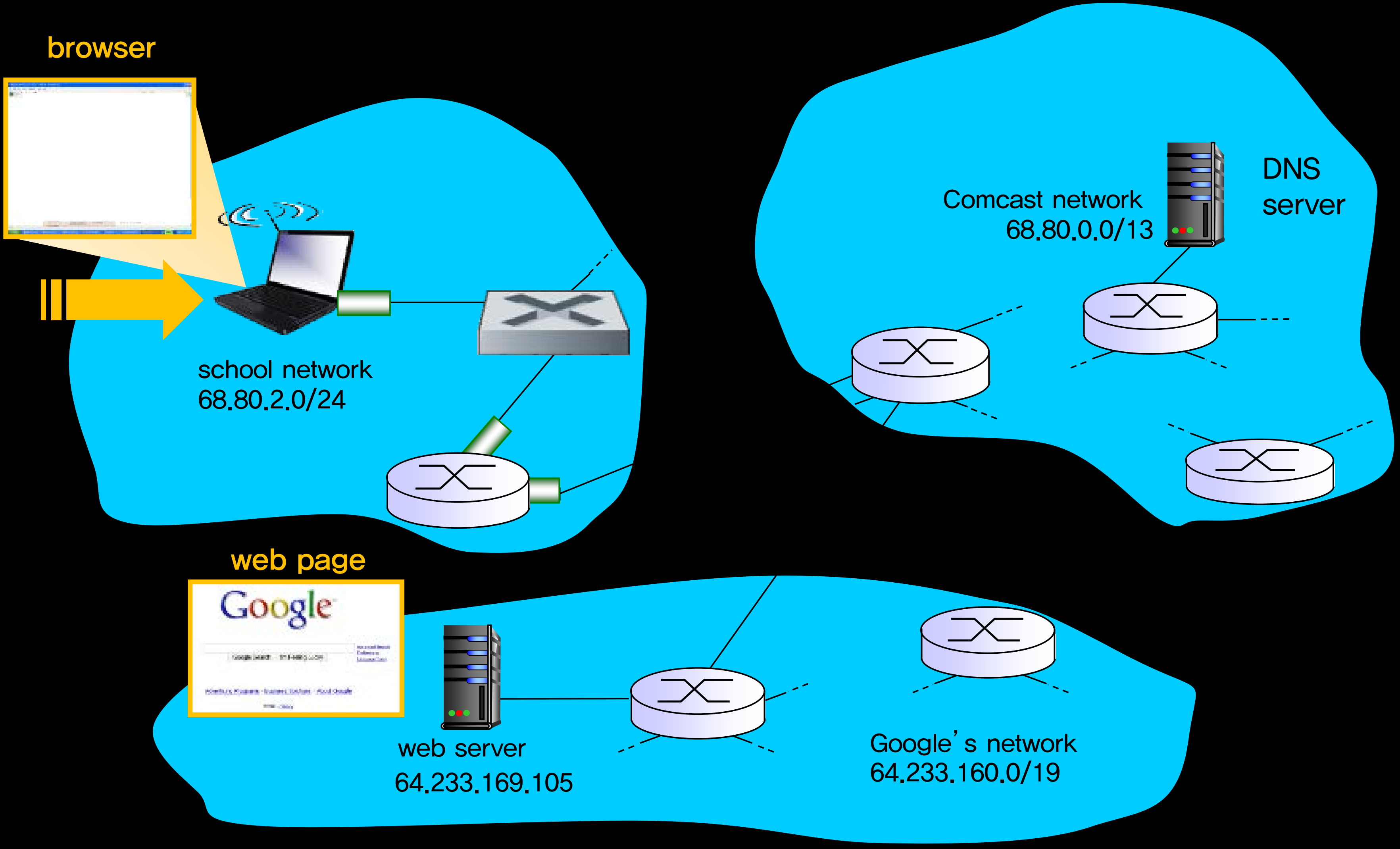


08. Web Request in Real Life

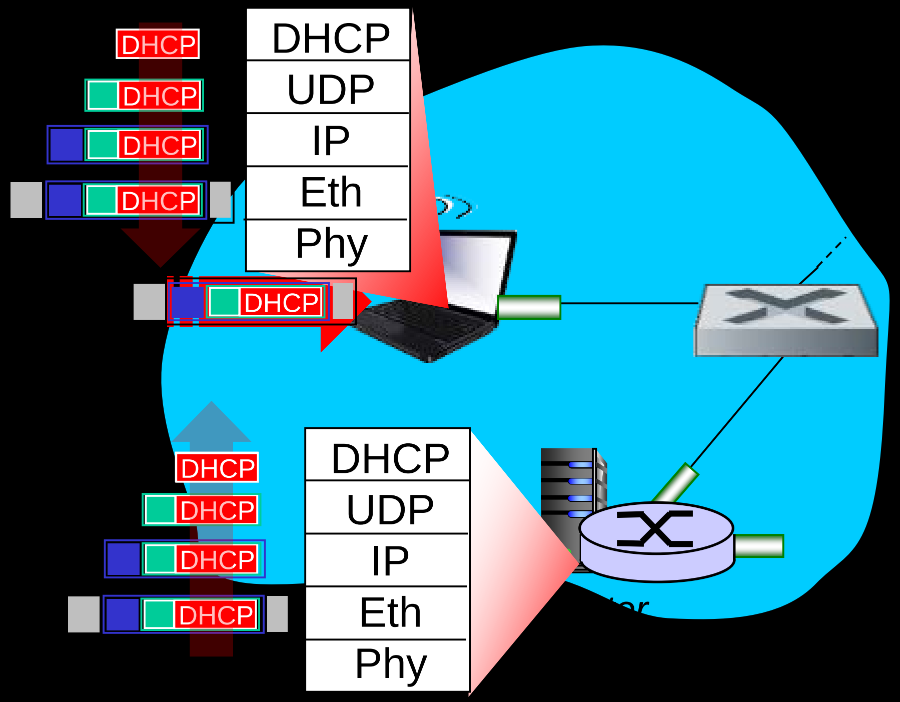
Synthesis: Web Request in Real Life

- Study on all protocol stacks completed!
  - 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

Scenario in Real Life

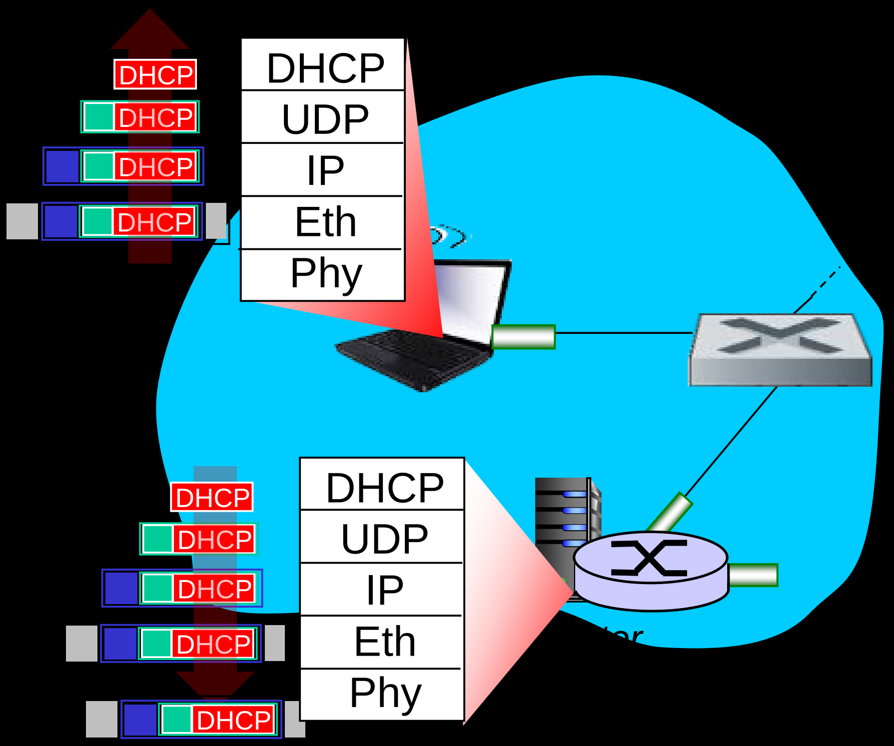


Connecting to the Internet: DHCP



- 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

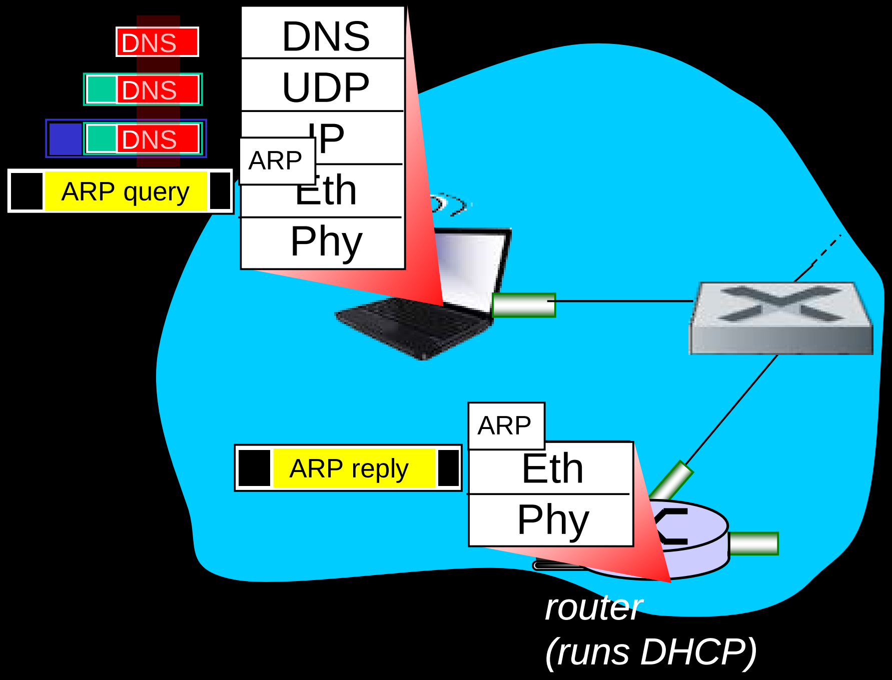
Connecting to the Internet



- 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

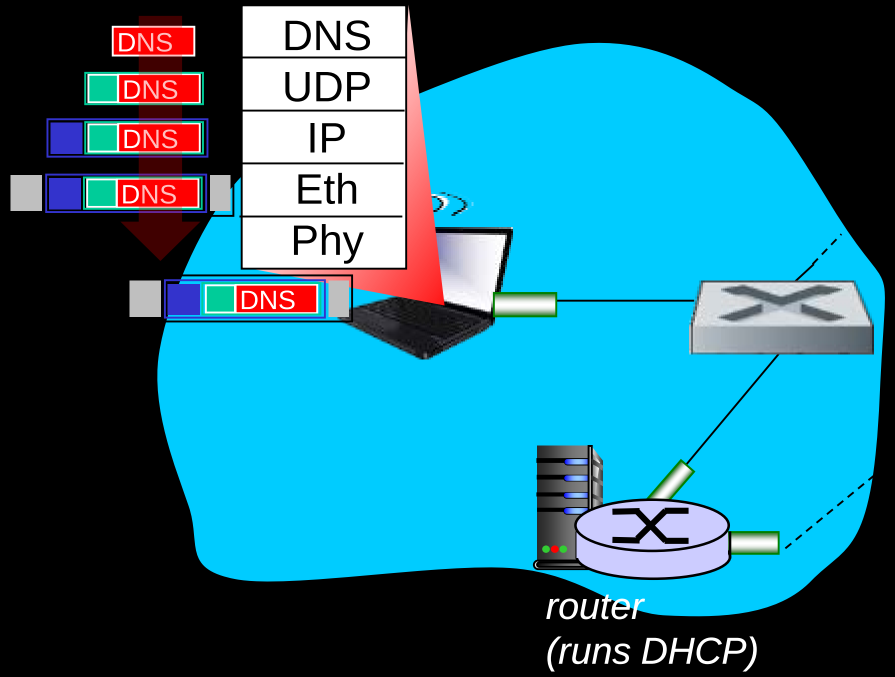
ARP (before DNS, before HTTP)

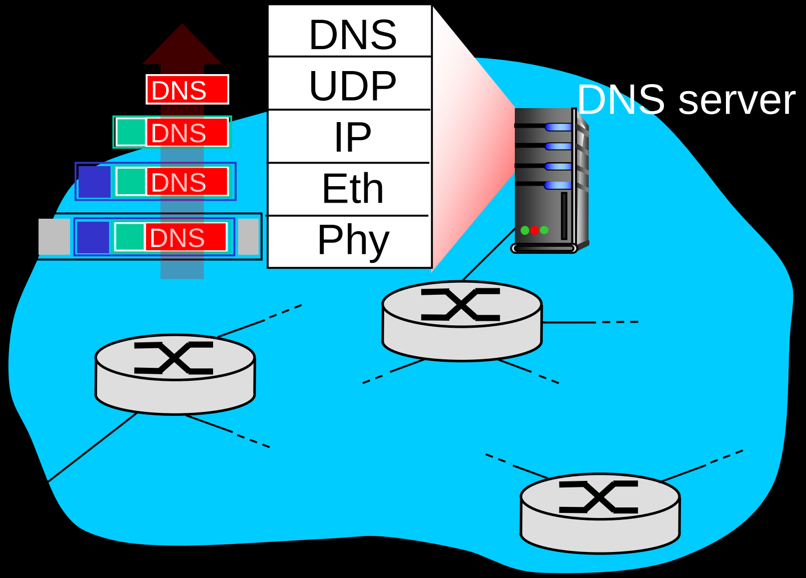


- Before sending HTTP request, need IP address of www.google.com: DNS
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: ARP
- ARP query broadcast, received by router, which replies with ARP reply giving MAC address of router interface

Client now knows MAC address of first hop router, so can now send frame containing DNS query

DNS Query/Reply

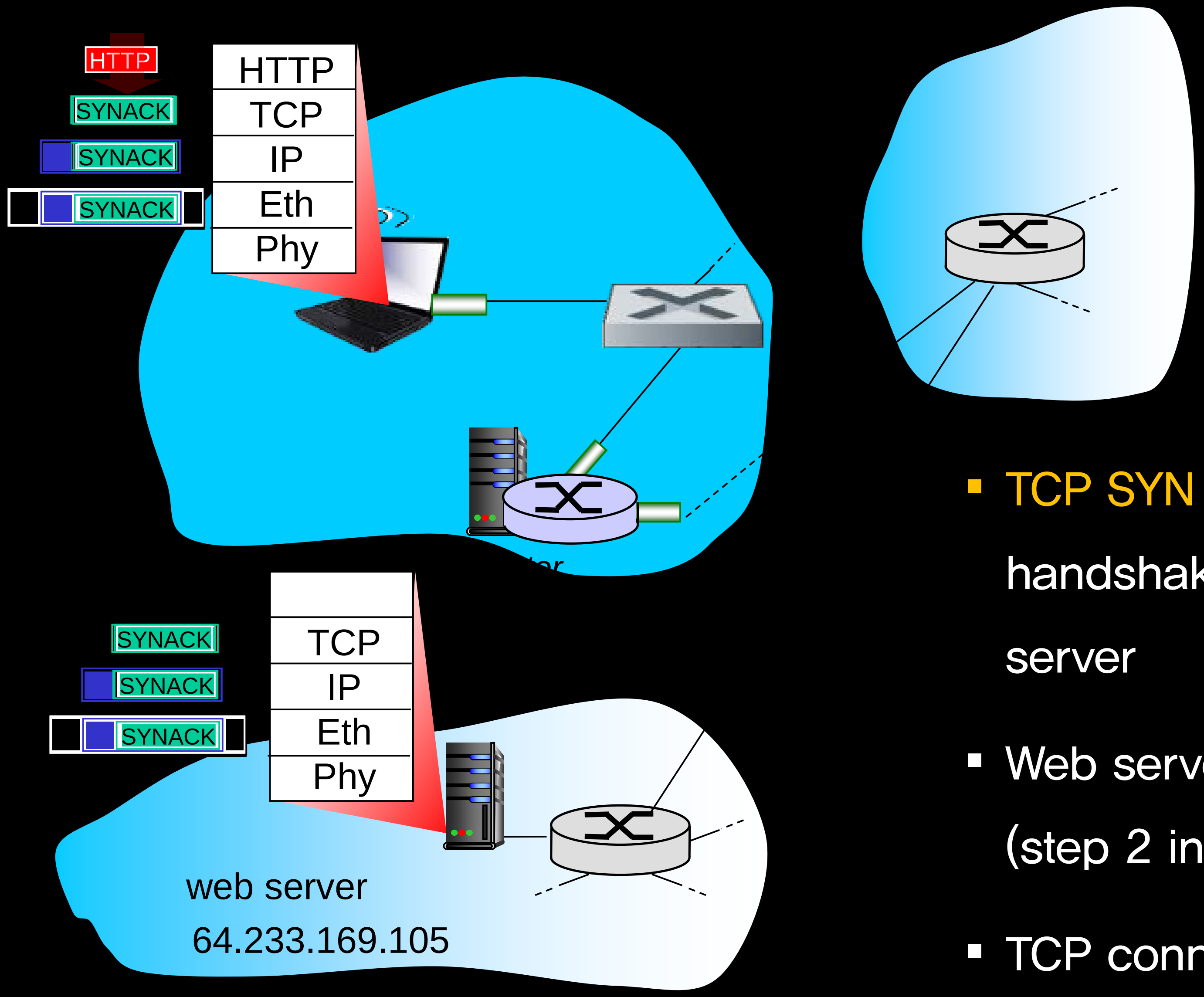




- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router

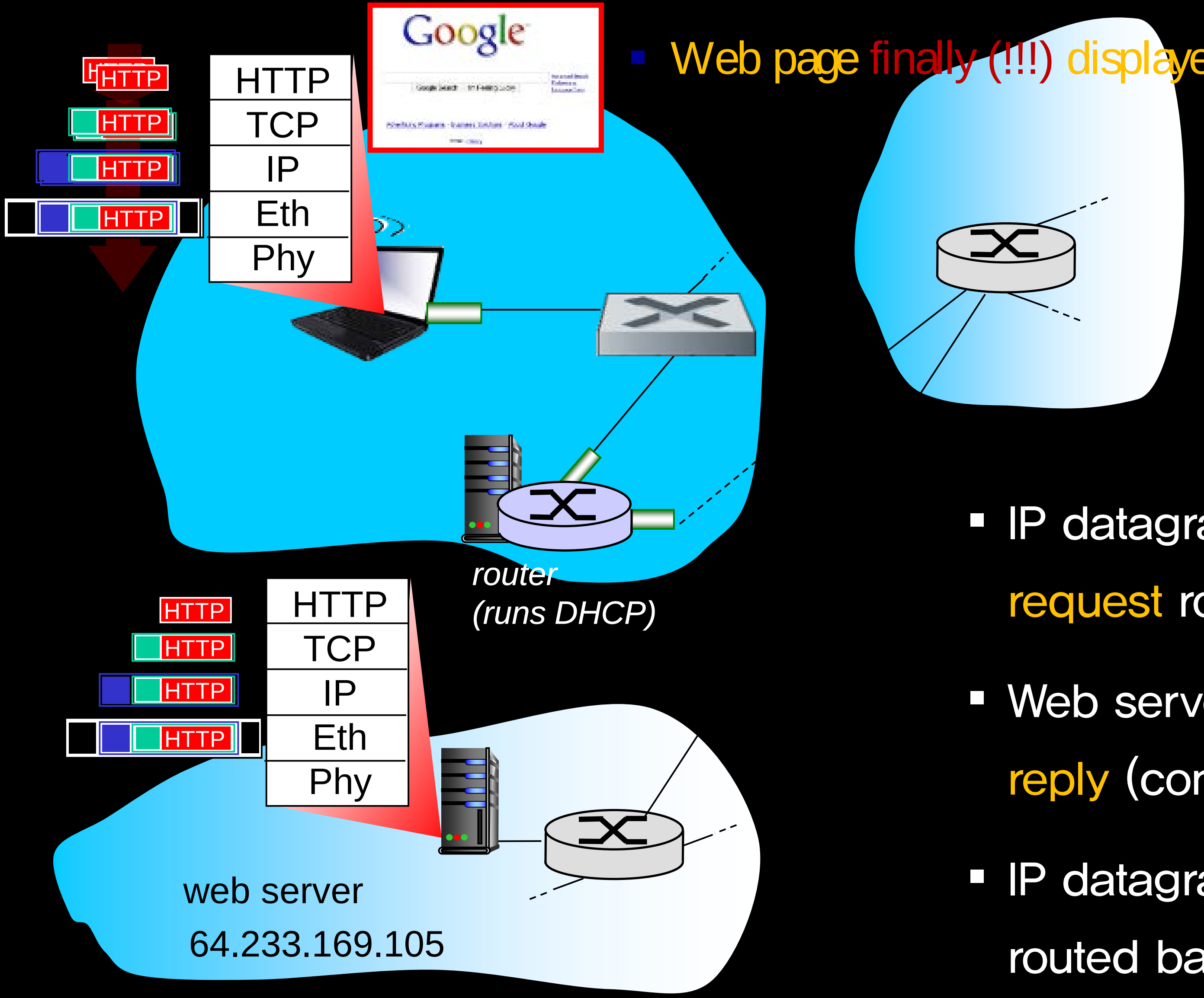
- Demuxed to DNS server
- DNS server replies to client with IP address of www.google.com

TCP Connection Carrying HTTP



- 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!

HTTP Request/Reply



- Web page finally (!!!) displayed!

- 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

Summary

Summary (1/2)

01 Link Layer Basics

- terminologies: node, link, frame
- services: framing, link access, error detection & correction

02 Error Detection & Correction

- cyclic redundancy check
- hamming code, convolutional code

03 Multiple Access Protocols

- distributed algorithm that determines how nodes share channel
- taxonomy: channel partitioning, taking turns, random access

04 MAC Protocols without Collision

- channel partitioning: FDMA, TDMA, CDMA
- taking turns: polling, token passing

Summary (2/2)

05

MAC Protocols with Collision

- ALOHA, slotted ALOHA
- CSMA, CSMA/CD

06

Address Resolution Protocol

- finds out MAC address with IP address
- ARP table: self–learning

07

Ethernet

- Ethernet frame structure
- Ethernet switches cause no collision

08

Web Request in Real Life

- DHCP, UDP, ARP ➜ IP address of first router and DNS
- DNS, TCP, HTTP ➜ find and connect target server