# Link Layer

Slides are adapted from the companion website of the book *Computer Networking: A Top-Down Approach by* Jim Kurose, Keith Ross

# Link layer: roadmap

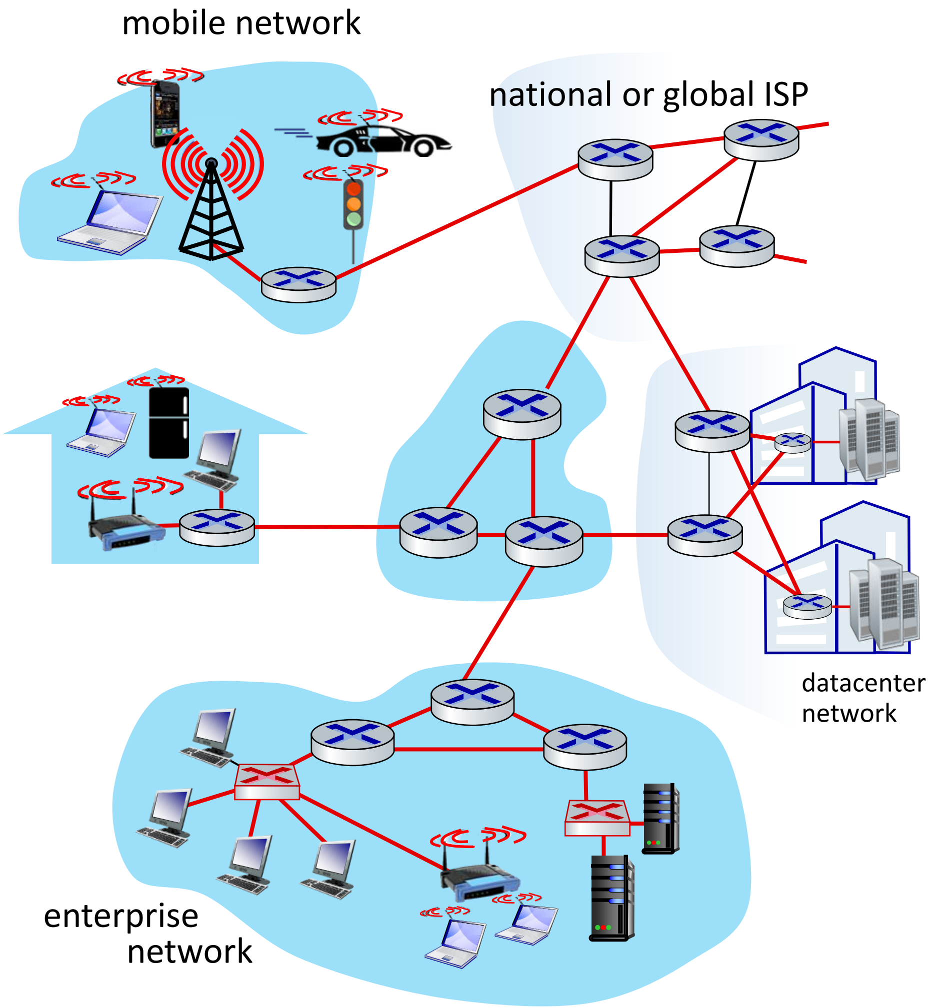
- introduction
- error detection, correction
- multiple access protocols
- LANs
  - addressing, ARP
  - Ethernet
  - switches
- data center networking
- putting it all together

# 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 a physically adjacent node over a link*



# Link layer: context

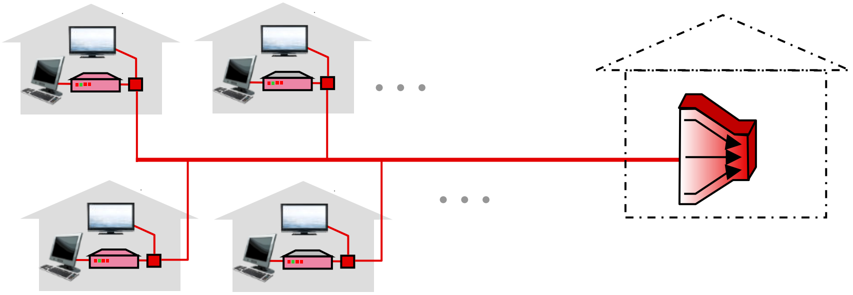
- datagram transferred by different link protocols over different links:
  - e.g., WiFi on first link, Ethernet on next link
- each link protocol provides different services
  - e.g., may or may not provide reliable data transfer over link

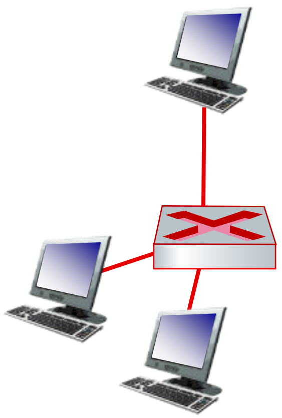
transportation analogy:

- trip from Hauz Khas to Saarbrucken
  - cab: Hauz Khas to DEL
  - plane: DEL to FRA
  - train: FRA to Saarbrucken
- tourist = datagram
- transport segment = communication link
- transportation mode = link-layer protocol
- travel agent = routing algorithm

# Link layer: services

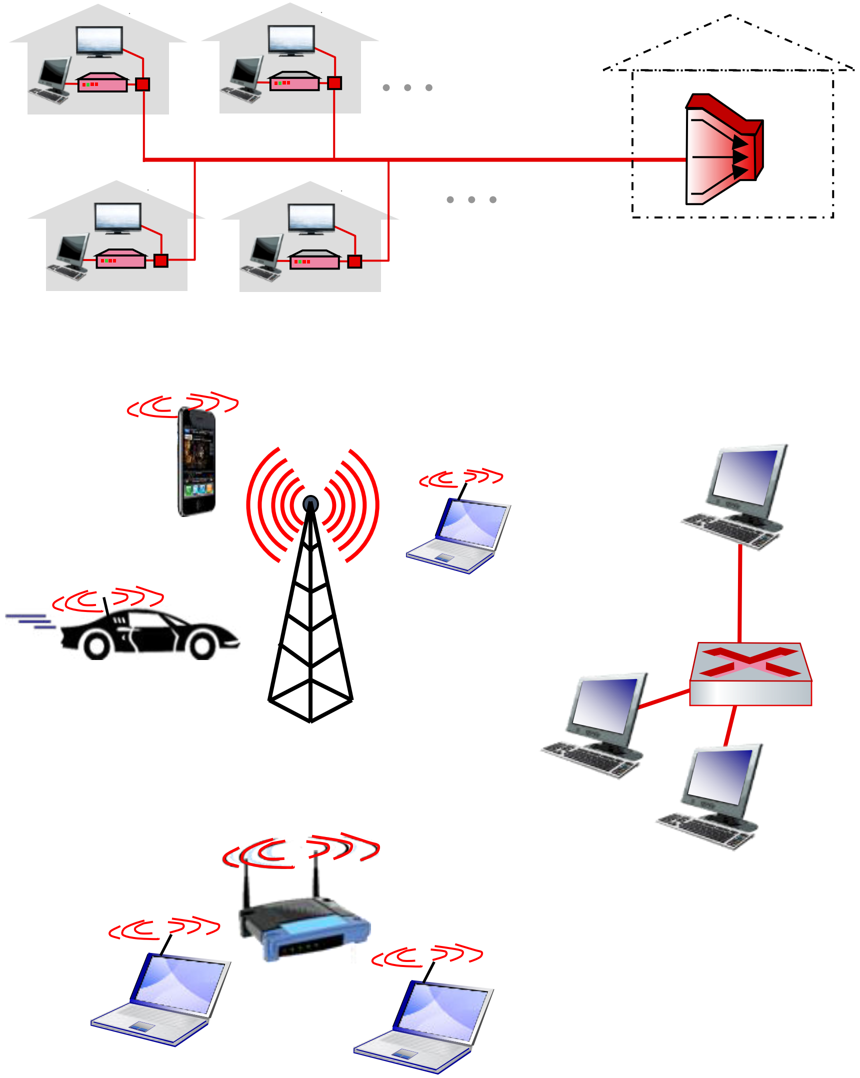
- framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - “MAC” addresses in frame headers identify source, destination (different from IP address!)
- reliable delivery between adjacent nodes
  - we already know how to do this!
  - seldom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





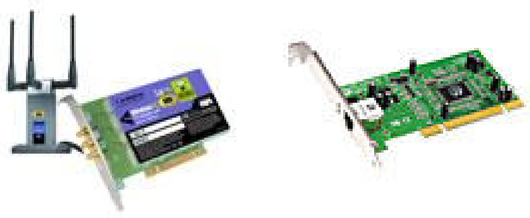
# Link layer: services (more)

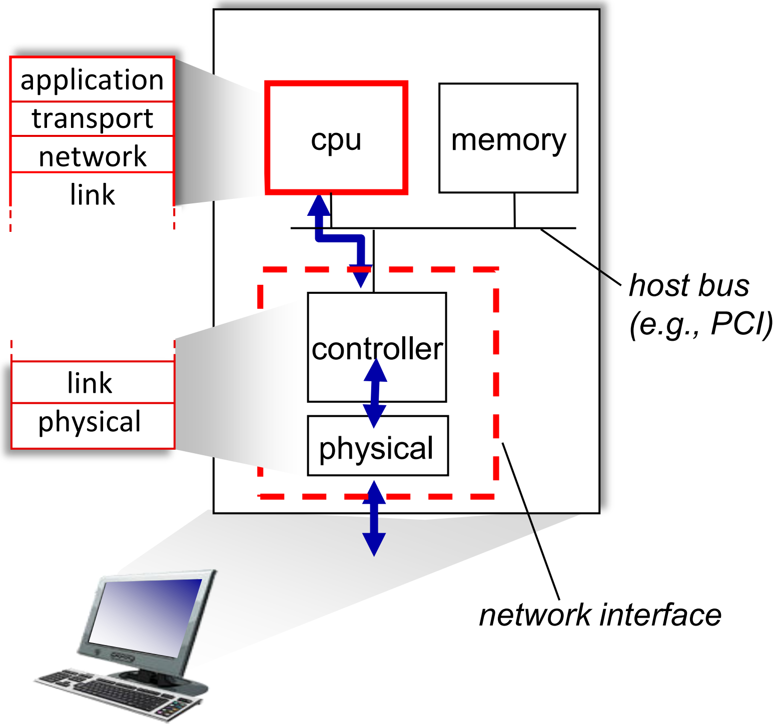
- flow control:
  - pacing between adjacent sending and receiving nodes
- error detection:
  - errors caused by signal attenuation, noise.
  - receiver detects errors, signals retransmission, or drops frame
- error correction:
  - receiver identifies *and corrects* bit error(s) without retransmission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



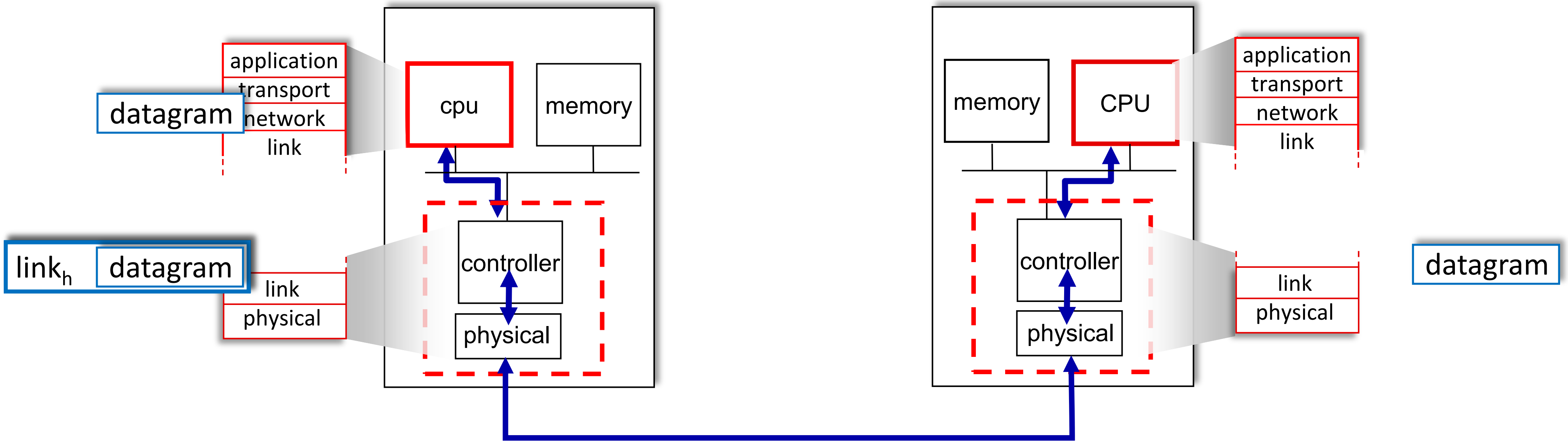
# Where is the link layer implemented?

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





# Interfaces communicating



sending side:

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

receiving side:

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

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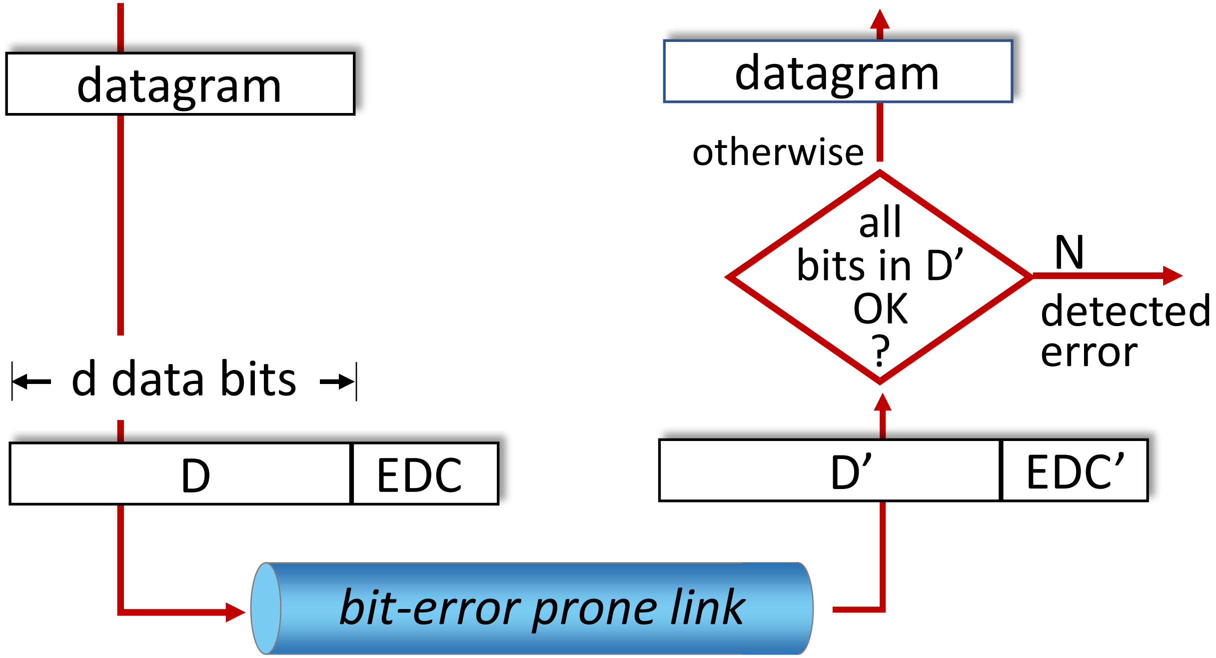
# Error detection

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

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



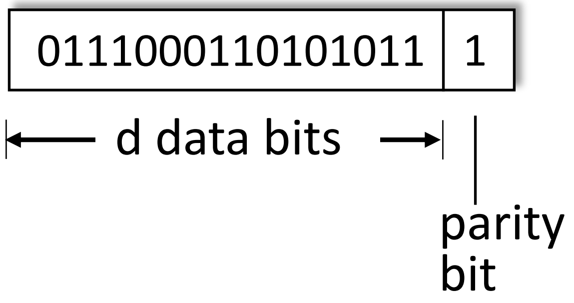
Error detection not 100% reliable!

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

# Parity checking

## single bit parity:

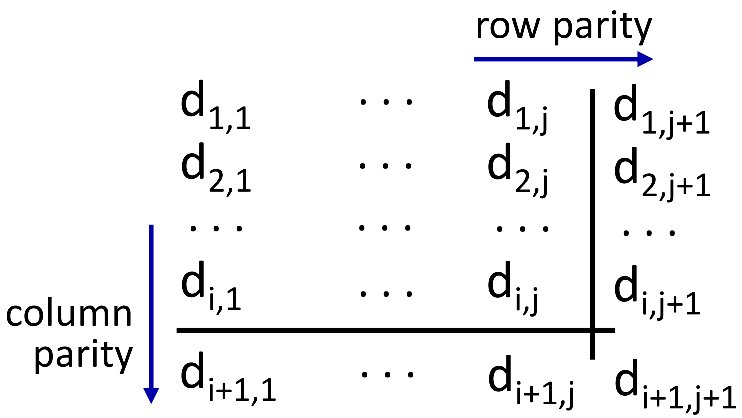
- detect single bit errors



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

## two-dimensional bit parity:

- detect *and correct* single bit errors

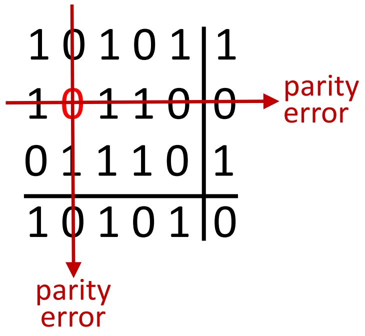


$$\begin{array}{ccc|c} d_{1,1} & \cdots & d_{1,j} & d_{1,j+1} \\ d_{2,1} & \cdots & d_{2,j} & d_{2,j+1} \\ \cdots & \cdots & \cdots & \cdots \\ d_{i,1} & \cdots & d_{i,j} & d_{i,j+1} \\ \hline d_{i+1,1} & \cdots & d_{i+1,j} & d_{i+1,j+1} \end{array}$$

no errors:

| | | | | | |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 1 | 0 | 0 |
| 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 | 1 | 0 |

detected and correctable single-bit error:



| | | | | | |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 1 |
| 1 | 0 | 1 | 1 | 0 | 0 |
| 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 | 1 | 0 |

# Internet checksum

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

**sender:**

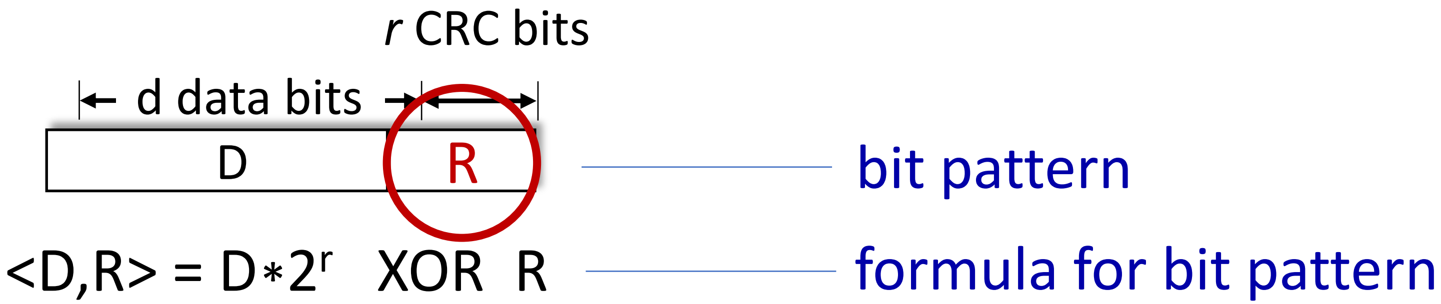
- treat contents of UDP segment (including UDP header fields and IP addresses) as sequence of 16-bit integers
- checksum: addition (one's complement sum) of segment content
- checksum value put into UDP checksum field

**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?*

# 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

$<D,R> = D*2^r$ 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)

# Cyclic Redundancy Check (CRC): example

We want:

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

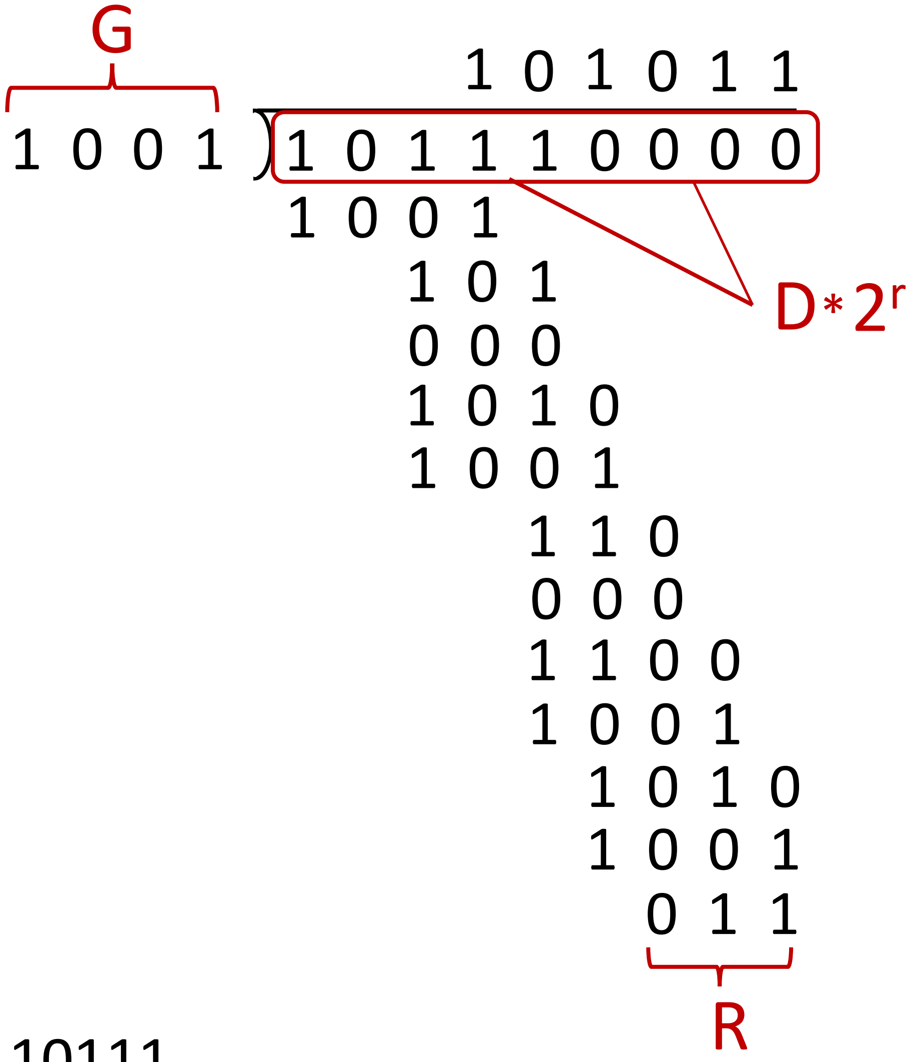
or equivalently:

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

or equivalently:

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

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



How to select G?

Often some standard value is used

CRC32 = 100000100110000010001110110110111

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# Multiple access links, protocols

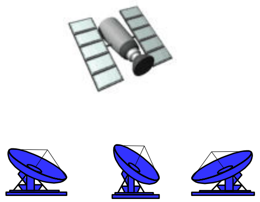
two types of “links”:

- 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

*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

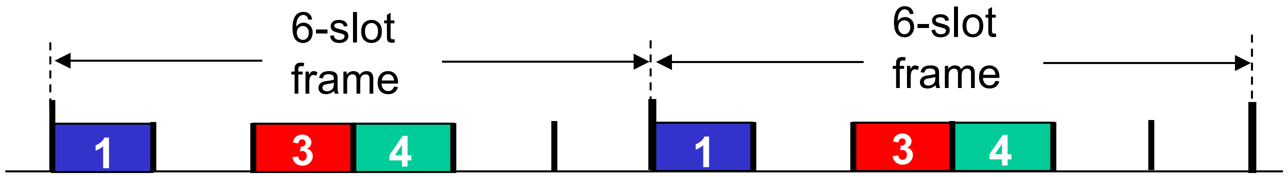
three broad classes:

- 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

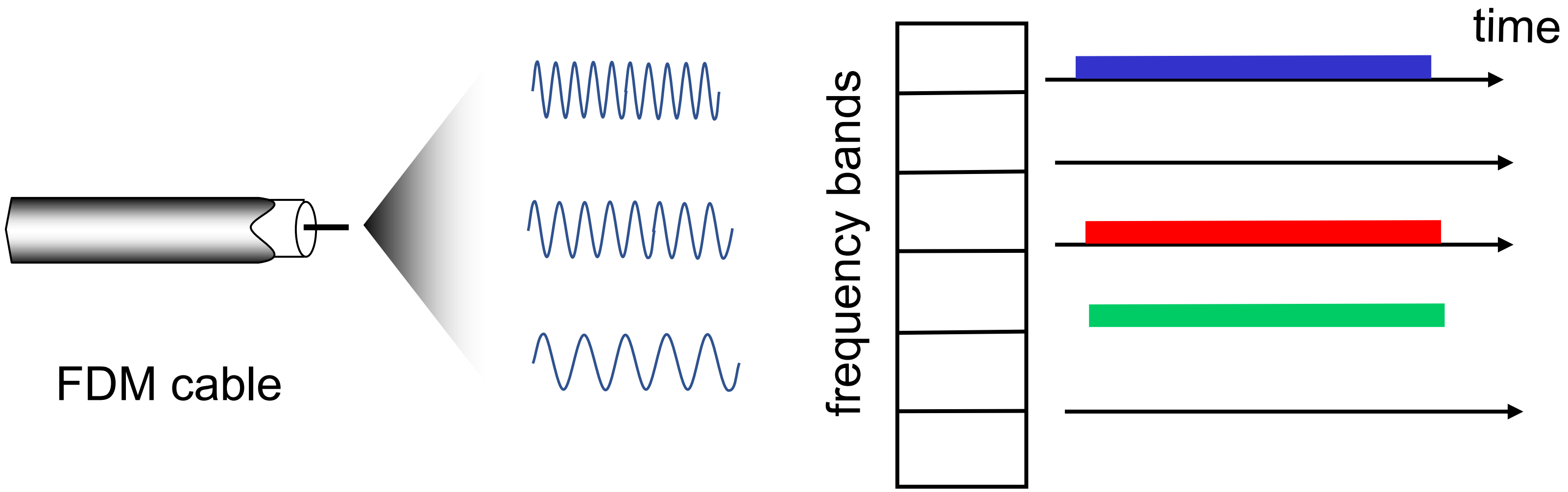
- access to channel in "rounds"
- each station gets fixed length slot (length = packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle



# Channel partitioning MAC protocols: FDMA

## 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



# Code Division Multiple Access (CDMA)

- unique "code" assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")
- encoding: original data XOR chipping sequence
- decoding: encoded data XOR chipping sequence
- Above is a simplified scheme. Actual CDMA used in wireless communication uses spread spectrum techniques.
- Code assignment is complex. See for example https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1453

# 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

# Slotted ALOHA

## assumptions:

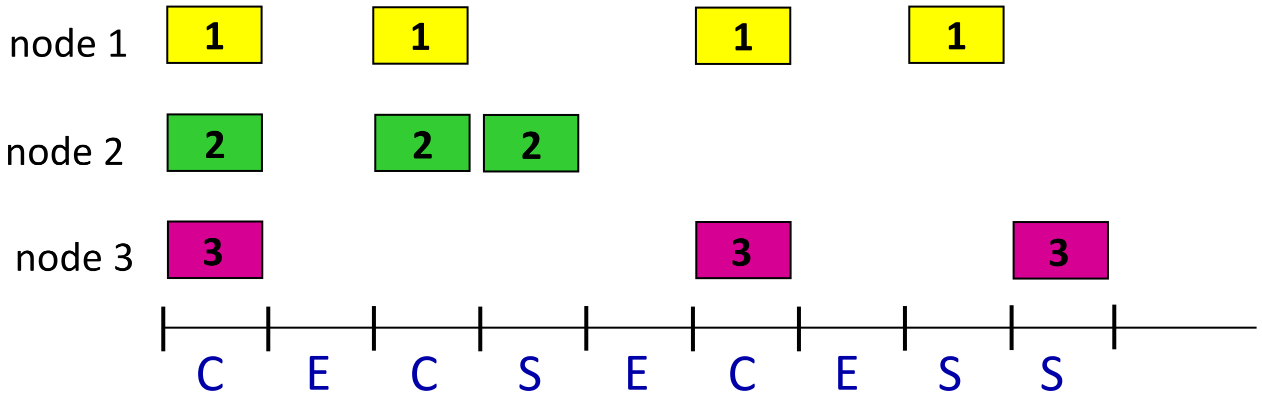
- all frames are of same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

## 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



C: collision
S: success
E: empty

## 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: Throughput

Let T be the frame time, i.e., the time required for 1 frame to be transmitted.

Let G be the number of transmission attempts per frame time.

The probability that $k$ frames are generated during the frame time is given by the Poisson distribution: $P(k) = G^k e^{-G}/k!$

The probability that 0 frames are generated ( $k = 0$ ) during the frame time is $e^{-G}$

For slotted ALOHA, the vulnerable time period for collision between two frames is the time duration of 1 slot = 1 frame time $T$.

In $T$ time, average number of transmission attempts is G.

The probability that 0 frames are initiated in the vulnerable time period will be $P(0) = e^{-G}$

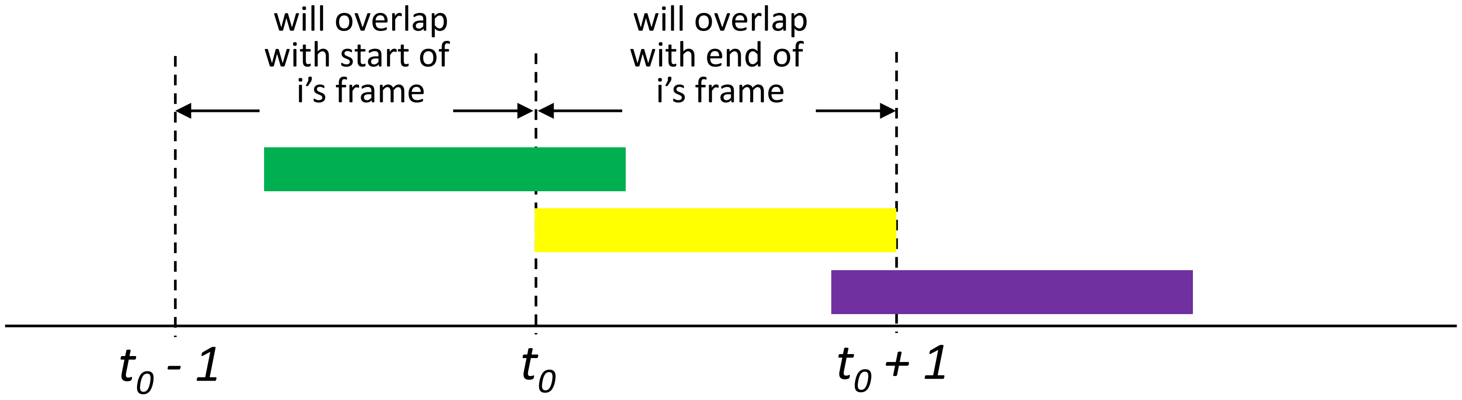
The throughput, $S$, is calculated as the number of transmission attempts per frame time, $G$, multiplied by the probability of success, P(0): $S = G.P(0)$ or $S = Ge^{-G}$

Maximum throughput of Slotted ALOHA occurs when G = 1.

The maximum throughput is thus $S_{max} = 1 \times e^{-1} = 1/e = 0.368$

# 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

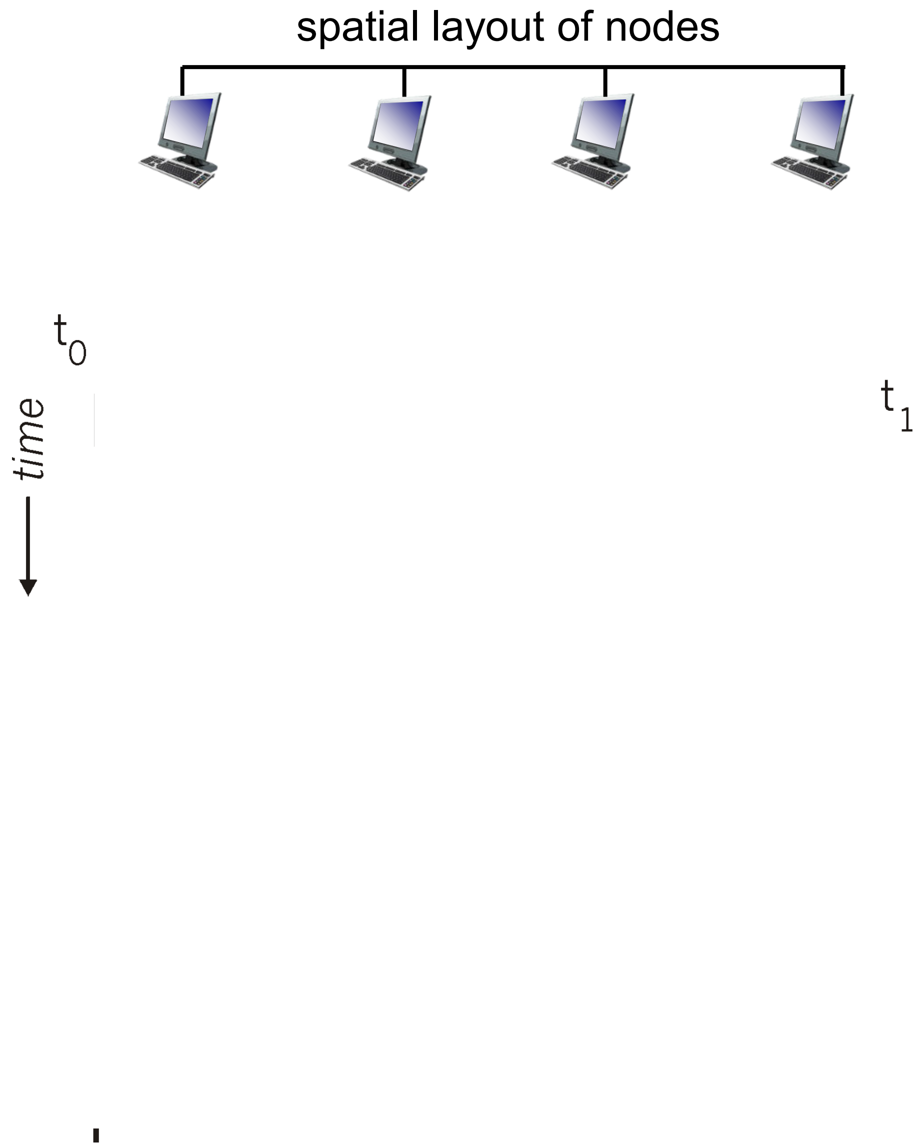
- human analogy: don't interrupt others!

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

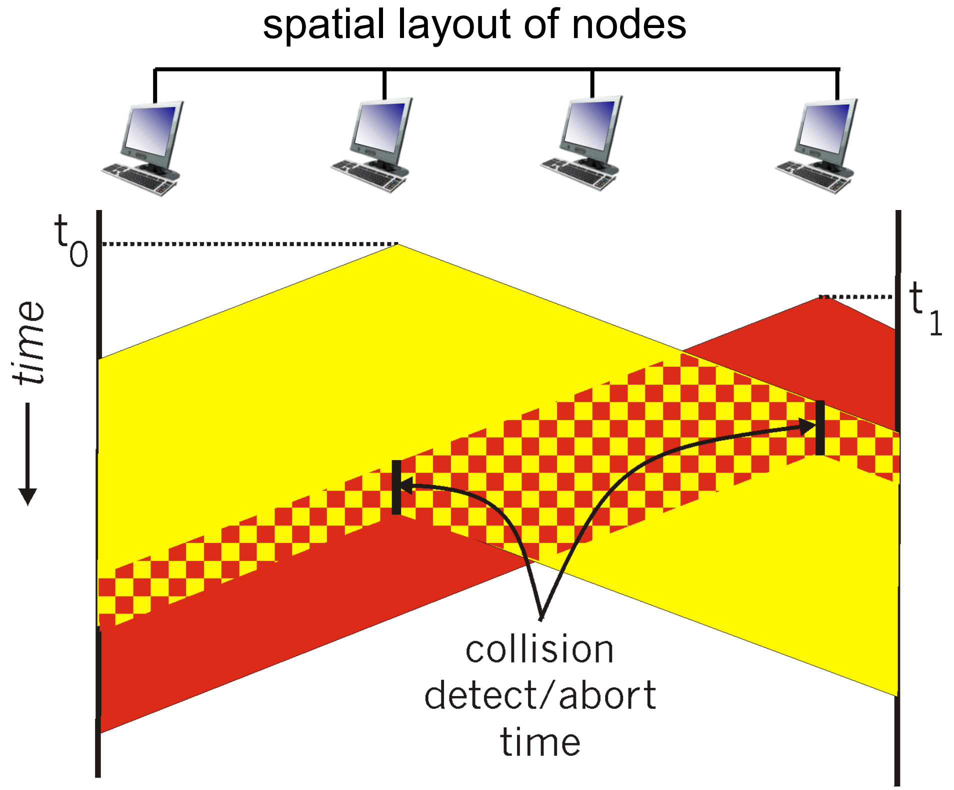
# CSMA: collisions

- 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



# 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 *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
   - more collisions: longer backoff interval

# CSMA/CD efficiency

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

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

- See https://www.sce.carleton.ca/faculty/lambadaris/courses/462/csma_cd.pdf for proof
- efficiency goes to 1
  - as $t_{prop}$ goes to 0
  - as $t_{trans}$ goes to infinity
- better performance than ALOHA: and simple, cheap, decentralized!

# "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

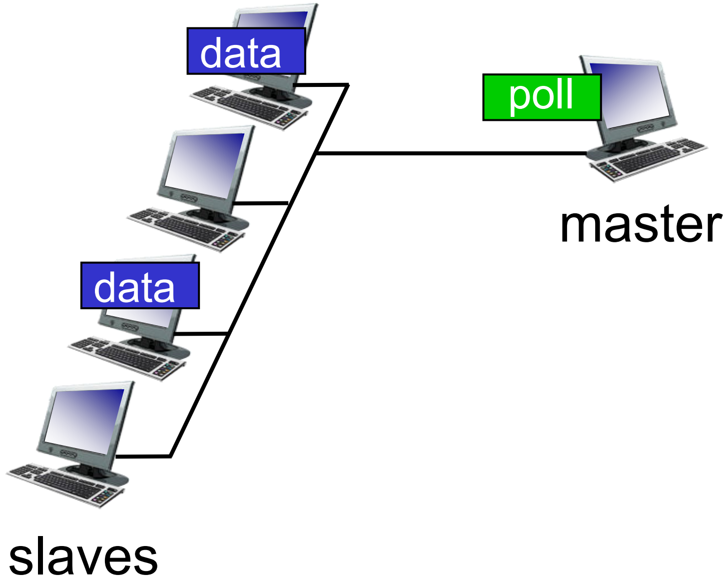
## "taking turns" protocols

- look for best of both worlds!

# “Taking turns” MAC protocols

polling:

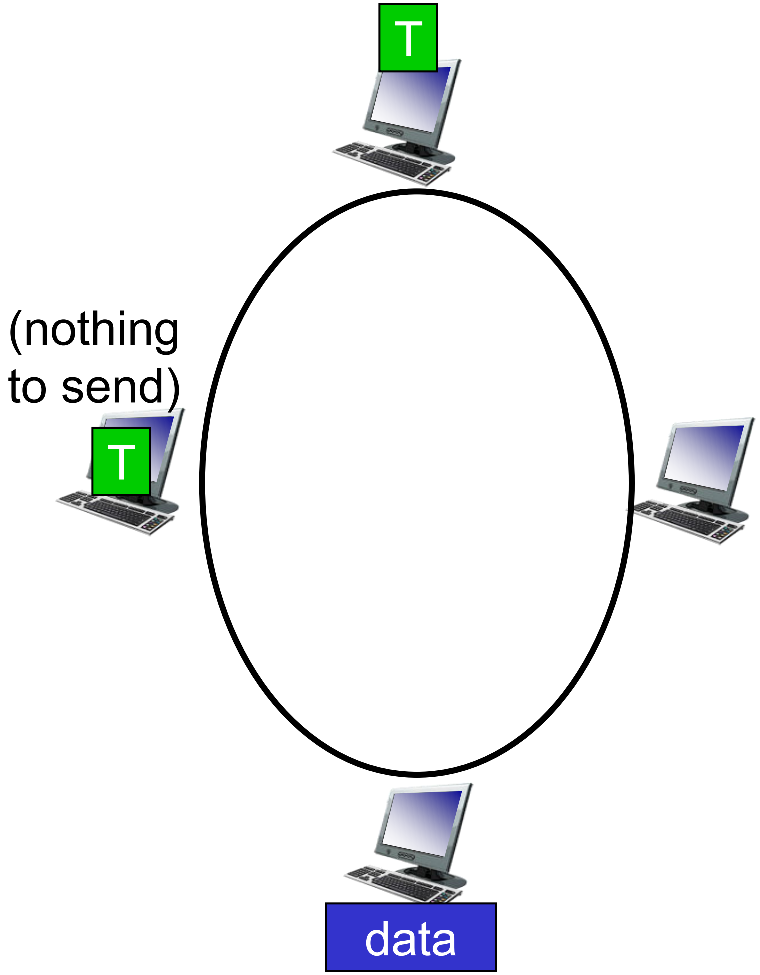
- master node “invites” other nodes to transmit in turn
- transmits if there is data to send
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)



# "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)



# Wireless link characteristics

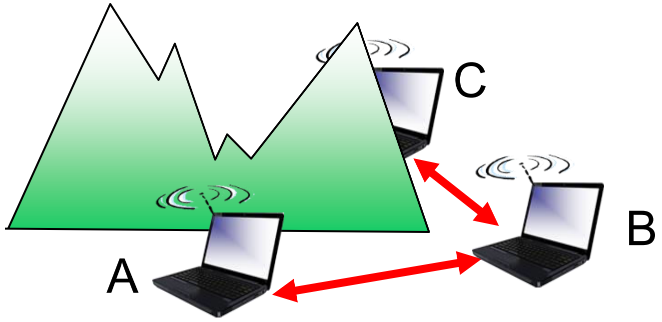
*important* differences from wired link ….

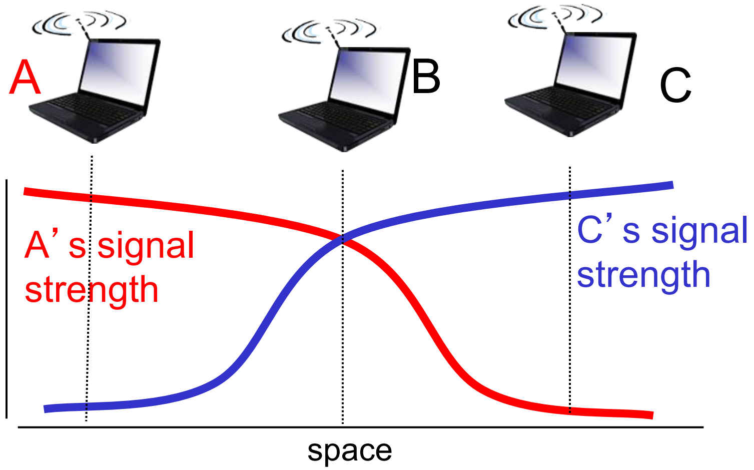
- decreased signal strength*:* radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
- multipath propagation: radio signal reflects off objects ground, arriving at destination at slightly different times

…. make communication across (even a point to point) wireless link much more “difficult”

# Wireless link characteristics

Multiple wireless senders, receivers create additional problems (beyond multiple access):





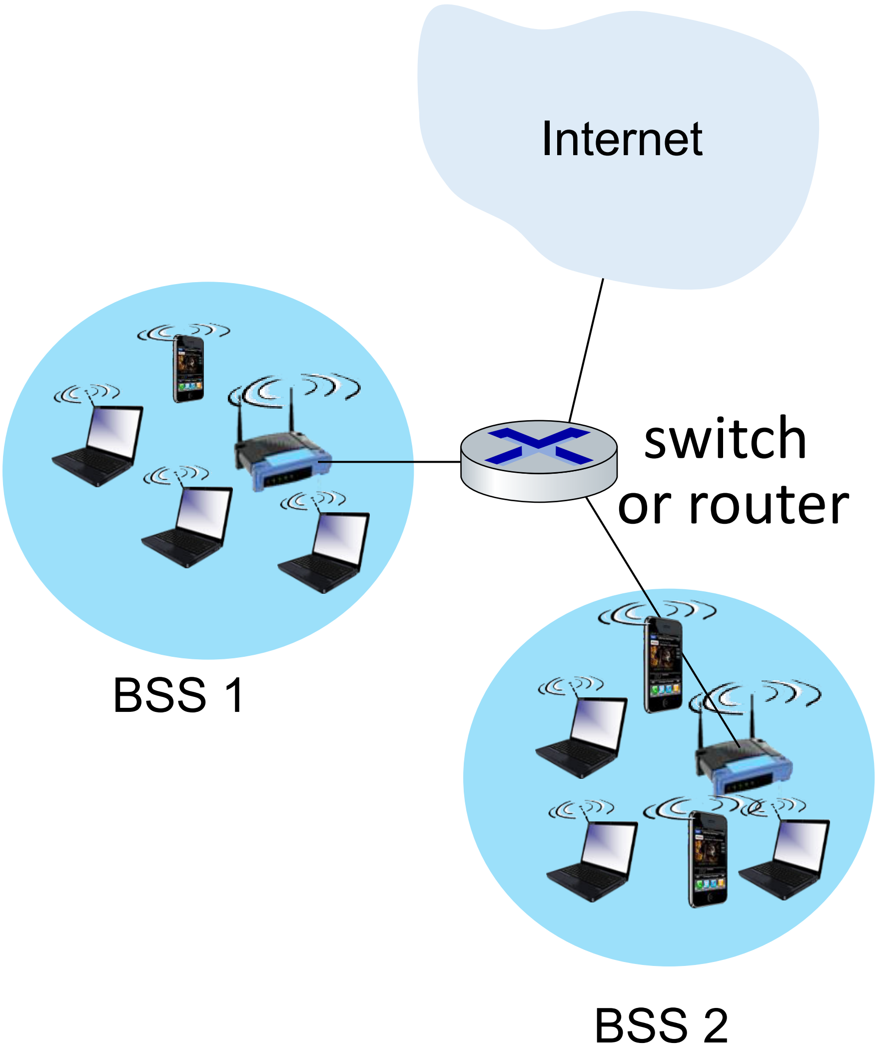
## Hidden terminal problem

- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B

## Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

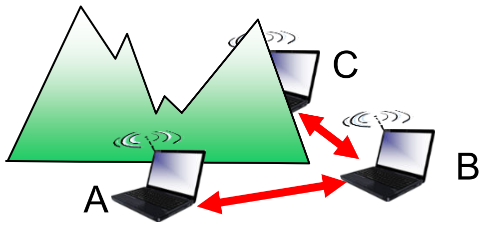
# 802.11 LAN/ WiFi architecture

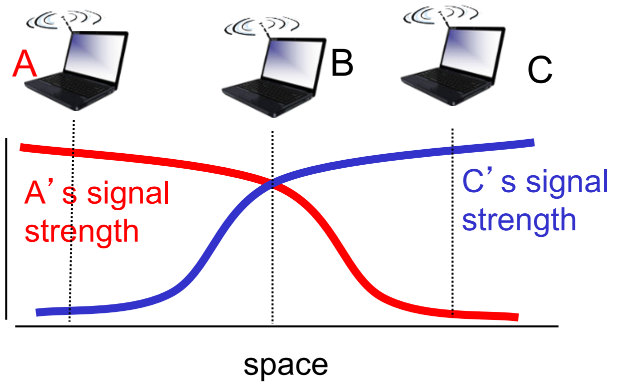


- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

# IEEE 802.11: multiple access

- avoid collisions: $2^+$ nodes transmitting at same time
- 802.11: CSMA - sense before transmitting
  - don’t collide with detected ongoing transmission by another node
- 802.11: *no* collision detection!
  - difficult to sense collisions: high transmitting signal, weak received signal due to fading
  - can’t sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/CollisionAvoidance





# IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

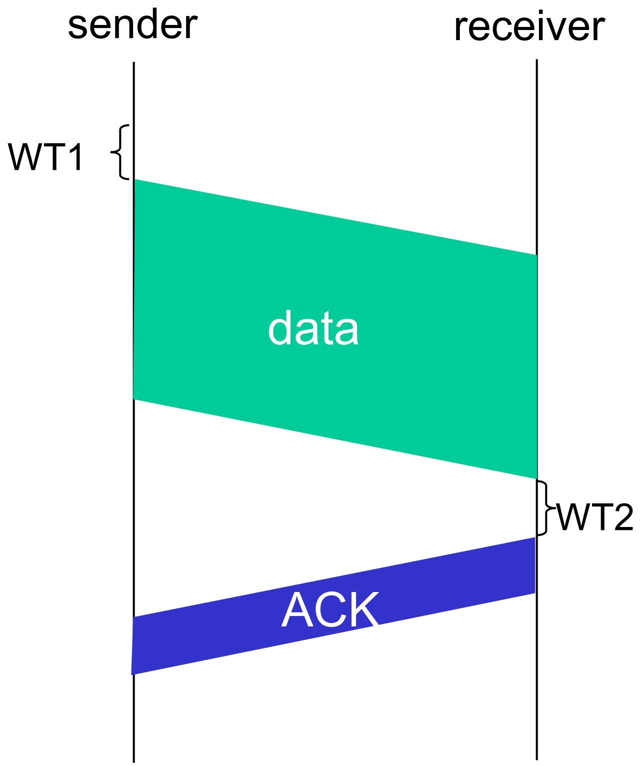
1 if sense channel idle for time WT1 (called DIFS)
then transmit entire frame (no CD)

2 if sense channel busy then

- start random backoff time
- timer counts down while channel idle
- transmit when timer expires
- if no ACK, increase random backoff interval, repeat 2

802.11 receiver

if frame received OK
return ACK after WT2 (called SIFS)
(ACK needed due to hidden terminal problem)

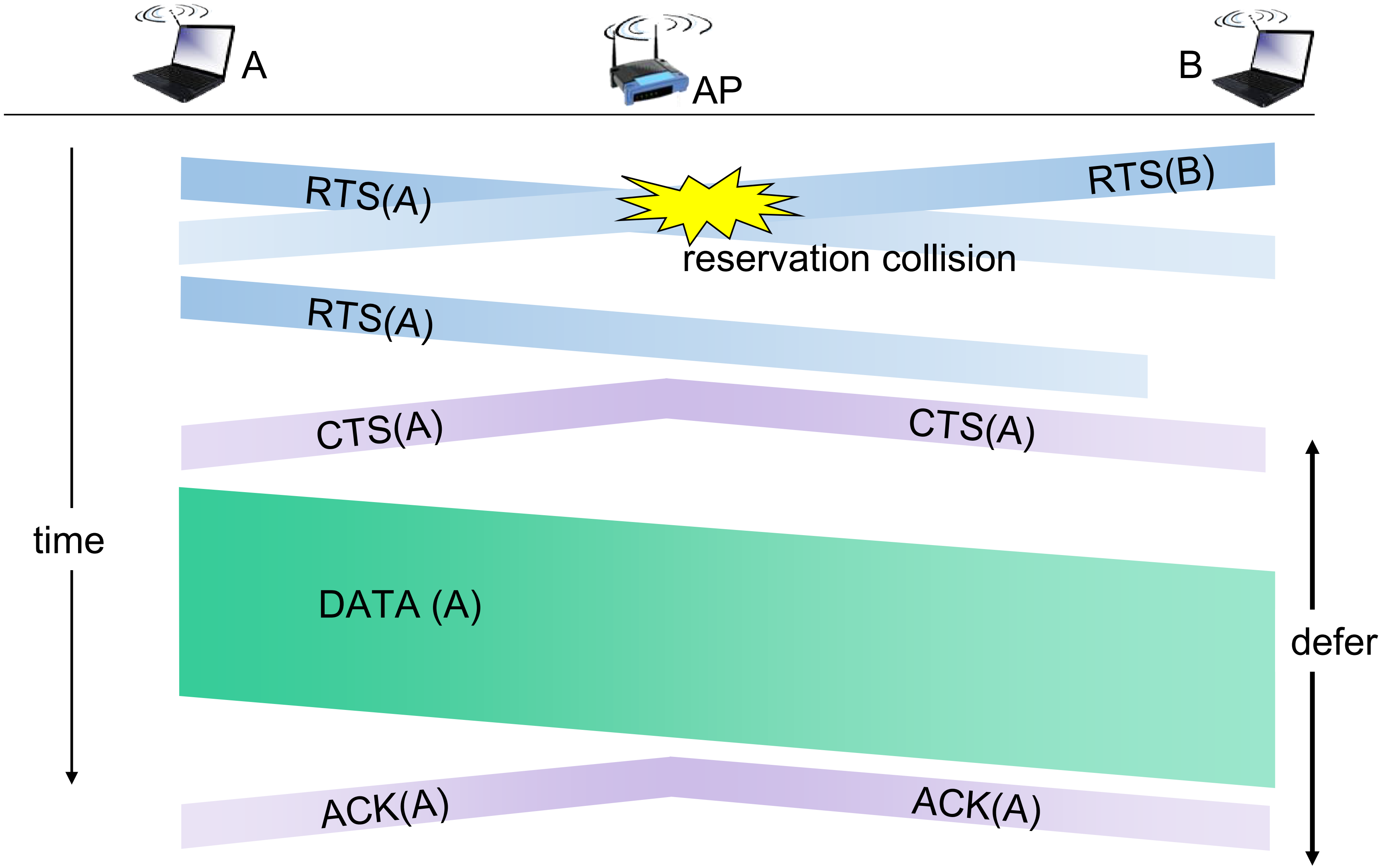


# Avoiding collisions

idea: sender "reserves" channel use for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

# Collision Avoidance: RTS-CTS exchange



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# MAC addresses

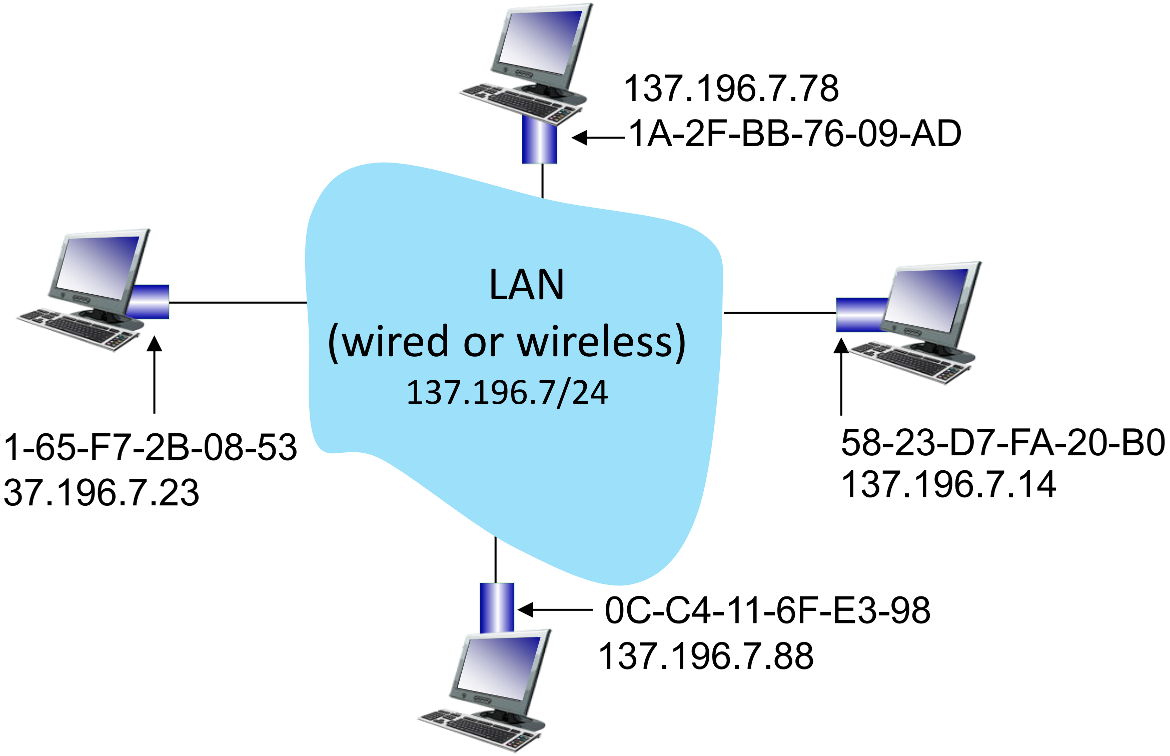
- 32-bit IP address:
  - *network-layer* address for interface
  - used for layer 3 (network layer) forwarding
  - e.g.: 128.119.40.136
- MAC (or LAN or physical or Ethernet) address:
  - function: used "locally" to get frame from one interface to another physically-connected interface (same subnet, in IP-addressing sense)
  - 48-bit MAC address (for most LANs) burned in NIC ROM, also sometimes software settable
  - e.g.: 1A-2F-BB-76-09-AD

*hexadecimal (base 16) notation*
*(each "numeral" represents 4 bits)*

# MAC addresses

each interface on LAN

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

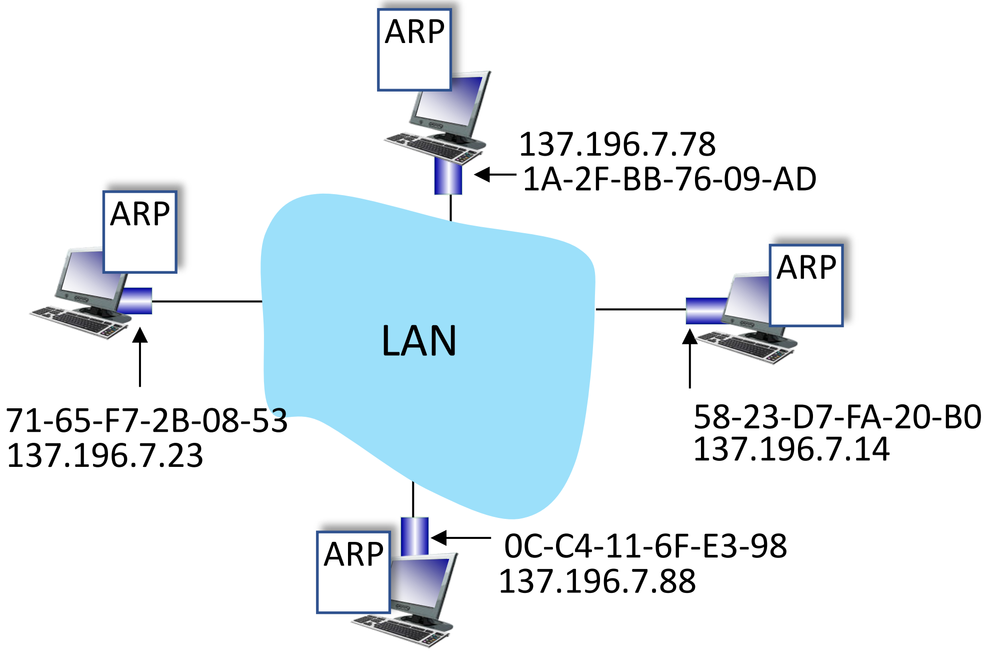


# MAC addresses

- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- analogy:
  - MAC address: like Social Security Number/Aadhar
  - IP address: like postal address
- MAC flat address: portability
  - can move interface from one LAN to another
  - IP address *not* portable: depends on IP subnet to which node is attached
- Random Mac address
  - See https://www.mathyvanhoef.com/2016/03/how-mac-address-randomization-works-on.html for details

# ARP: address resolution protocol

*Question:* how to determine interface's MAC address, knowing its IP address?



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

- IP/MAC address mappings for some LAN nodes:

  < IP address; MAC address; TTL>

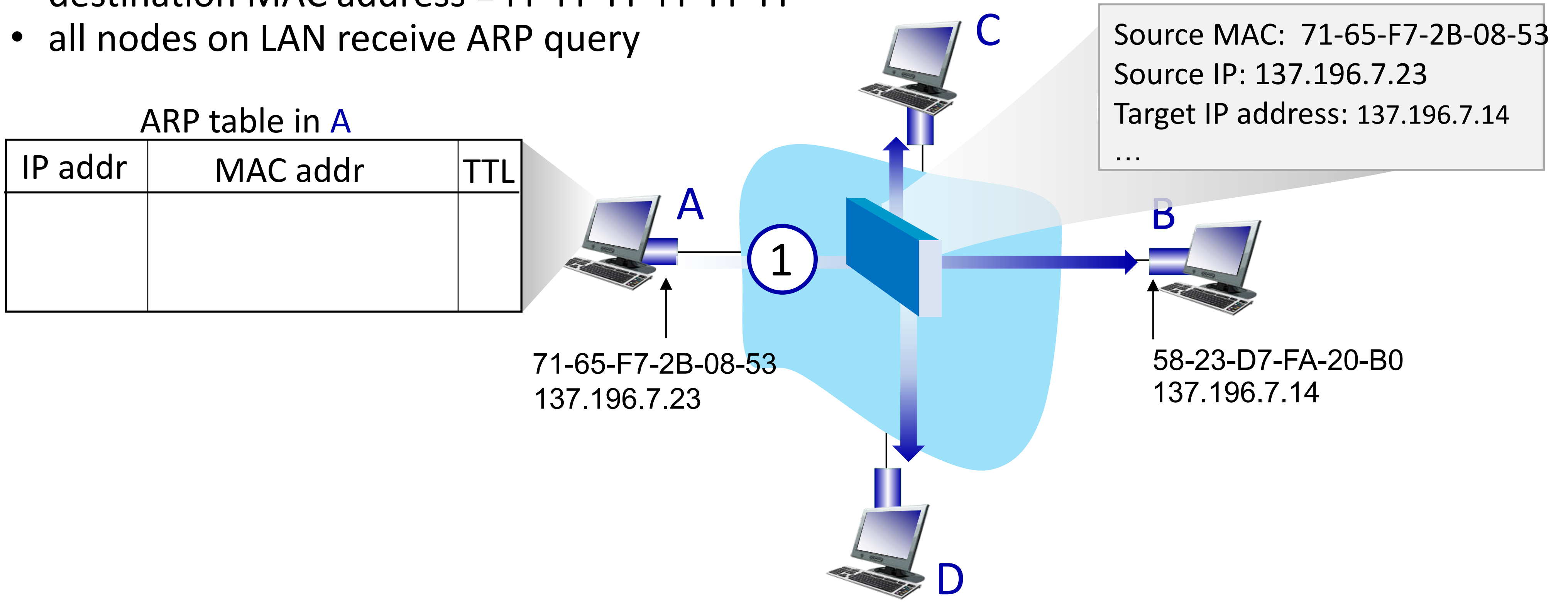
- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

# ARP protocol in action

## example: A wants to send datagram to B

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

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



ARP table in A

| IP addr | MAC addr | TTL |
|---|---|---|
| | | |

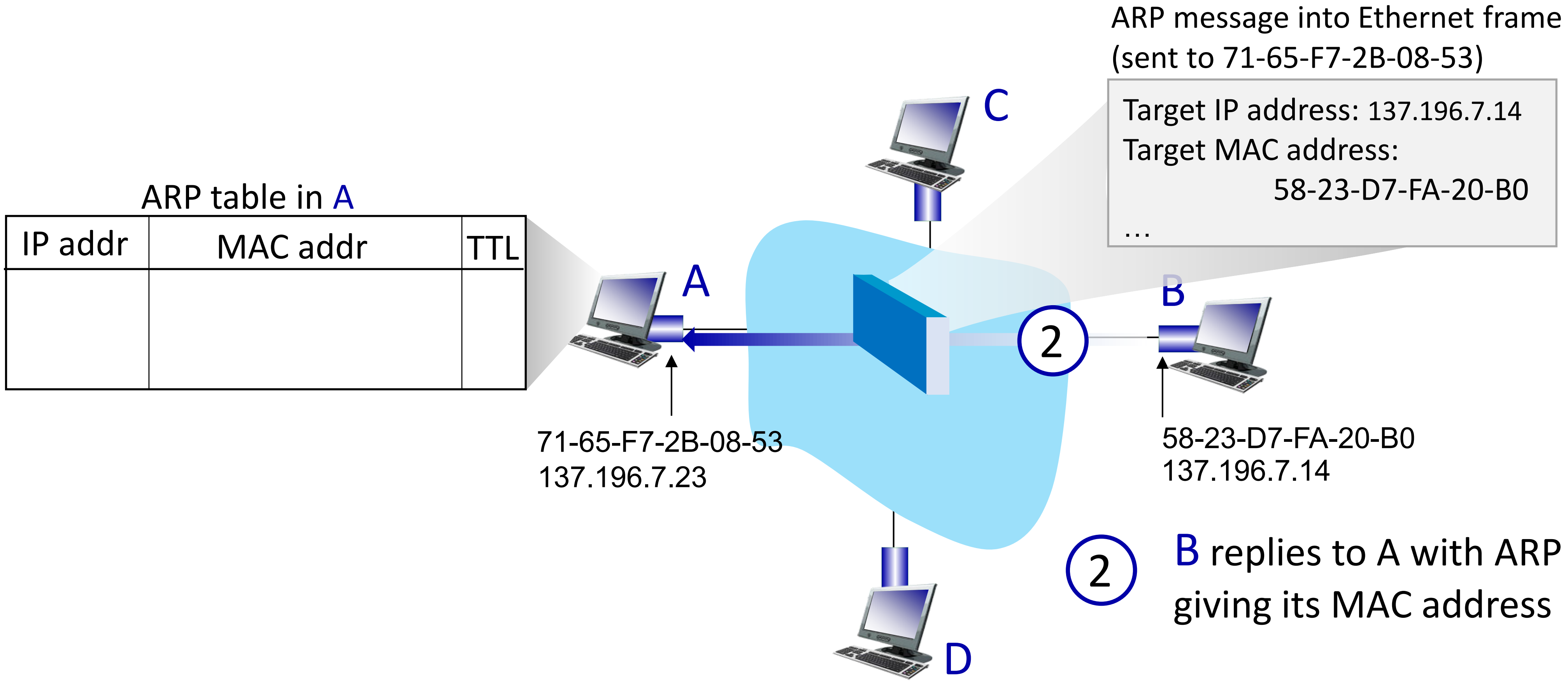
Ethernet frame (sent to FF-FF-FF-FF-FF-FF)

Source MAC: 71-65-F7-2B-08-53
Source IP: 137.196.7.23
Target IP address: 137.196.7.14
…

# 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 message into Ethernet frame
(sent to 71-65-F7-2B-08-53)

Target IP address: 137.196.7.14
Target MAC address:
58-23-D7-FA-20-B0
…

ARP table in A

| IP addr | MAC addr | TTL |
|---|---|---|
| | | |

② B replies to A with ARP response, giving its MAC address

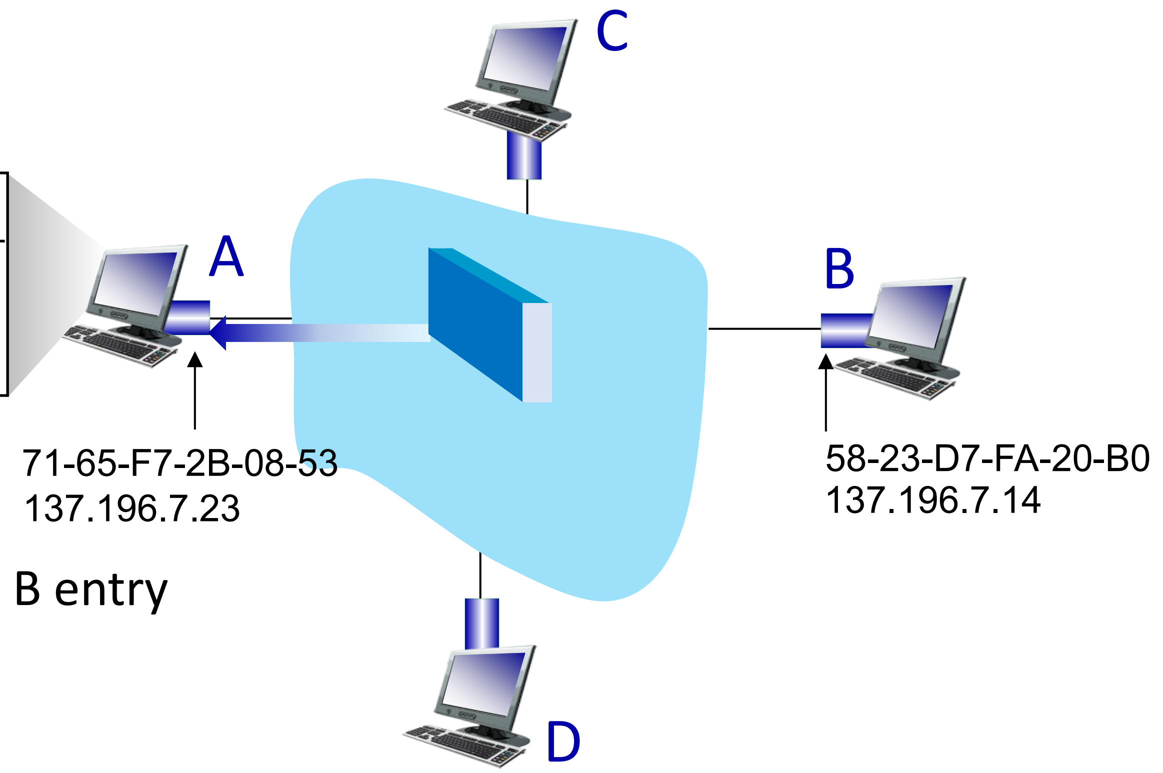
# ARP protocol in action

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 table in A

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

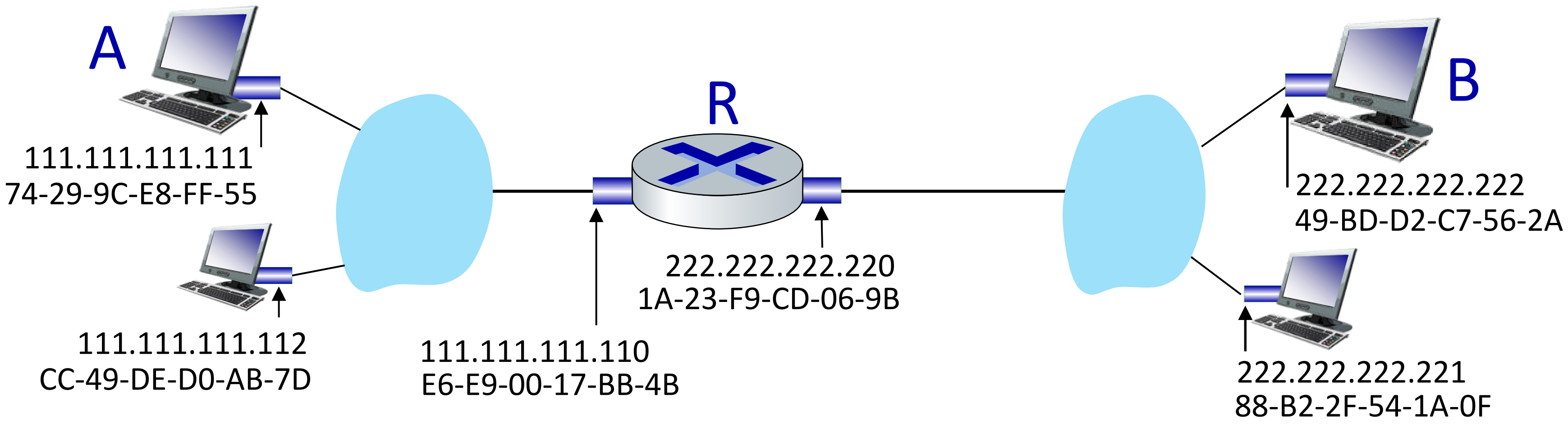


③ A receives B's reply, adds B entry into its local ARP table

# Routing to another subnet: addressing

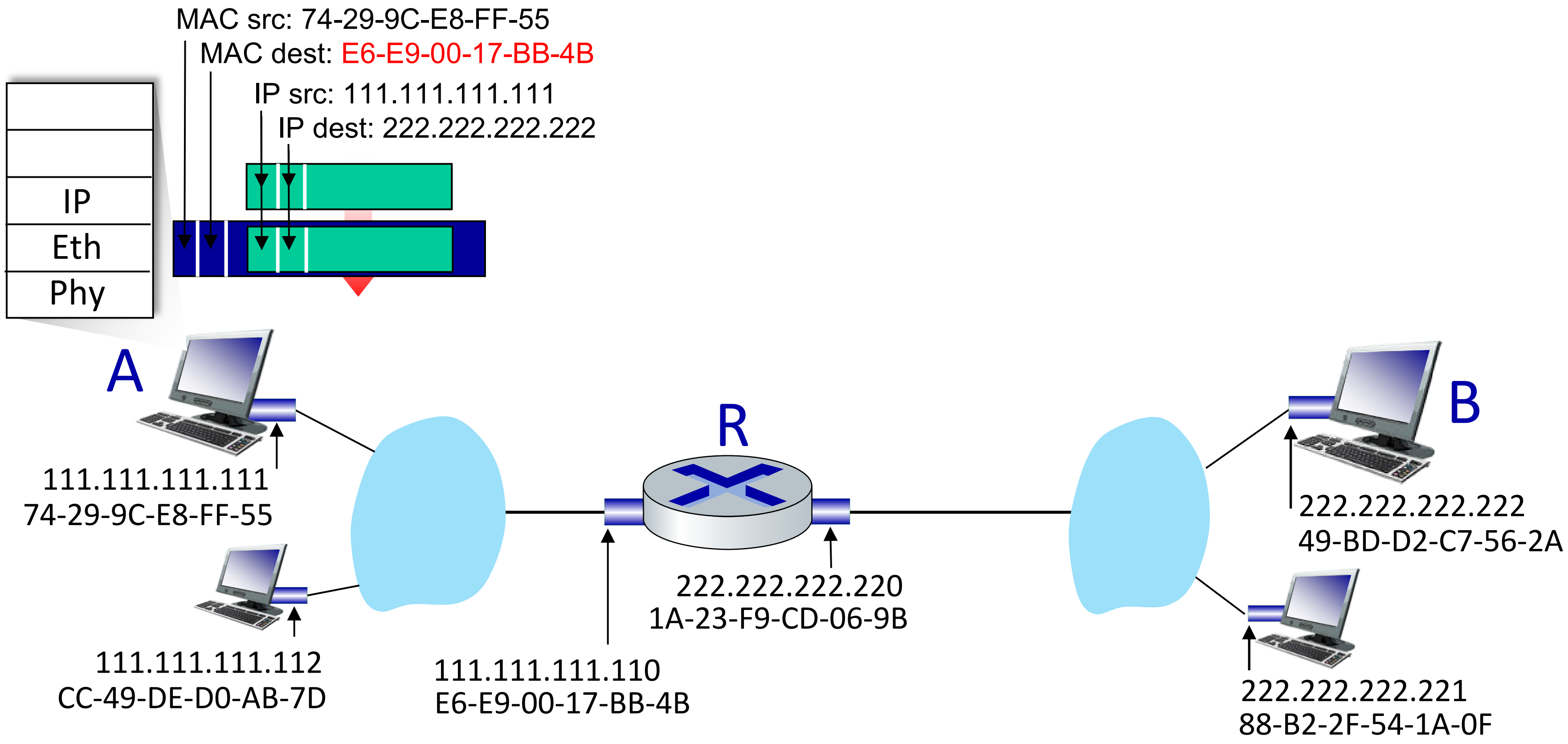
walkthrough: sending a  datagram from *A* to *B* via *R*

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



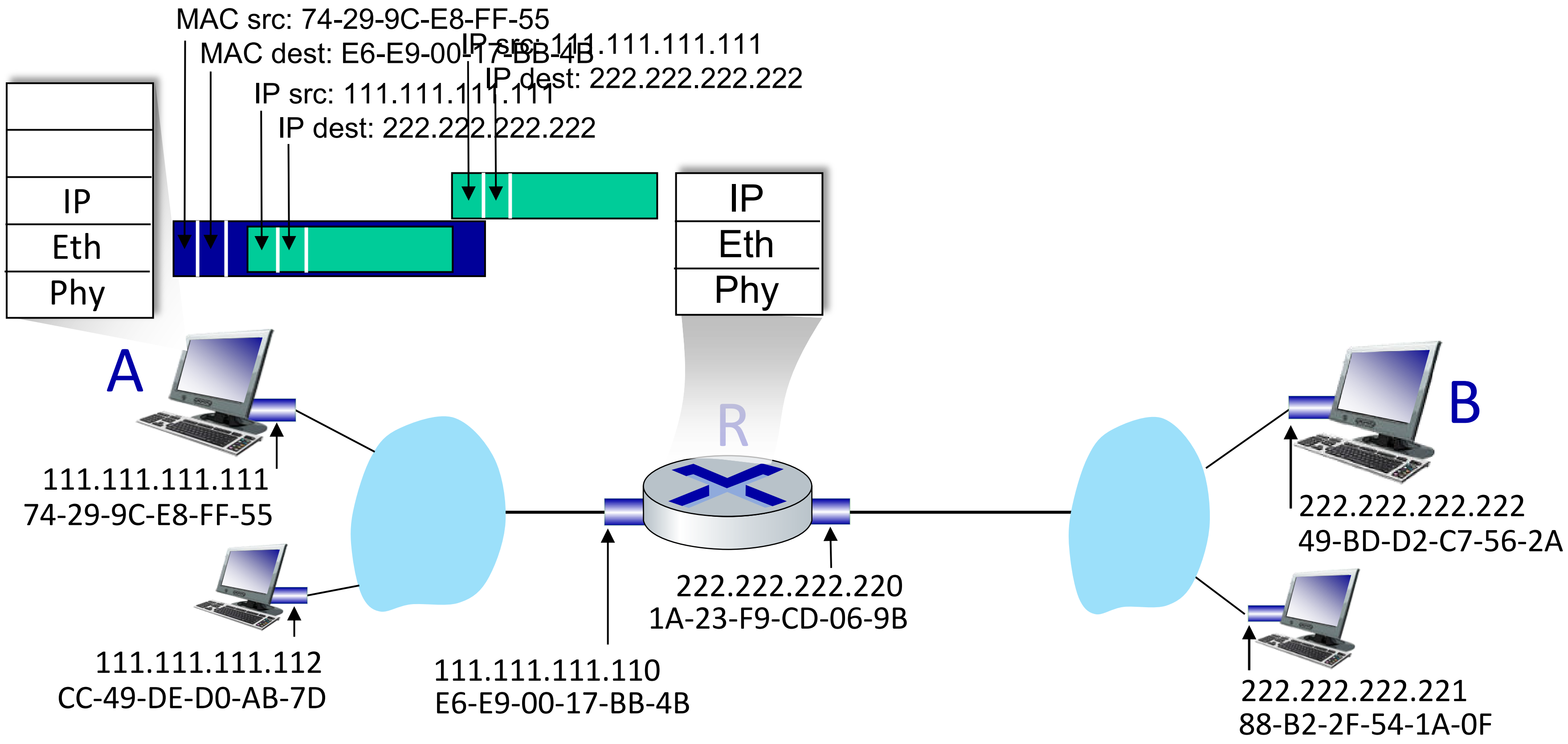
# Routing to another subnet: addressing

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



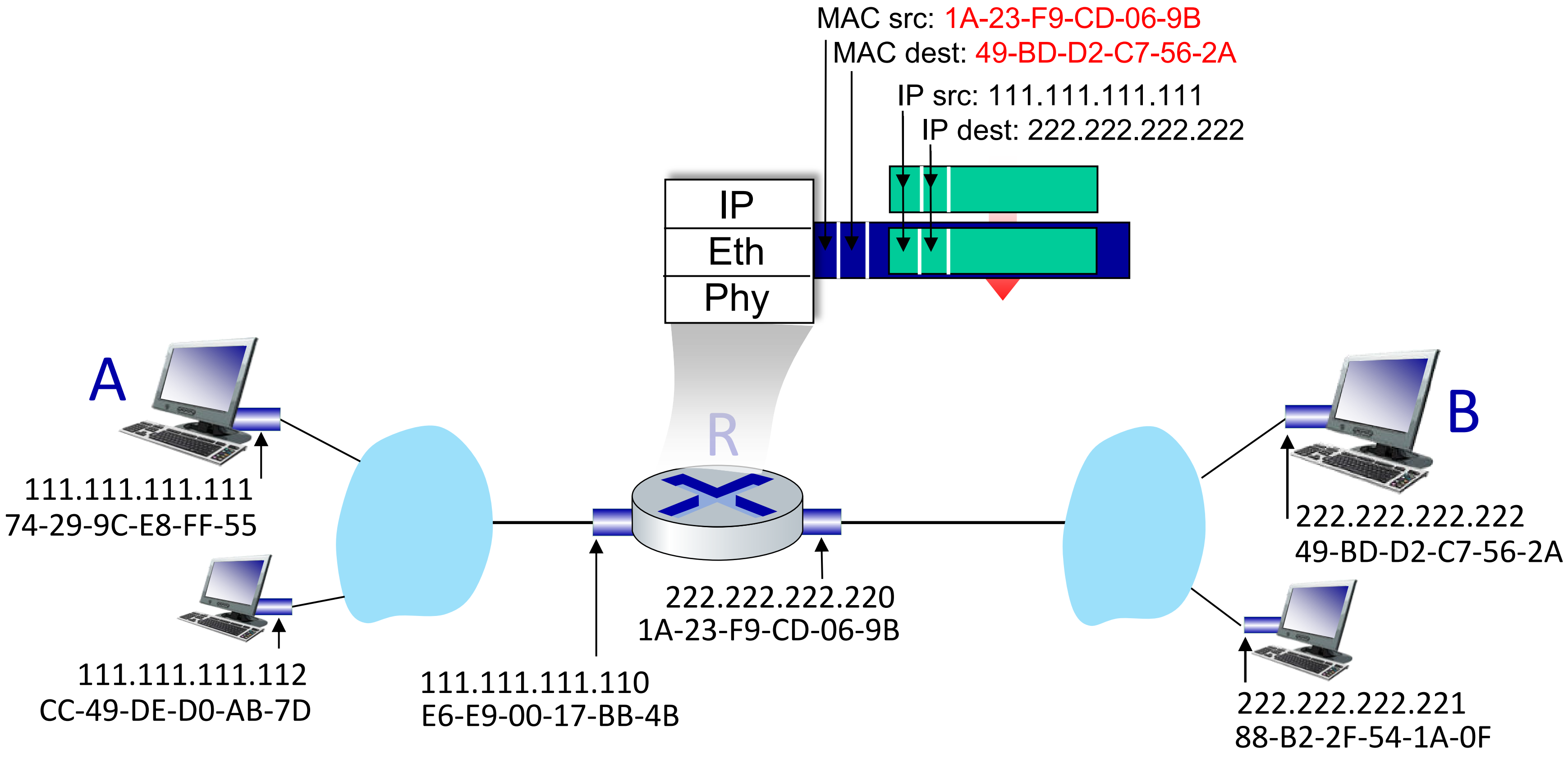
# Routing to another subnet: addressing

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



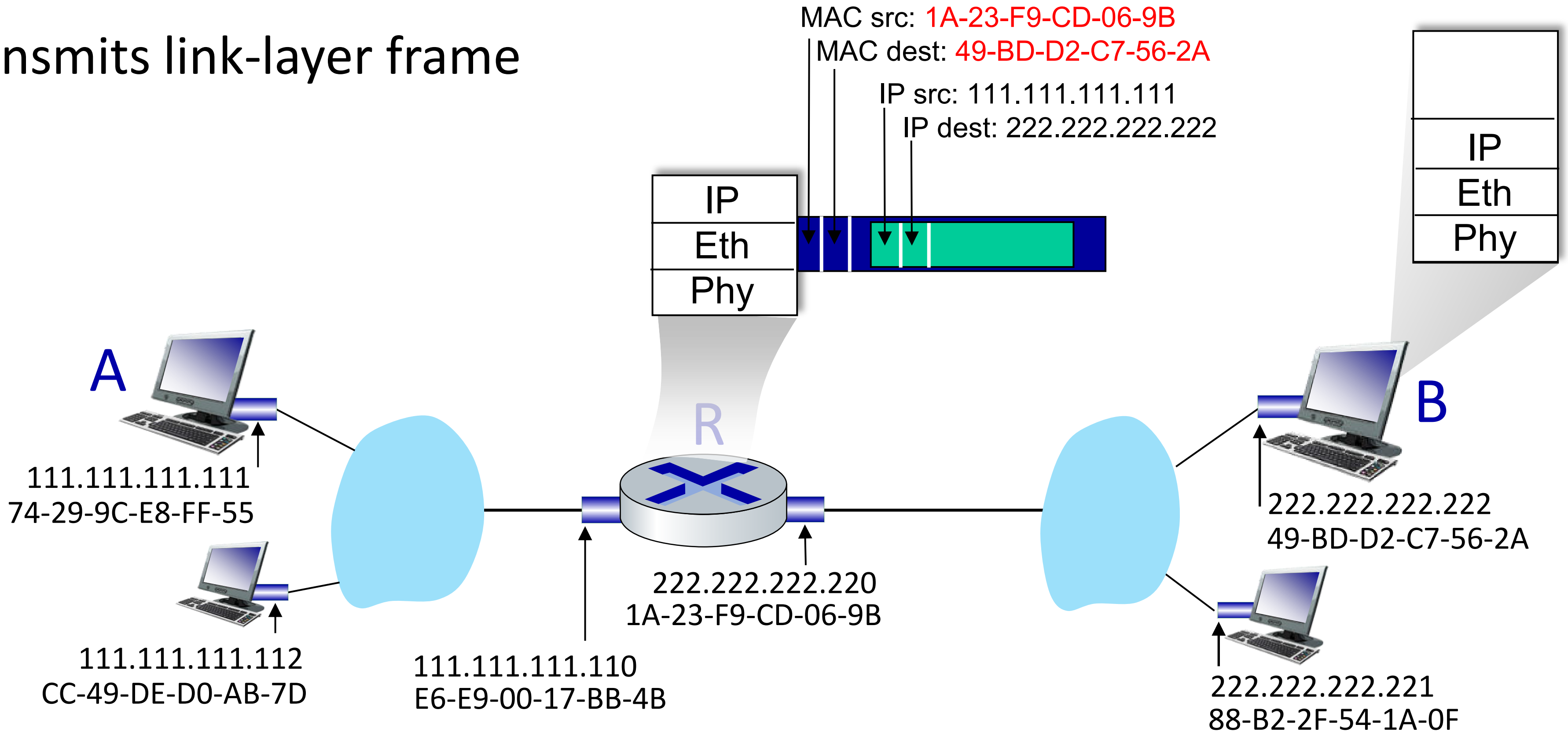
# Routing to another subnet: addressing

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



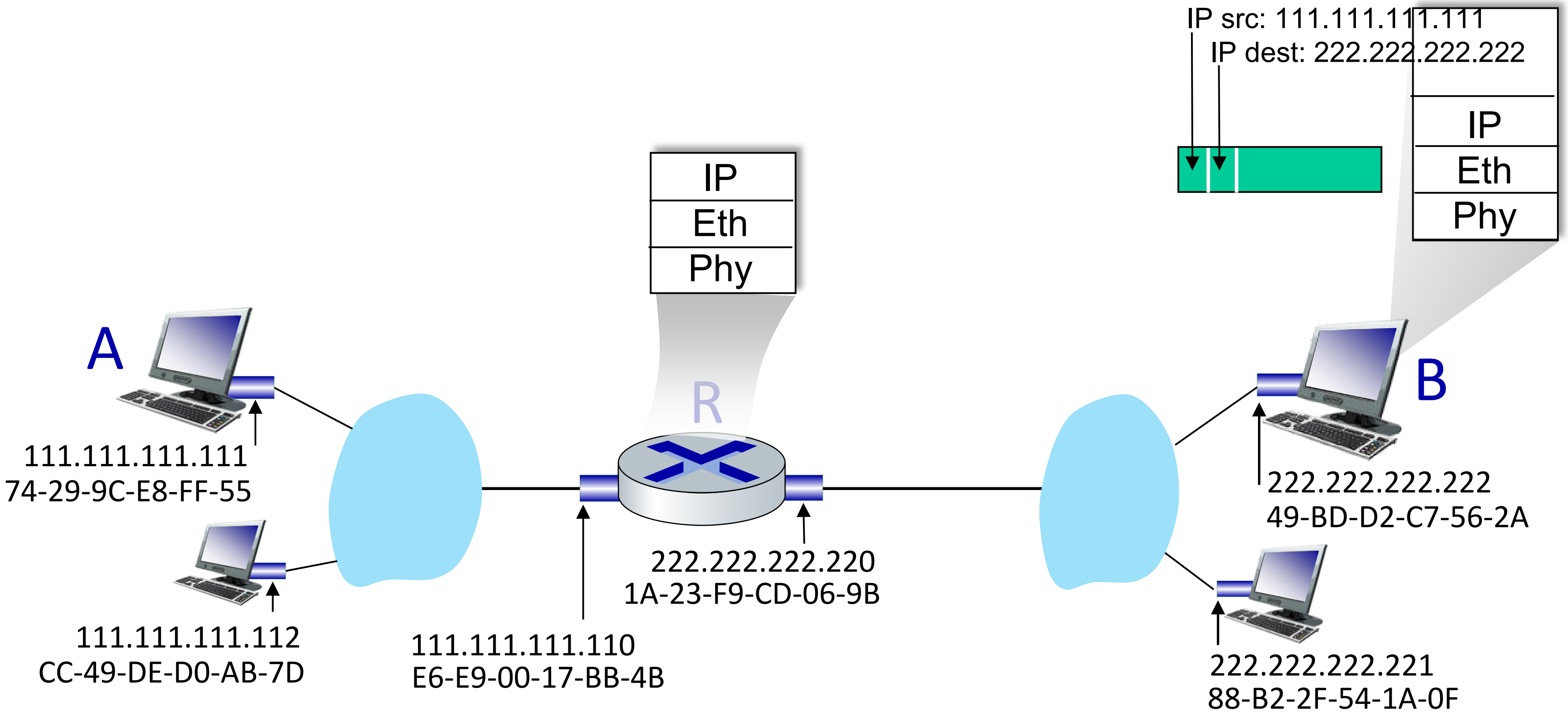
# Routing to another subnet: addressing

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



# Routing to another subnet: addressing

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



# Link layer, LANs: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
  - addressing, ARP
  - Ethernet
  - switches
- data center networking
- putting it all together

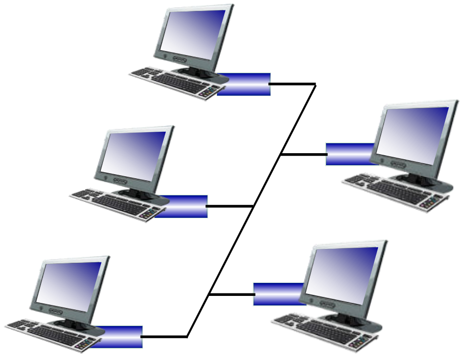
# Ethernet

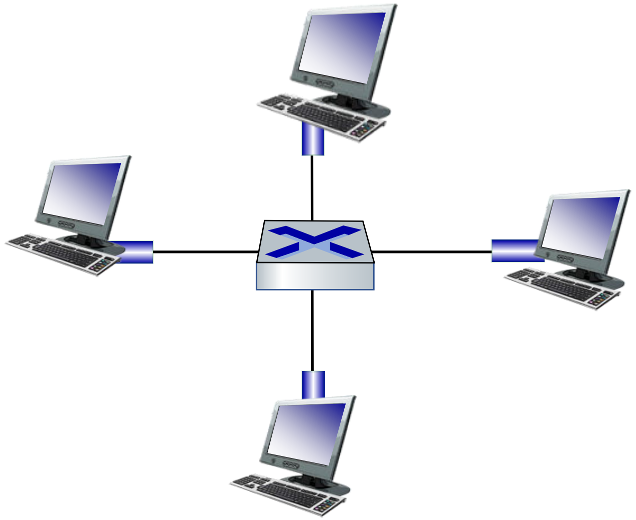
"dominant" wired LAN technology:

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

# 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


switched

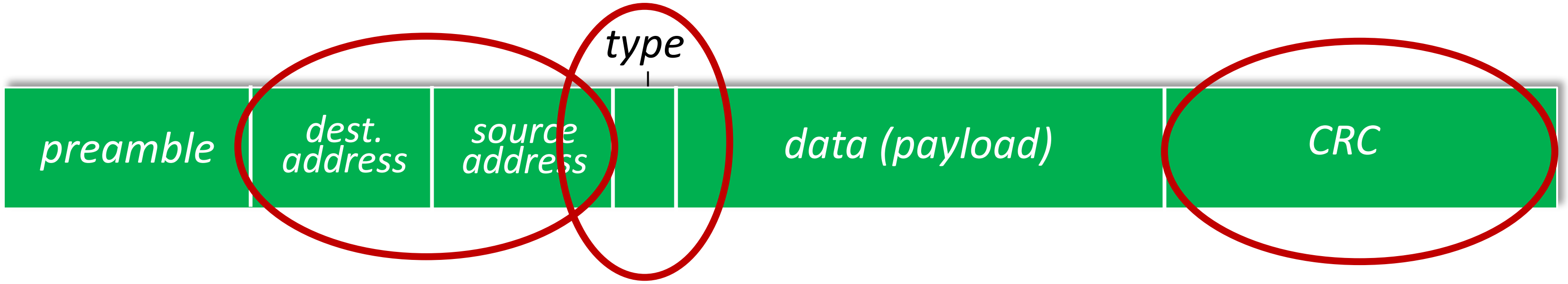
# Ethernet frame structure

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

*preamble:*

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

# Ethernet frame structure (more)



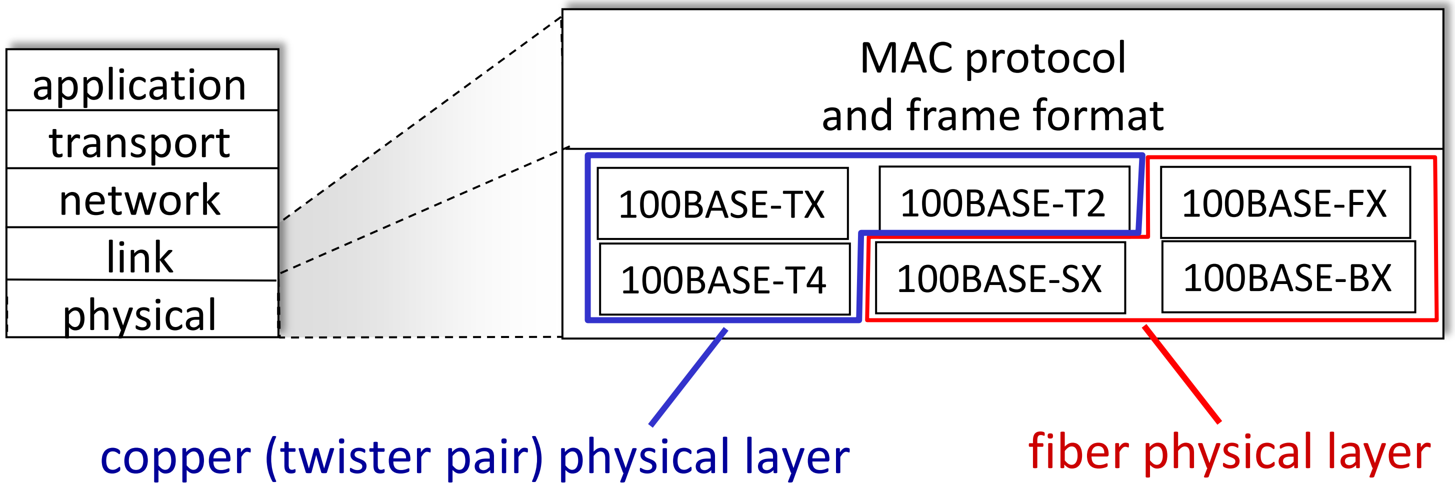
- addresses: 6 byte source, destination MAC addresses
  - if adapter receives frame with matching destination address, or with broadcast address (e.g., ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- type: indicates higher layer protocol
  - mostly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

# Ethernet: unreliable, connectionless

- connectionless: no handshaking between sending and receiving NICs
- unreliable: receiving NIC doesn't send ACKs or NAKs to sending NIC
    - data in dropped frames recovered only if initial sender uses higher layer rdt (e.g., TCP), otherwise dropped data lost
- Ethernet's MAC protocol: unslotted CSMA/CD with binary backoff

# 802.3 Ethernet standards: link & physical layers

- *many* different Ethernet standards
  - common MAC protocol and frame format
  - different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10 Gbps, 40 Gbps
  - different physical layer media: fiber, cable



# Link layer, LANs: roadmap

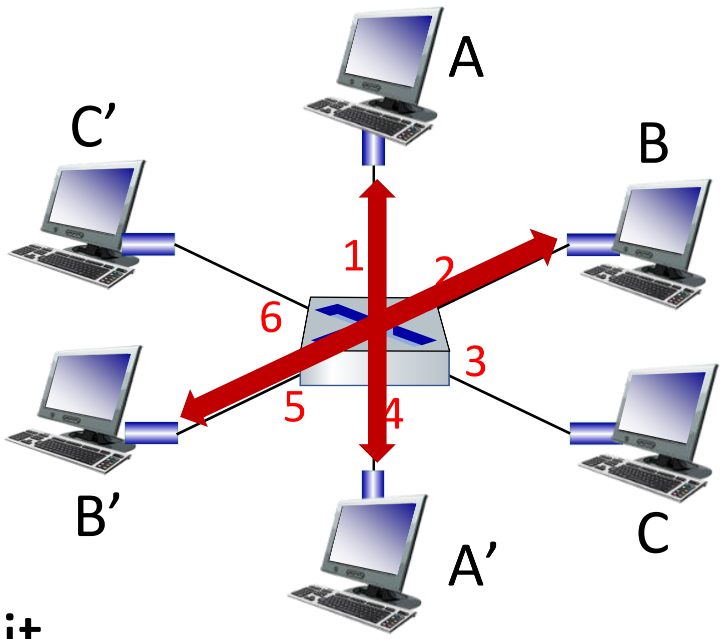
- introduction
- error detection, correction
- multiple access protocols
- LANs
  - addressing, ARP
  - Ethernet
  - switches
- data center networking
- putting it all together

# Ethernet switch

- Switch is a link-layer device: takes an *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, *selectively* forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- transparent: hosts *unaware* of presence of switches
- plug-and-play, self-learning
  - switches do not need to be configured

# Switch: multiple simultaneous transmissions

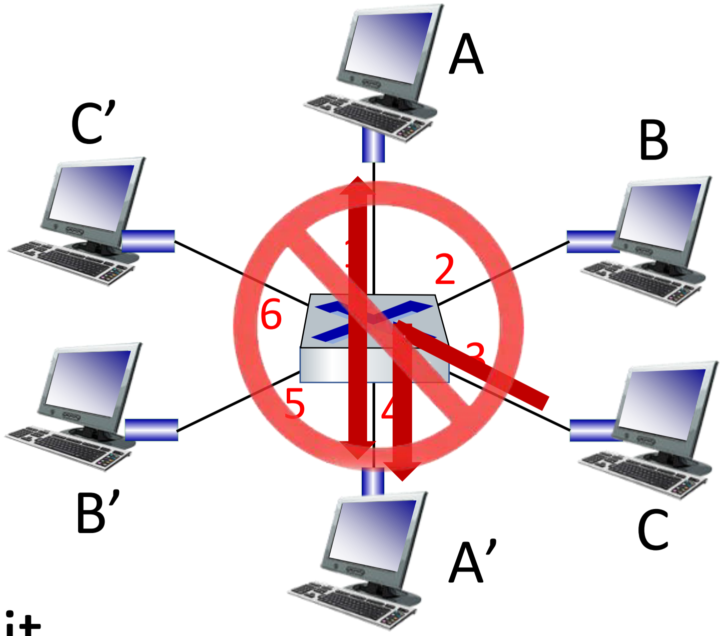
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, so:
  - no collisions; full duplex
  - each link is its own collision domain
- switching: A-to-A' and B-to-B' can transmit simultaneously, without collisions



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

# Switch: multiple simultaneous transmissions

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



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

# Switch forwarding table

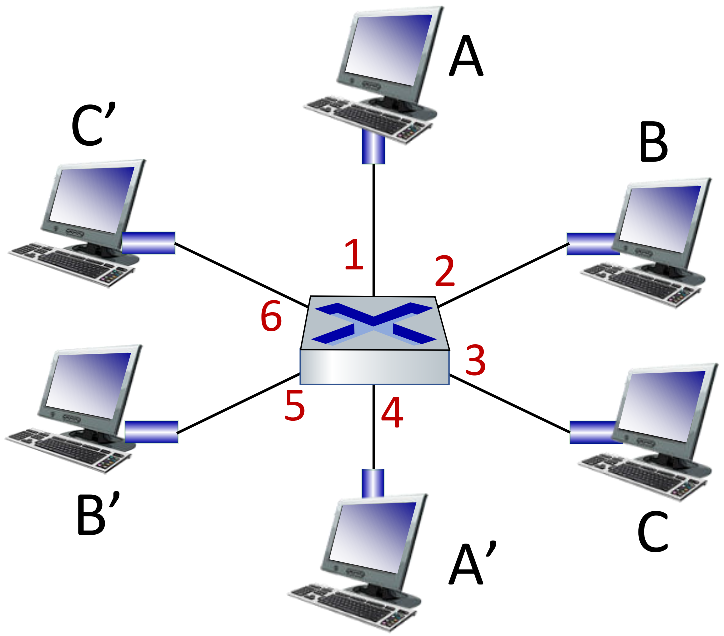
*Q:* how does switch know A' reachable via interface 4, B' reachable via interface 5?

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

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

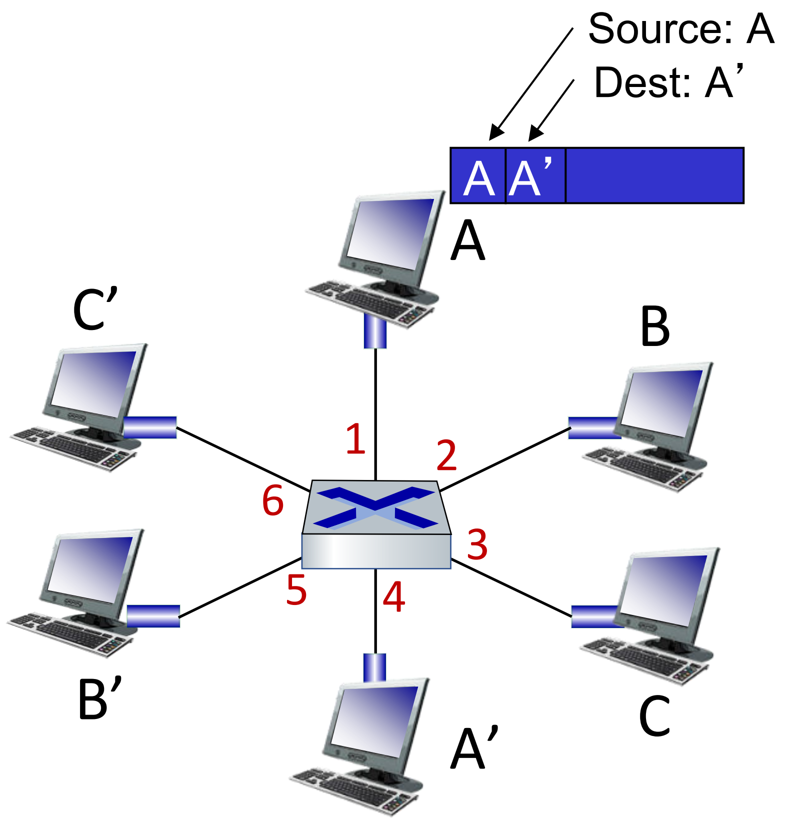
*Q:* how are entries created, maintained in switch table?

- something like a routing protocol?



# Switch: self-learning

- switch *learns* which hosts can be reached through which interfaces
  - when frame received, switch "learns" location of sender: incoming LAN segment
  - records sender/location pair in switch table



| MAC addr | interface | TTL |
|---|---|---|
| *A* | *1* | *60* |

*Switch table (initially empty)*

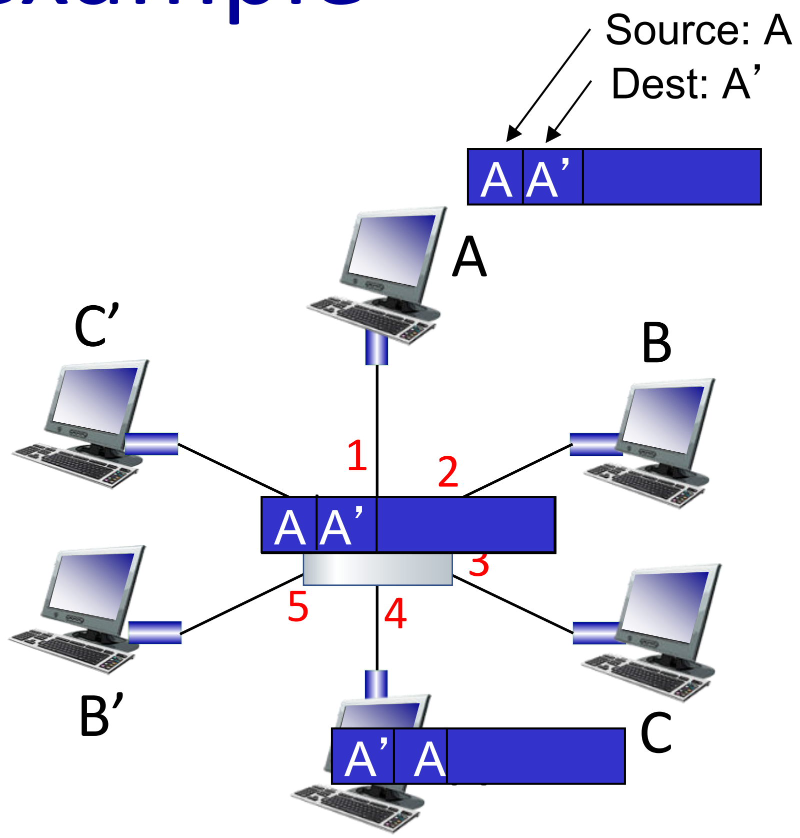
# Switch: frame filtering/forwarding

when frame received at switch:

```
    1. record incoming link, MAC address of sending host
    2. index switch table using MAC destination address
    3. if entry found for destination then
         {
            if destination on segment from which frame arrived
               then drop frame
               else forward frame on interface indicated by entry
         }
         else flood  /* forward on all interfaces except arriving interface */
```

# Self-learning, forwarding: example

- frame destination, A', location unknown: flood
- destination A location known: selectively send on just one link

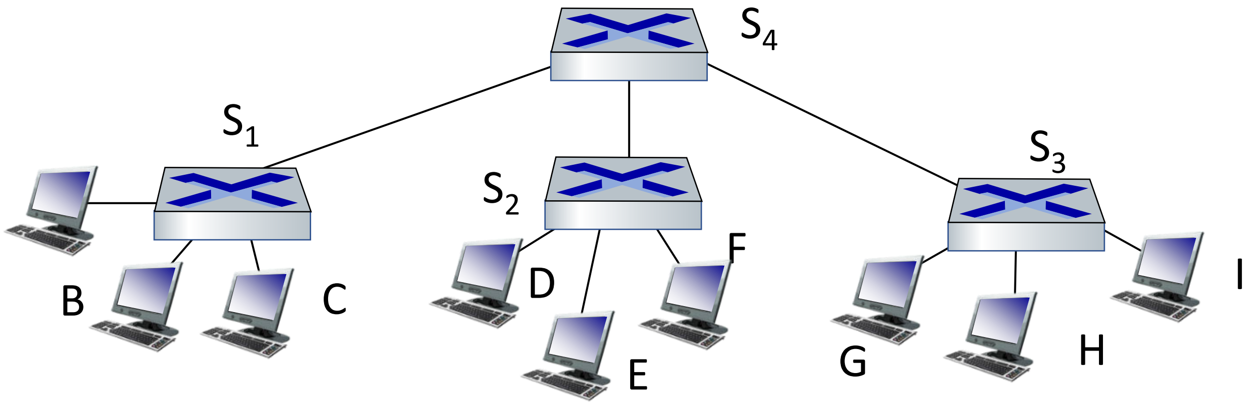


| MAC addr | interface | TTL |
|---|---|---|
| *A* | *1* | *60* |
| *A'* | *4* | *60* |

*switch table (initially empty)*

# Interconnecting switches

self-learning switches can be connected together:

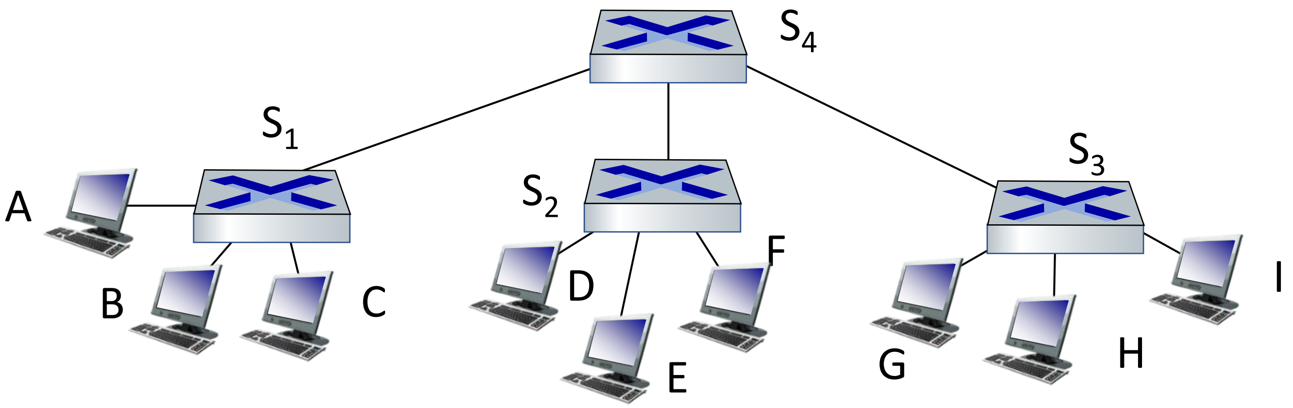


*Q:* sending from A to G - how does $S_1$ know to forward frame destined to G via $S_4$ and $S_3$?

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

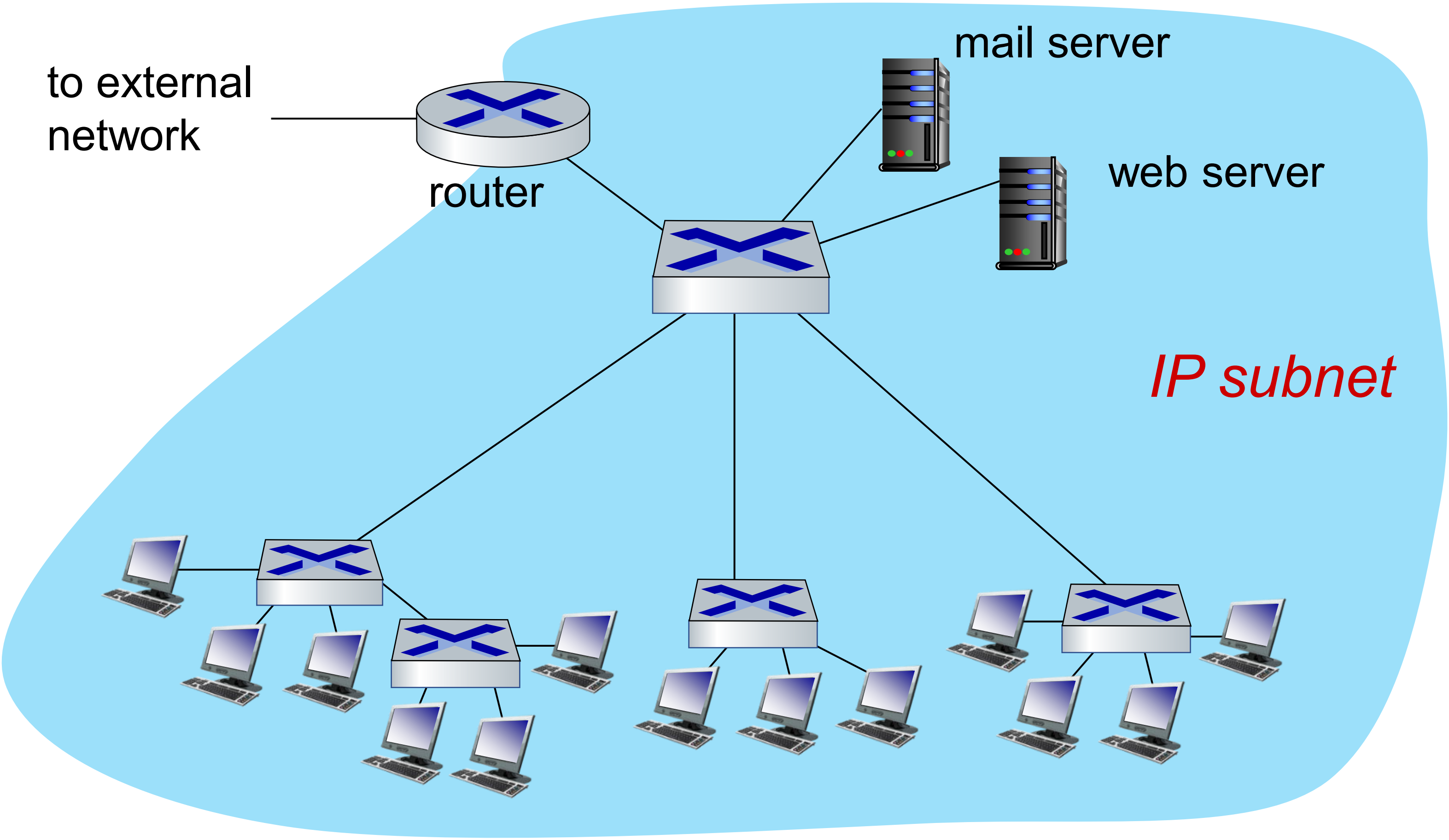
# Self-learning multi-switch example

Suppose C sends frame to I, I responds to C



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

# Small institutional network



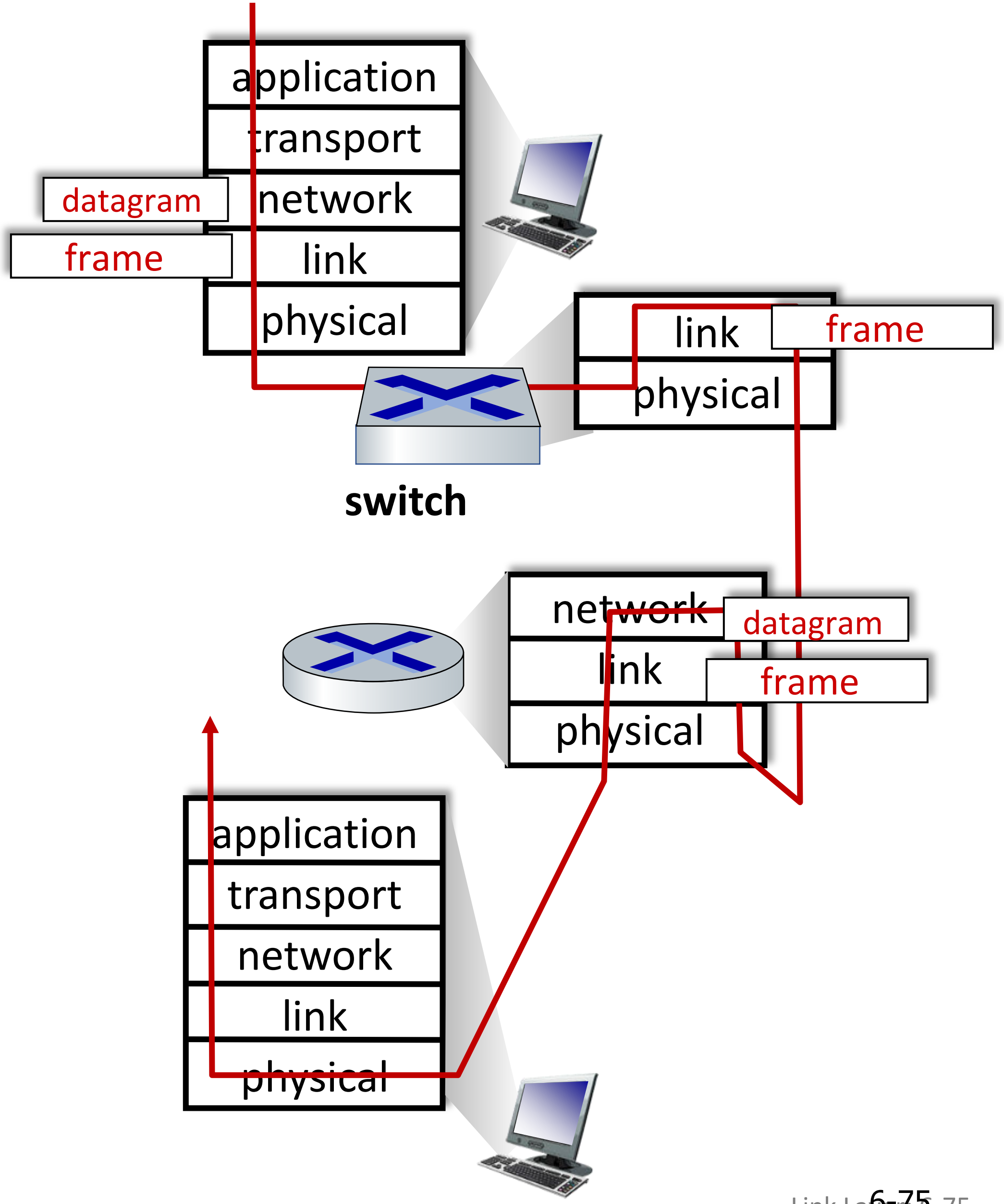
# Switches vs. routers

both are store-and-forward:

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

both have forwarding tables:

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



# Link layer, LANs: roadmap

- introduction
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# Datacenter networks

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

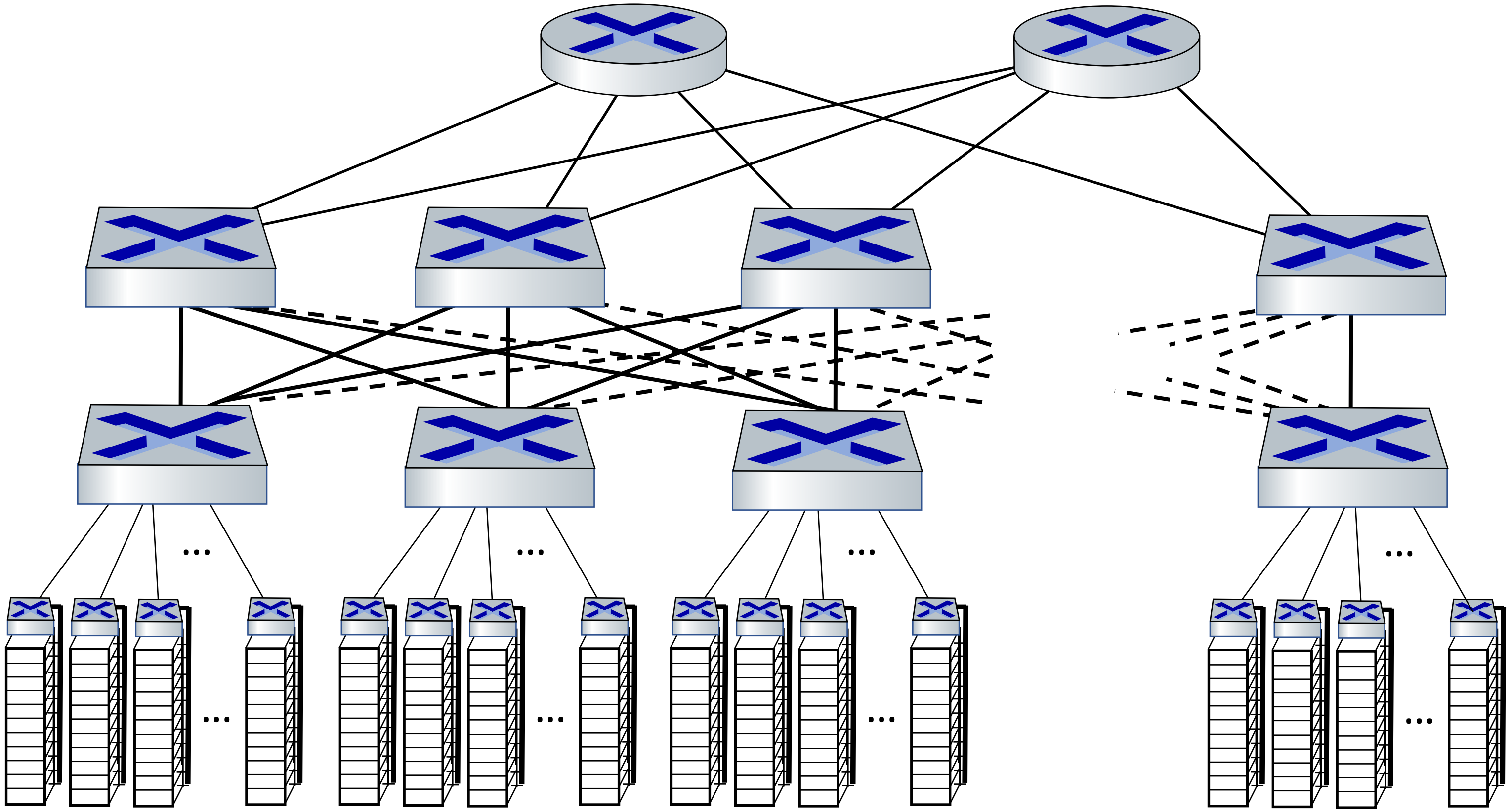
- e-business (e.g. Amazon)
- content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
- search engines, data mining (e.g., Google)

challenges:

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

Inside a 40-ft Microsoft container, Chicago data center

# Datacenter networks: network elements



**Border routers**

- connections outside datacenter

**Tier-1 switches**

- connecting to ~16 T-2s below

**Tier-2 switches**

- connecting to ~16 TORs below

**Top of Rack (TOR) switch**

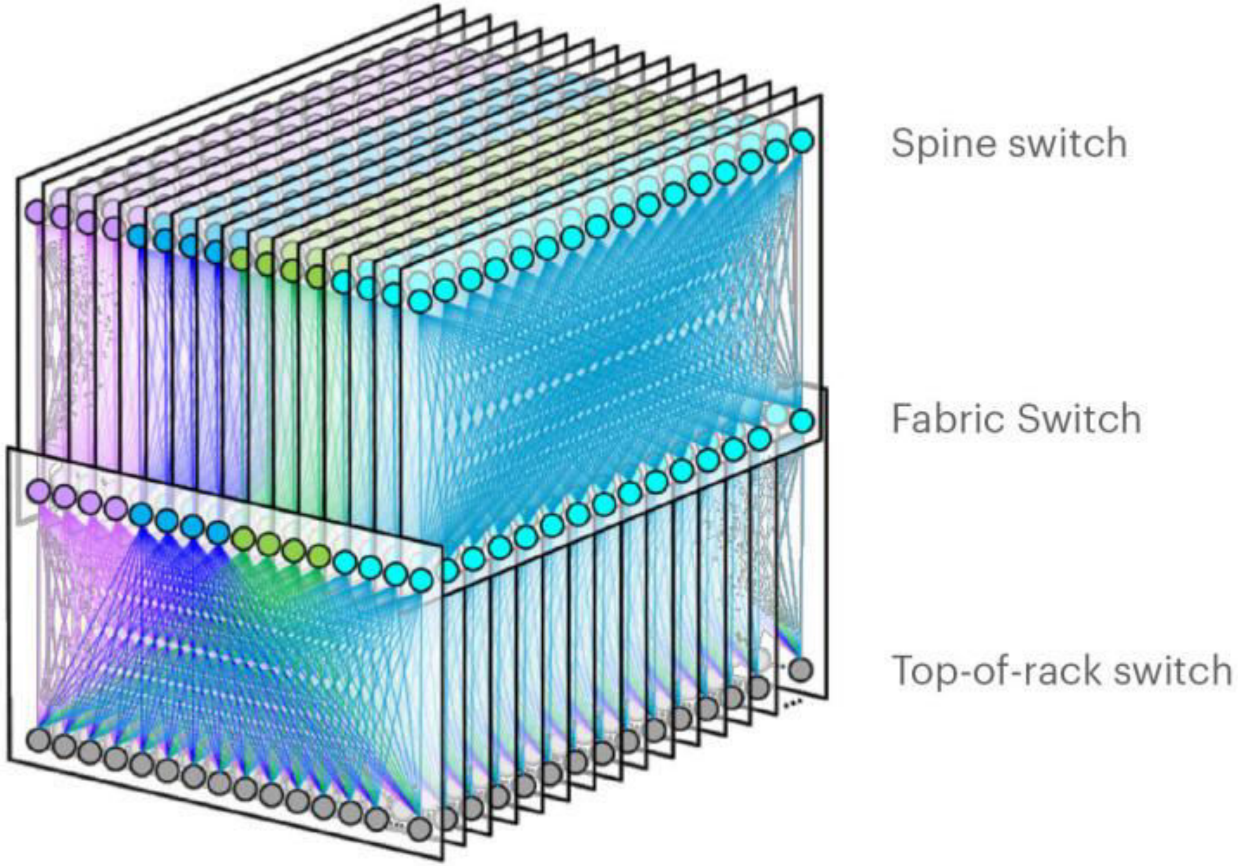
- one per rack
- 40-100Gbps Ethernet to blades

**Server racks**

- 20- 40 server blades: hosts

# Datacenter networks: network elements

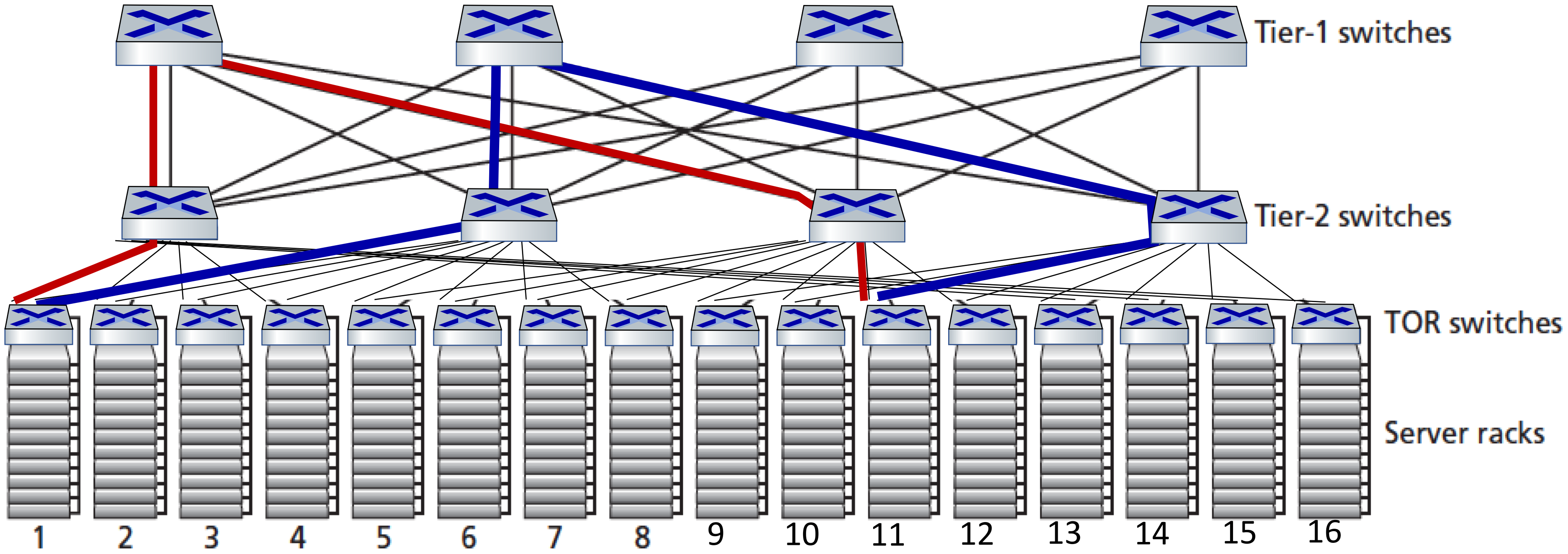
Facebook F16 data center network topology:



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

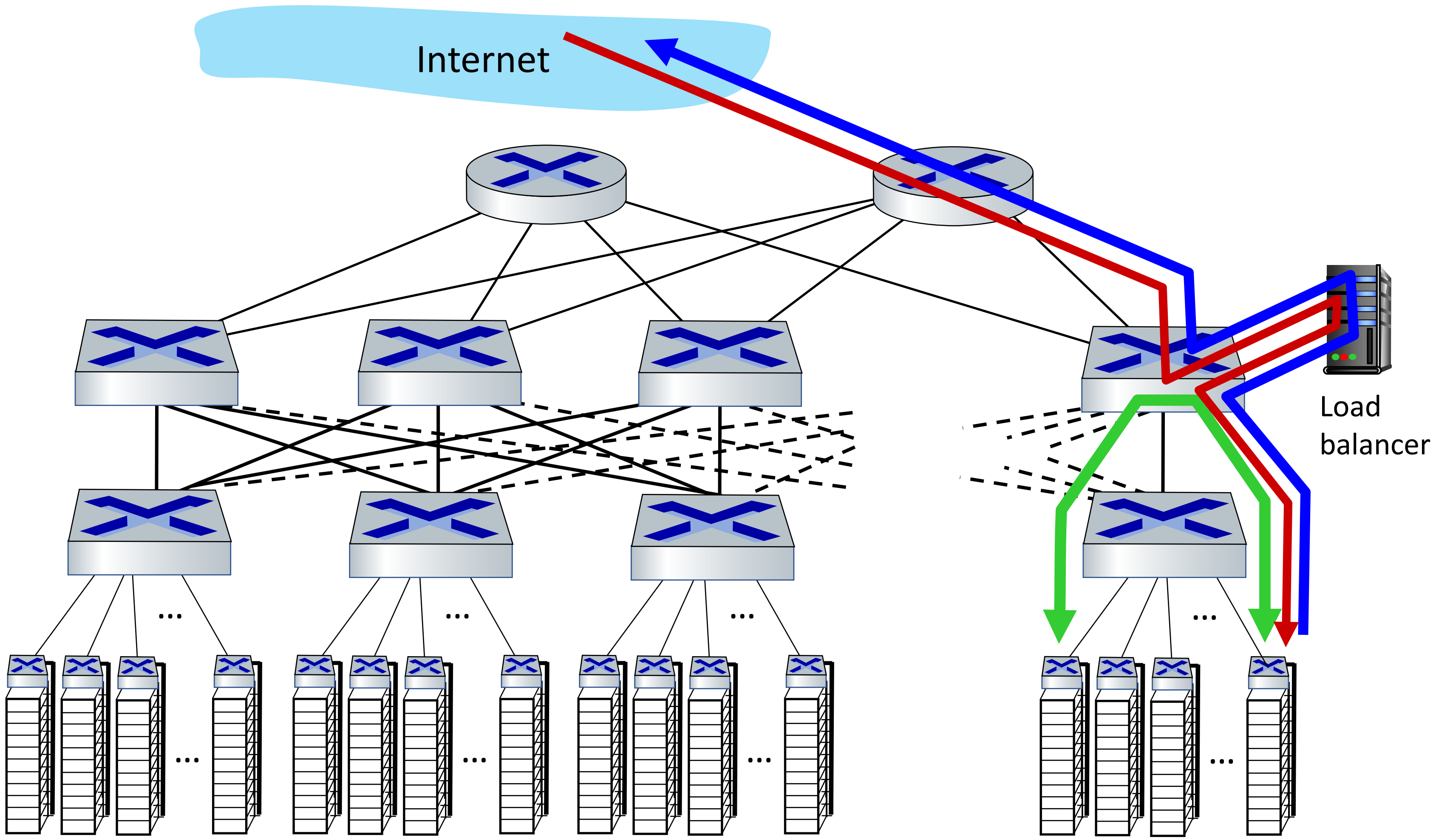
# Datacenter networks: multipath

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



two disjoint paths highlighted between racks 1 and 11

# Datacenter networks: application-layer routing



load balancer: application-layer routing

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

# Link layer, LANs: roadmap

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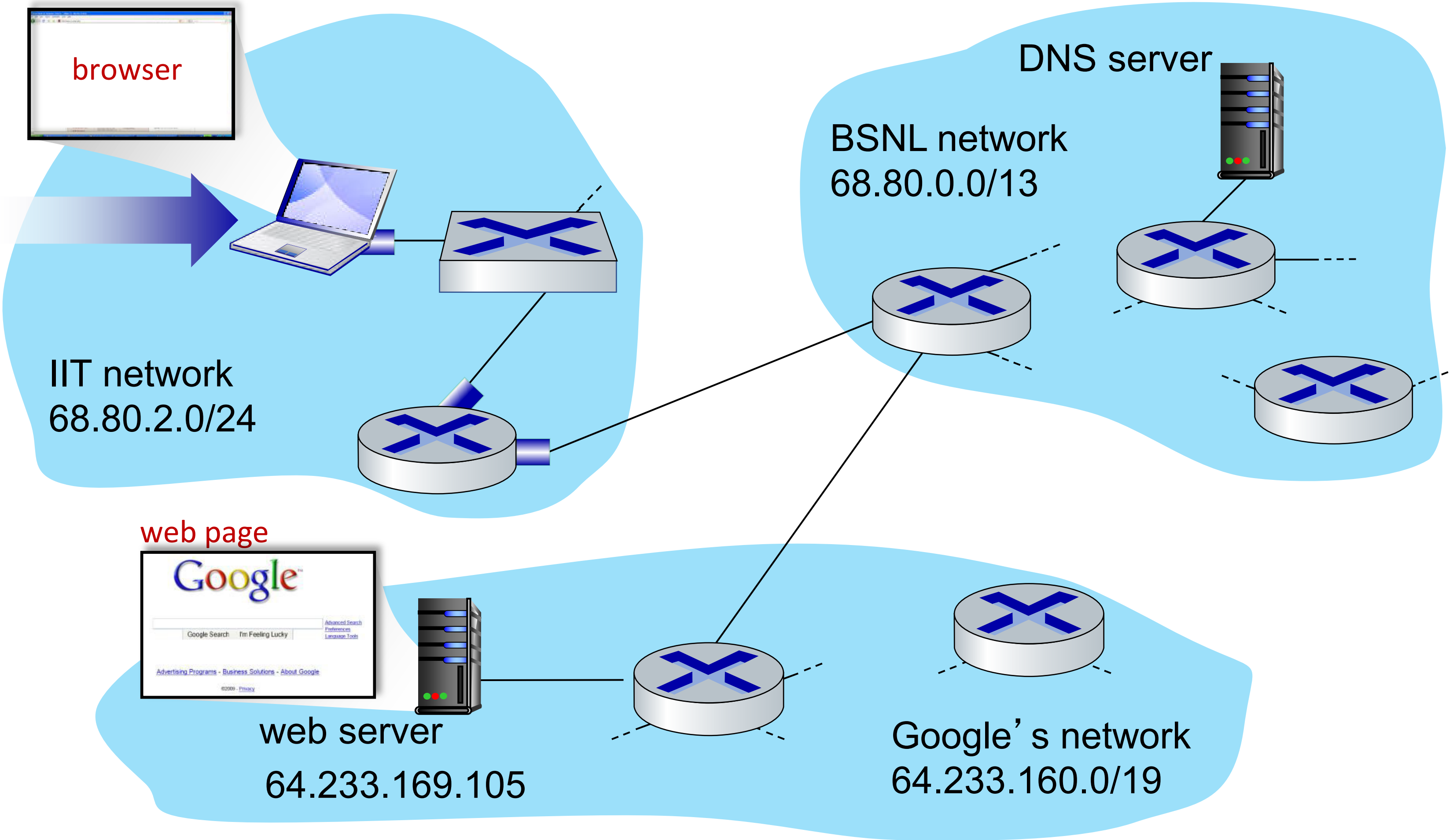
# Synthesis: a day in the life of a web request

- 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

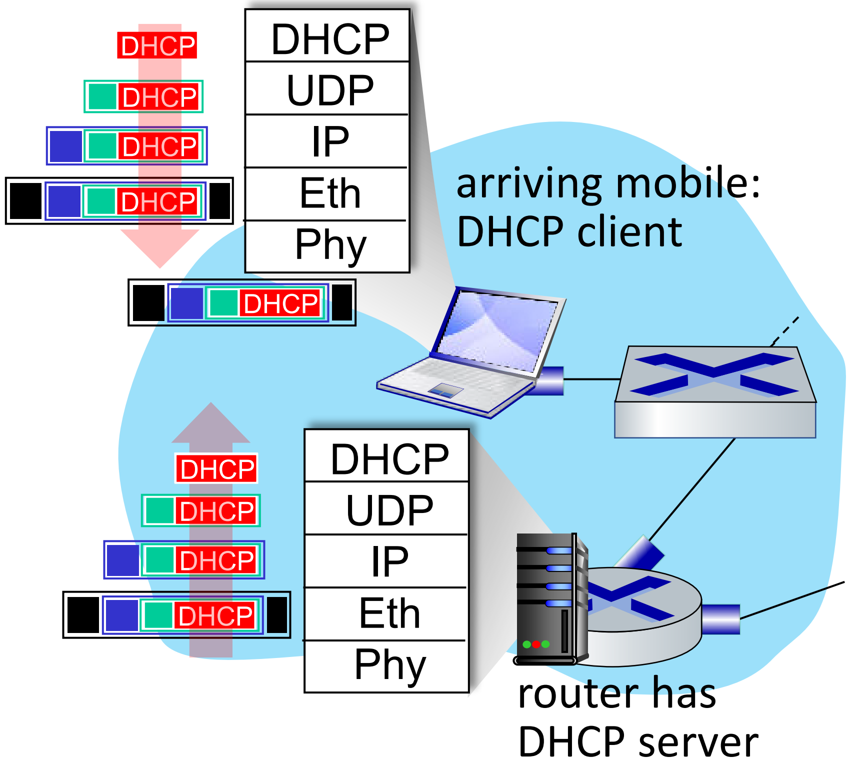


scenario:

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

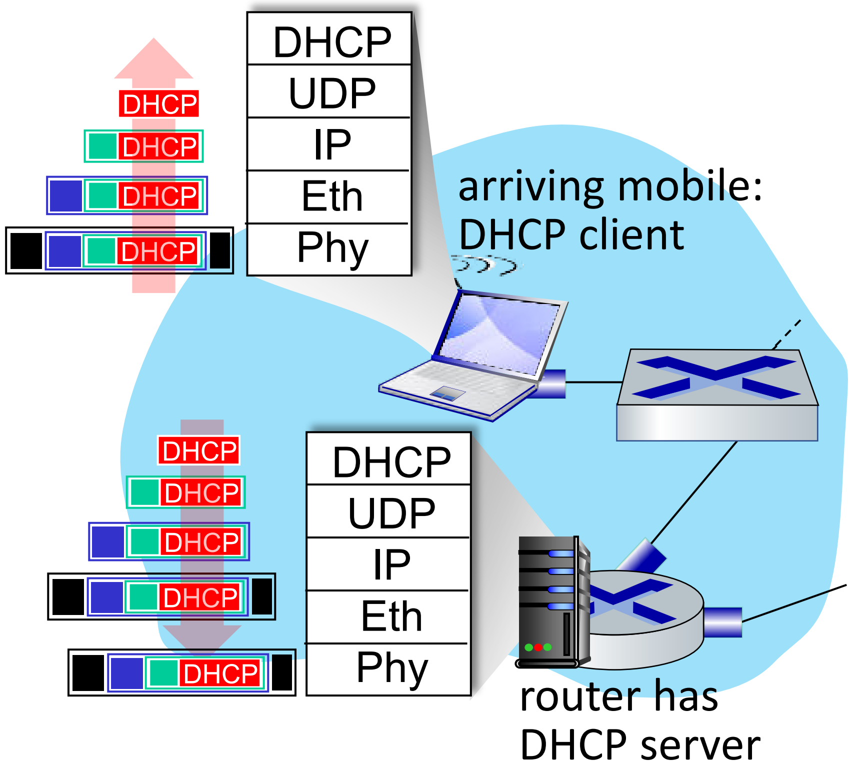
*Sounds simple!*

# 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

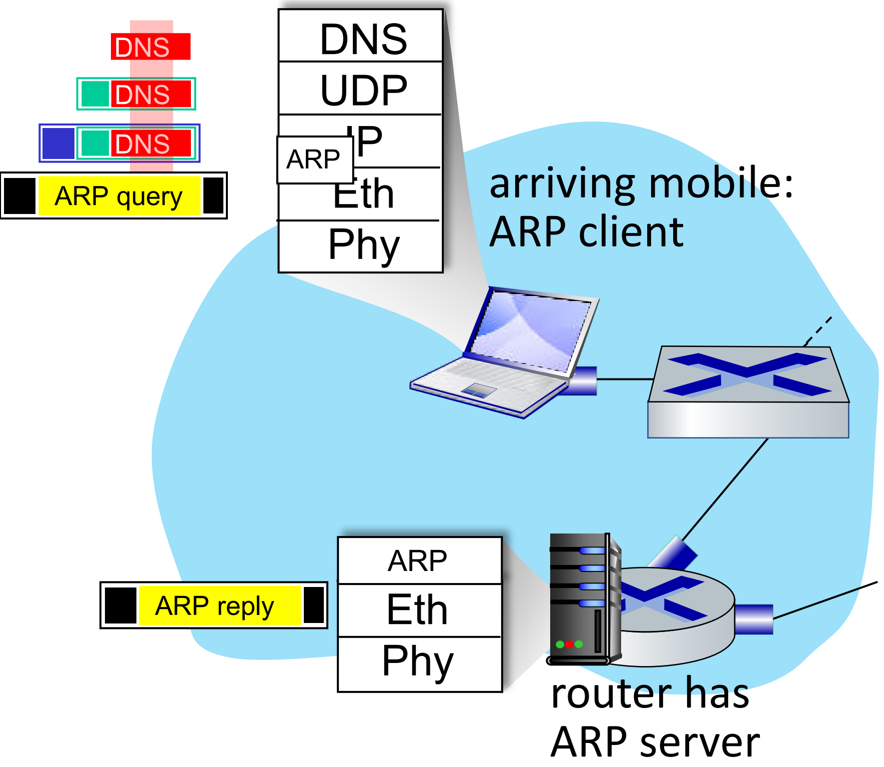
# A day in the life: connecting to the Internet



- 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

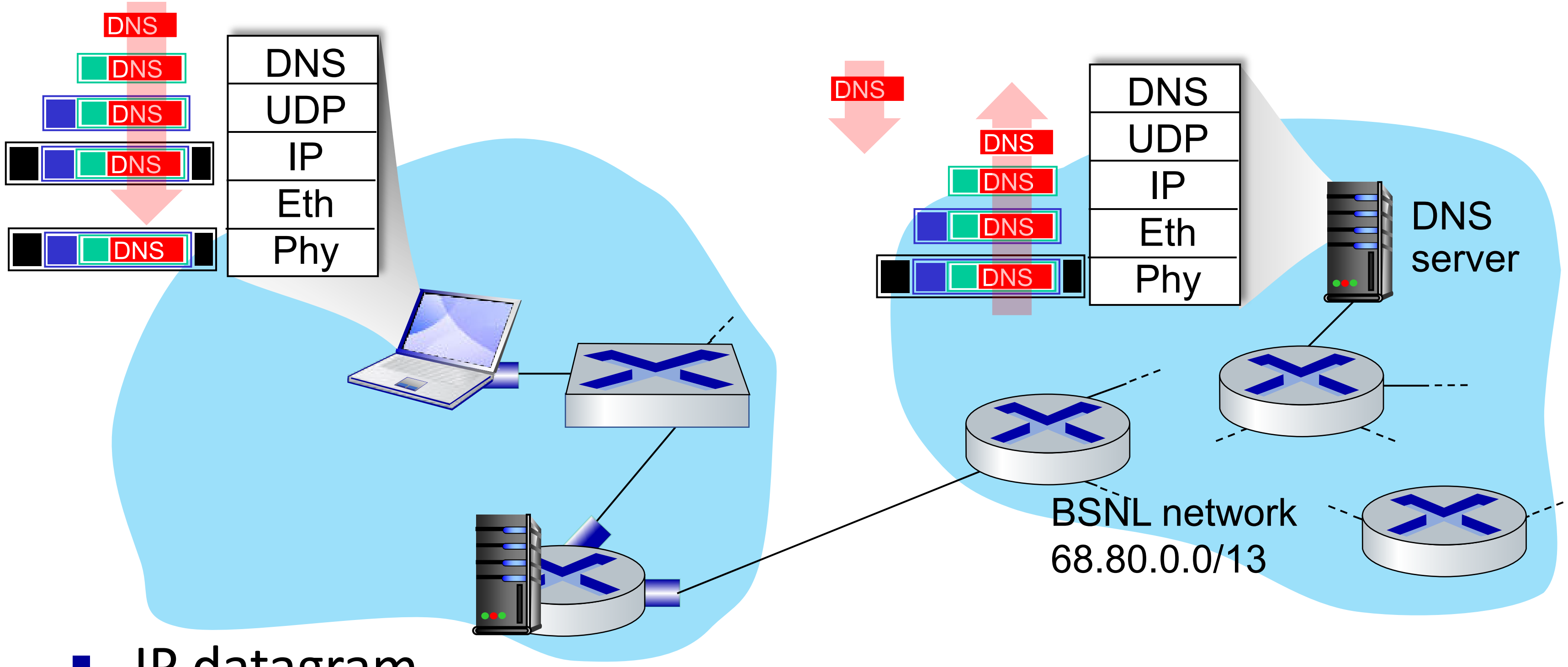
*Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router*

# 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

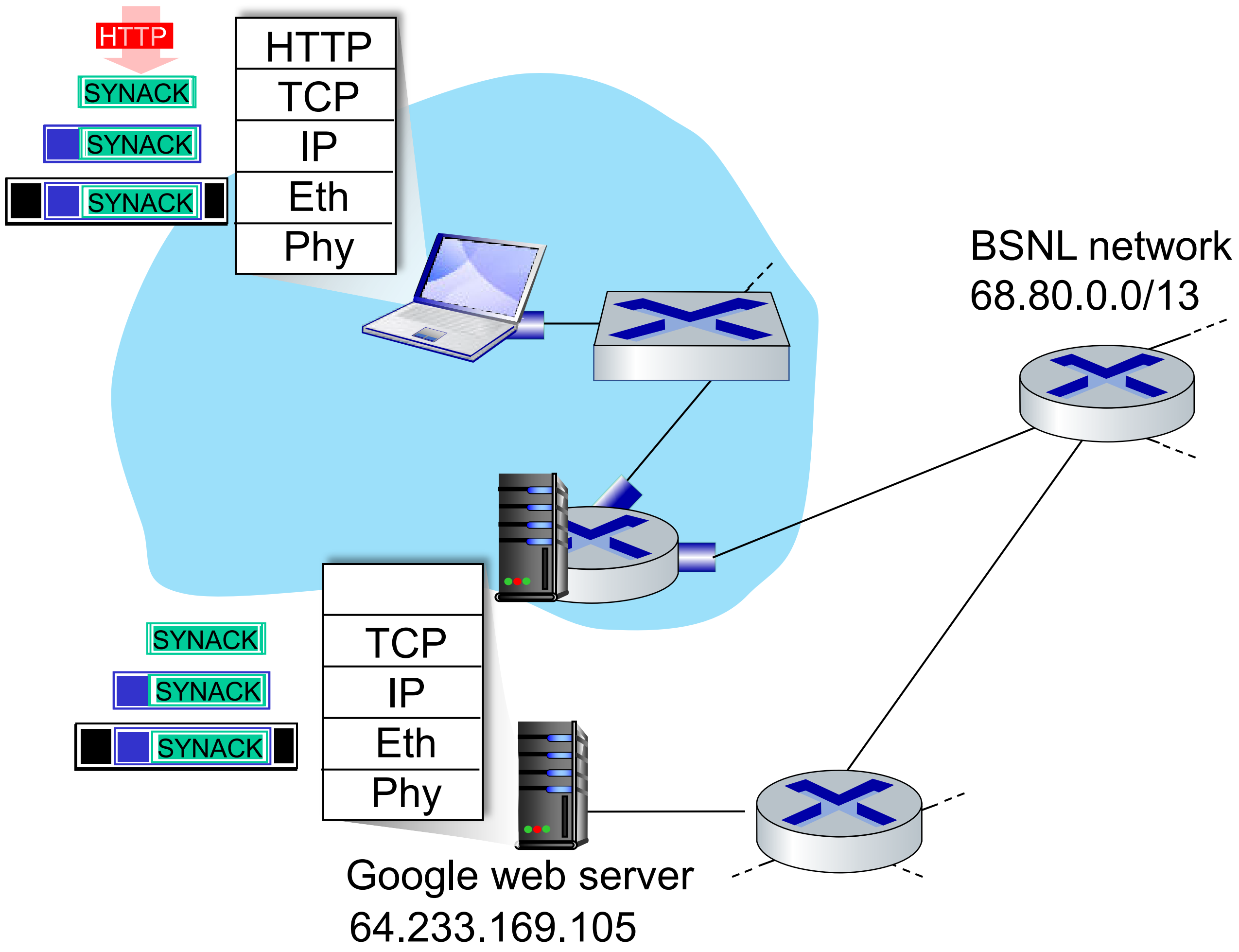


- demuxed to DNS
- DNS replies to client with IP address of www.google.com

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

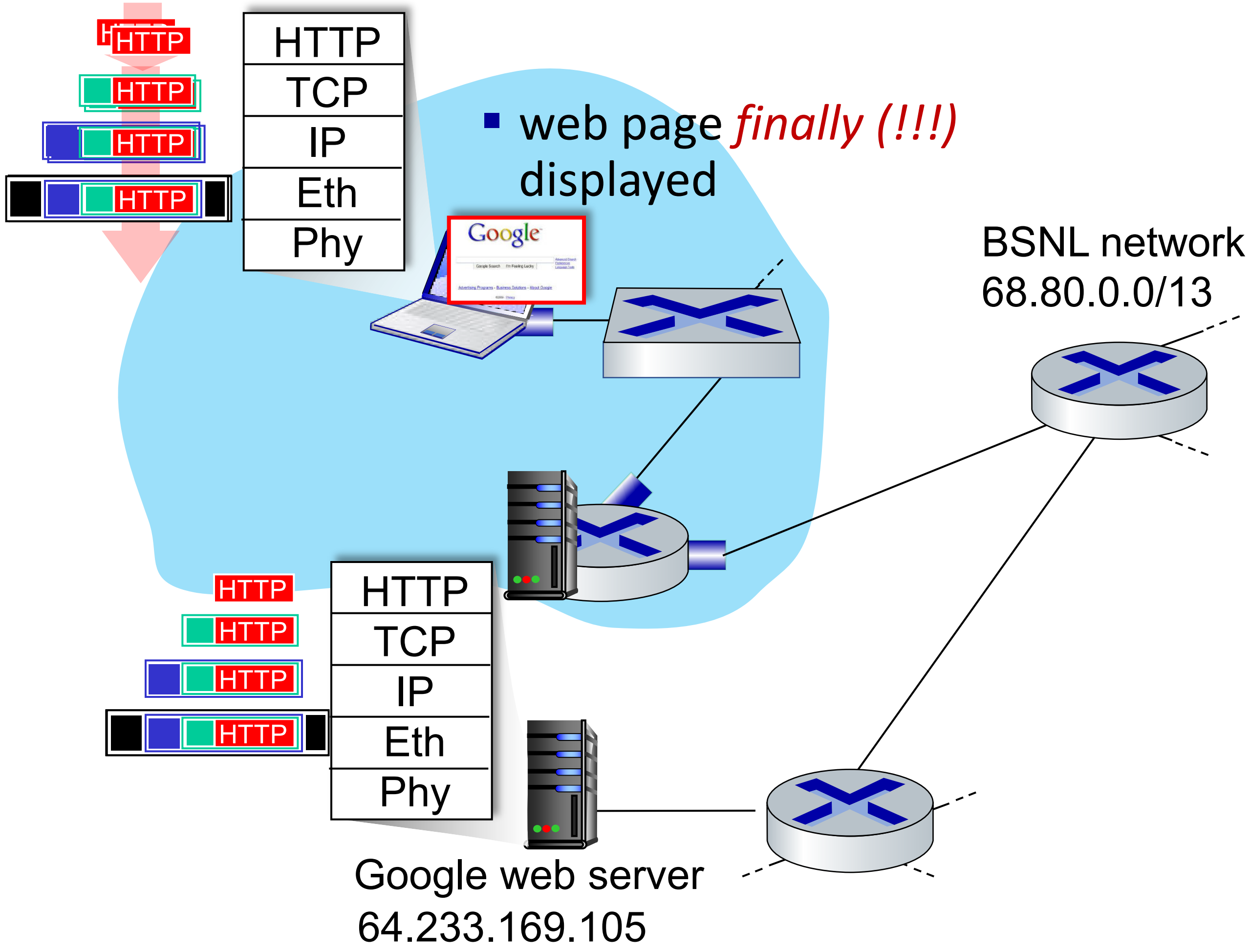
- IP datagram forwarded from campus network into BSNL network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server

# 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



- 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 datagram containing HTTP reply routed back to client