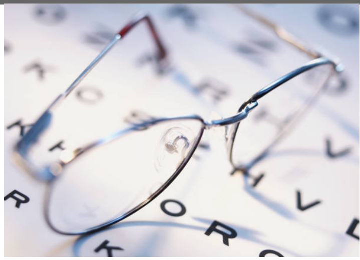
Link Layer/Physical Layer: Types of Links, MAC addresses, ARP, Ethernet, Multiple Access, Switching

Vivek Shah

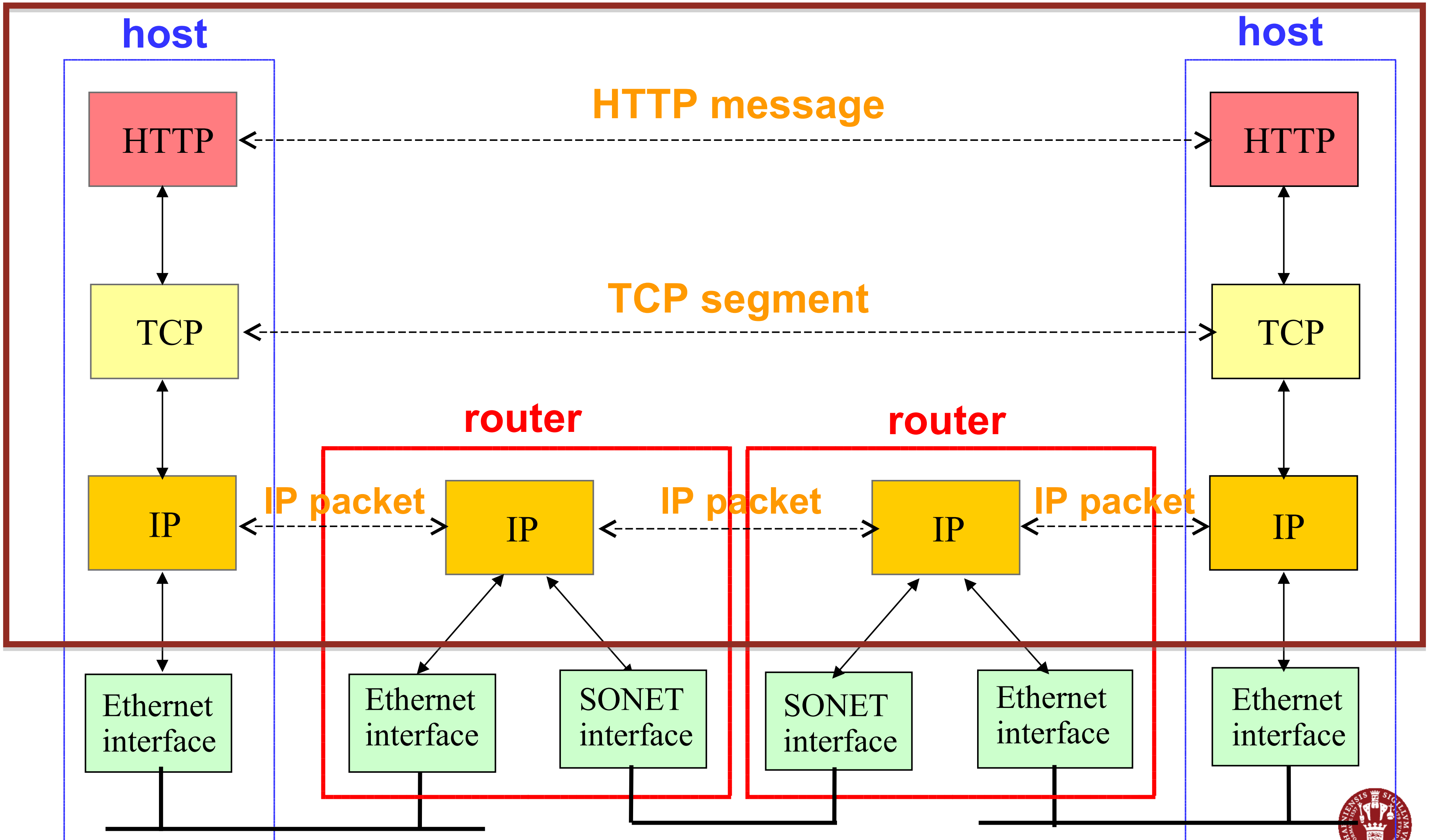
Based on slides compiled by Marcos Vaz Salles



What should we learn today?

- Link layer
  - Identify the main functions of the link layer: framing, error detection, and multiple access
  - Define the following methods for multiple access: channel partitioning, taking turns, random access
  - Describe what MAC addresses are as well as the Address Resolution Protocol (ARP)
  - Explain the multiple access mechanisms of Ethernet and their rationale
  - Define hubs, switches, and routers
  - Describe the self-learning mechanism used in switches to build forwarding tables
  - Discuss network configurations consisting of subnets and LAN segments

Recap: Our course so far…

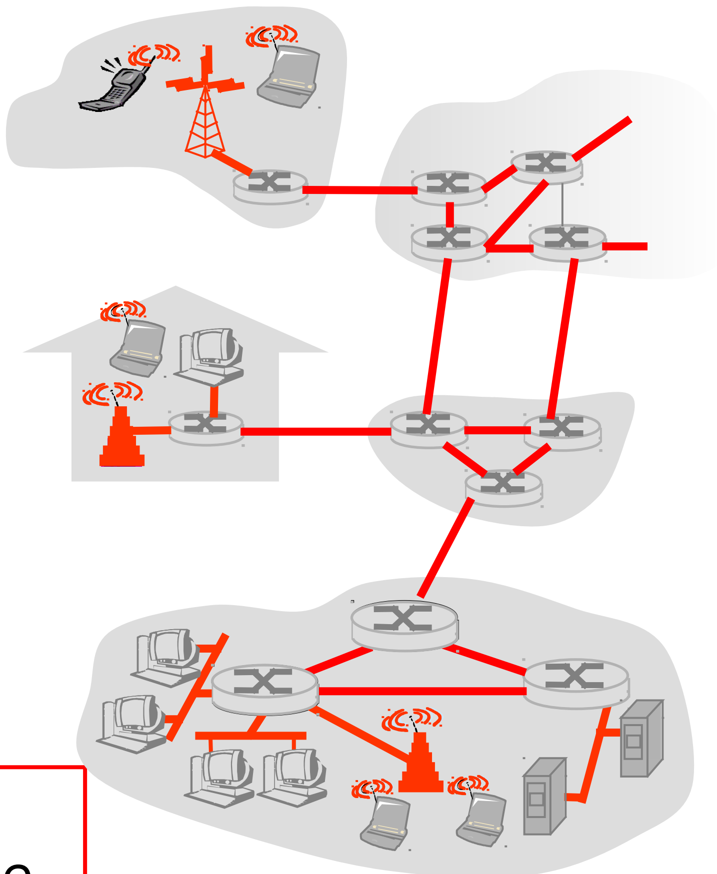


Source: Freedman (partial)

Link Layer: Introduction

Terminology:

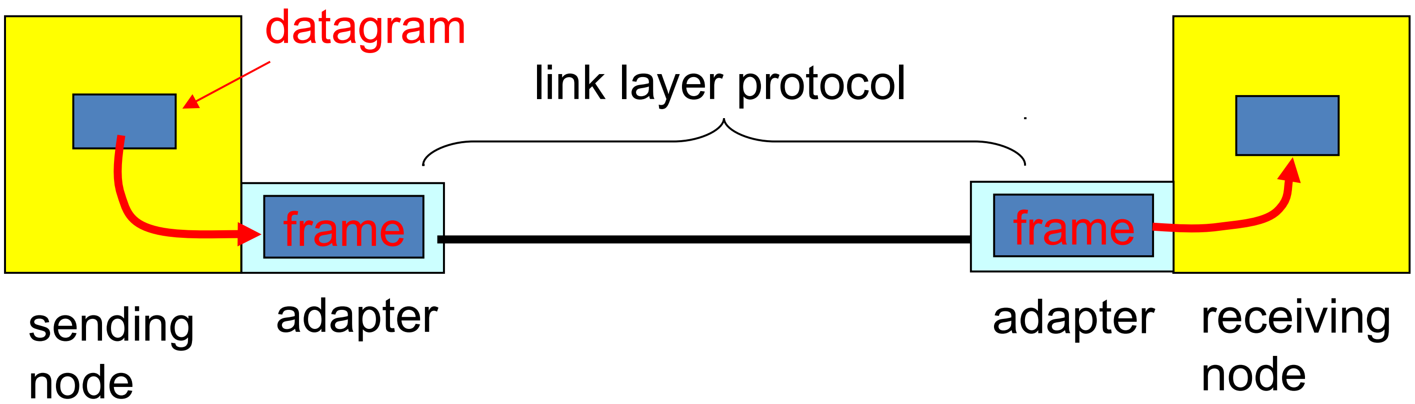
- hosts and routers are nodes
- communication channels that connect adjacent nodes along communication path are links
  - wired links
  - wireless links
  - LANs
- layer-2 packet is a frame, encapsulates datagram



data-link layer has responsibility of transferring datagram from one node to physically adjacent node over a link

Source: Kurose & Ross

Digital adaptors Communicating



- Link layer implemented in adaptor (network interface card)
  - Ethernet card, PCMCIA card, 802.11 card
- Sending side:
  - Encapsulates datagram in a frame
  - Adds error checking bits, flow control, etc.
- Receiving side
  - Looks for errors, flow control, etc.
  - Extracts datagram and passes to receiving node

Source: Freedman

Framing

- Break sequence of bits into a frame
  - Typically implemented by the network adaptor
- Sentinel-based
  - Delineate frame with special pattern (e.g., 01111110)

01111110	**Frame contents**	01111110

- Problem: what if special patterns occurs within frame?
- Solution: escaping the special characters
  - E.g., sender always inserts a 0 after five 1s
  - … and receiver always removes a 0 appearing after five 1s
- Similar to escaping special characters in C programs

Source: Freedman

Framing (Continued)

- Counter-based
  - Include the payload length in the header
  - … instead of putting a sentinel at the end
  - Problem: what if the count field gets corrupted?
    - Causes receiver to think the frame ends at a different place
  - Solution: catch later when doing error detection
    - And wait for the next sentinel for the start of a new frame

- Clock-based
  - Make each frame a fixed size
  - No ambiguity about start and end of frame
  - But, may be wasteful

Source: Freedman

Error Detection

- Errors are unavoidable
  - Electrical interference, thermal noise, etc.
- Error detection
  - Transmit extra (redundant) information
  - Use redundant information to detect errors
  - Extreme case: send two copies of the data
  - Trade-off: accuracy vs. overhead

Source: Freedman

Error Detection Techniques

- Parity check
  - Add an extra bit to a 7-bit code
  - Odd parity: ensure an odd number of 1s
    - E.g., 0101011 becomes 01010111
  - Even parity: ensure an even number of 1s
    - E.g., 0101011 becomes 01010110

- Checksum
  - Treat data as a sequence of 16-bit words
  - Compute a sum of all 16-bit words, with carries and wraparounds
  - Transmit the sum (1s complement of this) along with the packet

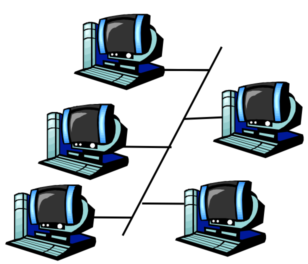
- Cyclic Redundancy Check (CRC)
  - See book

Source: Freedman (partial)

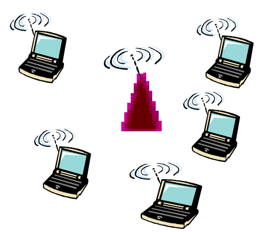
Multiple Access Links and Protocols

Two types of "links":

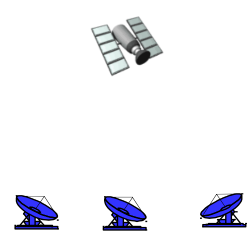
- point-to-point
  - PPP for dial-up access
  - point-to-point link between Ethernet switch and host
- broadcast (shared wire or medium)
  - old-fashioned Ethernet
  - upstream HFC
  - 802.11 wireless LAN



shared wire (e.g., cabled Ethernet)



shared RF (e.g., 802.11 WiFi)



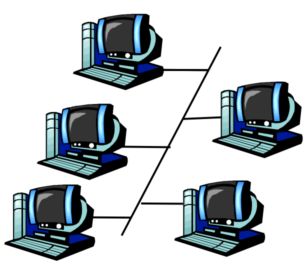
shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

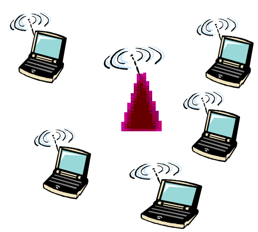
Source: Kurose & Ross

Multiple Access Protocol

- Single shared broadcast channel
  - Avoid having multiple nodes speaking at once
  - Otherwise, collisions lead to garbled data
- Multiple access protocol
  - Distributed algorithm for sharing the channel
  - Algorithm determines which node can transmit
- How would you design such a protocol?



shared wire (e.g., cabled Ethernet)



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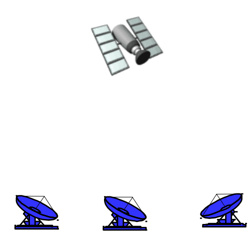


shared RF (satellite)

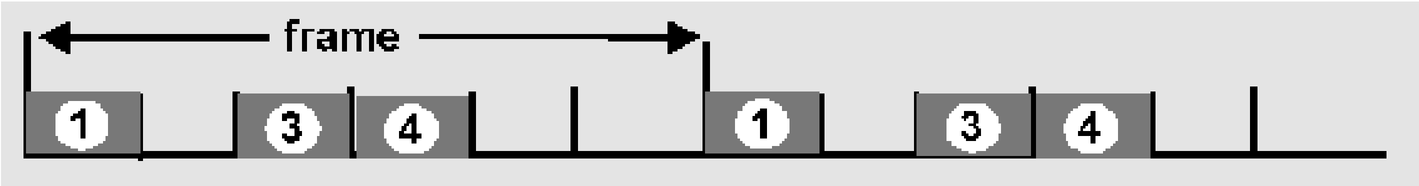
humans at a cocktail party (shared air, acoustical)

Source: Freedman (partial) / Kurose & Ross (partial)

Channel Partitioning: TDMA

TDMA: time division multiple access

- Access to channel in "rounds"
  - Each station gets fixed length slot in each round
- Time-slot length is packet transmission time
  - Unused slots go idle
- Example: 6-station LAN with slots 1, 3, and 4

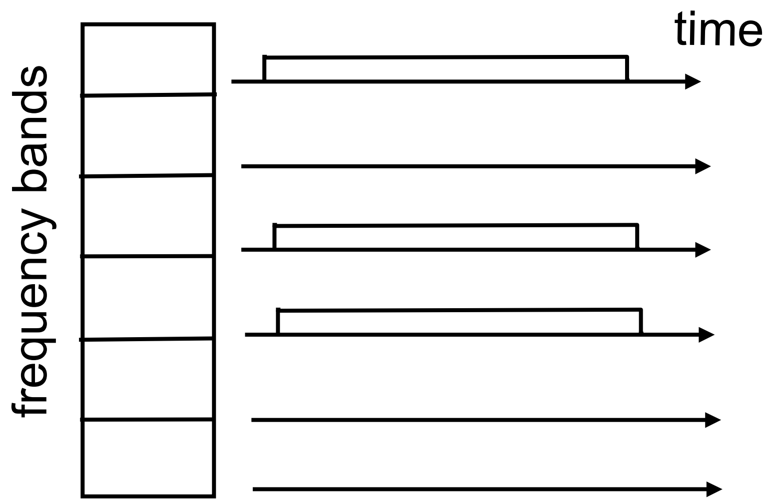


Source: Freedman

Channel Partitioning: FDMA

FDMA: frequency division multiple access

- Channel spectrum divided into frequency bands
  - Each station has fixed frequency band (Wifi channels 1-11)
- Unused transmission time in bands go idle
- Example: 6-station LAN with bands 1, 3, and 4



Source: Freedman

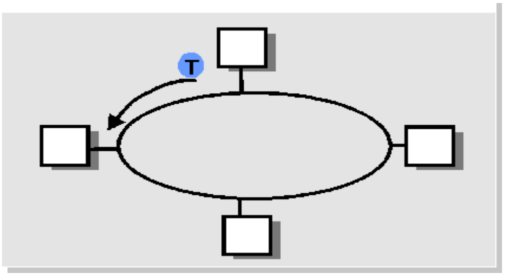
"Taking Turns" MAC protocols

Polling

- Primary node "invites" secondary nodes to transmit in turn
- Concerns:
  - Polling overhead
  - Latency
  - Single point of failure (primary)

Token passing

- Control token passed from one node to next sequentially
- Token message
- Concerns:
  - Token overhead
  - Latency
  - Single point of failure (token)



Source: Freedman

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

Source: Freedman

Key Ideas of Random Access

- Carrier Sense (CS)
  - *Listen before speaking, and don't interrupt*
  - Checking if someone else is already sending data
  - … and waiting till the other node is done

- Collision Detection (CD)
  - *If someone else starts talking at the same time, stop*
  - Realizing when two nodes are transmitting at once
  - …by detecting that the data on the wire is garbled

- Randomness
  - *Don't start talking again right away*
  - Waiting for a random time before trying again

Source: Freedman

MAC Addresses and ARP

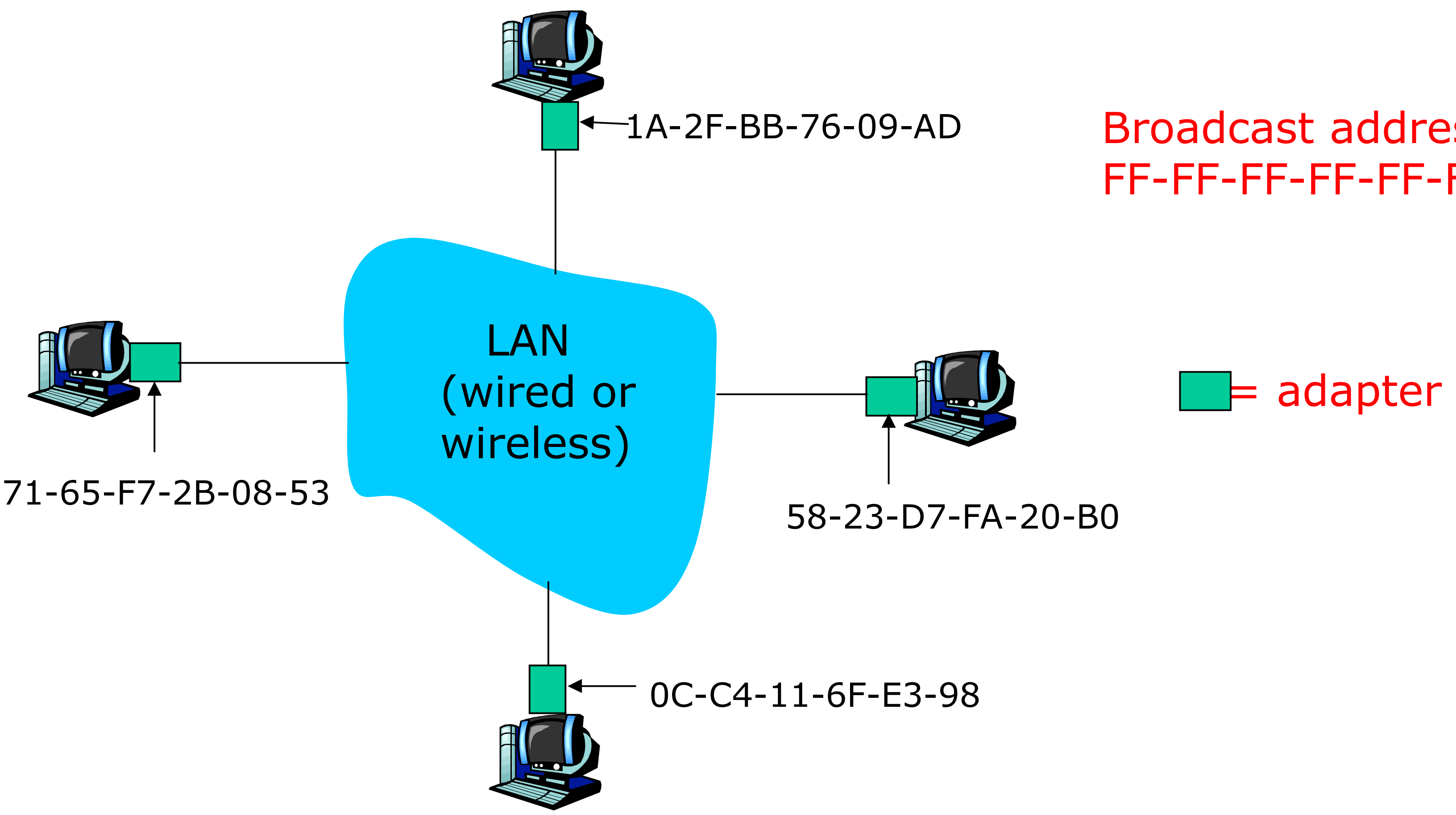
- 32-bit IP address:
  - *network-layer* address
  - used to get datagram to destination IP subnet

- MAC (or LAN or physical or Ethernet) address:
  - function: *get frame from one interface to another physically-connected interface (same network)*
  - 48 bit MAC address (for most LANs)
    - burned in NIC ROM, also sometimes software settable

Source: Kurose & Ross

LAN Addresses and ARP

Each adapter on LAN has unique LAN address



Broadcast address = FF-FF-FF-FF-FF-FF

Source: Kurose & Ross

LAN Address (more)

- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)

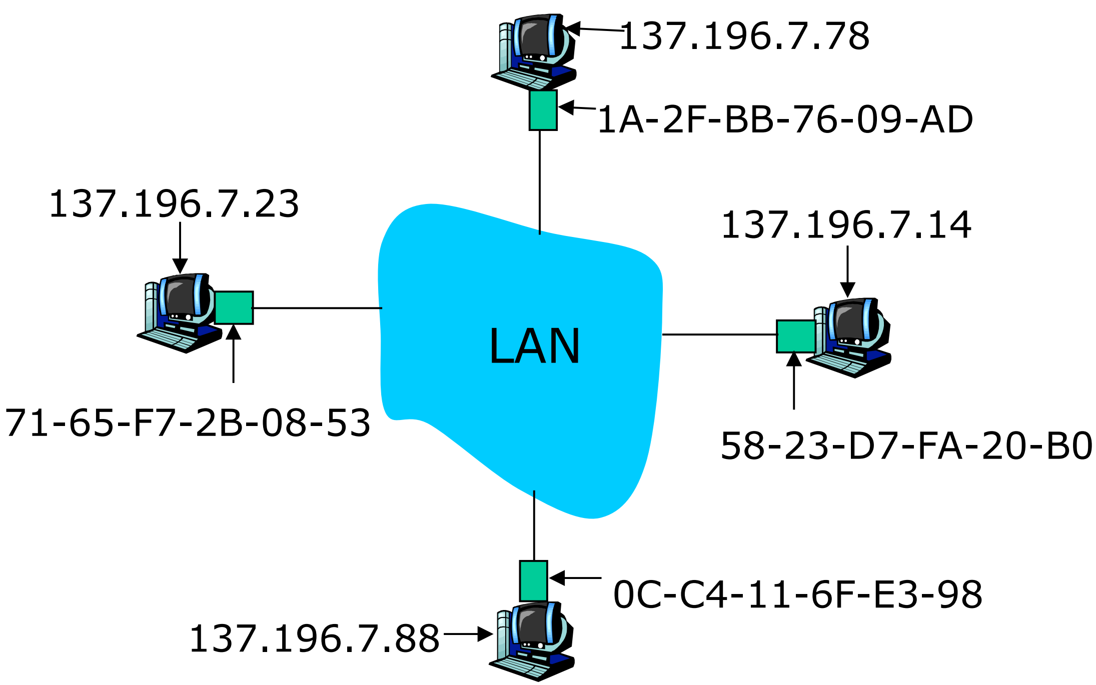
- Analogy:
  (a)MAC address: like Social Security Number
  (b) IP address: like postal address

- MAC flat address ➜ portability
  - can move LAN card from one LAN to another
- IP hierarchical address NOT portable
  - address depends on IP subnet to which node is attached

Source: Kurose & Ross

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)

Source: Kurose & Ross

ARP protocol: Same LAN (network)

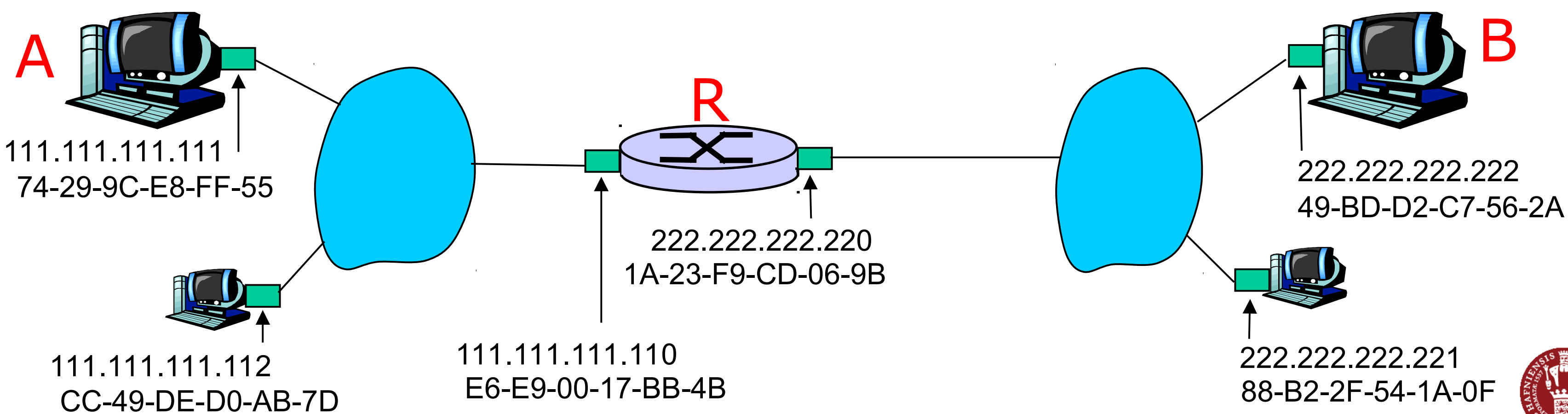
- A wants to send datagram to B, and B's MAC address not in A's ARP table.
- A broadcasts ARP query packet, containing B's IP address
  - dest MAC address = FF-FF-FF-FF-FF-FF
  - all machines on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's 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
- ARP is "plug-and-play":
  - nodes create their ARP tables *without intervention from net administrator*

Source: Kurose & Ross (partial)

Addressing: routing to another LAN

walkthrough: send datagram from A to B via R.

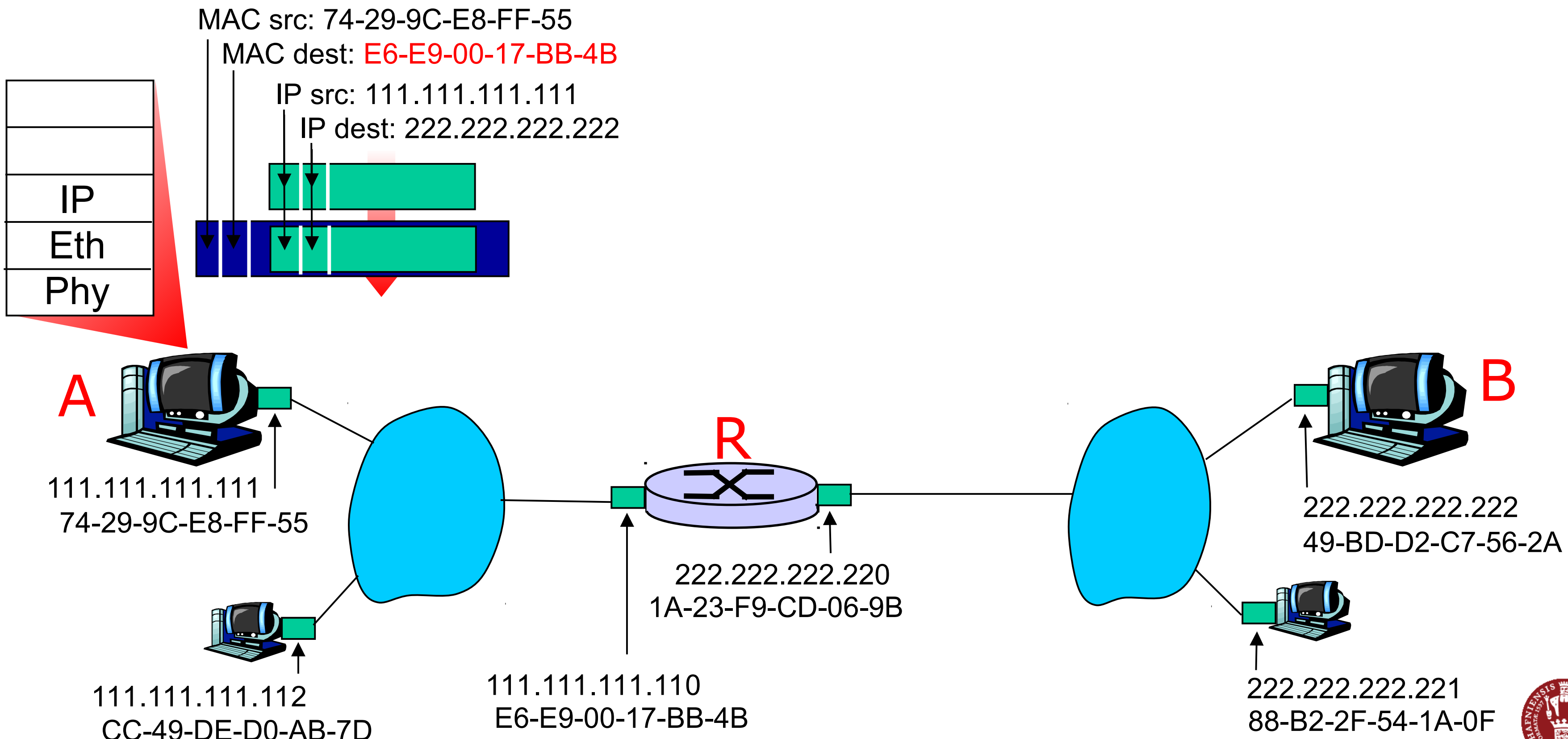
- focus on addressing - at both IP (datagram) and MAC layer (frame)
- assume A knows B's IP address
- assume A knows IP address of first hop router, R (how?)
- assume A knows MAC address of first hop router interface (how?)
- Assume R knows B's MAC address (how?)



Source: Kurose & Ross (partial)

Addressing: routing to another LAN

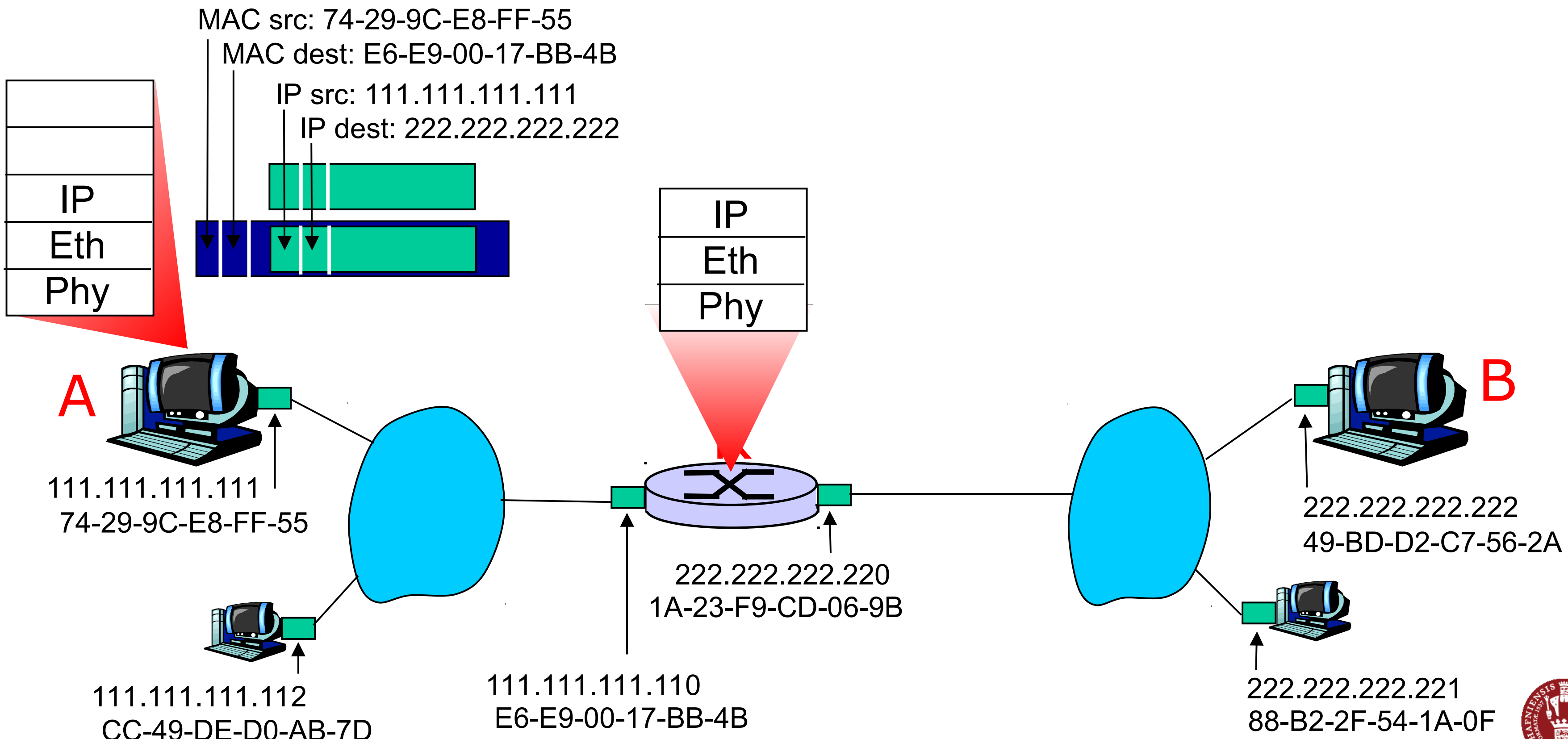
- A creates IP datagram with IP source A, destination B
- A creates link-layer frame with R's MAC address as dest, frame contains A-to-B IP datagram



Source: Kurose & Ross

Addressing: routing to another LAN

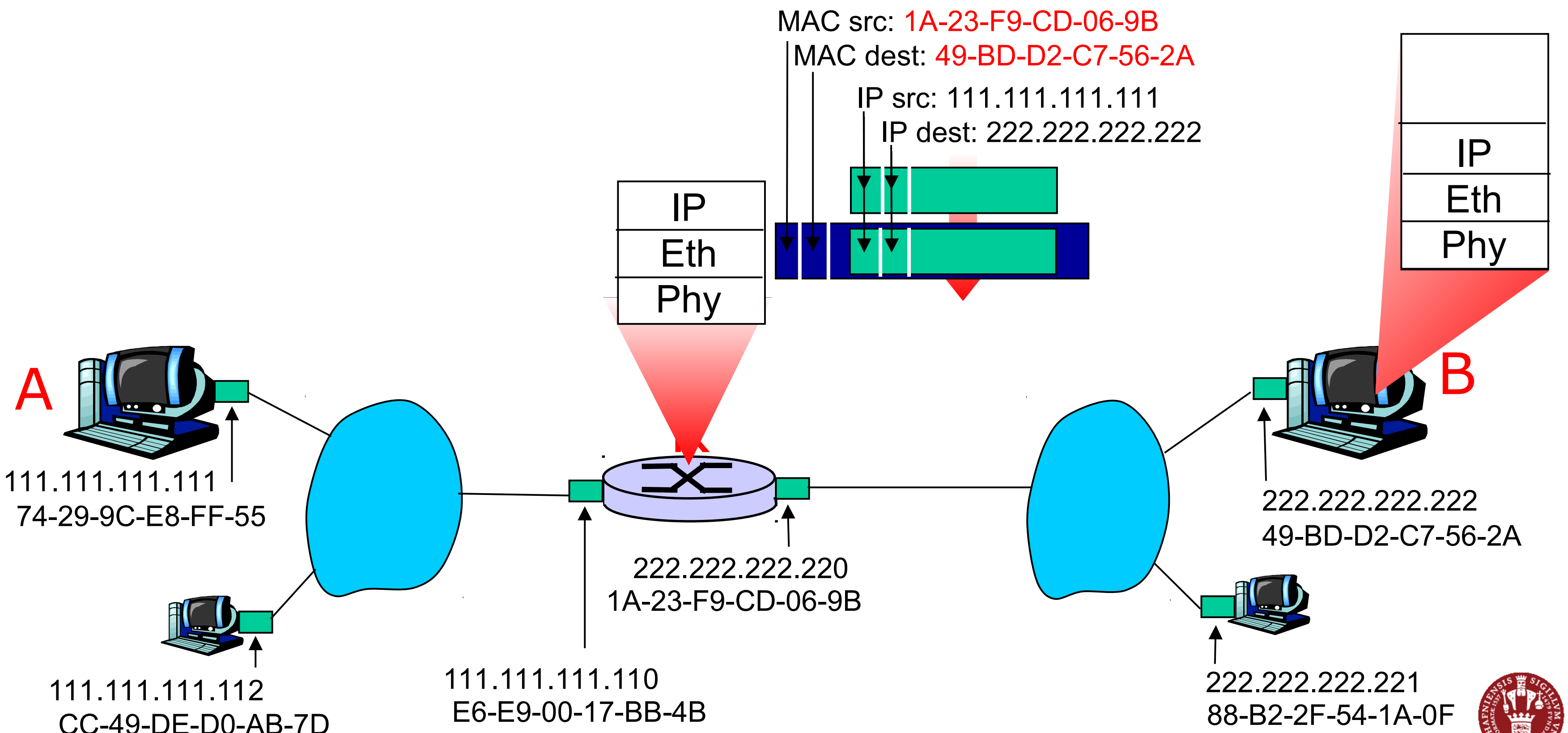
- frame sent from A to R
- frame received at R, datagram removed, passed up to IP



Source: Kurose & Ross

Addressing: routing to another LAN

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



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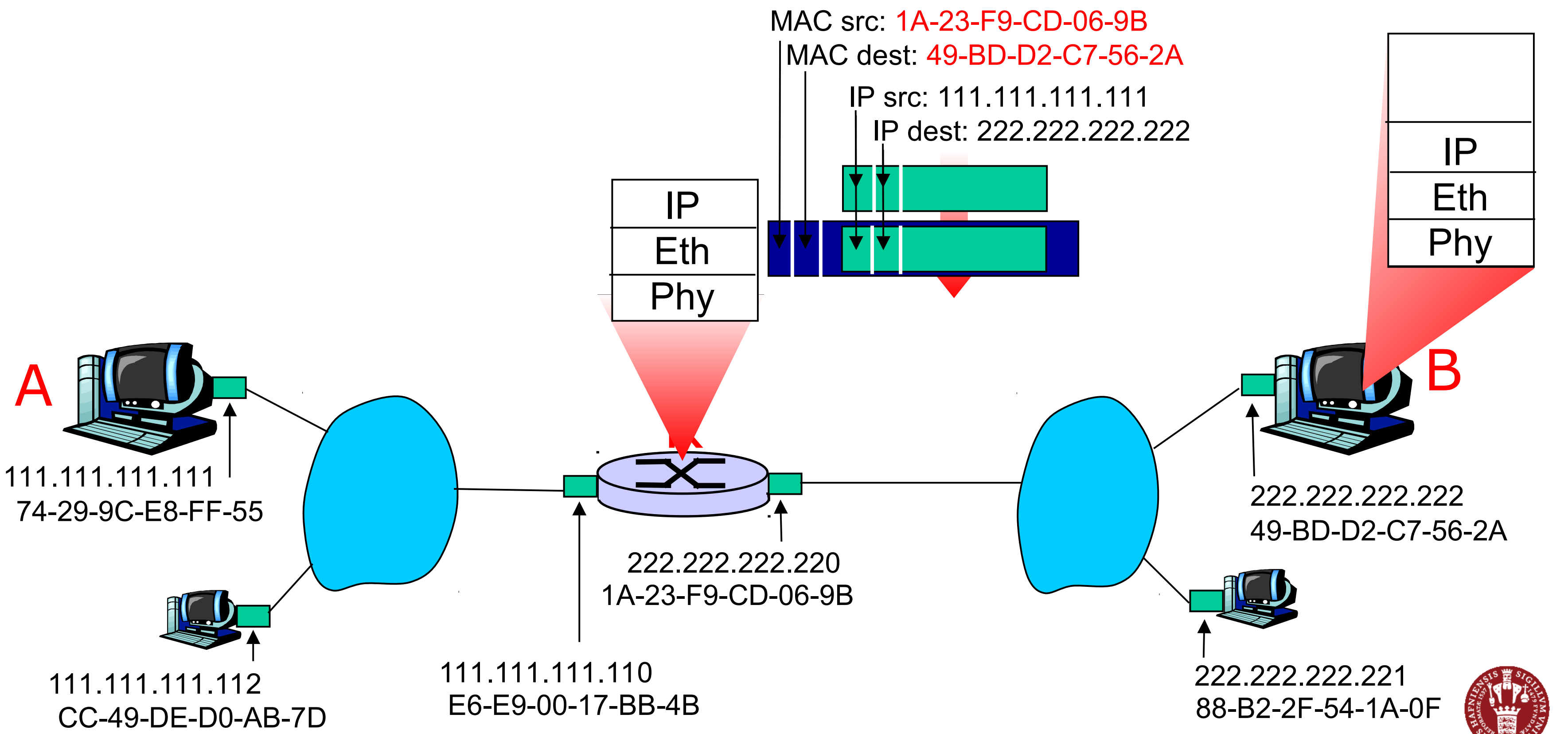

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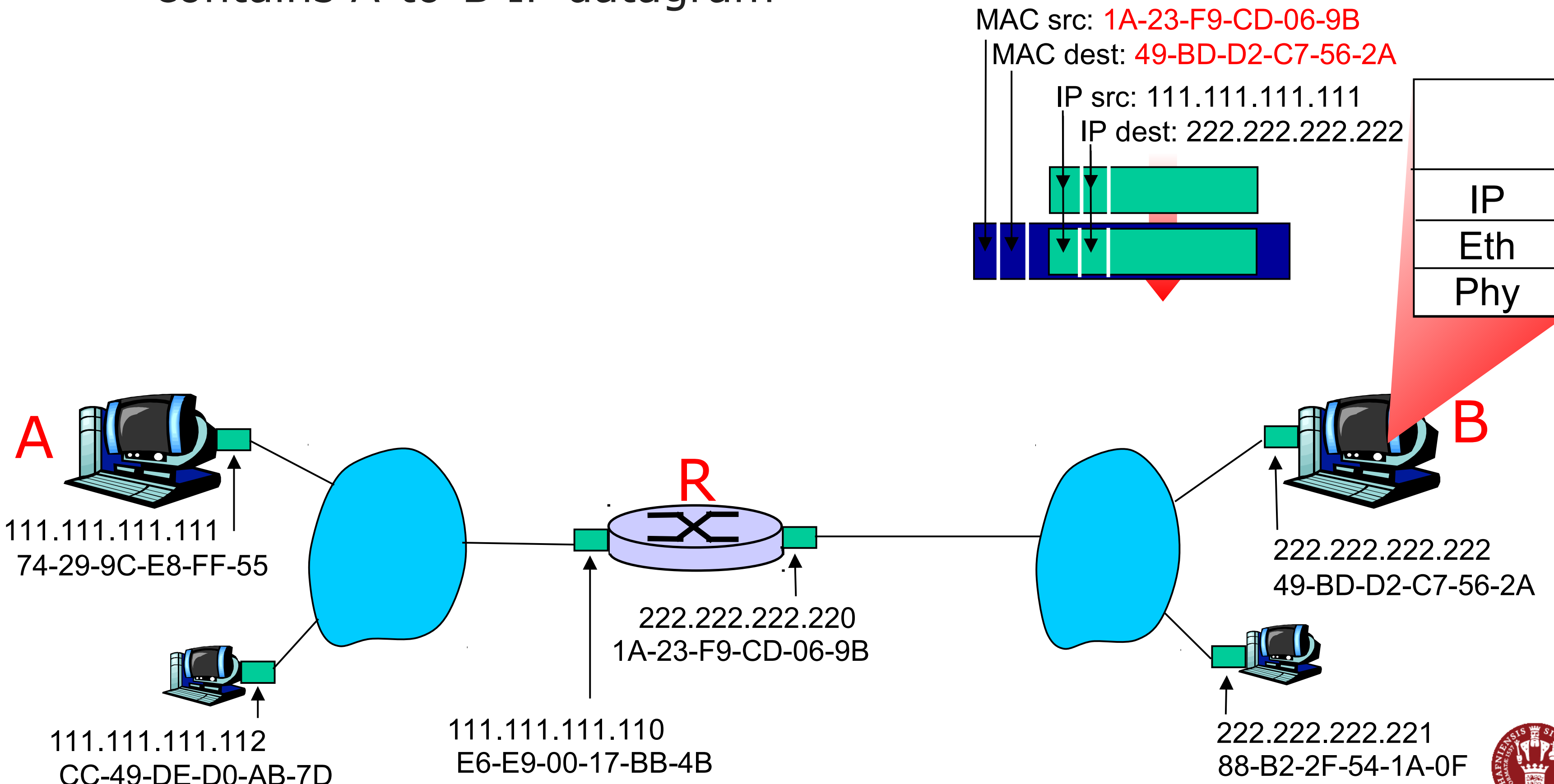
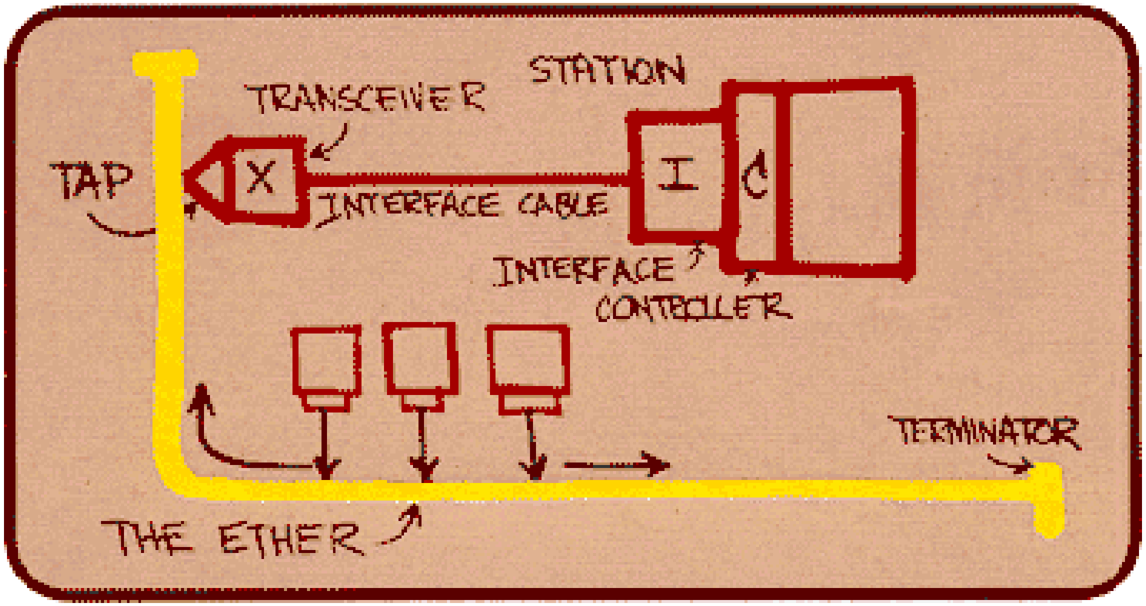


Source: Kurose & Ross

Ethernet

- Dominant wired LAN technology, first widely used
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10 Mbps – 10 Gbps



Metcalfe's Ethernet sketch

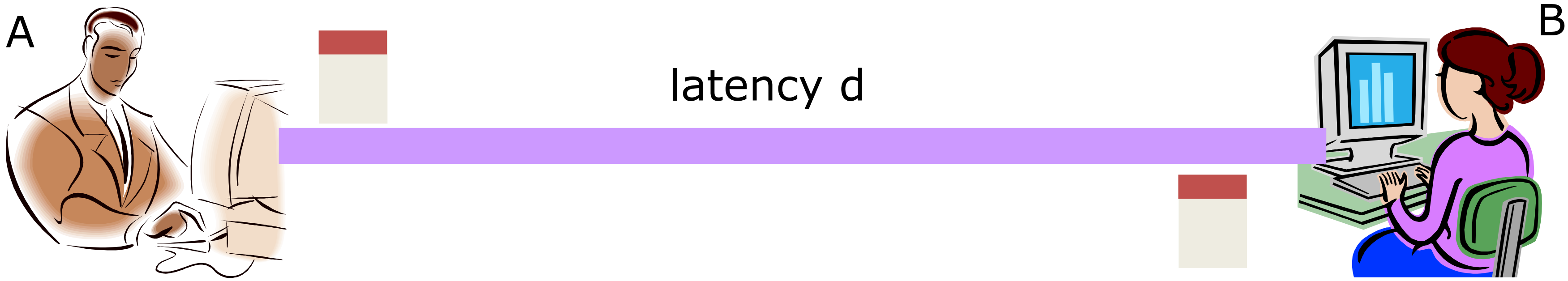
Source: Freedman

Ethernet Uses CSMA/CD

- **Carrier Sense (CS)**
  - *Listen before speaking, and don't interrupt*
  - wait for link to be idle before transmit
- **Collision Detection (CD)**
  - *If someone else starts talking at the same time, stop*
  - listen while transmitting
  - No collision: transmission complete
  - Collision: abort and send jam signal
- **Randomness (exponential back-off)**
  - *Don't start talking again right away*
  - After collision, wait a random time before retry
  - After m^{th} collision, choose K randomly from $\{0, \ldots, 2^m-1\}$
  - … and wait for K*64 byte times before retry

Source: Freedman (partial)

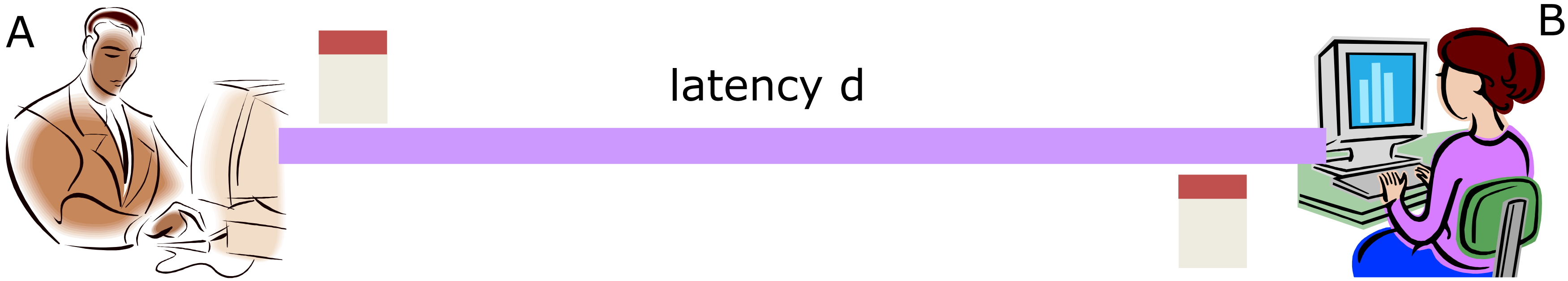
Limitations on Ethernet Length



- Latency depends on physical length of link
  - Time to propagate a packet from one end to the other
- Suppose A sends a packet at time t
  - And B sees an idle line just before time t+d, so transmits
- B detects a collision, and sends jamming signal
  - But A doesn't see collision till t+2d

Source: Freedman

Limitations on Ethernet Length



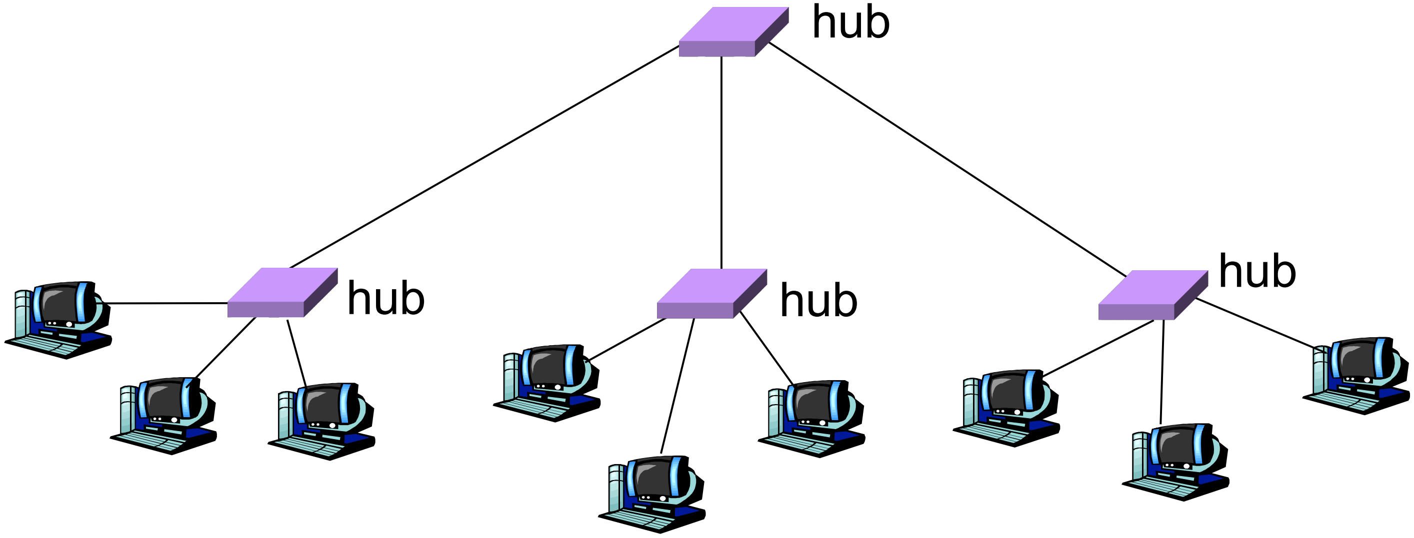
- A needs to wait for time 2d to detect collision
  - So, A should keep transmitting during this period
  - … and keep an eye out for a possible collision
- Imposes restrictions on Ethernet
  - Max length of wire: 2500 meters
  - Min length of packet: 512 bits (64 bytes)

Source: Freedman

Physical Layer: 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



Source: Kurose & Ross and Freedman (partial)

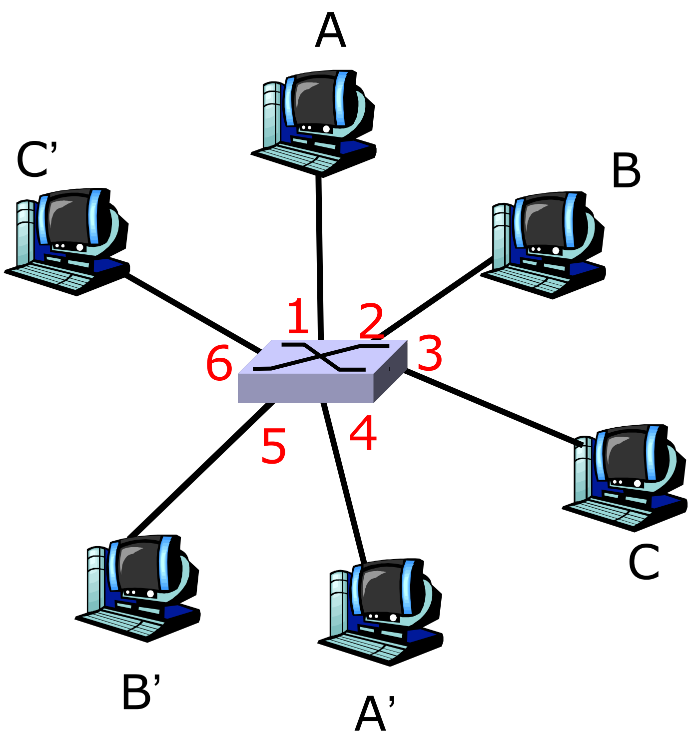
Limitations of Repeaters and Hubs

- One large shared link
  - Each bit sent everywhere, aggregate throughput limited
- Cannot support multiple LAN technologies
  - Does not buffer or interpret frames
  - So, can't interconnect different rates or formats
- Limitations on maximum nodes and distances

Source: Freedman

Link Layer: Switches

- Connects two or more LAN segments at the link layer
  - Extracts destination address from the frame
  - Looks up the destination in a table, forwards to appropriate
- Each segment can carry its own traffic
  - Concurrent traffic between LANs/host: A to B while A' to B'

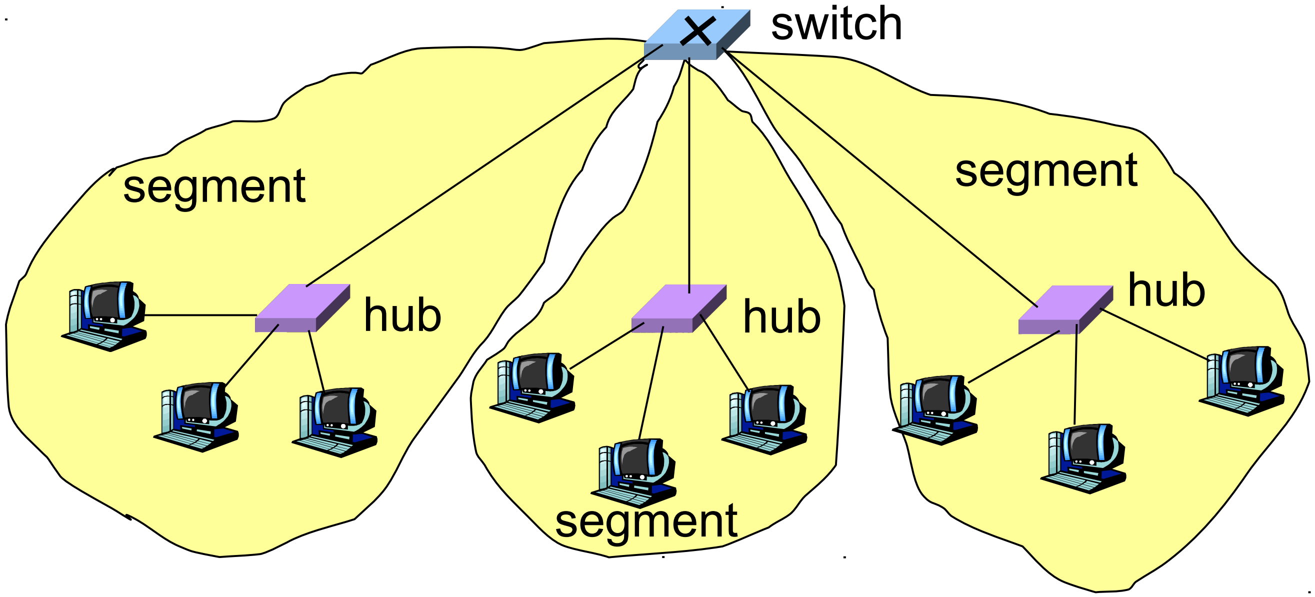


switch with six interfaces (1,2,3,4,5,6)

Source: Kurose & Ross and Freedman (partial)

Switches: Traffic Isolation

- Switch breaks subnet into LAN segments
- Switch filters packets
  - Frame only forwarded to the necessary segments
  - Segments can support separate transmissions



Source: Freedman (partial)

Advantages Over Hubs/Repeaters

- Only forwards frames as needed
  - E.g. to destination segments or for broadcast traffic
  - Reduces unnecessary traffic on segments
- Extends the geographic span of the network
  - Ethernet collisions (and distance limitations) only on segment
- Improves privacy by limiting scope of frames
  - Hosts can only "snoop" the traffic traversing *their* segment
- Can join segments using different technologies
- Allows for simultaneous transmissions

Source: Freedman (partial)

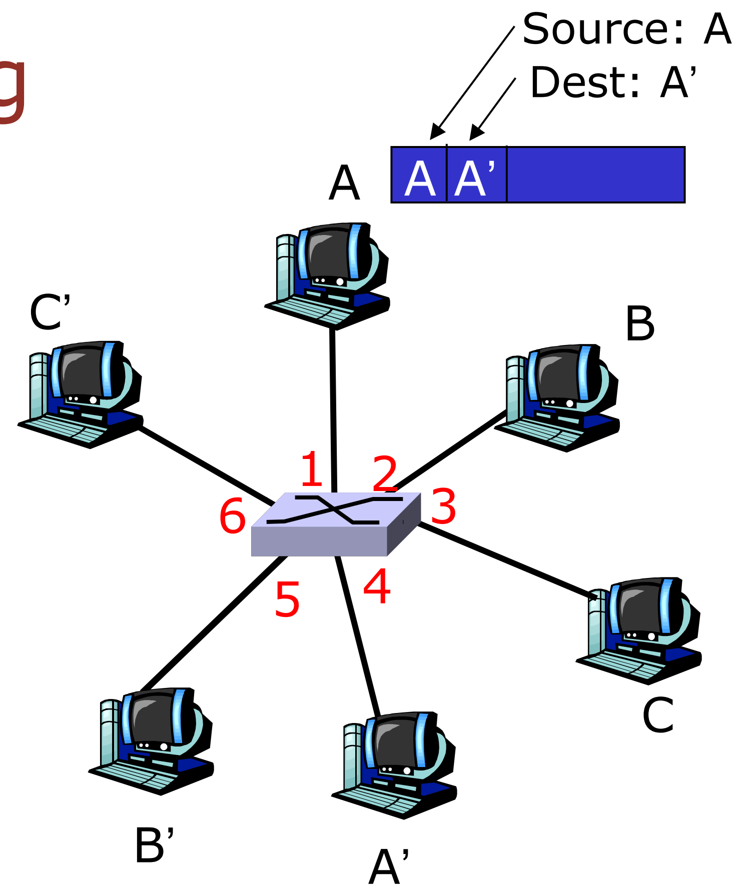
Disadvantages Over Hubs/Repeaters

- Delay in forwarding frames
  - Bridge/switch must receive frame, parse, lookup, and send
  - Storing and forwarding the packet introduces delay
  - Sol'n: cut-through switching (start send after receive header)
- Need to learn where to forward frames
  - Forwarding table: destination MAC → outgoing interface
  - Needs to construct forwarding table, ideally w/o static config
  - Sol'n: self-learning
- Higher cost
  - More complicated devices that cost more money

Source: Freedman

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



MAC addr	interface	TTL
A	1	60

Switch table (initially empty)

Source: Kurose & Ross

Switch: frame filtering/forwarding

When frame received:

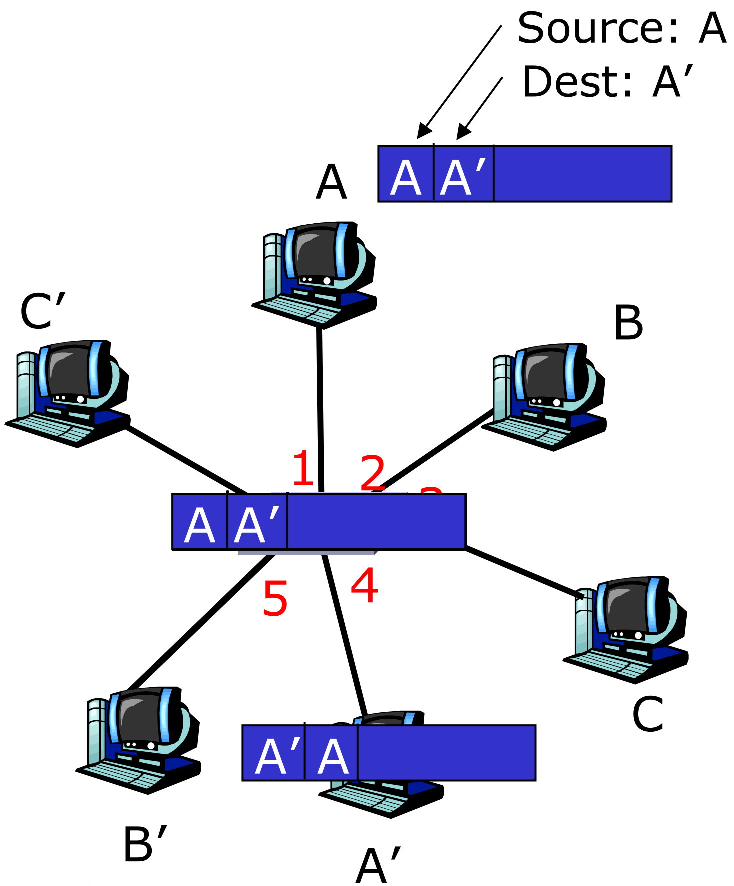
1. record link associated with sending host
2. index switch table using MAC dest address
3. if entry found for destination
   then {
   if dest on segment from which frame arrived
   then drop the frame
   else forward the frame on interface indicated
   }
   else flood

forward on all but the interface on which the frame arrived

Source: Kurose & Ross

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)

Source: Kurose & Ross

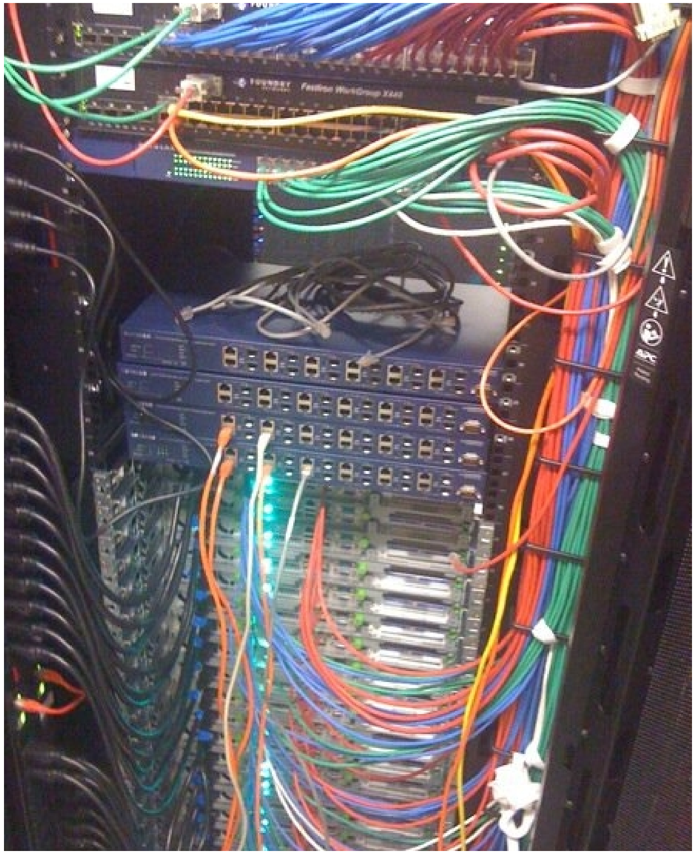
Comparing Hubs, Switches, Routers

	Hub / Repeater	Bridge / Switch	IP Router
Traffic isolation	no	yes	yes
Plug and Play	yes	yes	no
Efficient routing	no	no	yes
Cut through	yes	yes	no

Source: Freedman

High-density switching

Source: Freedman (partial)



Partial view of “rack”

48-port switch

Facebook rack

- Each rack has 42 U (“pizza boxes”)
- Typically servers + 1-2 “top-of-rack” switch(es)

Summary

- Link Layer
  - Framing, error detection, multiple access
  - Channel partitioning, taking turns, random access
  - MAC addresses and ARP
  - Ethernet, CSMA/CD
  - Hubs, switches, routers
  - Subnets, LAN segments, self-learning in switches