CS 352
Link Layer: Introduction

CS 352, Lecture 22.1

http://www.cs.rutgers.edu/~sn624/352

Srinivas Narayana

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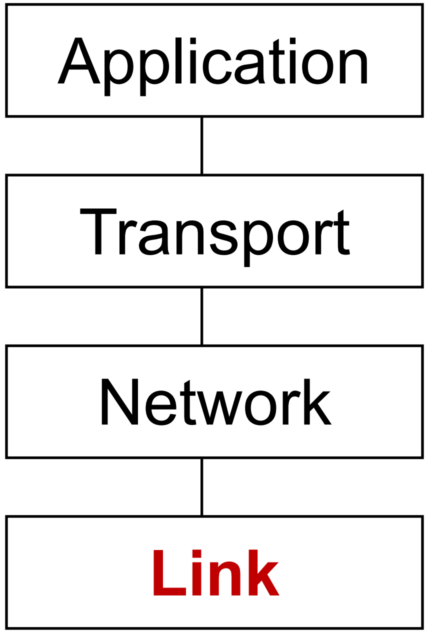
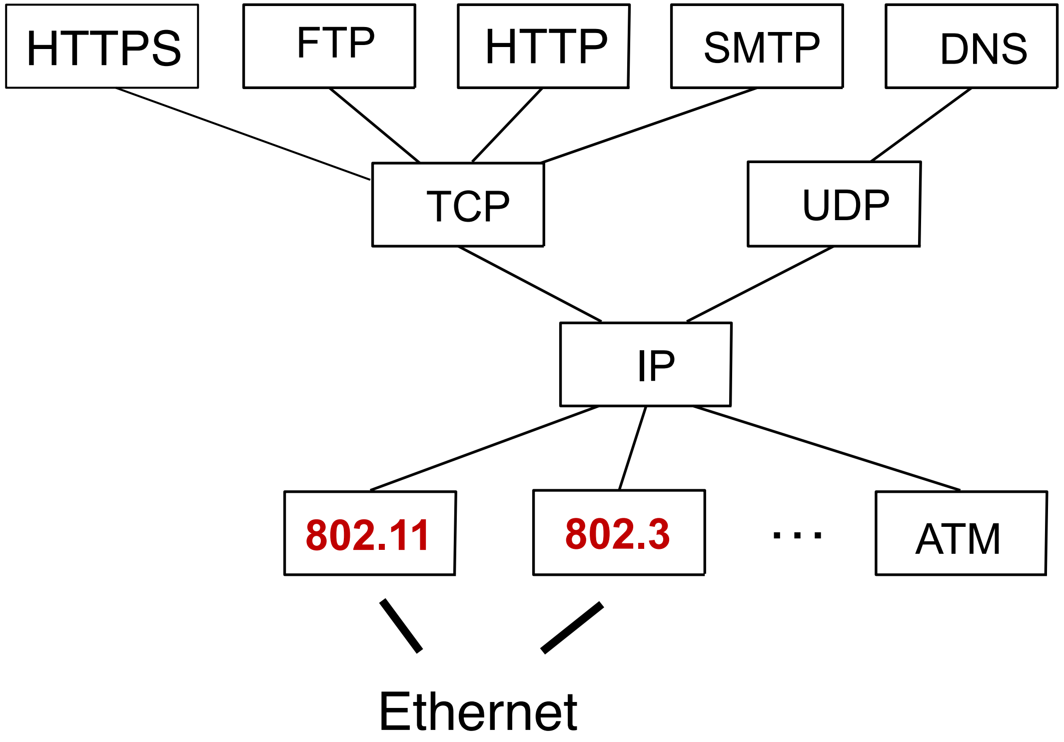
Link layer





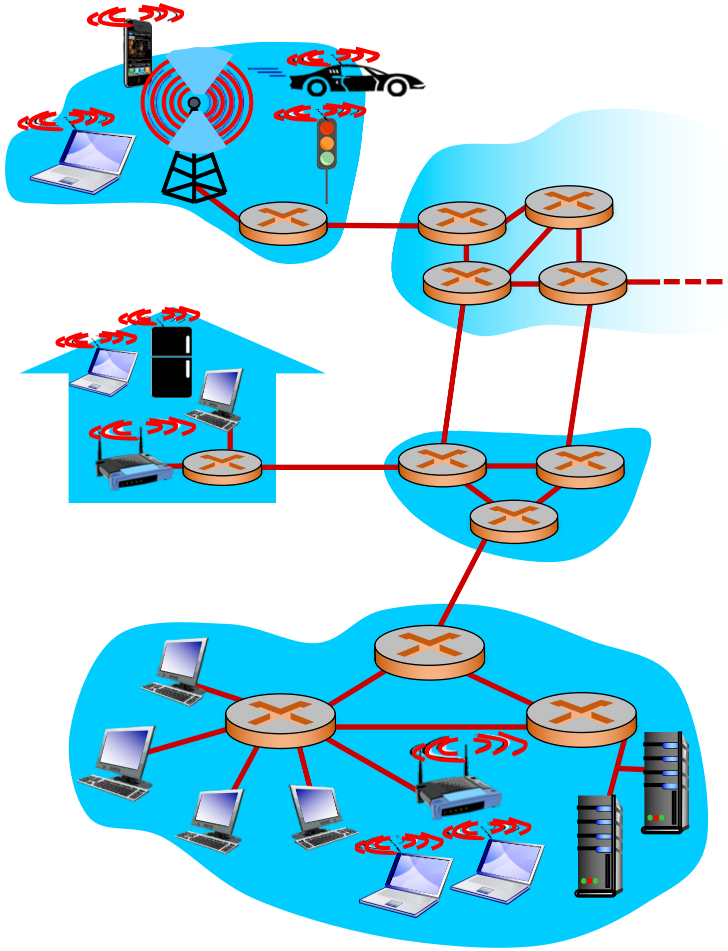
The main function of the link layer is link-local delivery: getting packets from one side of the link to the other.

Link layer: introduction

Terminology:

- Endpoints and routers: nodes
- communication channels that connect adjacent nodes along communication path: links
  - wired links, wireless links, local area networks (LANs)
- layer-2 packet: frame, encapsulates (IP) datagram

Link layer has the responsibility of transferring datagram from one node to physically adjacent node over a link.



Link layer: context

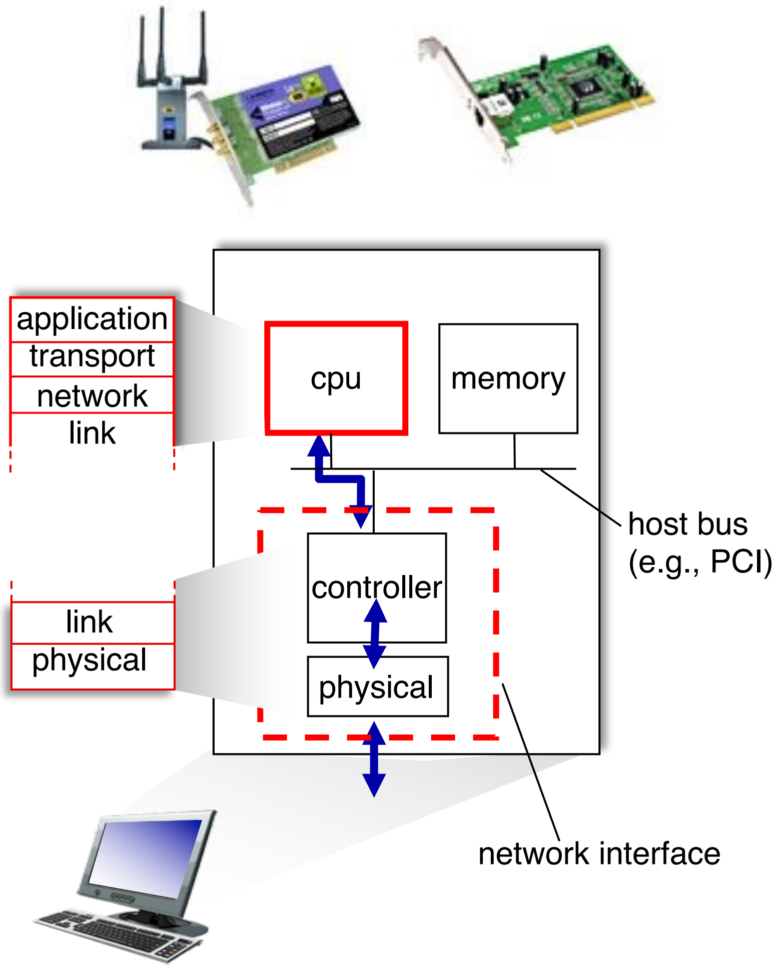
- Datagram transferred by different link layer protocols over different links
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- Each link layer protocol may provide different services
  - e.g., some links may provide additional reliability mechanisms

Analogy:

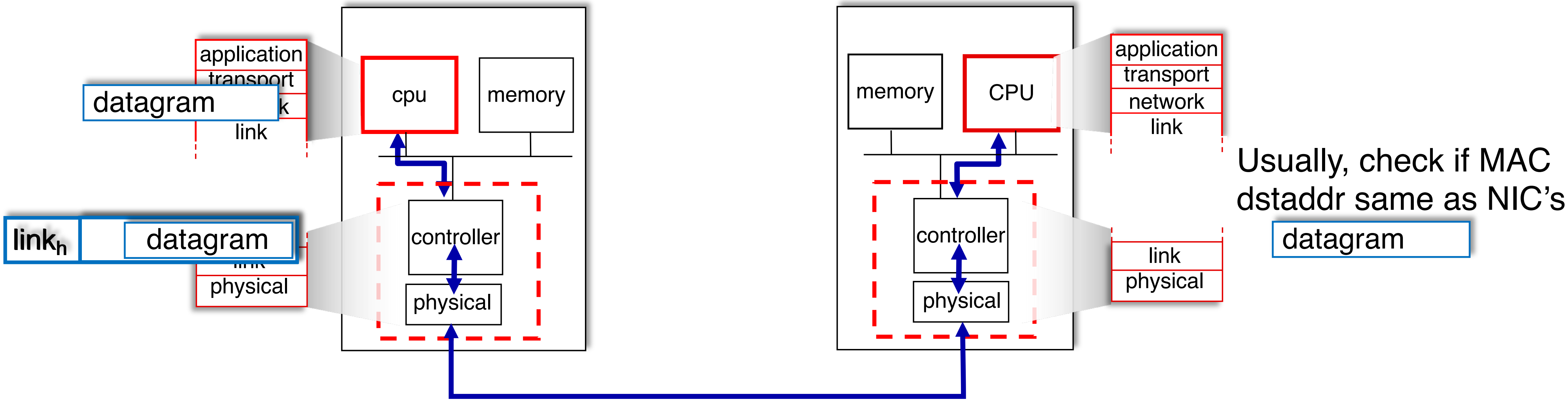
- trip from Piscataway, NJ to Palo Alto, CA
  - limo: Piscataway to JFK
  - plane: JFK to San Francisco
  - train: San Francisco to Palo Alto
- tourist = datagram
- transport segment (road/flight/rail) = communication link
- transportation mode (car/plane/train) = link layer protocol

Where is the link layer implemented?

- in every endpoint & router
- link layer implemented in network interface card (NIC)
  - Ethernet, WiFi card or chip
  - Router input and output ports
- At endpoint, attaches into its system buses (e.g., PCIe)
- combination of hardware, software, firmware



Interfaces communicating



sending side:

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

receiving side:

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

Link layer (MAC) addresses

Link layer addresses

- Review: we've looked at 32-bit IPv4 addresses
  - network-layer address for interface
  - used for layer 3 (network layer) forwarding
  - e.g.: 128.119.40.136
- MAC or physical or link-layer address
  - Used "locally" to get frame from one interface to another physically-connected interface (same subnet, in IP-addressing sense)
  - This course: Ethernet family of link layer protocols
  - 48-bit Ethernet MAC address burned in NIC ROM
    - Sometimes, the address can be set in software

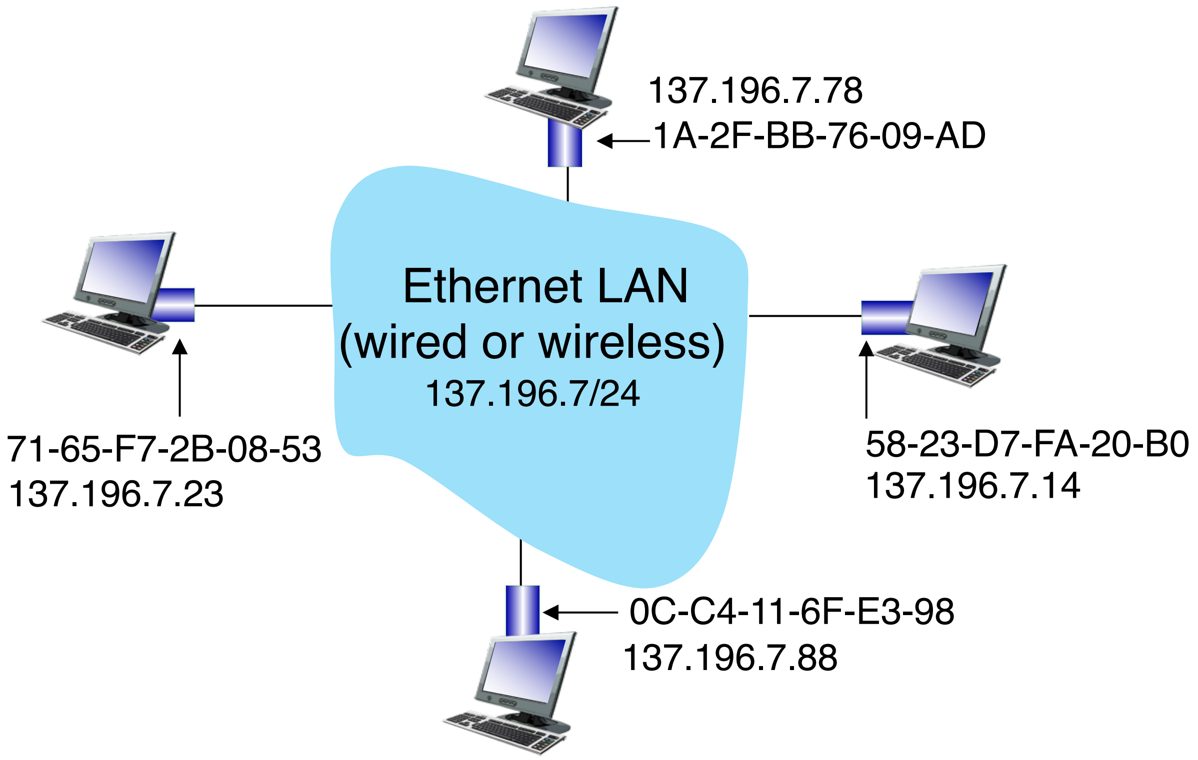
      - e.g.: 1A-2F-BB-76-09-AD

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

MAC addresses

each interface on LAN

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



MAC addresses

- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- Analogy:
  - MAC address: like Social Security Number
  - IP address: like postal address
- MAC is a flat address: portability
  - e.g., can move interface from one Ethernet LAN to another
  - Recall: IP address is not portable: depends on IP network to which node is attached

Link layer services

Link layer: services

- Line termination (serialize/deserialize)
  - Physical signaling (into the wire) & extracting digital signal (out of the wire)
  - Encapsulate datagram into frame (framing). Add header, trailer
- 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
- Medium access control
  - channel medium access in a shared medium:
  - “Who should talk?”

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This lecture

- Medium access control
  - channel medium access in a shared medium
  - “Who should talk?”

Next 2 lectures

Link layer: services: there's more!

- Reliable delivery between adjacent nodes
  - Seldom used on low bit-error links
  - Not strictly needed for functionality
  - An optimization that significantly improves performance over pure end-to-end reliable delivery over high-error-rate links (e.g., wireless)

- Flow control:
  - pacing between adjacent sending and receiving nodes
  - Used in lossless link layer technologies (e.g., Infiniband, lossless Ethernet)

Not covered in this course

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Next module:

Encoding, error detection, and error correction

CS 352
Encoding, Error Detection, and Correction

CS 352, Lecture 22.2

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Recall: Link layer services

- Line termination (serialize/deserialize)
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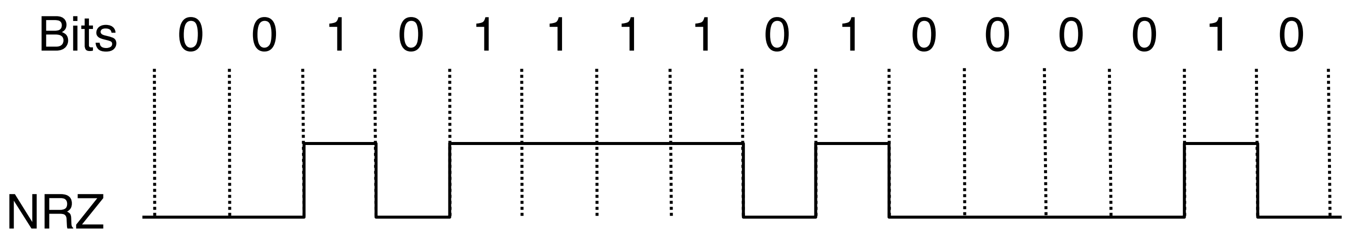
This module:

Encoding, error detection, and error correction

Handling digital and physical Information

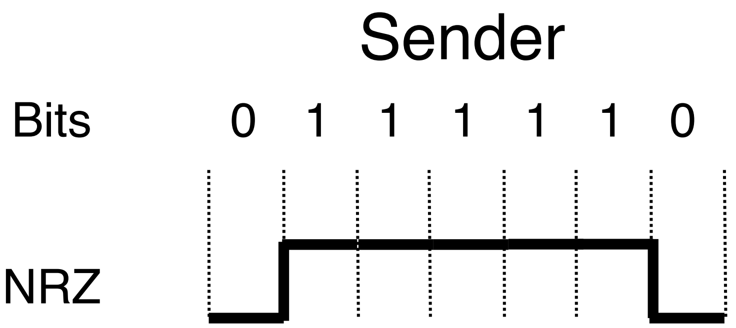
Encoding and Decoding

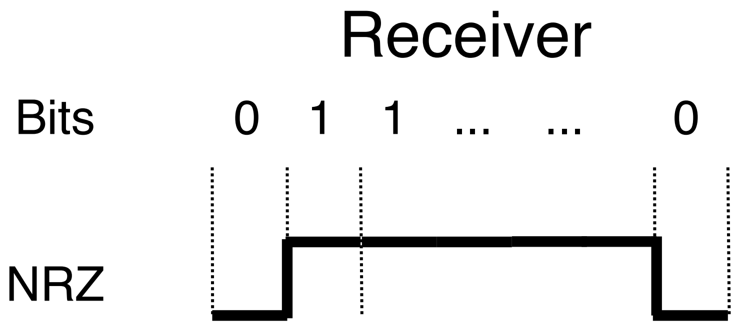
- Signals propagate over a physical medium
  - modulate electromagnetic waves
  - e.g., vary voltage
- Encode binary data onto signals
  - e.g., 0 as low signal and 1 as high signal
  - known as Non-Return to zero (NRZ)



Clock sync and recovery

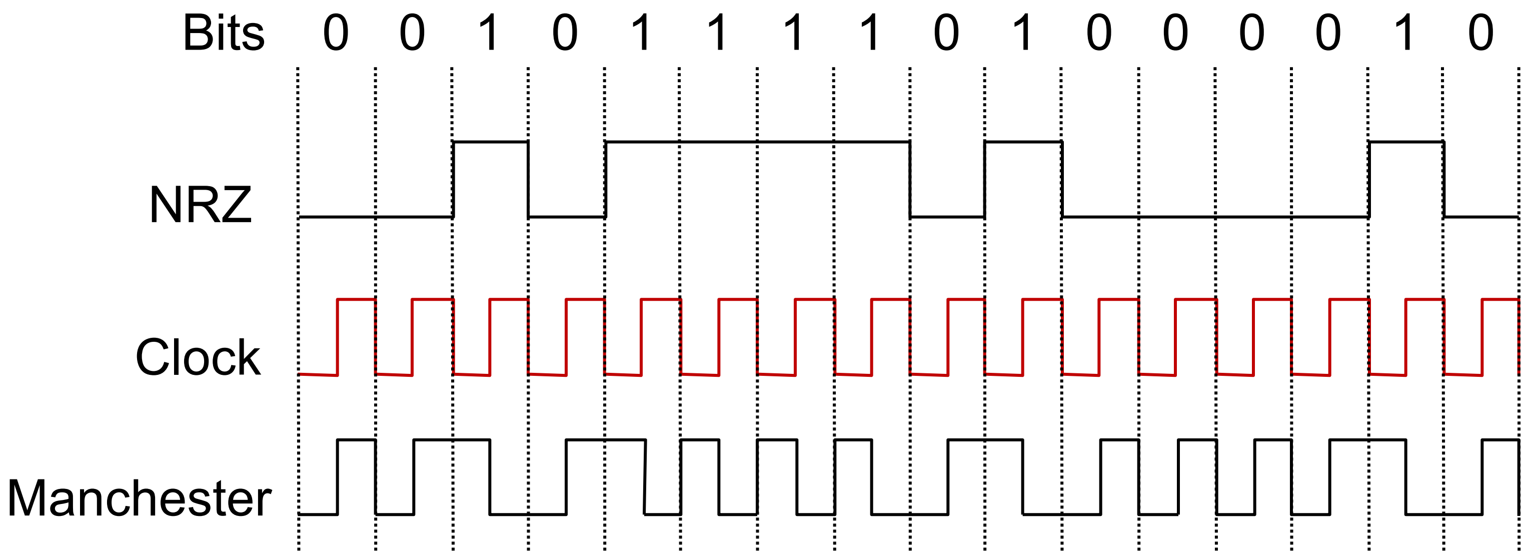
- Receiver needs to know when a symbol begins and ends
- One approach: send a clock signal together with data signal
  - Lowers data rate by 2x!
- Another approach: look for transitions in the data signal to re-synchronize the clock
- Long strings of 0s and 1s make synchronization challenging
- It's like trying to dance in sync without a beat





How many 1s?

Self-clocking encoding

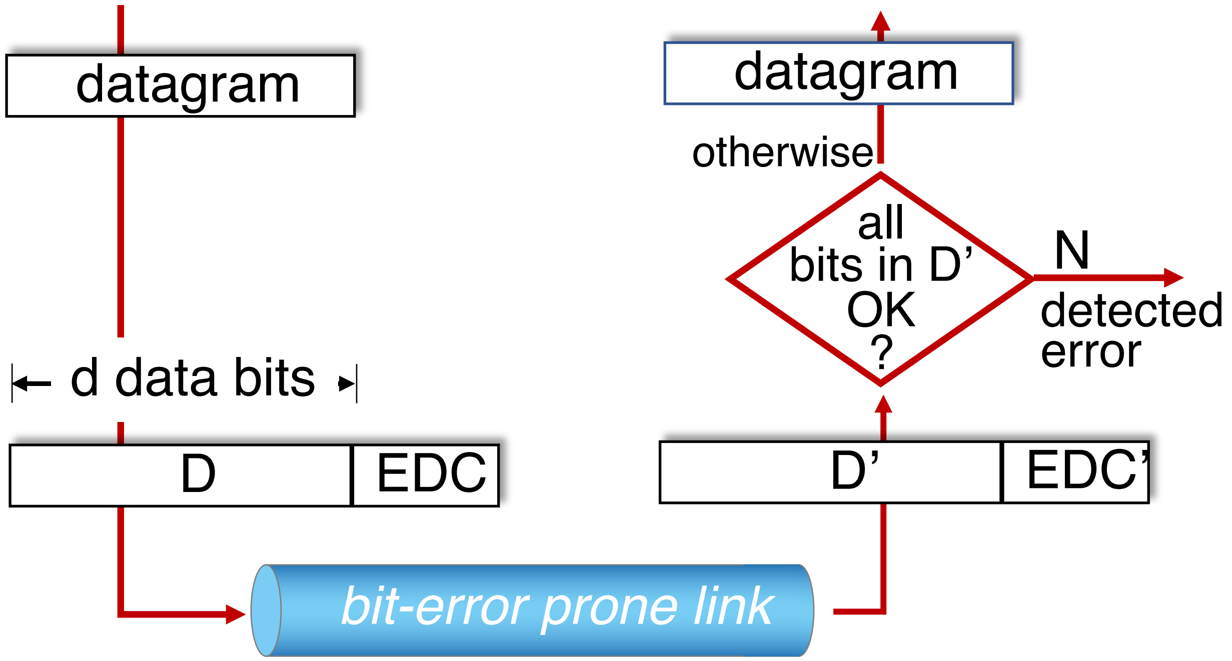


- Manchester encoding
- 0 encoded by a positive transition, 1 by a negative transition
- Construct using XOR(bit,clock)
- Used in early Ethernet standards (up to 10 Mbit/s)

Error Detection & Correction

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

0111000110101011	1

$\longleftarrow$ d data bits $\longrightarrow$ parity bit

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

two-dimensional bit parity:

- detect and correct single bit errors

row parity

column parity

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

no errors:

$$\begin{array}{ccccc|c}
1 & 0 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 & 1 & 0
\end{array}$$

detected and correctable single-bit error:

$$\begin{array}{ccccc|cl}
1 & 0 & 1 & 0 & 1 & 1 & \\
1 & 0 & 1 & 1 & 0 & 0 & \text{parity error} \\
0 & 1 & 1 & 1 & 0 & 1 & \\
\hline
1 & 0 & 1 & 0 & 1 & 0 & \\
 & \text{parity error} & & & & &
\end{array}$$

Review: Transport (UDP/TCP) checksum

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

sender:

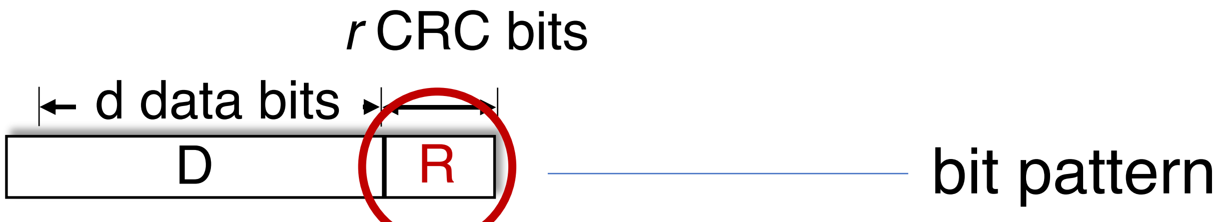
- treat contents of transport segment as sequence of 16-bit integers
- checksum: addition (roughly) of segment content
- checksum value put into UDP checksum field

receiver:

- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - Yes: *assume* no error
  - No: declare error

Cyclic Redundancy Check (CRC)

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



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

Goal: choose *r* CRC bits, R, such that <D,R> exactly divisible by G

Do all arithmetic mod 2: all additions, subtractions replaced by XOR

- receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!
- can detect all burst errors (continuous bit errors) less than r+1 bits
- widely used in practice (Ethernet, 802.11 WiFi)

Cyclic Redundancy Check (CRC): example

We want:

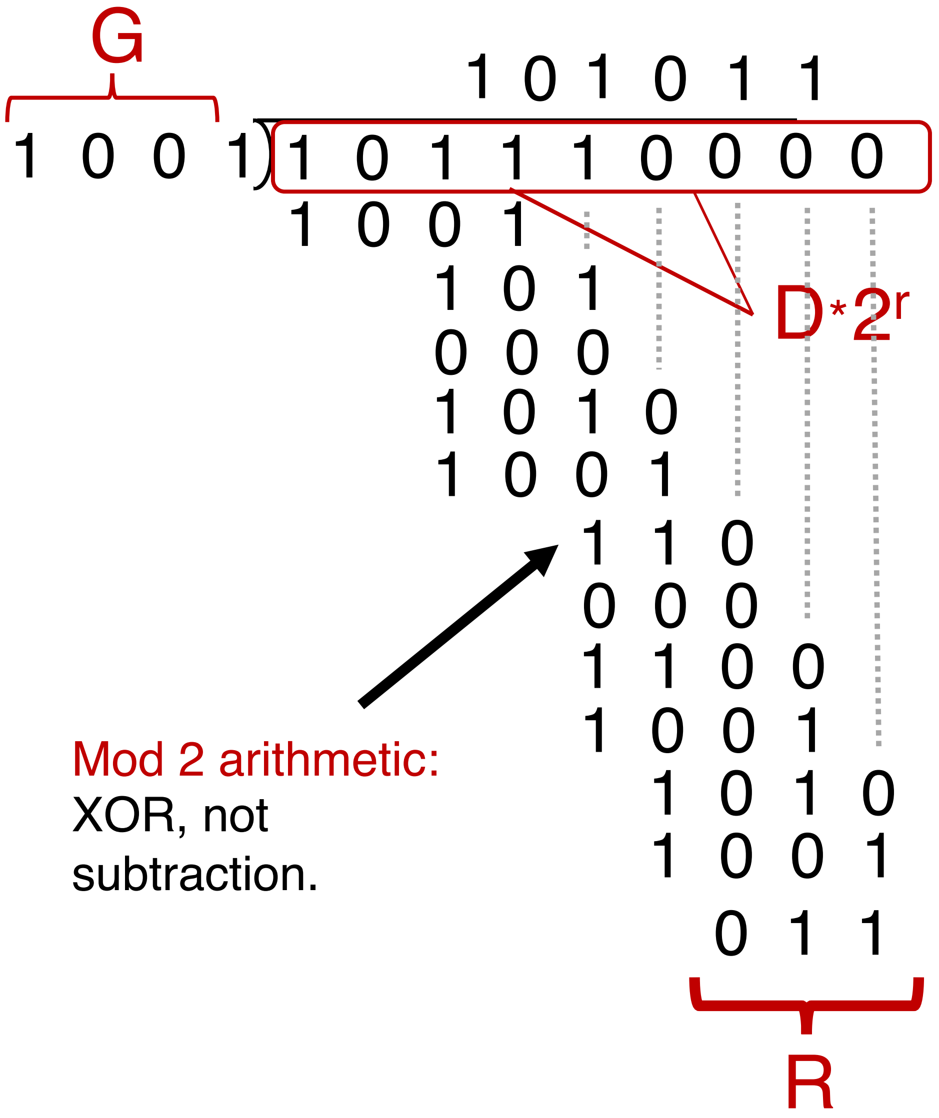
$$D \cdot 2^r \ \ XOR \ \ R = nG$$

or equivalently:

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

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

Perform long division to compute the remainder. E.g., D = 101110, G = 1001



How CRC is computed in software:
https://www.kernel.org/doc/html/latest/staging/crc32.html

Summary

- Self-clocking encoding useful to synchronize sender & receiver
- Error detection and correction mechanisms:
  - Parity bits: single or a few bits of error
  - CRCs: bursty errors up to a certain size
- Error detection and correction codes widely used across many computer systems

CS 352
Connecting Multiple Endpoints into a Single Network

CS 352, Lecture 22.3

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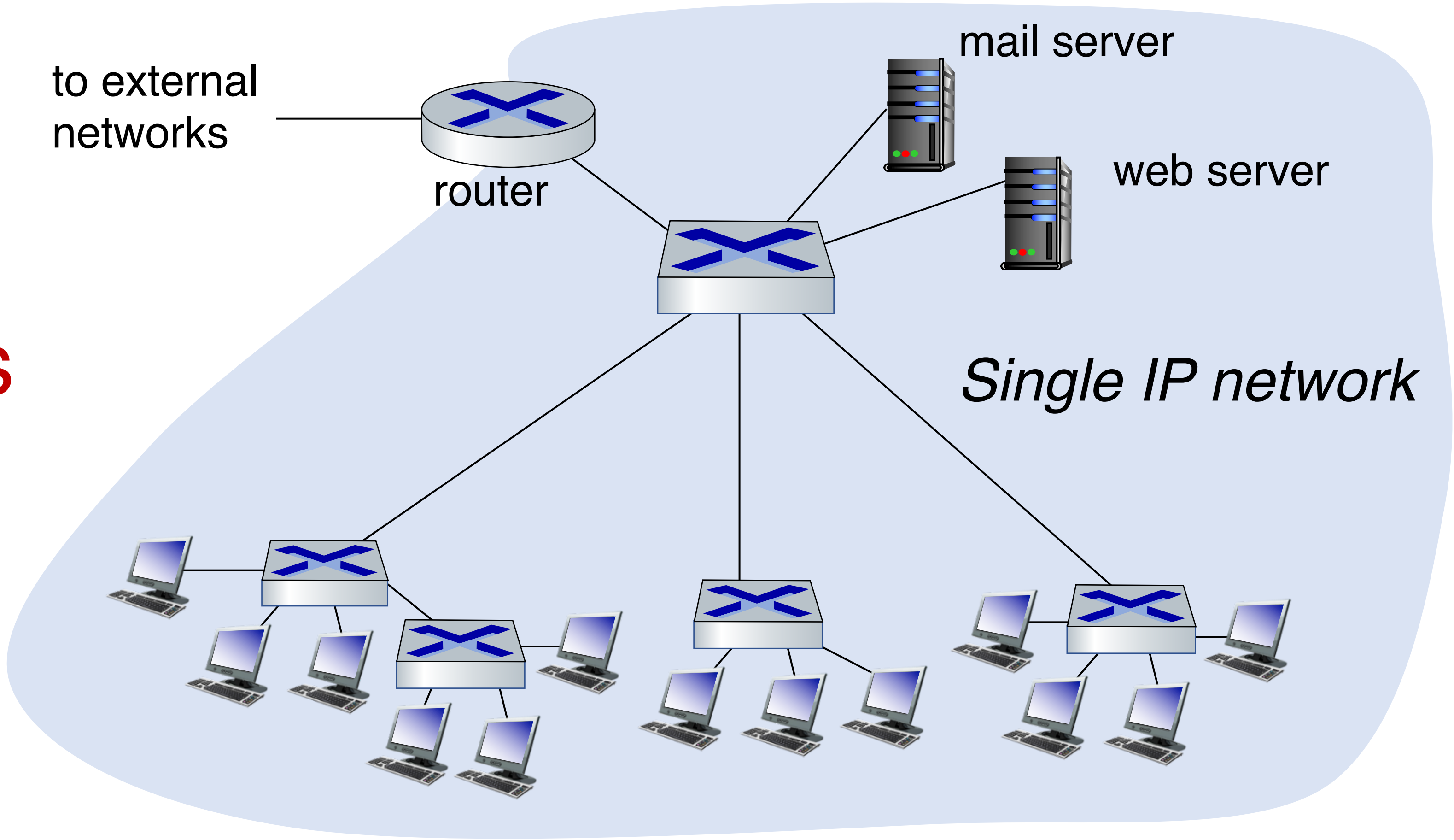
A small organizational network today



Switches

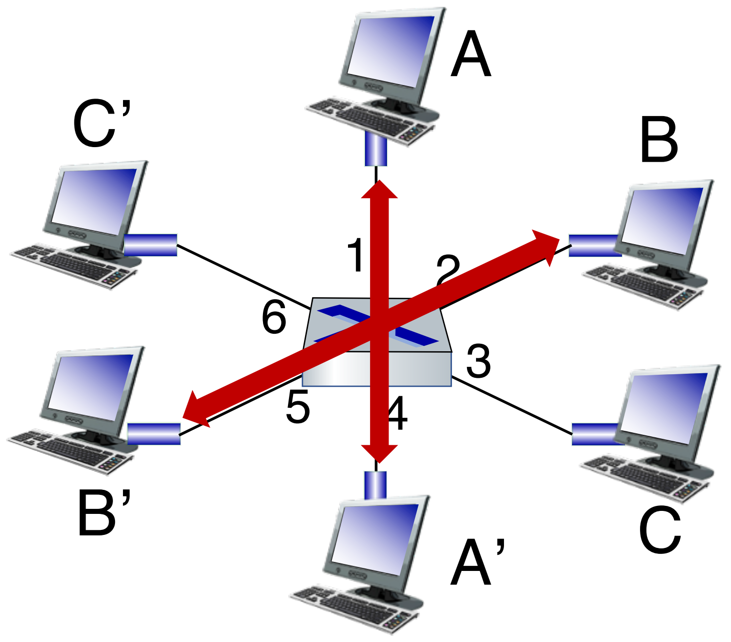
Located in switching closets, connect directly to endpoints.

Switching

- A switch is a link-layer device
  - Examine incoming frame's destination MAC address
  - Selectively forward frame to one-or-more outgoing links when frame is to be forwarded
  - Can store link layer frames in switch buffers
- Transparent: hosts unaware of presence of switches
- Plug-and-play, self-learning
  - Switches do not need to be configured

Switch: multiple simultaneous transmissions

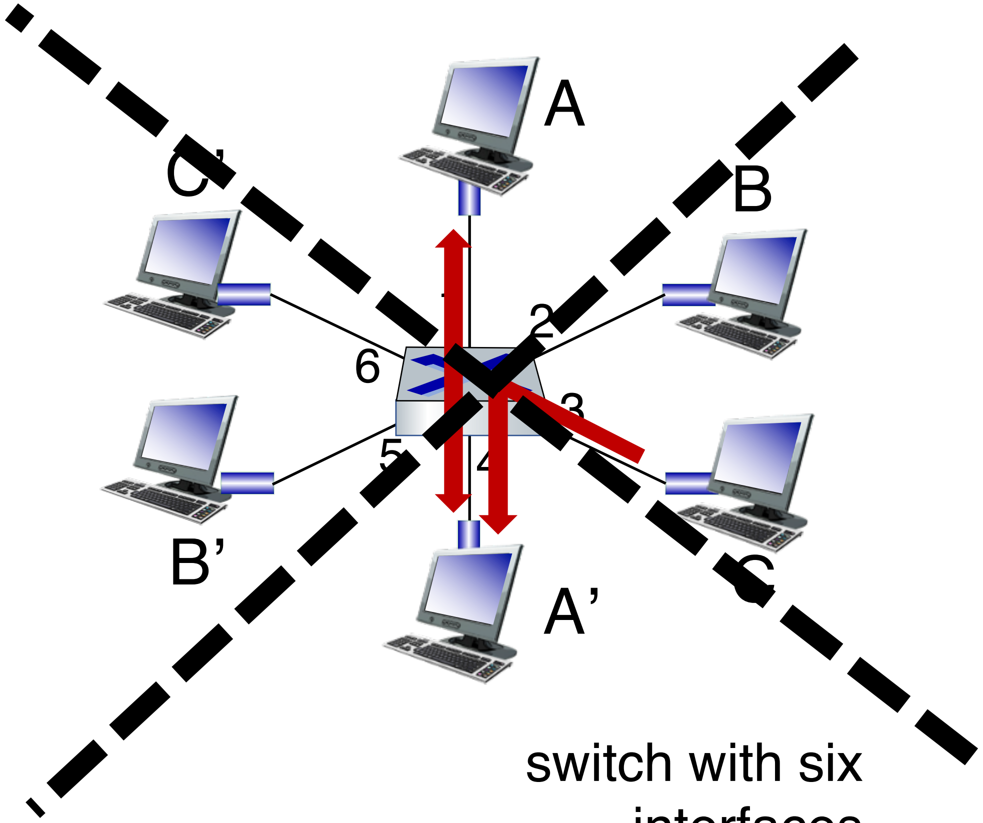
- hosts have dedicated, direct connection to switch
- switches buffer packets
- Same link layer protocol used on each incoming link
  - full duplex links
  - No medium access control needed (more next lecture)
- switching: A-to-A' and B-to-B' can transmit simultaneously



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

Switch: multiple simultaneous transmissions

- hosts have dedicated, direct connection to switch
- switches buffer packets
- Same link layer protocol used on each incoming link
  - full duplex links
  - No medium access control needed (more next lecture)
- switching: A-to-A' and B-to-B' can transmit simultaneously
- However, A → A' and C → A' can't happen simultaneously



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

Switched LAN

- If switches don’t need to be configured, how can switches route to the correct endpoints?

- Process known as MAC learning or layer-2 bridging
  - a configuration-free, learning-based routing protocol

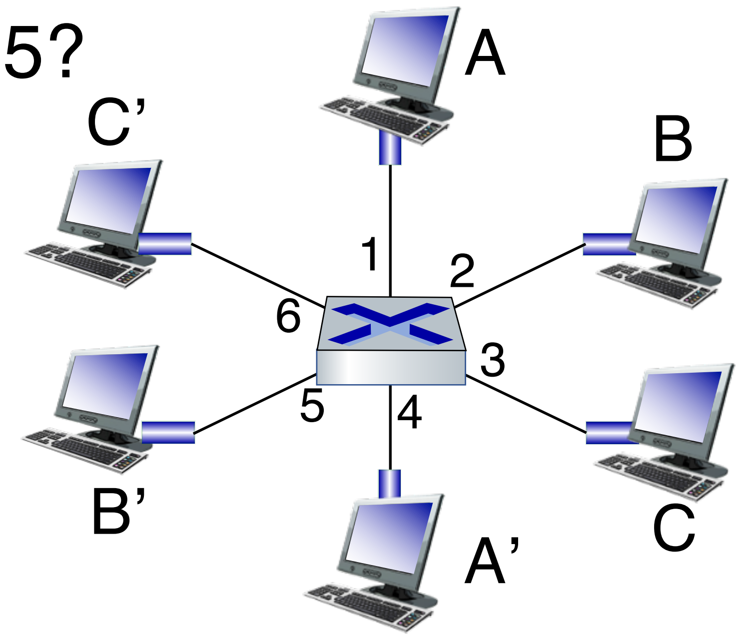
Switch forwarding table

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

Each switch has a MAC table.

Each entry:

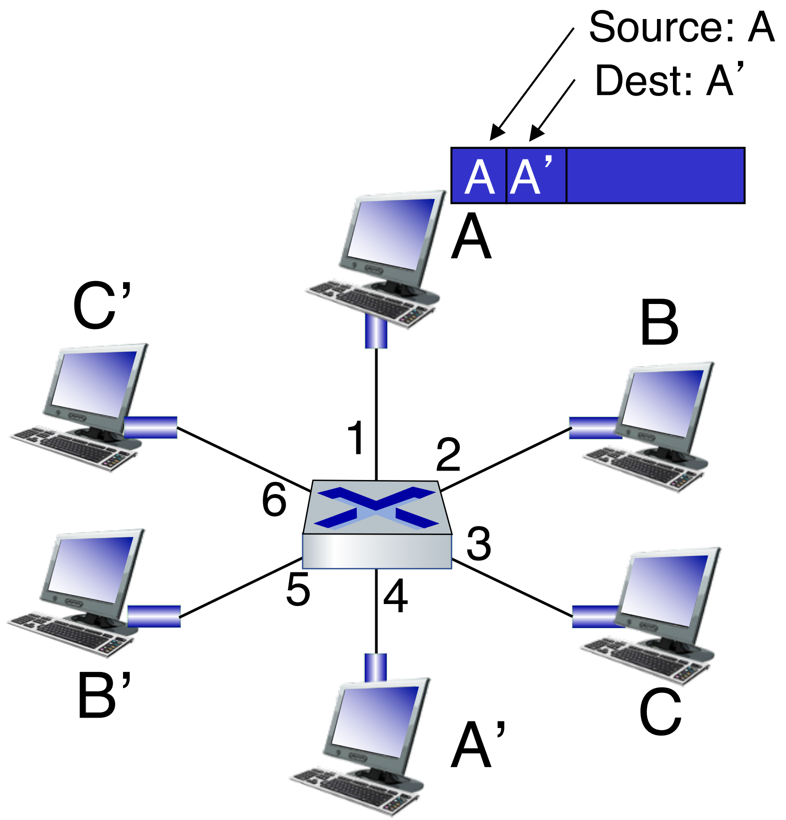
- (MAC address of host, interface to reach host, timestamp)
- looks like a forwarding table!



How are entries created and maintained in the MAC table?

MAC 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)

MAC learning: frame forwarding

when a frame received at switch:

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

MAC	port	TTL
A	*1*	*60*

Flooding is only acceptable because all endpoints are in the same org/IP network.

Forwarding: Example

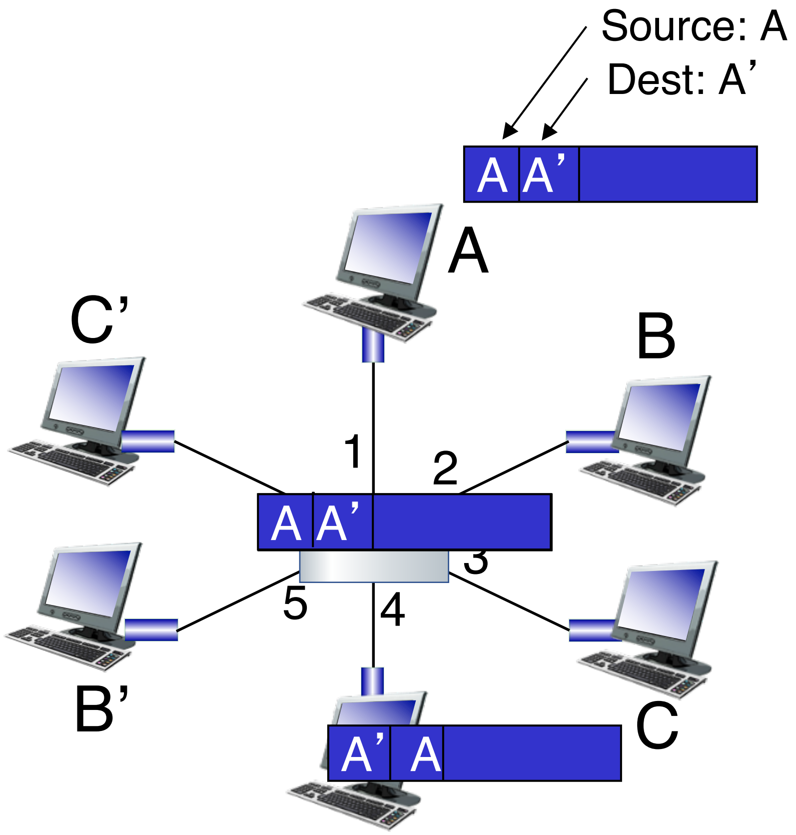
- frame destination A'. Interface unknown (not in table)

  flood

- destination A location known:

  Selectively send on one link

- Subsequent A ←→A' packets not flooded

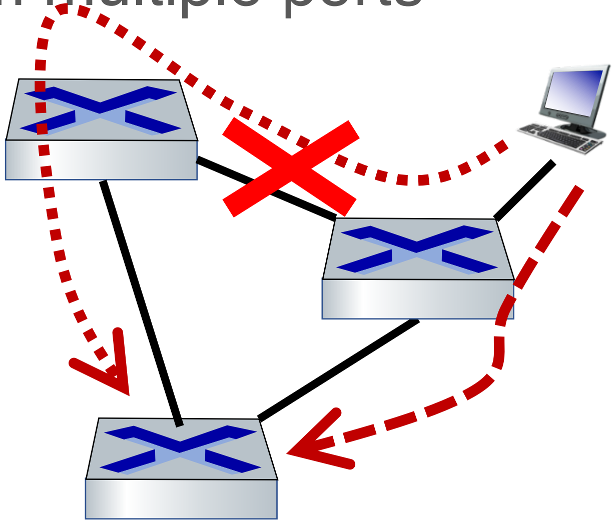


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

switch table (initially empty)

Interconnecting switches

- MAC learning switches can be connected together
  - The algorithm works the same way!
- Complication: what if there are loops in the switch topology?
  - Flooding may result in the same packet arriving from multiple ports
- Ethernet: spanning tree protocol
  - Switches discover the switch-level graph
  - Process akin to link state advertisements flooding
  - Then, switches use a loop-free subset of links
    - A spanning tree of the network graph



Switches vs. routers

Both can store, buffer, and forward.

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

Both have forwarding tables.

- routers: compute forwarding tables using routing algorithms, link configurations, and announced IP addresses
- switches: learn forwarding table using flooding and learning MAC addresses

Summary

- Enterprises often use switches for their ease of configuration and plug-and-play nature
  - Switched Ethernet: popular in dorms and office buildings
- Switches can discover endpoints
- Flooding facilitates reachability across endpoints. Only possible as all endpoints part of the same IP network
- MAC learning records where endpoints send from, enabling the discovery of endpoint-port associations without prior knowledge