Internet Technology

11. Data Link Layer

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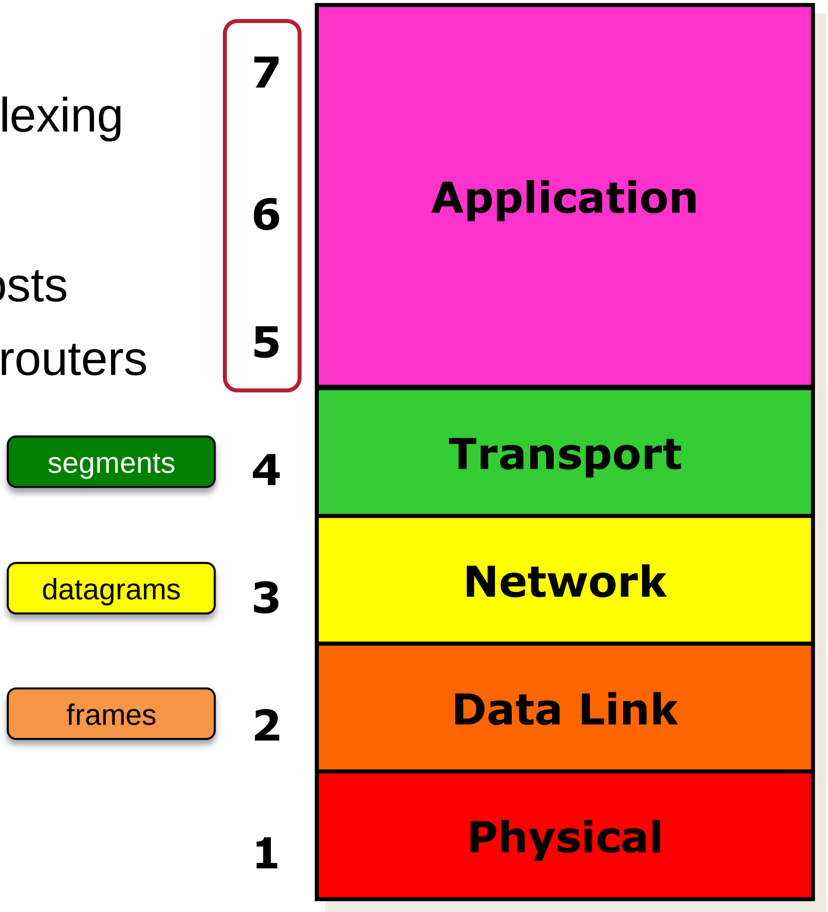
Data Link Layer

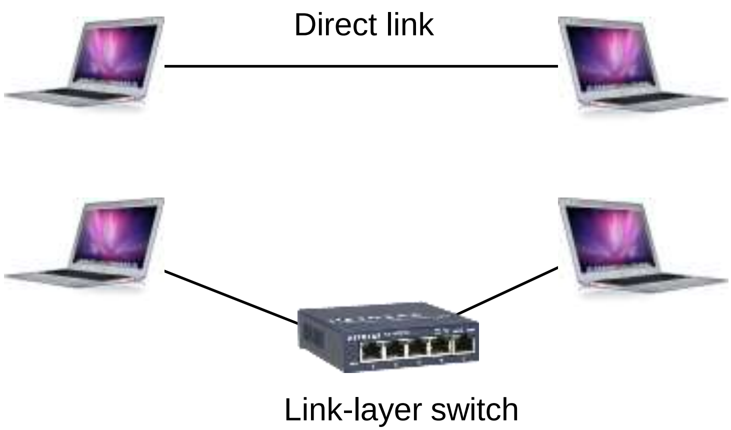
- Transport Layer (4)
  - Logical connection between processes
  - Transport layer multiplexing & demultiplexing
- Network Layer (3)
  - End-to-end communication between hosts
  - Possibly through multiple networks via routers
- Data Link Layer (2)
  - Deals with individual communication links



Internet Protocol Layers

Link Layer

- Data is encapsulated in a link-level frame
- MAC = Medium Access Control
  - Protocol for transmitting and receiving frames at the link layer
- Error detection & correction
  - Detect (and possibly correct) errors in the frame
- MAC Address
  - Link-layer address



Error Detection & Correction

Error Detection & Correction Goals

Why do we want this at the link layer?

- Drop a bad frame at the receiver
  - If the link layer detects it, no overhead checking at the network/transport layers
  - No need to forward the packet (avoid wasting network bandwidth)
  - Avoid end-to-end delay of having the receiver detect & sender retransmission

- Attempt to correct errors
  - Avoid the need to reject bad packets & retransmit

Parity

- Simplest form of error detection: add one bit (parity bit)
  - Even parity
    - Set the parity bit such that there is an even number of 1 bits

      01110000 ⇒ 011100001
  - Odd parity
    - Set the parity bit such that there is an odd number of 1 bits

      01110000 ⇒ 011100000
- An even number of bit errors will be undetected
- In real life, bit errors typically occur in bursts
  - Multiple consecutive bits get corrupted

Two-Dimensional Parity

- Break up *d* bits into *i* rows and *j* columns
- Generate a parity bit per row and per column
  - For a single bit error, we can identify the row & column of the bit

Example: `1011 0001 1100 1110` with even parity:

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

We can transmit: `1011 0001 1100 1110` 1101 1000 1

Two-Dimensional Parity

For a single bit error, we can identify the row & column of the corrupted bit

We sent: 1011 0001 1100 1110 1101 1000 1

They got: 1011 0011 1100 1110 1101 1000 1

Place this back into the grid:

Here's the bad bit

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

Bad parity

Bad parity

By identifying the row & column, we can identify the bad bit

Error Correction

- Two-dimensional parity
  - Simple example of an error correcting code (ECC)
- Error correcting codes
  - Invented by Richard Hamming in 1950
  - Common types of ECCs
    - Reed-Solomon codes (used in CDs, DVDs, disk drives)
    - Hamming codes (ECC memory)
    - Low-density parity-check, LDPC (802.11n, 10G Ethernet)
    - Viterbi codes (cellular LTE)
- Forward Error Correction (FEC)
  - Data transmission that uses ECC in the message
  - The receiver can correct some errors without the need for retransmission

Checksums

- Checksum = treat the bits of a packet as a set of integers
  - Perform operations on those integers
- Internet checksum
  - We saw this in IP, UDP, TCP, ICMP, OSPF, and IGMP headers
    - Treat data as 16-bit chunks
    - Sum it up (add one for each carry)
    - Take a 1s complement of the result
  - Simple, easy to compute efficiently (important!)
  - BUT very weak protection against errors
- Cyclic Redundancy Check (CRC)
  - Much more robust checksum
  - More compute intensive (hence not appealing at higher layers)
  - Done with dedicated hardware at the transceiver

Cyclic Redundancy Check

- Polynomial code
- Works well for detecting burst errors: a sequence of bad bits
- *n*-bit CRC code will usually detect an error burst up to *n* bits
  - Will detect longer bursts with a probability of $1\text{-}2^{-n}$
  - Example: Ethernet uses a 32-bit CRC
    - Detects up to 32 consecutive bad bits
    - Detects longer streams of bad bits 99.99999997671% of the time
    - That is, there's a 2.329×10^{-10} chance that the CRC will not detect bit errors >32 bits

How is a CRC calculated?

- CRC performed by division: all subtractions replaced with XOR

  $a \oplus b = a + b = a - b$ if we ignore carries and borrows

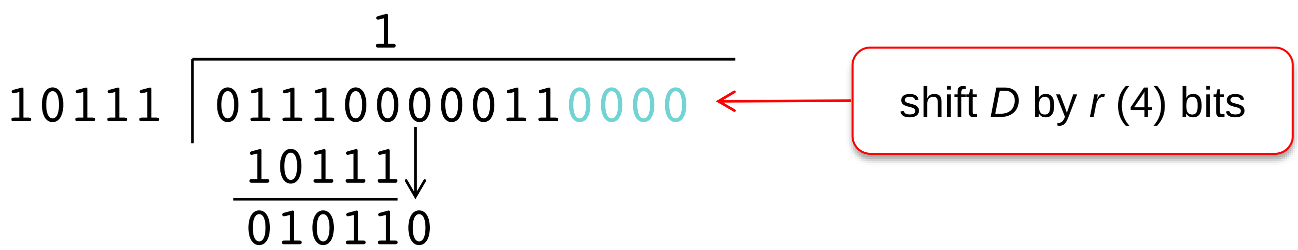
a	b	$a \oplus b$
0	0	0
0	1	1
1	0	1
1	1	0

- To send a message *D* with *d* data bits
  - Compute CRC code *R* with *r* bits
  - Transmit *D*, *R*
- Receiver and transmitter agree upon a Generator, *G*
  - *G* has *r*+1 bits; starts with 1
  - CRC = *R* = remainder of $\frac{D \times 2^r}{G}$

$D \times 2^r$ is *D* left-shifted by *r* bits

CRC calculation example

- We want to send *D* = 01110000011
- Assume the generator bits are 10111 (*r* = 4; *G* has *r* + 1 bits)
- Perform a division (but with xor instead of subtraction with borrowing)



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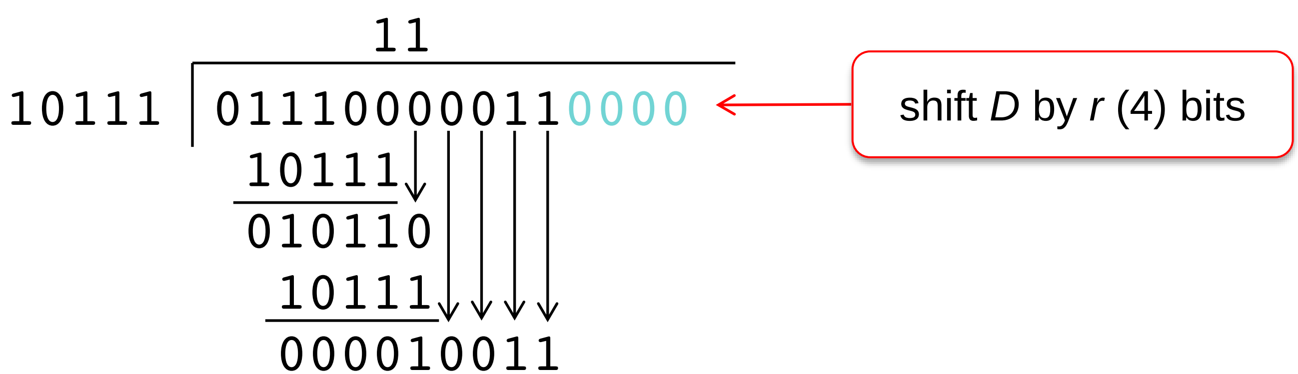

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- Perform a division (but with xor instead of subtraction with borrowing)

```
                1100010101
        ___________________
10111 | 011100000110000
         10111
         ------
         010110
          10111
          ---------
          000010011
              10111
              -------
              0010000
                10111
                -------
                0011100
                  10111
                  -----
                   1011
```

shift *D* by *r* (4) bits

R = 1011

CRC = 1011

Transmit (*D*, *R*) = **011100000111011**

CRC verification example

- We received *D* = 01110000011 1011
- Same Generator, *G* = 10111 (*r* = 4; G has r+1 bits)
- Perform the same division (no shift; we have 4 CRC bits at the right

```
              1100010101
        ----------------
 10111 | 011100000111011
          10111
         ------
          010110
           10111
          ------
           000010011
                10111
               ------
                0010010
                  10111
                -------
                  0010111
                    10111
                  -------
                     0000
```

No need to shift
We have our CRC bits

R = 0
Correct!

If the remainder = 0
then no error detected

CRC Generators

- Ethernet uses a 32-bit CRC generator (CRC-32)
  - `0x04C11DB7`
  - Also used by FDDI, ZIP, and PNG

Multiple Access Protocols

Categories of link layer access protocols

- Types of links
  - Point-to-point links connect one sender with one receiver
    - No conflict for access
  - Broadcast links have multiple nodes connected to the same channel
- Broadcast links have a multiple access problem
  - How do you coordinate multiple senders?
  - Collision: when two nodes transmit at the same time
    - Signals from both get damaged
- Three categories of multiple access protocols
  1. Channel partitioning
  2. Random access
  3. Taking turns

Channel Partitioning Protocols

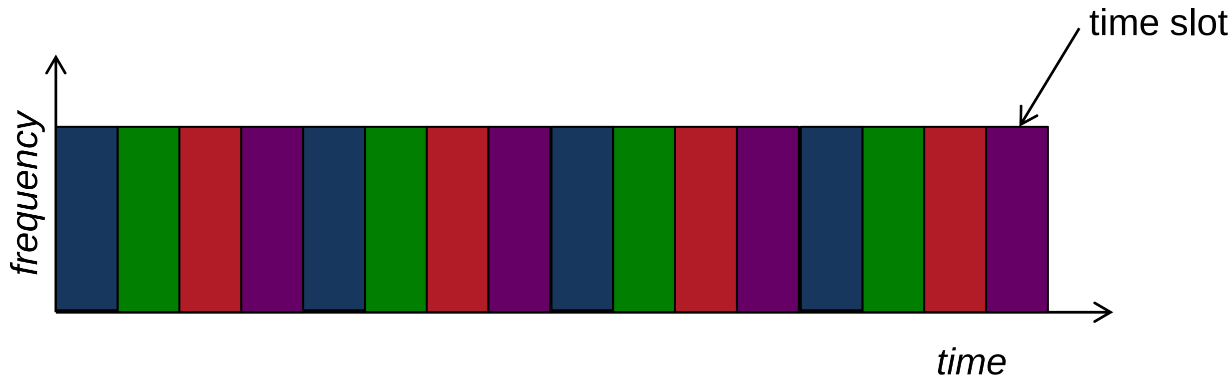
1. Time division multiplexing (TDM)
   - Divide a channel into time slots
   - A node can transmit only during its allocated time slot

2. Frequency division multiplexing (FDM)
   - Divide a channel into frequency bands

- If a channel has a bandwidth *R* and there are *N* nodes
  - Both TDM and FDM are fair: each node gets bandwidth = *R/N*
  - BUT a node gets *R/N* even if no other node needs to transmit!

TDM vs. FDM

FDM: Frequency Division Multiplexing



TDM: Time Division Multiplexing

Random Access Protocols

- Node has full use of the channel
- No scheduled time slots as in TDM
- If there is a collision
  - Colliding nodes wait a random time & retransmit
  - The nodes will (usually) pick different intervals & not collide next time

Slotted ALOHA

- One of the oldest random access protocols
- Not used anymore but useful to study
- Environment
  - All frames *L* bits
  - Time divided into 1-frame slots of *L*/*R* seconds (*R*=bandwidth)
  - Nodes are synchronized and transmit at the start of a slot
- If there's a collision
  - All transmitting nodes detect it during transmission
  - Retransmit on the next slot with probability *p*
  - Otherwise skip the slot and try again: retransmit with probability *p*

Slotted ALOHA

- Efficiency
  - Time slots with collisions: wasted
  - Time slots with no transmissions: also wasted
- P(success for 1 node) = P(one node transmits) × P(N-1 do not)

$$= \underbrace{p}_{\text{P(one node transmits)}} \times \underbrace{(1-p)^{N-1}}_{\text{P}(N-1\text{ do not})}$$

$$= p(1-p)^{N-1}$$

- P(success for all nodes) = $Np(1-p)^{N-1}$
- Maximum efficiency
  - Find p that maximizes the expression
  - Take limit of $N \to \infty$
  - This is $1/e \approx 0.37$
    - 37% slots have useful data; 37% are empty; 26% have collisions
  - A 1 Gbps link will behave like a 370 Mbps link!

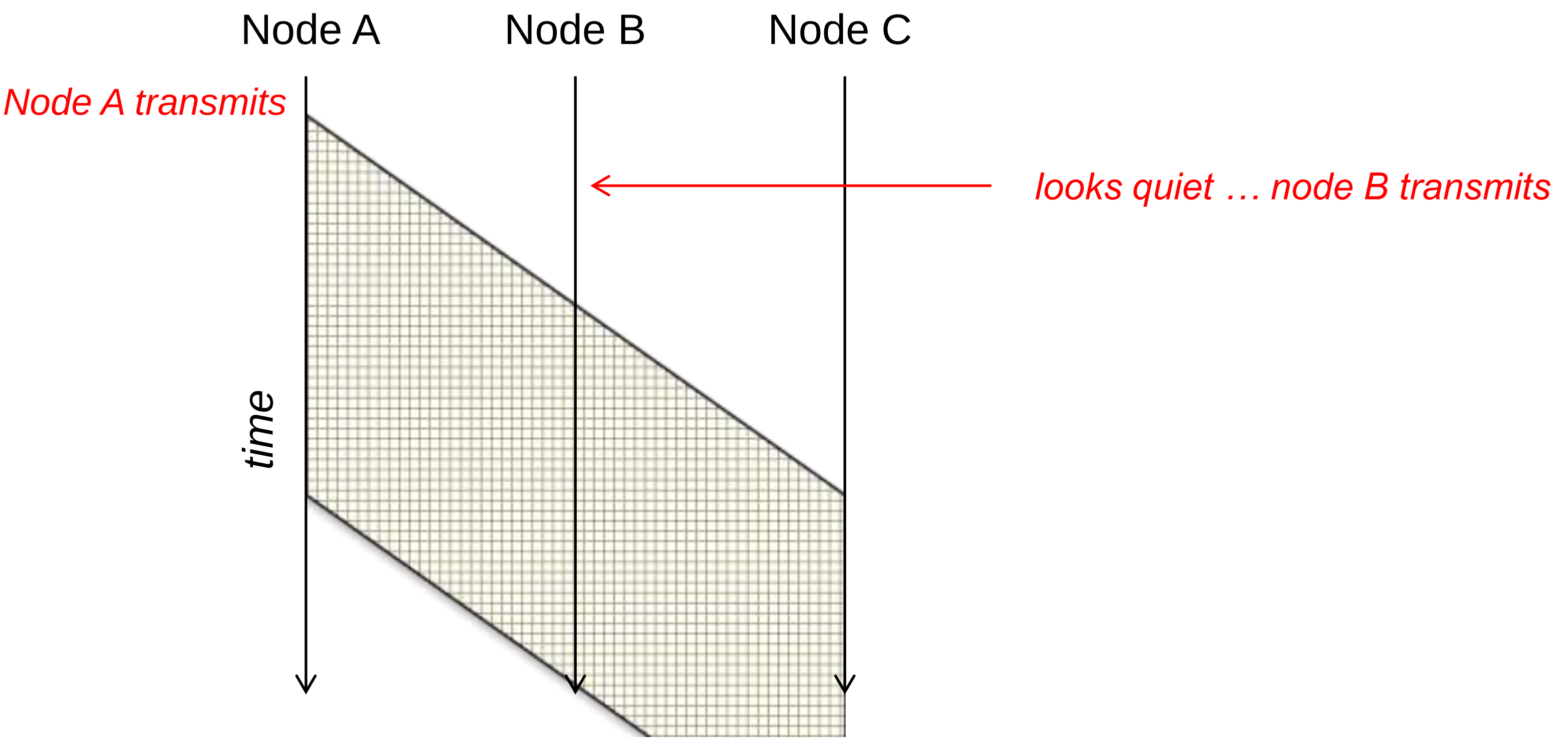
CSMA/CD

Carrier Sense Multiple Access with Collision Detection

- Carrier Sensing
  - Listen first
  - If the channel has communications, wait until it is clear
- Collision Detection
  - If you are transmitting but detect a collision, stop transmitting
  - Wait a random time interval and try again (sense & transmit)

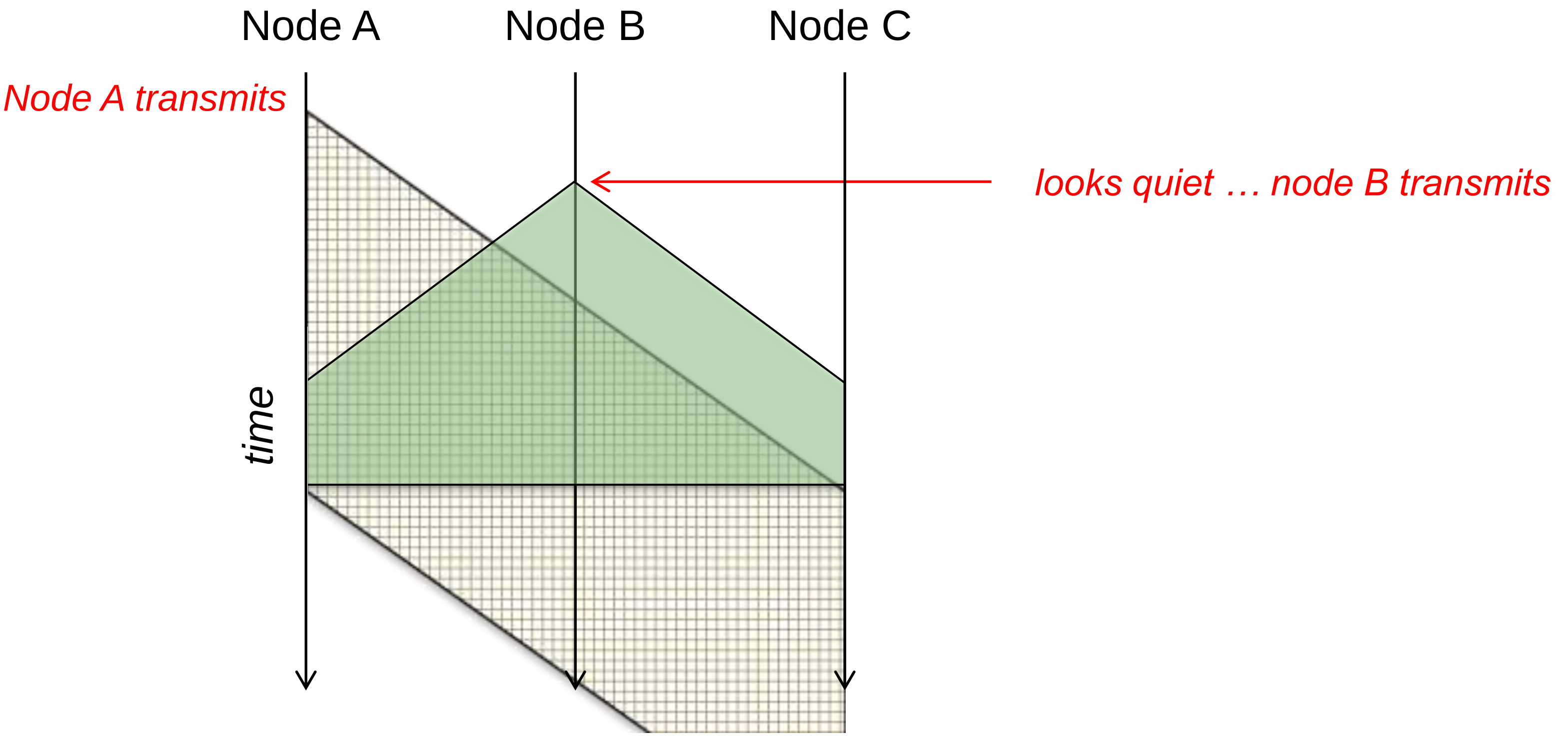
How do collisions occur?

- Node A senses quiet & transmits
- Remember propagation delay?
  - It takes time for the signal to reach other nodes
  - ~2×10^8 m/s = 5 nanoseconds per meter



How do collisions occur?

- Node A senses quiet & transmits
- A short while later…
  – Node B senses quiet because the signal from A didn't reach it
  – Node B transmits



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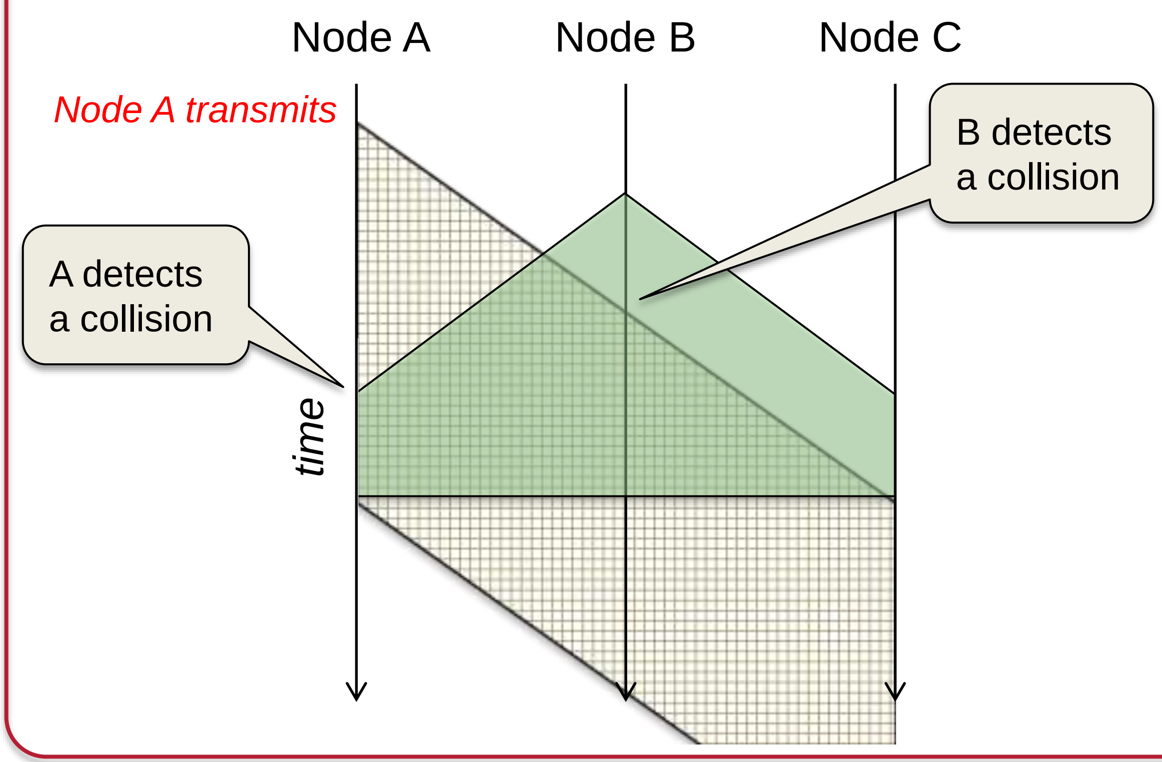


Collision Detection

- A node listens while it is transmitting
- As soon as it detects a collision
  - Stop transmitting
  - Wait a random interval

  - We'd like a possibly long interval if there are many nodes sending
  - We'd like a short interval if there are few transmitters
  - BUT … we don't know what's going on!

Binary Exponential Backoff

- If a frame experienced *b* collisions (*b* = backoff count)
- Choose a delay *W* with equal probability from 0 … 2^b-1
  - 1st time {0, 1} | 2nd time {0 … 3}
  - 3rd time {0 … 7} | 4th time {0 … 15}
  - 5th time {0 … 31} | 6th time {0 … 63}
- Ethernet: a delay is *W* × 512 bit-times
  - 512 bit-times = time to send 512 bits = 5.12 μs for 100 Mbps
  - Backoff count limit (maximum *b*) = 10
  - 10 or more collisions: choose a delay {0 … 1023}
- Status
  - CSMA/CD is not needed with switched Ethernet
  - Binary Exponential Backoff also used in DOCSIS cable modems

Multiple Access via Taking Turns

- Goal: ensure that each node can get a fair throughput
  - Close to *R*/*N* bps for bandwidth *R* and *N* nodes
- Polling protocol (used by Bluetooth)
  - Master polls each of the nodes to see if they want to transmit
  - No collisions or empty slots
  - But: polling delay & chance of master dying
- Token passing protocol
  - Special frame, a token, is passed around nodes in some sequence
  - If a node has it, it can transmit & then forward the token
  - Decentralized & efficient
  - But: failure of a node can stop the network

Ethernet

Ethernet technology

- Mid-1970s: created at Xerox by Bob Metcalfe
  - 2.74 Mbps Ethernet over 9.5mm thick coax
- 1980s
  - Standardized in 1985 as IEEE 802.3
  - & 10BASE-5 (9.5mm coax) & 10BASE-2 (5mm coax)
- 1990:
  - 10BASE-T over twisted pair wiring @ 10 Mbps
  - Category 3 UTP (unshielded twisted pair) wiring with RJ45 connectors
- 1995: Fast Ethernet: 100BASE-TX over cat 5 UTP
- 1999: Gigabit Ethernet: 1000BASE-T over cat 5e
- 2006: 10 Gb Ethernet: 10GBASE-T over cat 6a
- 2010: 100GbE / 40GbE 40GBASE-T over cat 8

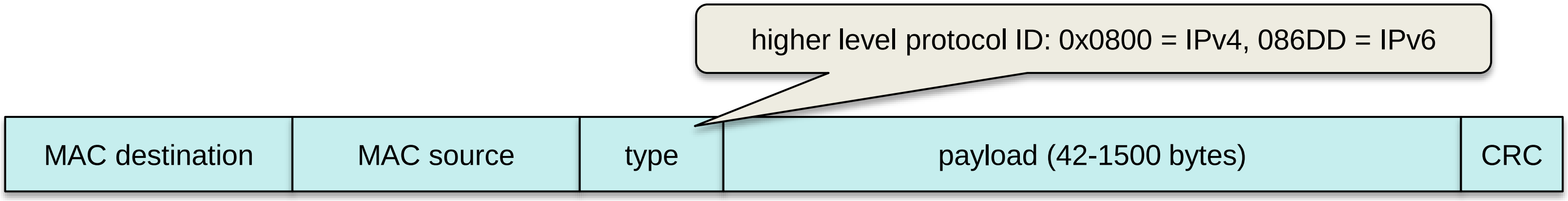
100BASE-TX, 10BASE-T, etc.
- Deal with data encoding

Category 3, 5, 6, 7
- Deal with cable specifications

Connectors
- 8P8C (RJ45)

Ethernet Frame

- 8 bytes: preamble & start-of-frame delimiter
- Variable size data: 42-1500 bytes
  - No length field: the transceiver grabs the entire frame
- Interframe gap: at least 96 bit wait time



- Jumbo frames: maximum size 8000 bytes
- Super Jumbo frames (SJF): maximum size > 8000 bytes

MAC = Media Access Control = link-layer address

See https://en.wikipedia.org/wiki/EtherType for protocol IDs

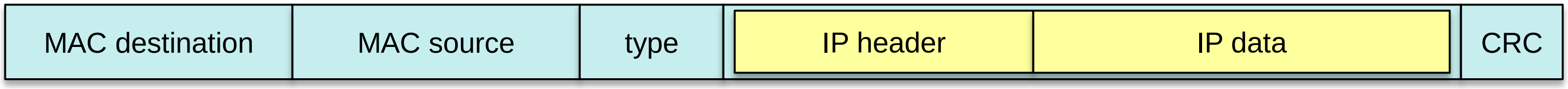
Link Layer Addressing

Link-Layer Addressing

- Each NIC has a unique link-layer address
  - MAC address – *unrelated to IP address*
- LAN communication at layer 2 needs MAC addresses
  - An Ethernet transceiver cannot send a frame to an IP address!
- E.g., Ethernet uses a EUI-48 address
  - EUI = *Extended Unique Identifier*; managed by IEEE
  - Used in Ethernet, 802.11, Bluetooth, and a few other networks
  - 48-bit address (6 bytes long)
  - E.g., `c8:2a:14:3f:92:d1` (my iMac)
  - Globally unique address
    - First three bytes: identify manufacturer
    - Next three bytes: assigned by manufacturer
    - Flat address space

Find MAC address given an IP address

- We need to send a datagram to an IP address
- It is encapsulated in an Ethernet frame and a MAC address



- How do we know what MAC address to use?

Address Resolution Protocol (ARP)

- ARP table
  - Kernel table mapping IP addresses & corresponding MAC addresses
  - OS uses this to fill in the MAC header given an IP destination address
  - What if the IP address we want is not in the cache?
- ARP Messages
  - A host creates an ARP query packet & broadcasts it on the LAN
    - Ethernet broadcast MAC address: `ff:ff:ff:ff:ff:ff`
  - All adapters receive it
    - If an adapter's IP address matches the address in the query, it responds
    - Response is sent to the MAC address of the sender

HW Protocol (ethernet)	Protocol type (e.g., IPv4)	MAC addr length	query/ response	sender MAC addr	sender IP addr	target MAC addr	target IP addr

ARP packet structure

see the **arp** command on Linux/BSD/Windows/OS X

My ARP cache

```
# arp -a
crapper.pk.org (192.168.60.129) at f0:f7:55:bb:17:26 [ether] on eth0
air.pk.org (192.168.60.143) at 28:37:37:19:65:96 [ether] on eth0
? (192.168.60.182) at d0:23:db:77:ff:5a [ether] on eth0
? (192.168.60.174) at a4:67:06:65:21:f8 [ether] on eth0
? (192.168.60.169) at 68:96:7b:09:bc:2a [ether] on eth0
nas.pk.org (192.168.60.136) at 00:0d:a2:01:84:79 [ether] on eth0
? (192.168.60.179) at f8:1e:df:d7:4a:1b [ether] on eth0
? (192.168.60.176) at 18:b4:30:0a:c7:d7 [ether] on eth0
? (192.168.60.181) at e8:06:88:90:2d:1e [ether] on eth0
? (192.168.60.186) at e4:8b:7f:ac:5b:10 [ether] on eth0
pk-imac.pk.org(192.168.60.153) at c8:2a:14:3f:92:d1 [ether] on eth0
tc.pk.org (192.168.60.138) at 00:1e:52:f5:b5:e3 [ether] on eth0
net.pk.org (192.168.60.131) at d0:67:e5:01:ec:5b [ether] on
eth0box.pk.org (192.168.60.132) at 00:1f:16:f7:92:67 [ether] on eth0
tc.pk.org (192.168.60.137) at 00:1e:52:f5:b5:e3 [ether] on eth0
```

- Timeout on Linux systems: `/proc/sys/net/ipv4/neigh/eth0/gc_stale_time`
  - Default = 60 seconds
- Windows (Vista & Later)
  - Timeout = random value between 15 and 45 seconds
  - But remains cached longer if used during that time

IPv6: Neighbor Discovery

- IPv6 does not support ARP
  - Neighbor Discovery accomplishes the same thing as ARP
    - Extends ICMP (ICMPv6) with new commands
    - Neighbor Advertisement (NA) and Neighbor Solicitation (NS) commands
- Host A wants to contact Host B
  - ICMPv6 Type 135 (Neighbor Solicitation) message
    - Host A's source address
    - **Solicited-Node Multicast destination address**
      - IPv6 prefix of `ff02:0:0:0:0:1:ff00`
      - IPv6 address suffix of the last 24 bits of Host B's IP address
    - Data: Host A's MAC address
  - Link Layer address: multicast mapping of IPv6 multicast address
- Host B responds
  - ICMPv6 Type 136 (Neighbor Advertisement) message
  - Datagram addressed to Node A

Every IPv6 host must listen on its *solicited-node* multicast address

Transmitting a datagram

Three possibilities

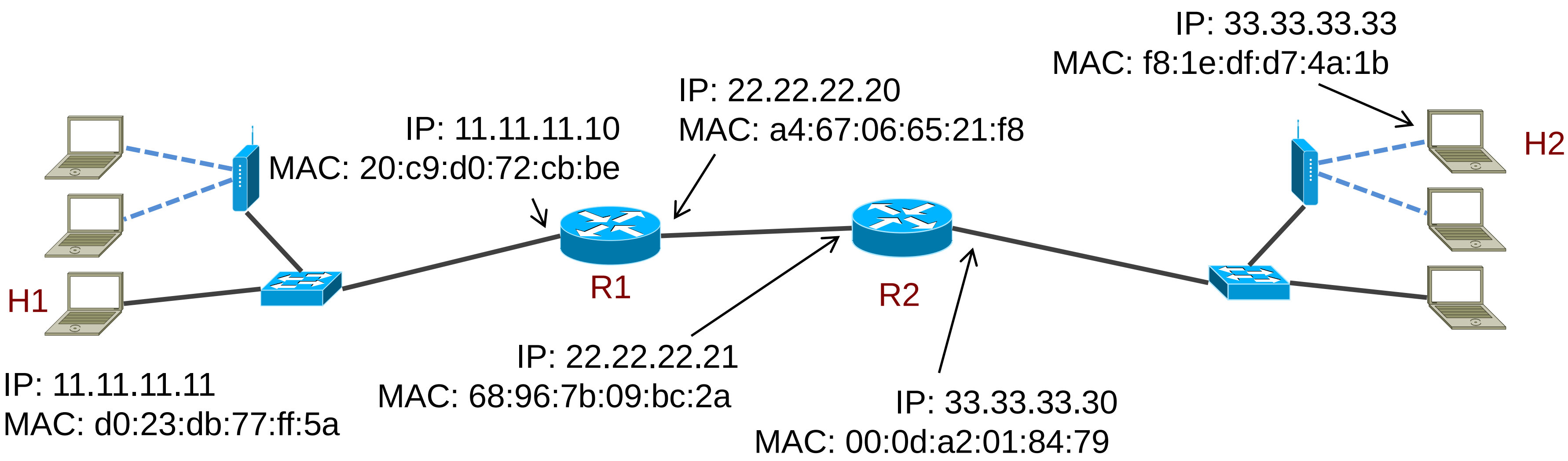
1. We need to send to a host on our subnet (LAN)
   - We can do this at the link layer
   - We just need to find the MAC address that corresponds to the destination's IP address
2. We need to send to a host outside of our subnet
   - We need to get the datagram to a connected router
   - The datagram may pass through multiple routers
3. We need to send a multicast datagram
   - Convert it to link-layer multicast

What if we need to send outside our LAN?

We need to get the datagram to a router

– Each router has an IP address (and a MAC address) for each interface

– Find the MAC address for the IP address of the router interface

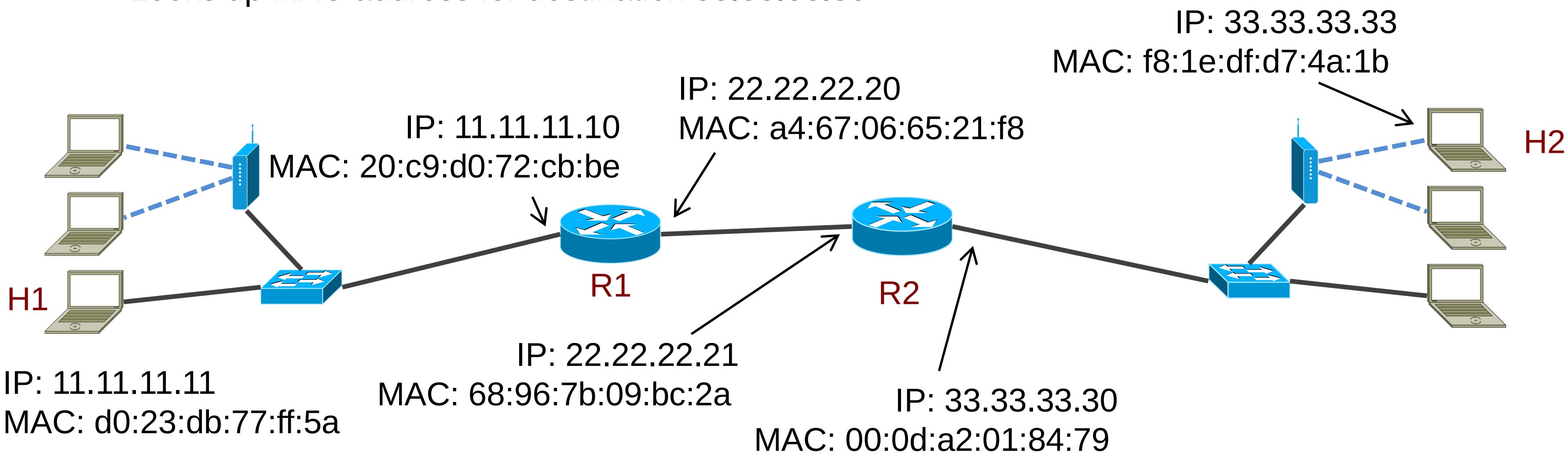


What if we to send outside our LAN?

<u>IP datagram, source=11.11.11.11 destination=33.33.33.33</u>

1. H1 looks up the route to H2: needs to send to router R1
   – Looks up MAC address for 11.11.11.10; sends frame to 68:96:7b:09:bc:2a
2. Router R1 needs to route to R2
   – Forwards to interface with IP addr 22.22.22.20
   – Looks up MAC address for 22.22.22.21; sends IP datagram to 68:96:7b:09:bc:2a
3. Router R2 forwards to interface with IP addr 33.33.33.30
   – Looks up MAC address for destination 33.33.33.33

Routers also use ARP



Link-Layer (Ethernet) multicasting

- Ethernet supports multicast in one (or both) of two ways:
  - Packets filtered based on *hash(multicast_address)*
    - Some unwanted packets may pass through
    - Simplified circuitry
  - Exact match on small number of addresses
    - If host needs more, put LAN card in multicast promiscuous mode
      - Receive all hardware multicast packets

- In either case:
  - Link-layer driver must check to see if the packet is really targeted to the system

Example: hardware support for multicast

Intel 82546EB

- Dual Port Gigabit Ethernet Controller
- 10/100/1000 BaseT Ethernet

Supports:

- 16 exact MAC address matches
- 4096-bit hash filter for multicast frames
- promiscuous unicast & promiscuous multicast transfer modes

Broadcom BCM57762

- 10/100/1000BASE-T Ethernet PCIe Controller
- Used in Apple's Thunderbolt-Ethernet adapter

Supports:

- 1 exact MAC address match (may be reprogrammed up to 4 times)
- Hash filter for multicast frames
  - 128-bit 7-bit CRC hash
  - or 256-bit 8-bit CRC hash
- promiscuous mode (accept all frames)

IP multicast on a LAN

- IP driver must translate 28-bit IP multicast group to a multicast Ethernet address
  - IANA allocated range of Ethernet MAC addresses for multicast
  - Copy least significant 23 bits of IP address to MAC address
    - 01:00:5e:xx:xx:xx ← Bottom 23 bits of IP address

```
               IP addr: 1110dddd dddddddd dddddddd dddddddd
MAC addr: 00000001 00000000 01011110 dddddddd dddddddd dddddddd
```

- Send out multicast Ethernet packet
  - Payload contains multicast IP packet

- Notice something?
  - The IP layer needs to filter out addresses that it is not subscribed to

IPv6 multicast on a LAN

- IPv6 multicast addresses have a 112-bit group ID and start with ff00
- IP driver must translate 128-bit IP multicast address to a multicast Ethernet address
  - Copy least significant 32 bits of IPv6 address to MAC address
    - 33:33:xx:xx:xx:xx

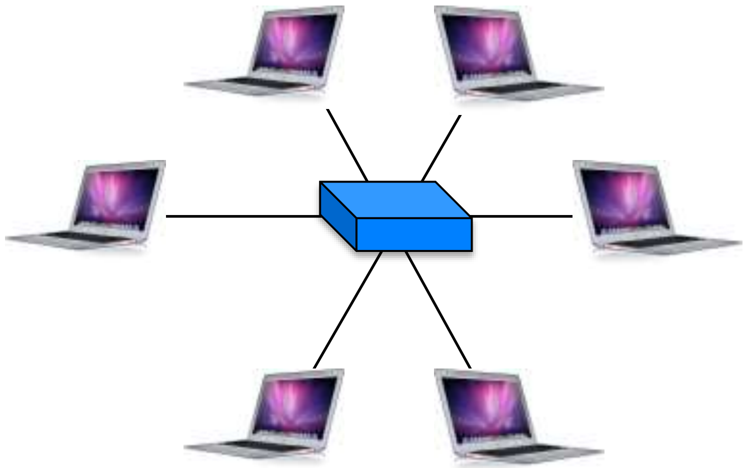
```
IP addr: <ignore top 96 bits> dddddddd dddddddd dddddddd dddddddd
                              ↓↓↓↓↓↓↓↓ ↓↓↓↓↓↓↓↓ ↓↓↓↓↓↓↓↓ ↓↓↓↓↓↓↓↓
MAC addr: 00110011 001100011 dddddddd dddddddd dddddddd dddddddd
```

See http://tools.ietf.org/html/rfc2464

Switched LANs

Ethernet Evolution

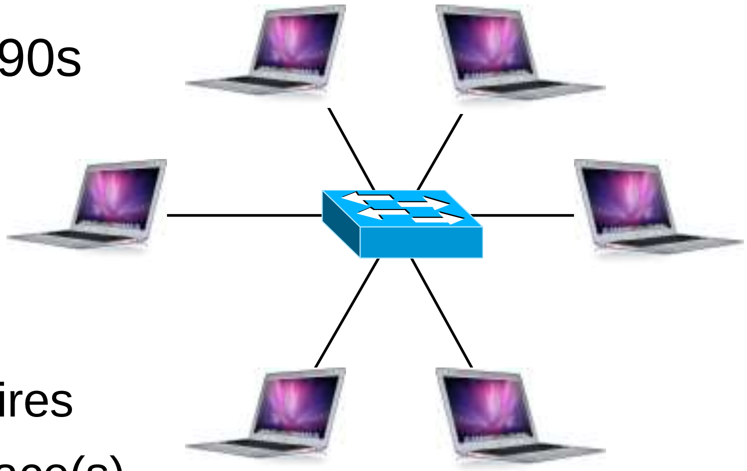
- Ethernet started as a broadcast LAN with a shared bus topology
  - All packets were visible by all adapters
  - This is why we needed CSMA/CD



- Coax gave way to twisted pair
  - Category 5 (Cat 5) cable
  - Star topology
  - Dedicated cable for each adapter
  - Cables plugged into a hub

- Ethernet hub
  - Simulates a bus-based LAN
  - Every bit received on an interface is transmitted onto every other interface

Switched Ethernet



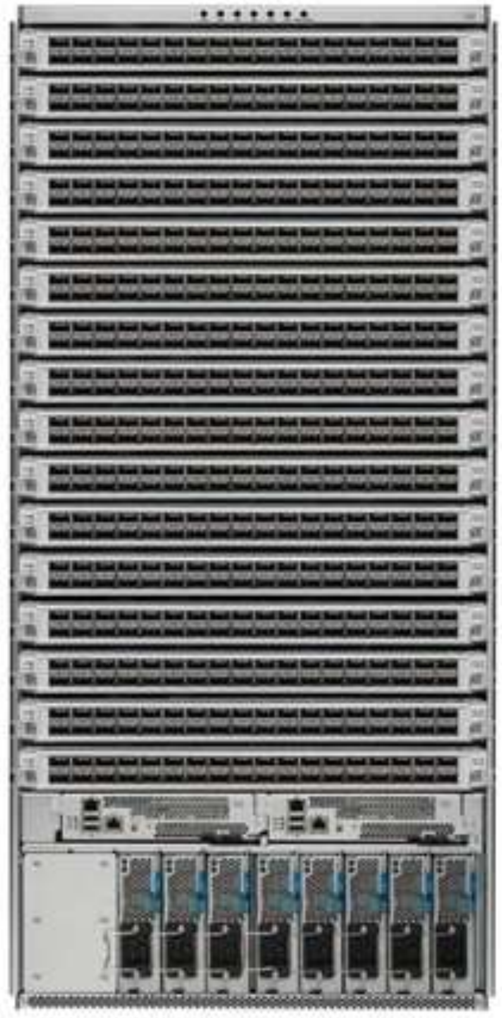
- Hubs gave way to switches in the mid-1990s
- Same star topology … but smarter
  - Like a hub, transparent to hosts
  - Full duplex: separate receive vs. transmit wires
  - Forwards received frames to the right interface(s)
- Works *sort of* like a router
  - Link layer forwarding
  - But

    Invisible – **frames are never addressed to the switch**

    Self-learning: it learns what address is at which interface

TP-Link Switch

- 8 1-GbE ports



Cisco Nexus 9516 Switch

- 1/10/40 GbE
- 21-rack-unit chassis
- Up to 576 1/10 Gb ports

Inside an Ethernet Switch

Switch table (also known as MAC address table)

- Contains entries for known MAC addresses & their interface

- **Forwarding & filtering**: a frame arrives for some destination address *D*
  - Look up *D* in the switch table to find the interface
  - If found & the interface is the same as the one the frame arrived on
    - Discard the frame (**filter**)
  - If found & a different interface
    - **Forward** the frame to that interface: queue if necessary
  - If not found
    - Forward to ALL interfaces

Building the switch table

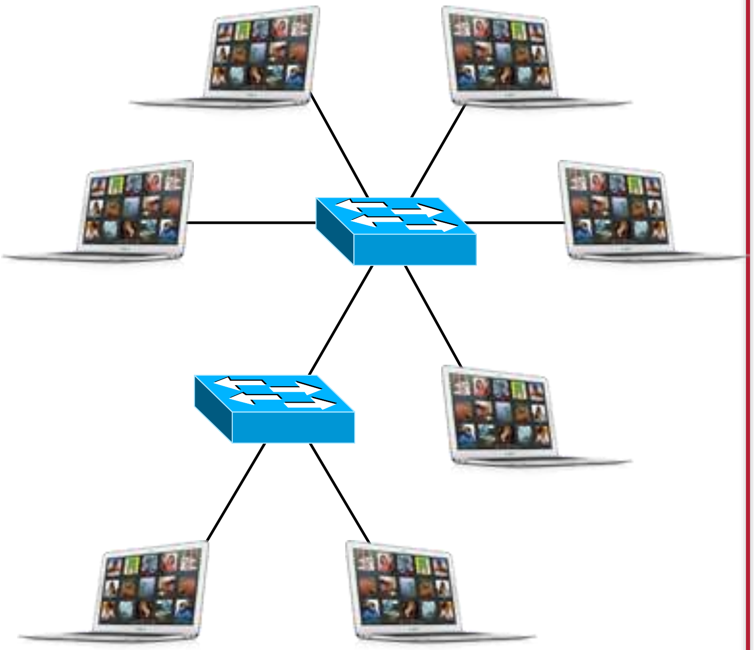
A switch is self-learning

- Switch table (MAC address → interface): initially empty
- Whenever a frame is received, associate the interface with the source MAC address in the frame
- Delete switch table entries if they have not been used for some time

- What about multicast?
  - Treat it like broadcast (simplest)
  - Some switches can snoop on IGMP join/leave messages
  - Some switches (Cisco) support downloading a local multicast table from the local router
- What about promiscuous mode?
  - Need a managed switch – configure port for *monitor* mode or *port mirroring*

Building the switch table

- A switch interface can be associated with multiple MAC addresses
  - Cascaded links
  - Multicast addresses (if supported)



Example Ethernet Switch

Intel FM2112 Ethernet Switch

- 24 ports
- 1G / 10G links
- Crossbar switch built with shared memory and a crossbar
- 750 Gb/s bandwidth
- 16 banks of 64KB memory for packet payload; headers queued & scheduled separately (1 MB total)
- Switch element scheduler manages frame data & forwarding
  - Up to 4096 packets can be in the switch at one time
- Multicast/broadcast replication
- 16K (16,384) entry MAC address table
  - Binary (0/1) age: “new” refreshed whenever the entry is accessed
  - An age clock periodically purges “old” (non-refreshed) entries

ASIX AX88655

- 5 port
- 10/100/1000 Mbps
- 4K (4096) MAC address table
- 128K byte SRAM packet buffer
- Multicast/broadcast replication

http://www.intel.com/content/dam/www/public/us/en/documents/datasheets/ethernet-switch-fm2112-datasheet.pdf

Switching

- Huge benefit: no collisions
  - No need for CSMA/CD
- Support heterogeneous links
  - 1 Gbps, 100 Mbps, fiber links, etc.
- Management
  - Disable ports
  - Prioritize ports
  - Collect statistics
  - Enable port monitoring (mirroring)

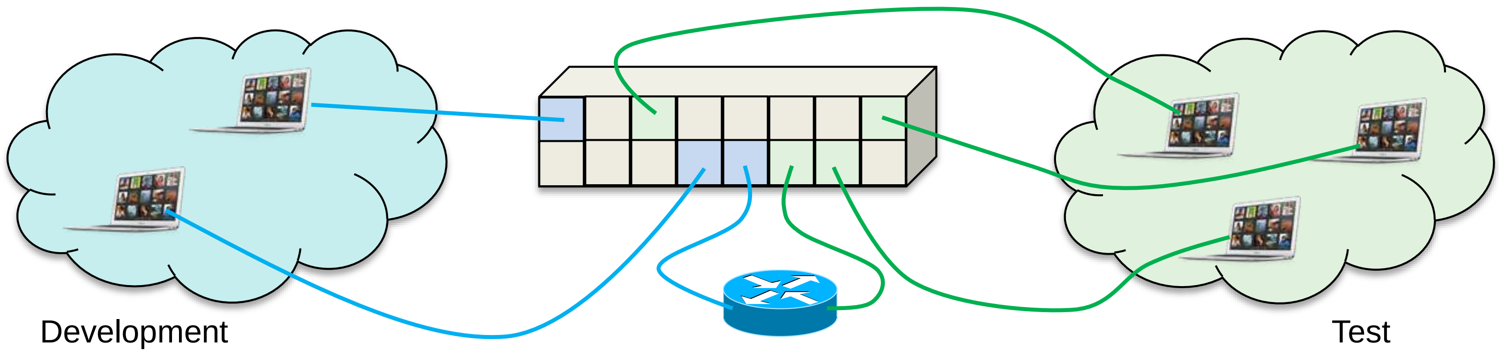
Virtual Local Area Networks (VLANs)

VLANs

- A switch + cables creates a local area network (LAN)
- We use LANs to
  - Isolate broadcast traffic from other groups of systems
  - Isolate users into groups
  - What if users move? What if switches are inefficiently used?
- Virtual Local Area Networks (VLANs)
  - Create multiple virtual LANs over one physical switch infrastructure
  - Network manager can assign a switch's ports to a specific VLAN
  - Each VLAN is a separate broadcast domain

Inter-VLAN routing

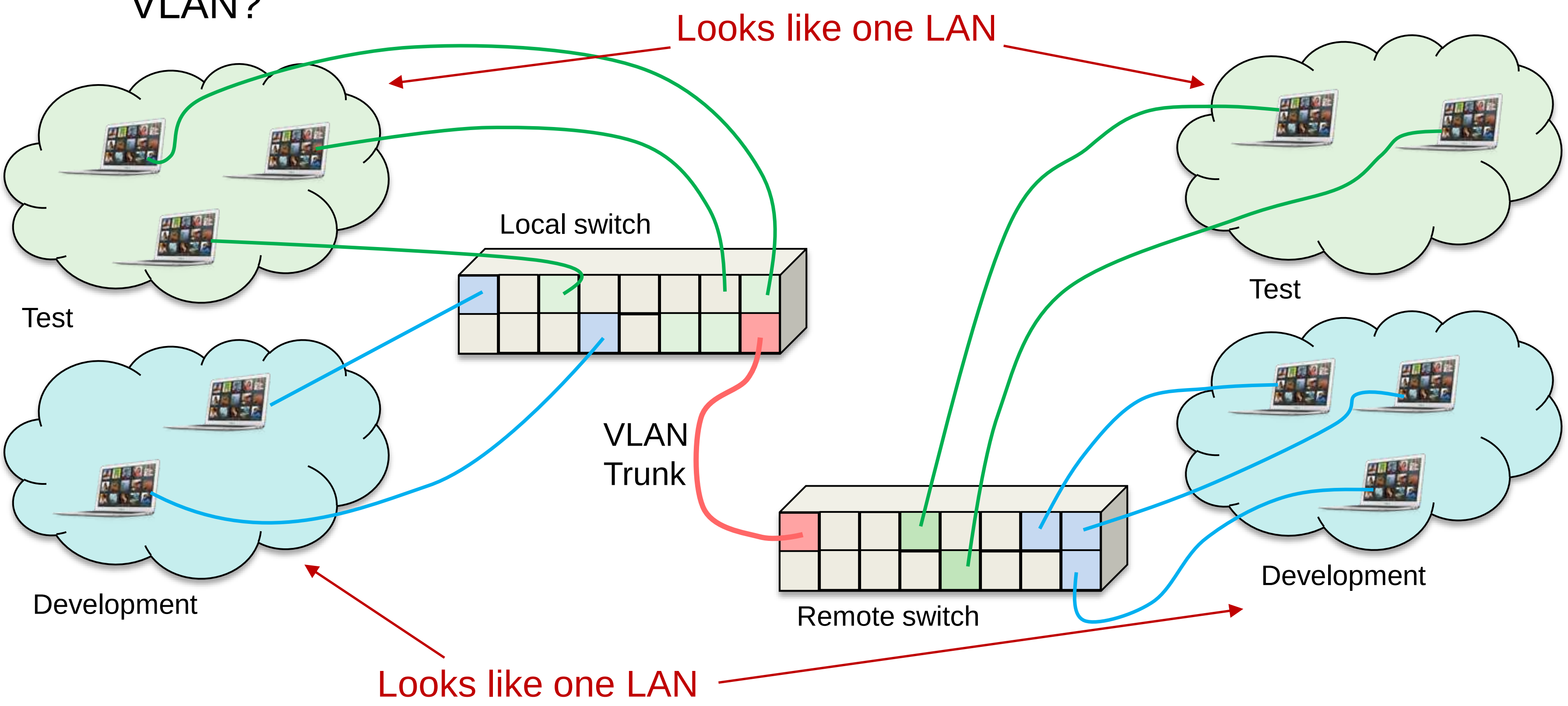
- If we have multiple VLANs, how do we route between them?
  - As with physical LANs, connect a port from each one to a router



- VLAN switches often integrate a router in them to make this easy

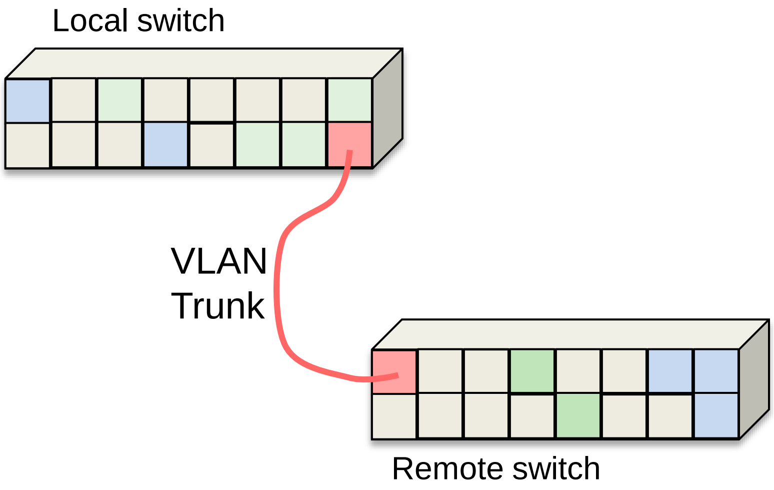
VLAN Trunking

- How about extending VLANs to multiple locations?
  - VLAN Trunking: a single connection between two VLAN-enabled switches carries all traffic for all VLANs
  - How does the switch do multiplexing/demultiplexing of traffic to the correct VLAN?



VLAN Trunking

- Extended Ethernet frame format
  - 802.1Q for frames on an Ethernet trunk
- 4-byte VLAN tag added to the frame
  - 2-byte Tag Protocol ID
  - 2-byte Tag Control Information: 12-bit VLAN ID, 3-bit priority field
- Switch adds VLAN tag for traffic on the trunk
- Switch removes VLAN tag upon receipt
  - Traffic in the trunk is sent to the appropriate VLAN based on VLAN ID



The end