14:
Ethernet, Hubs, Bridges, Switches, Other Technologies used at the Link Layer, ARP

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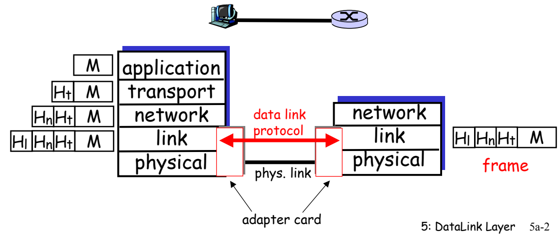
Link Layer: Implementation

- Typically, implemented in "adapter"
  - e.g., PCMCIA card, Ethernet card
  - typically includes: RAM, DSP chips, host bus interface, and link interface



Link Layer Services

- Framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - implement channel access if shared medium,
  - 'physical addresses' used in frame headers to identify source, dest
    - different from IP address!
- Reliable delivery between two physically connected devices:
  - we learned how to do reliable delivery over an unreliable link
  - seldom used on low bit error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

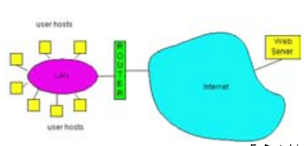
Link Layer Services (more)

- Flow Control:
  - pacing between sender and receivers
- *Error Detection:*
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame
- Error Correction:
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission

LAN technologies

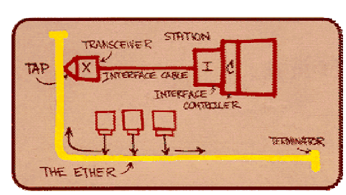
Data link layer so far:
- services, error detection/correction, multiple access

Next: LAN technologies
- Ethernet
- hubs, bridges, switches
- 802.11
- PPP
- ATM



Ethernet

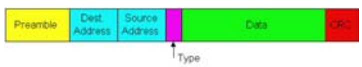
"dominant" LAN technology:
- cheap $20 for 100Mbs!
- first widely used LAN technology
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10, 100, 1000 Mbps



Metcalfe's Ethernet sketch

Ethernet Frame Structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in Ethernet frame

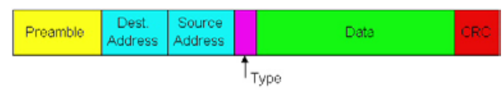


Preamble:

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

Ethernet Frame Structure (more)

- Addresses: 6 bytes, frame is received by all adapters on a LAN and dropped if address does not match
- Type: indicates the higher layer protocol, mostly IP but others may be supported such as Novell IPX and AppleTalk)
- CRC: checked at receiver, if error is detected, the frame is simply dropped



Ethernet: uses CSMA/CD

```
A: sense channel, if idle
   then {
         transmit and monitor the channel;
         If detect another transmission
           then {
             abort and send jam signal;
             update # collisions;
             delay as required by exponential backoff algorithm;
             goto A
             }
          else {done with the frame; set collisions to zero}
      }
   else {wait until ongoing transmission is over and goto A}
```


Ethernet's CSMA/CD (more)

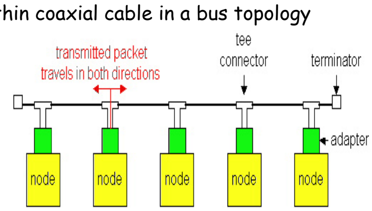
Jam Signal: make sure all other transmitters are aware of collision; 48 bits;

Exponential Backoff:

- *Goal*: adapt retransmission attempts to estimated current load
  - heavy load: random wait will be longer
- first collision: choose K from {0,1}; delay is K x 512 bit transmission times
- after second collision: choose K from {0,1,2,3}…
- after ten or more collisions, choose K from {0,1,2,3,4,…,1023}

Ethernet Technologies: 10Base2

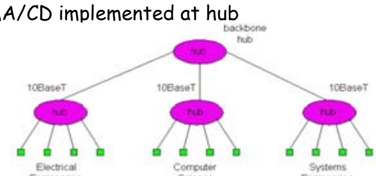
- 10: 10Mbps; 2: under 200 meters max cable length
- thin coaxial cable in a bus topology



- repeaters used to connect up to multiple segments
- repeater repeats bits it hears on one interface to its other interfaces: physical layer device only!

10BaseT and 100BaseT

- 10/100 Mbps rate; latter called "fast ethernet"
- T stands for Twisted Pair
- Hub to which nodes are connected by twisted pair, thus "star topology"
- CSMA/CD implemented at hub



10BaseT and 100BaseT (more)

- Max distance from node to Hub is 100 meters
- Hub can disconnect "jabbering adapter"
- Hub can gather monitoring information, statistics for display to LAN administrators

Gbit Ethernet

- use standard Ethernet frame format
- allows for point-to-point links and shared broadcast channels
- in shared mode, CSMA/CD is used; short distances between nodes to be efficient
- uses hubs, called here "Buffered Distributors"
- Full-Duplex at 1 Gbps for point-to-point links

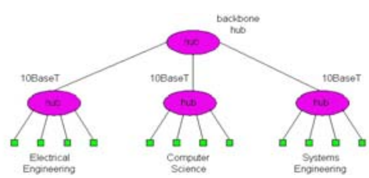
Ethernet Limitations

Q: Why not just one big Ethernet?

- Limited amount of supportable traffic: on single LAN, all stations must share bandwidth
- limited length: 802.3 specifies maximum cable length
- large "collision domain" (can collide with many stations)
- How can we get around some of these limitations?

Hubs

- Physical Layer devices: essentially repeaters operating at bit levels: repeat received bits on one interface to all other interfaces
- Hubs can be arranged in a hierarchy (or multi-tier design), with backbone hub at its top



Hubs (more)

- Each connected LAN referred to as LAN **segment**
- Hubs do not isolate collision domains: node may collide with any node residing at any segment in LAN
- Hub Advantages:
  - simple, inexpensive device
  - Multi-tier provides graceful degradation: portions of the LAN continue to operate if one hub malfunctions
  - extends maximum distance between node pairs (100m per Hub)

Hub limitations

- single collision domain results in no increase in max throughput
  - multi-tier throughput same as single segment throughput
- individual LAN restrictions pose limits on number of nodes in same collision domain and on total allowed geographical coverage
- cannot connect different Ethernet types (e.g., 10BaseT and 100baseT)

Bridges

- Link Layer devices: operate on Ethernet frames, examining frame header and selectively forwarding frame based on its destination
- Bridge isolates collision domains since it buffers frames
- When frame is to be forwarded on segment, bridge uses CSMA/CD to access segment and transmit

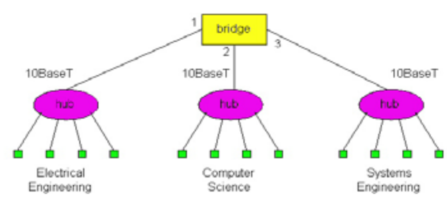
Bridges (more)

- Bridge advantages:
  - Isolates collision domains resulting in higher total max throughput, and does not limit the number of nodes nor geographical coverage
  - Can connect different type Ethernet since it is a store and forward device
  - Transparent: no need for any change to hosts LAN adapters

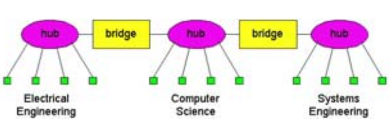
Bridges: frame filtering, forwarding

- bridges filter packets
  - same-LAN -segment frames not forwarded onto other LAN segments
- forwarding:
  - how to know which LAN segment on which to forward frame?
  - looks like a routing problem (more shortly!)

Backbone Bridge



Interconnection Without Backbone



- Not recommended for two reasons:
  - single point of failure at Computer Science hub
  - all traffic between EE and SE must path over CS segment

Bridge Filtering

- bridges *learn* which hosts can be reached through which interfaces: maintain filtering tables
  - when frame received, bridge "learns" location of sender: incoming LAN segment
  - records sender location in filtering table
- filtering table entry:
  - (Node LAN Address, Bridge Interface, Time Stamp)
  - stale entries in Filtering Table dropped (TTL can be 60 minutes)

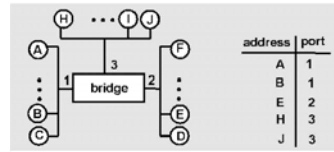
Bridge Filtering

- filtering procedure:

```
if destination is on LAN on which frame was received
    then drop the frame
    else { lookup filtering table
           if entry found for destination
             then forward the frame on interface indicated;
             else flood;    /* forward on all but the interface
               on                                which the frame
               arrived*/
         }
```

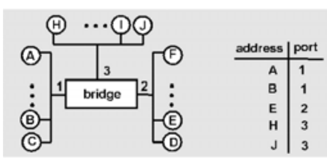

Bridge Learning: example

Suppose C sends frame to D and D replies back with frame to C



- C sends frame, bridge has no info about D, so floods to both LANs
  - bridge notes that C is on port 1
  - frame ignored on upper LAN
  - frame received by D

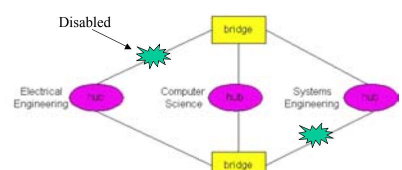
Bridge Learning: example



- D generates reply to C, sends
  - bridge sees frame from D
  - bridge notes that D is on interface 2
  - bridge knows C on interface 1, so *selectively* forwards frame out via interface 1

Bridges Spanning Tree

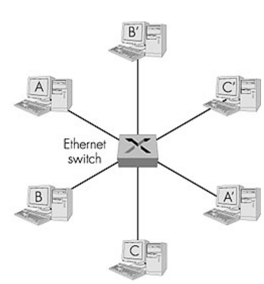
- for increased reliability, desirable to have redundant, alternate paths from source to dest
- with multiple simultaneous paths, cycles result - bridges may multiply and forward frame forever
- solution: organize bridges in a spanning tree by disabling subset of interfaces



Spanning Tree Algorithm

Ethernet Switches

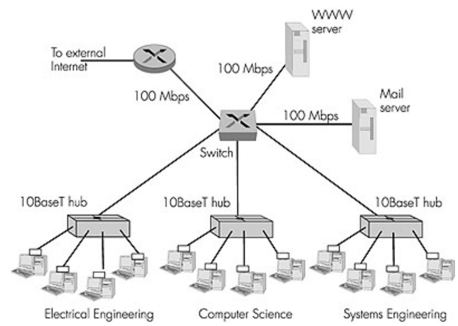
- Sophisticated bridges
  - Switches usually switch in hardware, bridges in software
  - large number of interfaces
- Like bridges, layer 2 (frame) forwarding, filtering using LAN addresses
- Can support combinations of shared/dedicated, 10/100/1000 Mbps interfaces



Switching

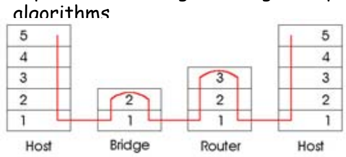
- Switching: A-to-B and A'-to-B' simultaneously, no collisions
- cut-through switching: frame forwarded from input to output port without awaiting for assembly of entire frame
  - slight reduction in latency
- Store and forward switching: entire frame received before transmission out an output port
- Fragment-free switching: compromise, before send out the output port receive enough of the packet to do some error checking (ex. detect and drop partial frames)

Common Topology



Bridges vs. Switches vs. Routers

- Switches = sophisticated multi-port bridges
- All store-and-forward devices
  - routers: Layer 3 (network layer) devices
  - Bridges/switches are Layer 2 (Link Layer) devices
- routers maintain routing tables, implement routing algorithms
- Bridges/switches maintain filtering tables, implement filtering, learning and spanning tree algorithms



Routers vs. Bridges

Bridges + and -

\+ Bridge operation is simpler requiring less processing bandwidth

\- Topologies are restricted with bridges: a spanning tree must be built to avoid cycles

\- Bridges do not offer protection from broadcast storms (endless broadcasting by a host will be forwarded by a bridge)

Routers vs. Bridges

Routers + and -

\+ arbitrary topologies can be supported, cycling is limited by TTL counters (and good routing protocols)

\+ provide firewall protection against broadcast storms

\- require IP address configuration (not plug and play)

\- require higher processing bandwidth

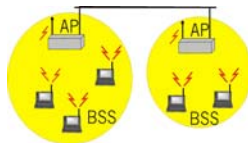
- bridges do well in small (few hundred hosts) while routers used in large networks (thousands of hosts)

Summary

- Layer 3 Devices (Network Layer)
  - Router
- Layer 2 Devices (Link Layer)
  - Bridge
  - Switch
- Layer 1 Devices (Physical Layer)
  - Repeaters
  - Hubs

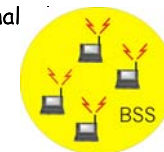
IEEE 802.11 Wireless LAN

- wireless LANs: untethered (often mobile) networking
- IEEE 802.11 standard:
  - MAC protocol
  - unlicensed frequency spectrum: 900Mhz, 2.4Ghz
- **Basic Service Set (BSS)** (a.k.a. "cell") contains:
  - **wireless hosts**
  - **access point (AP): base station**
- **BSS's combined to form distribution system (DS)**



Ad Hoc Networks

- Ad hoc network: IEEE 802.11 stations can dynamically form network *without* AP
- Applications:
  - "laptop" meeting in conference room, car
  - interconnection of "personal
  - battlefield
- IETF MANET (Mobile Ad hoc Networks) working group



IEEE 802.11 MAC Protocol: CSMA/CA

802.11 CSMA: sender

- if sense channel idle for **DISF** sec.

  then transmit entire frame (no collision detection)

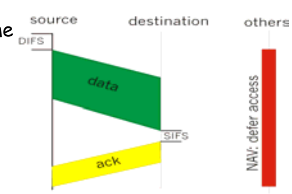
-if sense channel busy

  then binary backoff

802.11 CSMA receiver:

if received OK

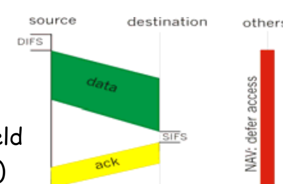
return ACK after **SIFS**



IEEE 802.11 MAC Protocol

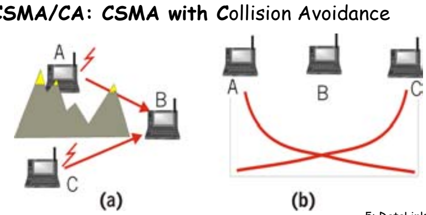
802.11 CSMA Protocol: others

- **NAV**: Network Allocation Vector
- 802.11 frame has transmission time field
- others (hearing data) defer access for NAV time units



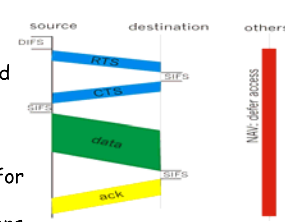
Hidden Terminal effect

- hidden terminals: A, C cannot hear each other
  - obstacles, signal attenuation
  - collisions at B
- goal: avoid collisions at B
- ***CSMA/CA: CSMA with* Collision *Avoidance***



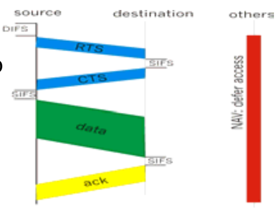
Collision Avoidance: RTS-CTS exchange

- CSMA/CA: explicit channel reservation
  - sender: send short RTS: request to send
  - receiver: reply with short CTS: clear to send
- CTS reserves channel for sender, notifying (possibly hidden) stations
- avoid hidden station collisions



Collision Avoidance: RTS-CTS exchange

- RTS and CTS short:
  - collisions less likely, of shorter duration
  - end result similar to collision detection
- IEEE 802.11 allows:
  - CSMA
  - CSMA/CA: reservations
  - polling from AP

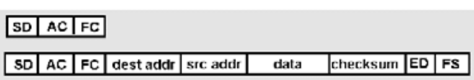


Token Passing: IEEE802.5 standard

- 4 Mbps
- max token holding time: 10 ms, limiting frame length

- SD, ED mark start, end of packet
- AC: access control byte:
  - token bit: value 0 means token can be seized, value 1 means data follows FC
  - priority bits: priority of packet
  - reservation bits: station can write these bits to prevent stations with lower priority packet from seizing token after token becomes free

Token Passing: IEEE802.5 standard



- FC: frame control used for monitoring and maintenance
- source, destination address: 48 bit physical address, as in Ethernet
- data: packet from network layer; checksum: CRC
- FS: frame status: set by dest., read by sender
  - set to indicate destination up, frame copied OK from ring
- limited number of stations: 802.5 have token passing delays at each station

Point to Point Data Link Control

- one sender, one receiver, one link: easier than broadcast link:
  - no Media Access Control
  - no need for explicit MAC addressing
  - e.g., dialup link, ISDN line
- popular point-to-point DLC protocols:
  - PPP (point-to-point protocol)
  - HDLC: High level data link control

PPP Design Requirements [RFC 1557]

- packet framing: encapsulation of network-layer datagram in data link frame
  - carry network layer data of any network layer protocol (not just IP) *at same time*
  - ability to demultiplex upwards
- bit transparency: must carry any bit pattern in the data field
- error detection (no correction)
- connection livenes: detect, signal link failure to network layer
- network layer address negotiation: endpoint can learn/configure each other's network address

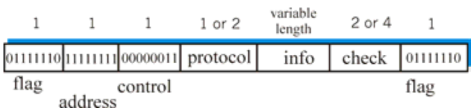
PPP non-requirements

- no error correction/recovery
- no flow control
- out of order delivery OK
- no need to support multipoint links (e.g., polling)

Error recovery, flow control, data re-ordering all relegated to higher layers!|

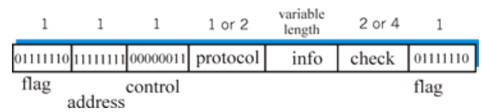
PPP Data Frame

- Flag: delimiter (framing)
- Address: does nothing (only one option)
- Control: does nothing; in the future possible multiple control fields
- Protocol: upper layer protocol to which frame delivered (eg, PPP-LCP, IP, IPCP, etc)



PPP Data Frame

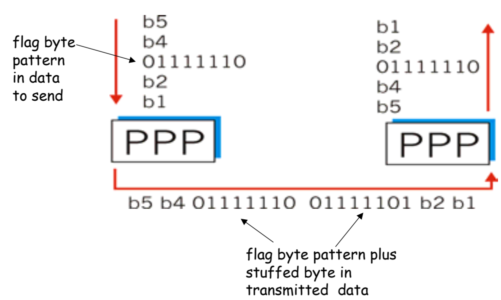
- info: upper layer data being carried
- check: cyclic redundancy check for error detection



Byte Stuffing

- "data transparency" requirement: data field must be allowed to include flag pattern <01111110>
  - Q: is received <01111110> data or flag?
- Sender: adds ("stuffs") extra < 01111110> byte after each < 01111110> *data* byte
- Receiver:
  - two 01111110 bytes in a row: discard first byte, continue data reception
  - single 01111110: flag byte

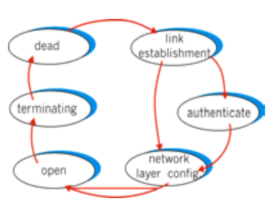
Byte Stuffing



PPP Data Control Protocol

Before exchanging network-layer data, data link peers must

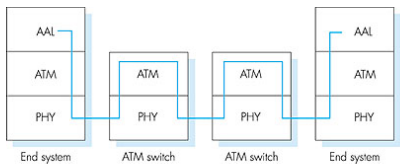
- configure PPP link (max. frame length, authentication)
- learn/configure network layer information
  - for IP: carry IP Control Protocol (IPCP) msgs (protocol field: 8021) to configure/learn IP address



IP over Other Wide Area Network Technologies

- ATM
- Frame Relay
- X-25

ATM architecture

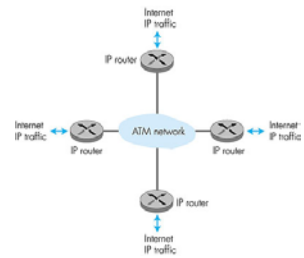


- **Adaptation layer (AAL): only at edge of ATM network**
  - data segmentation/reassembly
  - roughly analogous to Internet transport layer
- ATM layer: "network" layer
  - Virutal circuits, routing, cell switching
- physical layer

ATM: network or link layer?

Vision: end-to-end transport: "ATM from desktop to desktop"
- ATM *is* a network technology

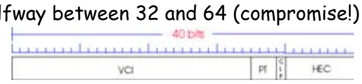
Reality: used to connect IP backbone routers
- "IP over ATM"
- ATM as switched link layer, connecting IP routers



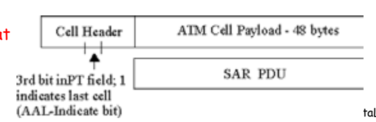
ATM Layer: ATM cell

- 5-byte ATM cell header
- 48-byte payload
  - Why?: small payload -> short cell-creation delay for digitized voice
  - halfway between 32 and 64 (compromise!)

Cell header



Cell format

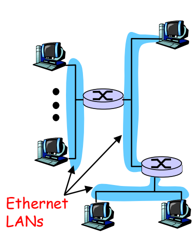


ATM cell header

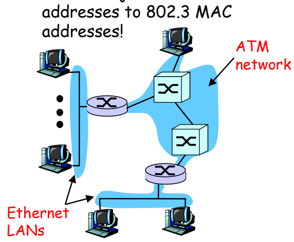
- **VCI:** virtual channel ID
  - will *change* from link to link thru net
- **PT:** Payload type (e.g. RM cell versus data cell)
- **CLP:** Cell Loss Priority bit
  - CLP = 1 implies low priority cell, can be discarded if congestion
- **HEC:** Header Error Checksum
  - cyclic redundancy check

IP-Over-ATM

Classic IP only
- 3 "networks" (e.g., LAN segments)
- MAC (802.3) and IP addresses

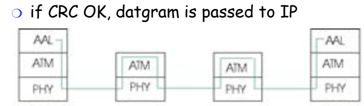


IP over ATM
- replace "network" (e.g., LAN segment) with ATM network
- IP addresses -> ATM addressesjust like IP addresses to 802.3 MAC addresses!



Datagram Journey in IP-over-ATM Network

- at Source Host:
  - IP layer finds mapping between IP, ATM dest address (using ARP)
  - passes datagram to AAL5
  - AAL5 encapsulates data, segments to cells, passes to ATM layer
- ATM network: moves cell along VC to destination (uses existing one or establishes another)
- at Destination Host:
  - AAL5 reassembles cells into original datagram
  - if CRC OK, datgram is passed to IP



X.25 and Frame Relay

Like ATM:

- wide area network technologies
- virtual circuit oriented
- origins in telephony world
- can be used to carry IP datagrams and can thus be viewed as Link Layers by IP protocol just like ATM

X.25

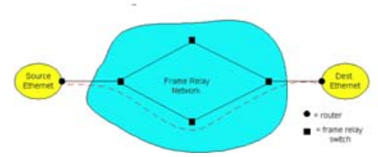
- X.25 builds VC between source and destination for each user connection
- Per-hop control along path
  - error control (with retransmissions) on each hop
  - per-hop flow control using credits
    - congestion arising at intermediate node propagates to previous node on path
    - back to source via back pressure

IP versus X.25

- X.25: reliable in-sequence end-end delivery from end-to-end
  - "intelligence in the network"
- IP: unreliable, out-of-sequence end-end delivery
  - "intelligence in the endpoints"
- 2000: IP wins
  - gigabit routers: limited processing possible

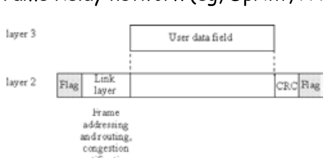
Frame Relay

- Designed in late '80s, widely deployed in the '90s
- Frame relay service:
  - no error control
  - end-to-end congestion control



Frame Relay (more)

- Designed to **interconnect** corporate customer LANs
  - typically permanent VC's: "**pipe**" carrying aggregate traffic between two routers
  - switched VC's: as in ATM
- corporate customer **leases** FR service from public Frame Relay network (eg, Sprint, ATT)



Frame Relay (more)

flags	address	data	CRC	flags

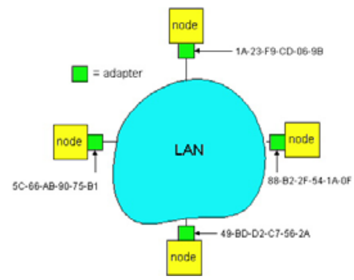
- Flag bits, 01111110, delimit frame
- Address = address and congestion control
  - 10 bit VC ID field
  - 3 congestion control bits
    - FECN: forward explicit congestion notification (frame experienced congestion on path)
    - BECN: congestion on reverse path
    - DE: discard eligibility

Frame Relay -VC Rate Control

- Committed Information Rate (CIR)
  - defined, "guaranteed" for each VC
  - negotiated at VC set up time
  - customer pays based on CIR
- DE bit: Discard Eligibility bit
  - Edge FR switch measures traffic rate for each VC; marks DE bit
  - DE = 0: high priority, rate compliant frame; deliver at "all costs"
  - DE = 1: low priority, eligible for discard when congestion

LAN Addresses

Each adapter on LAN has unique LAN address



LAN Addresses vs IP Addresses

32-bit IP address (128 bit IPv6):

- *network-layer* address
- used to get datagram to destination network (recall IP network definition)

LAN (or MAC or physical) address:

- used to get datagram from one interface to another physically-connected interface (same network)
- 48 bit MAC address (for most LANs) burned in the adapter ROM

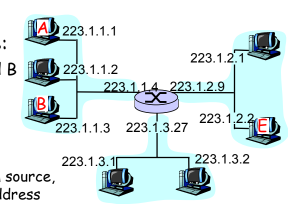
LAN Address vs IP Addresses (more)

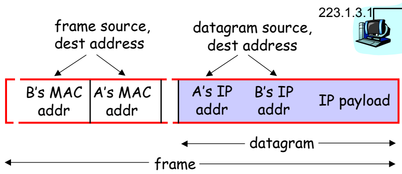
- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- Analogy:
  - (a) MAC address: like Social Security Number
  - (b) IP address: like postal address
- MAC flat address => portability
  - can move LAN card from one LAN to another
- IP hierarchical address NOT portable
  - depends on network to which one attaches

Recall earlier routing discussion

Starting at A, given IP datagram addressed to B:

- look up net. address of B, find B on same net. as A
- link layer send datagram to B inside link-layer frame

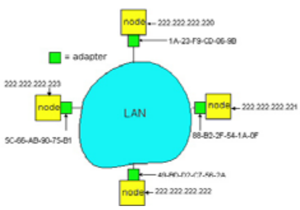




Question:

How can we determine the MAC address of B given B's IP address?

ARP: Address Resolution Protocol



- Each IP node (Host, Router) on LAN has ARP module, 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)

ARP protocol

- A knows B's IP address, wants to learn physical address of B
- A broadcasts ARP query pkt, containing B's IP address
  - all machines on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) physical layer address
- A caches (saves) IP-to-physical address pairs until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed

Hands-on: arp

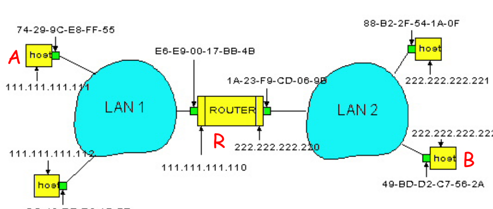
- arp *ipaddress*
  - Return the MAC address associated with the given IP address
- arp –a
  - List the contents of the local ARP cache
- arp –s hostname macAddress
  - Used by the system administrator to add a specific entry to the local ARP cache

ARP in ATM Nets

- ATM network needs destination ATM address
  - just like Ethernet needs destination Ethernet address
- IP/ATM address translation done by ATM ARP (Address Resolution Protocol)
  - ARP server in ATM network performs broadcast of ATM ARP translation request to all connected ATM devices
  - hosts can register their ATM addresses with server to avoid lookup

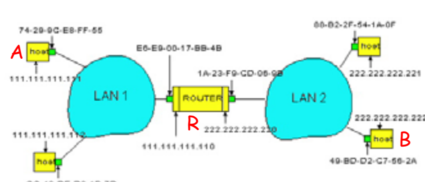
Routing to another LAN

walkthrough: routing from A to B via R



- In routing table at source Host, find router 111.111.111.110
- In ARP table at source, find MAC address E6-E9-00-17-BB-4B, etc

- A creates IP packet with source A, destination B
- A uses ARP to get R's physical layer address for 111.111.111.110
- A creates Ethernet frame with R's physical address as dest, Ethernet frame contains A-to-B IP datagram
- A's data link layer sends Ethernet frame
- R's data link layer receives Ethernet frame
- R removes IP datagram from Ethernet frame, sees its destined to B
- R uses ARP to get B's physical layer address
- R creates frame containing A-to-B IP datagram sends to B



Summary

- principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing, ARP
- various link layer technologies
  - Ethernethubs, bridges, switches
  - IEEE 802.11 LANs
  - PPP
  - ATM, X.25, Frame Relay
- journey down the protocol stack now *OVER!*
  - Next stops: security, network management(?)