

Chapter 5: The Data Link Layer

(last updated 26/04/04)

Our goals:

- ❑ understand principles behind data link layer services:
 - error detection, correction
 - sharing a broadcast channel: multiple access
 - link layer addressing
 - reliable data transfer, flow control: *done!*
- ❑ instantiation and implementation of various link layer technologies

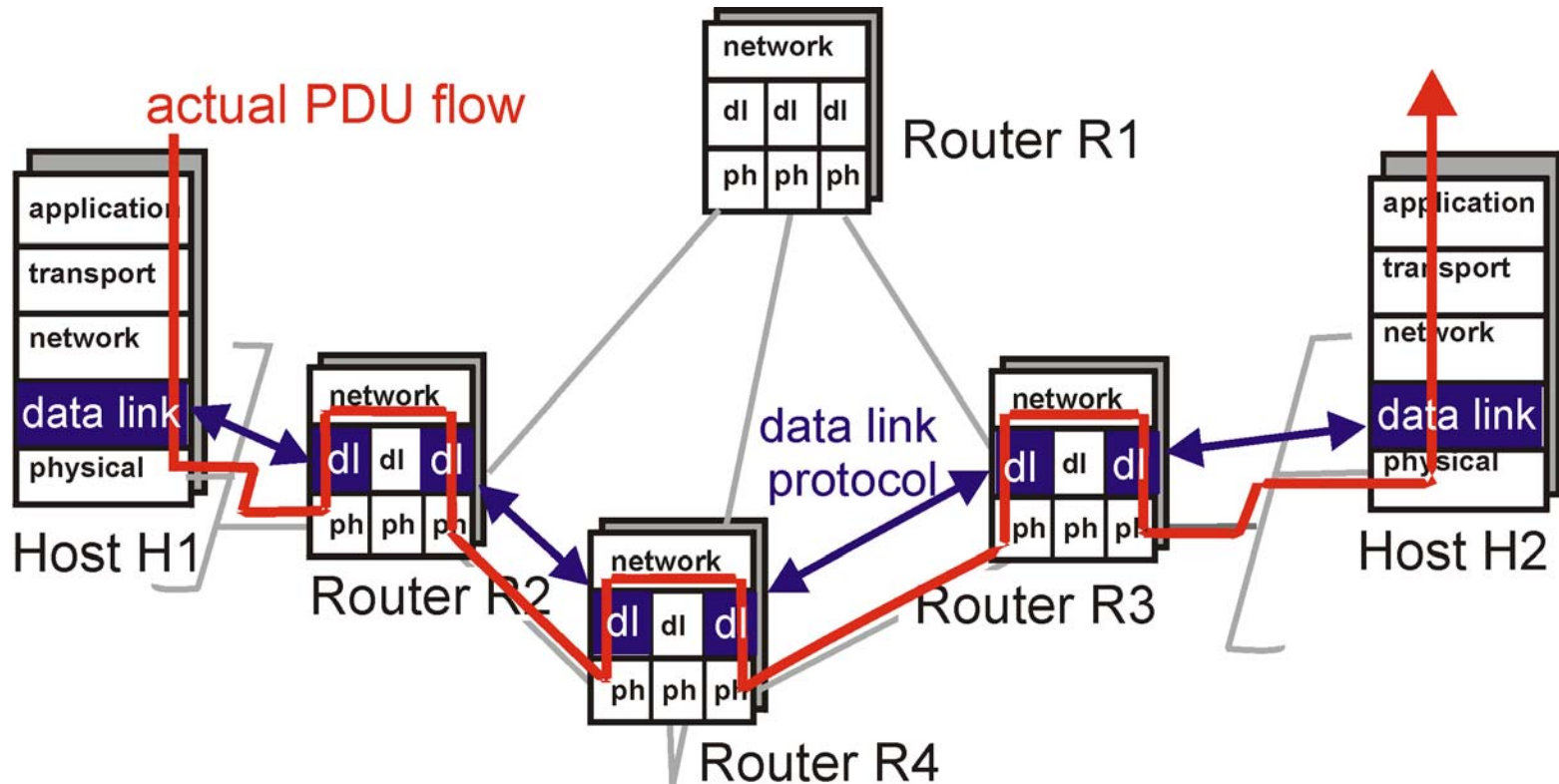
Overview:

- ❑ link layer services
- ❑ error detection, correction
- ❑ multiple access protocols and LANs
- ❑ link layer addressing, ARP
- ❑ specific link layer technologies:
 - Ethernet
 - hubs, bridges, switches
 - ATM

Chapter 5 outline

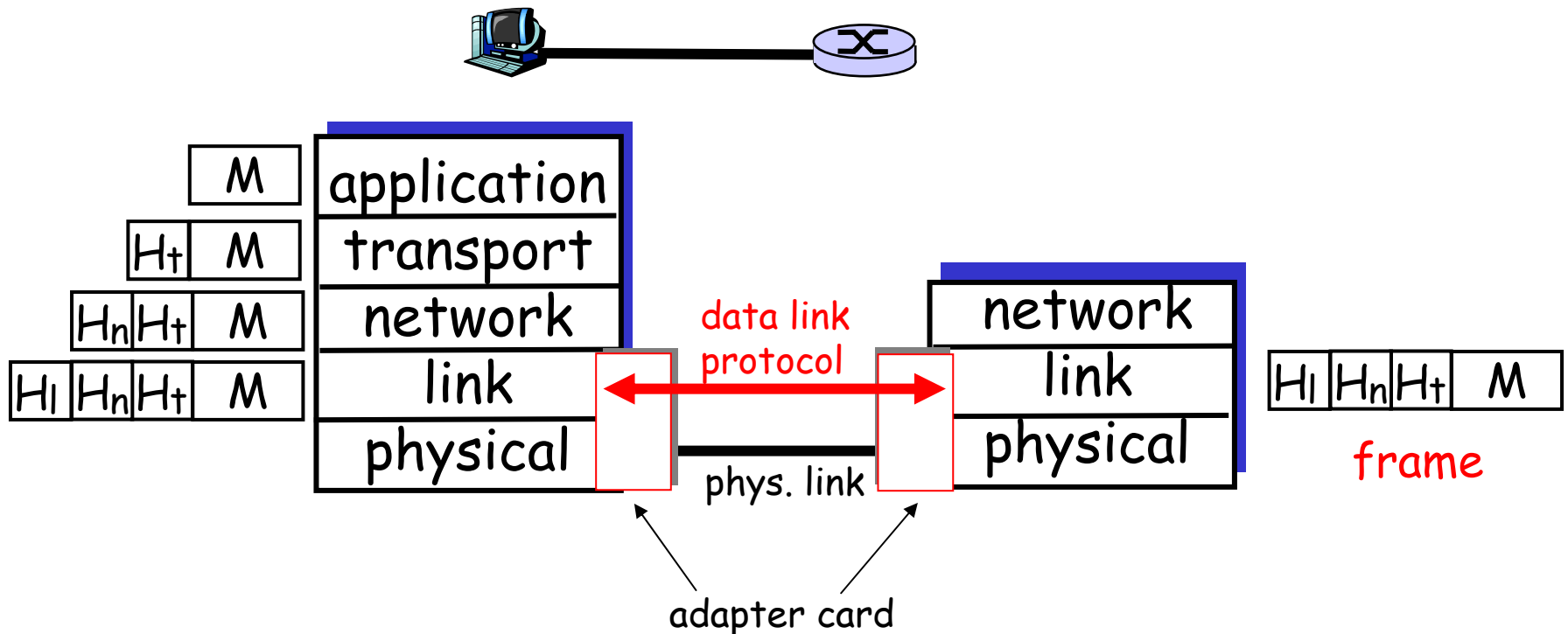
- ❑ 5.1 Introduction and services
- ❑ 5.2 Error detection and correction
- ❑ 5.3 Multiple access protocols
- ❑ 5.4 LAN addresses and ARP
- ❑ 5.5 Ethernet
- ❑ 5.6 Hubs, bridges, and switches
- ❑ 5.7 Wireless links and LANs
- ❑ 5.8 PPP
- ❑ 5.9 ATM
- ❑ 5.10 Frame Relay

Link Layer: setting the context



Link Layer: setting the context

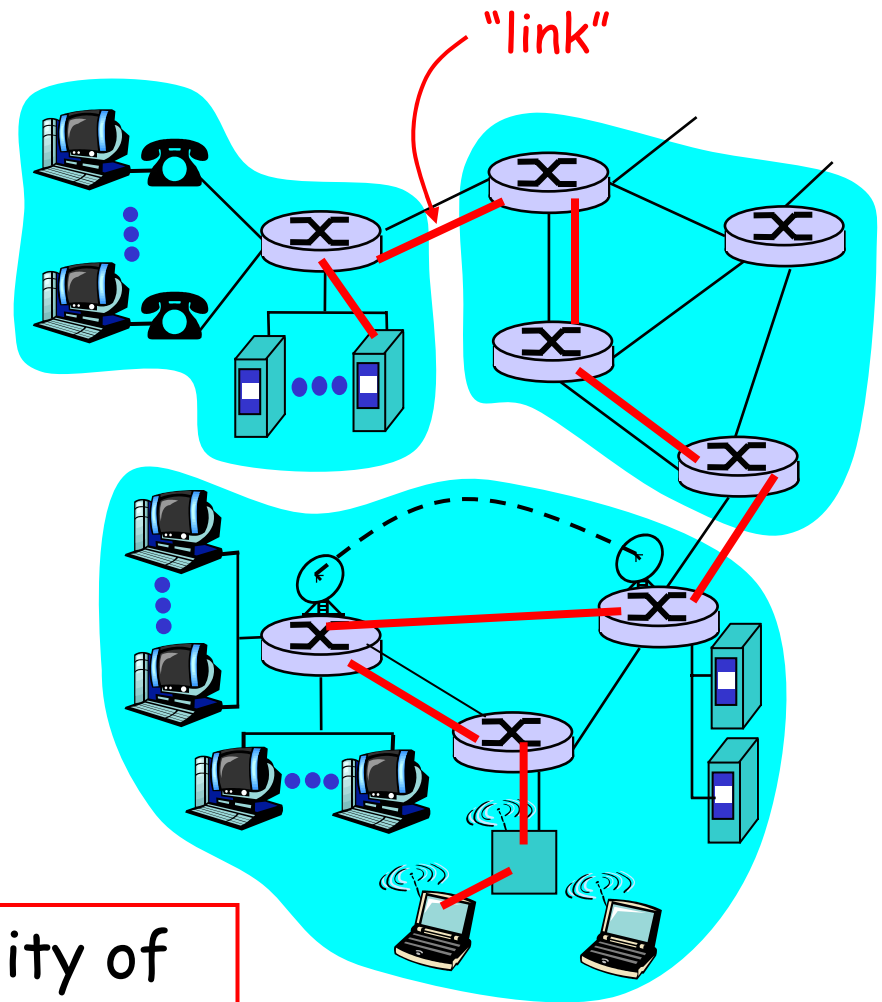
- two *physically connected* devices:
 - host-router, router-router, host-host
- unit of data: *frame*



Link Layer: setting the context

Some terminology:

- ❑ hosts and routers are **nodes** (bridges and switches too)
- ❑ communication channels that connect adjacent nodes along communication path are **links**
 - wired links
 - wireless links
 - LANs
- ❑ 2-PDU is a **frame**, encapsulates datagram



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

Link layer: context

- ❑ Datagram transferred by different link protocols over different links:
 - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- ❑ Each link protocol provides different services
 - e.g., may or may not provide rdt over link

transportation analogy

- ❑ trip from Princeton to Lausanne
 - limo: Princeton to JFK
 - plane: JFK to Geneva
 - train: Geneva to Lausanne
- ❑ tourist = **datagram**
- ❑ transport segment = **communication link**
- ❑ transportation mode = **link layer protocol**
- ❑ travel agent = **routing algorithm**

Link Layer Services

❑ Framing, link access:

- encapsulate datagram into frame, adding header, trailer
- channel access if shared medium
- 'physical addresses' used in frame headers to identify source, dest
 - different from IP address!

❑ Reliable delivery between adjacent nodes

- we learned how to do this already (chapter 3)!
- 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 adjacent sending and receiving nodes

□ *Error Detection:*

- errors caused by signal attenuation, noise.
- receiver detects presence of errors:
 - signals sender for retransmission or drops frame

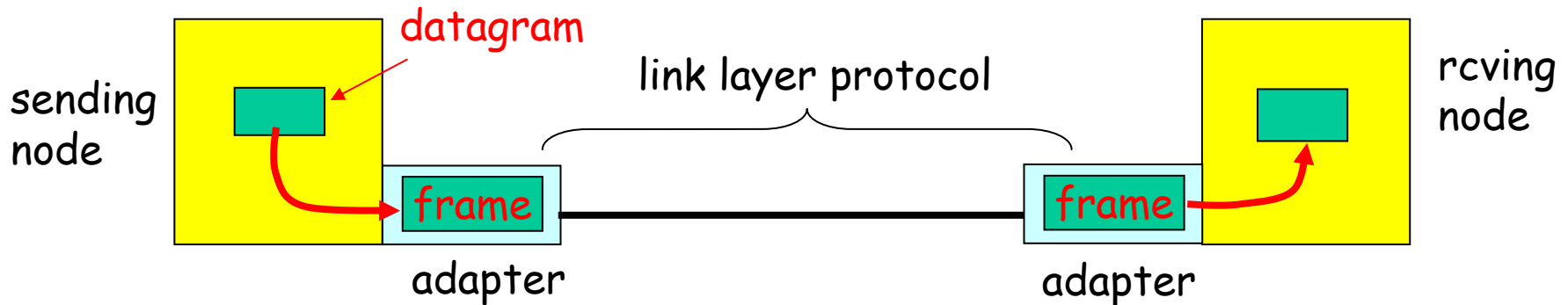
□ *Error Correction:*

- receiver identifies *and corrects* bit error(s) without resorting to retransmission

□ *Half-duplex and full-duplex*

- with half duplex, nodes at both ends of link can transmit, but not at same time

Adaptors Communicating



- ❑ link layer implemented in "adaptor" (aka NIC)
 - Ethernet card, PCMCIA card, 802.11 card
 - typically includes: RAM, DSP chips, host bus interface, and link interface
- ❑ sending side:
 - encapsulates datagram in a frame
 - adds error checking bits, rdt, flow control, etc.

- ❑ receiving side
 - looks for errors, rdt, flow control, etc
 - extracts datagram, passes to rcvng node
- ❑ adapter is semi-autonomous
- ❑ link & physical layers

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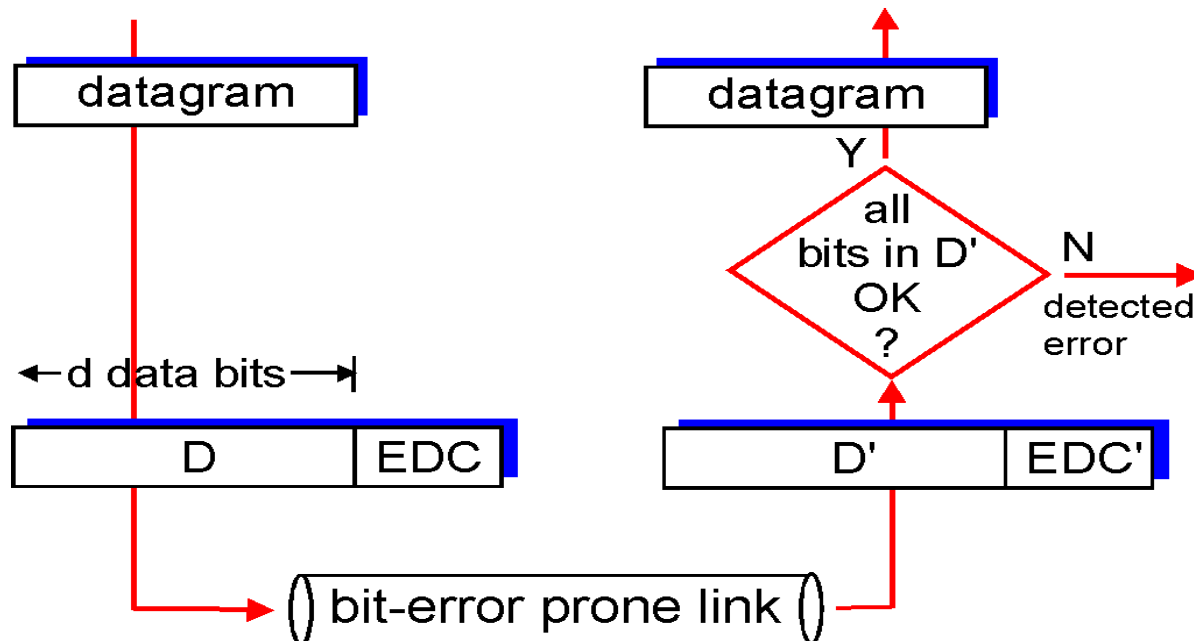
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Error Detection

EDC= Error Detection and Correction bits (redundancy)

D = Data protected by error checking, may include header fields

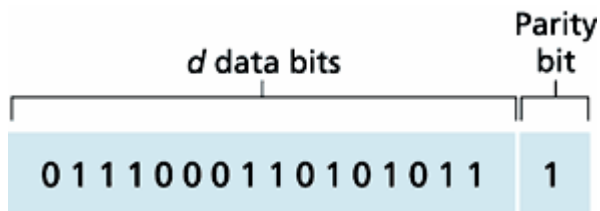
- Error detection not 100% reliable!
 - protocol may miss some errors, but rarely
 - larger EDC field yields better detection and correction



Parity Checking

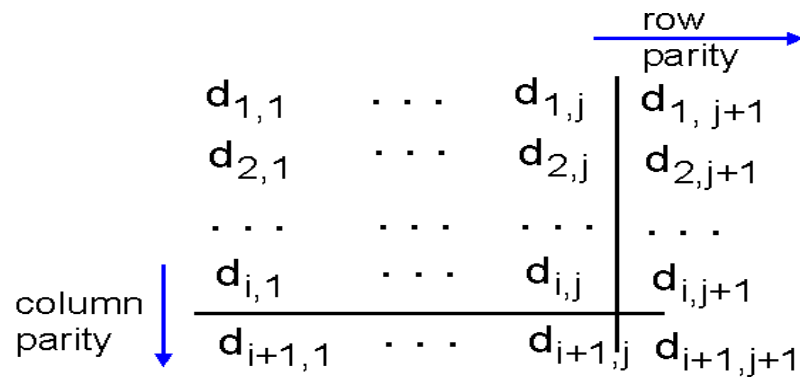
Single Bit Parity:

Detect single bit errors



Two Dimensional Bit Parity:

Detect *and correct* single bit errors



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

no errors

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

parity
error

*correctable
single bit error*

Internet checksum

Goal: detect "errors" (e.g., flipped bits) in transmitted segment (note: used at transport layer *only*)

Sender:

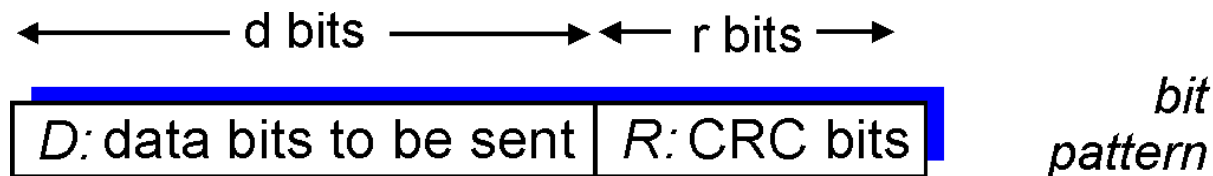
- ❑ treat segment contents as sequence of 16-bit integers
- ❑ checksum: addition (1's complement sum) of segment contents
- ❑ sender puts checksum value into UDP checksum field

Receiver:

- ❑ compute checksum of received segment
- ❑ check if computed checksum equals checksum field value:
 - NO - error detected
 - YES - no error detected. *But maybe errors nonetheless?*

Checksumming: Cyclic Redundancy Check

- view data bits, D , as coefficients of polynomial
- choose $r+1$ bit pattern (generator), G
- goal: choose r CRC bits, R , such that
 - $\langle D, R \rangle$ exactly divisible (*polynomial division*) by G (modulo 2)
 - receiver knows G , divides $\langle D, R \rangle$ by G . If non-zero remainder: error detected!
 - can detect all burst errors less than $r+1$ bits
- widely used in practice (ATM, HDCL)



$$D * 2^r \text{ XOR } R$$

mathematical formula

- Bits in word are coefficients of polynomial

$$D = 101110 \quad \text{then} \quad D(x) = x^5 + x^3 + x^2 + x$$

- Arithmetic on coefficients is mod 2

$$(x+1)^2 = x^2 + 1$$

In particular $P(x) + P(x) = 0$

- $R(x)$ is the remainder of $P(x)$ divided by $G(x)$ if

$$P(x) = A(x) G(x) + R(x) \quad \text{where} \quad \deg(R) < \deg(G)$$

- $G(x)$ divides $P(x) + R(x)$ since

$$P(x) + R(x) = A(x) G(x) + R(x) + R(x) = A(x) G(x)$$

- $2^r D$ corresponds to $x^r D(x)$

- Given D and G ,

- CRC finds $R(x)$, remainder when $x^r D(x)$ is divided by $G(x)$.
- R is word corresponding to $R(x)$.
- CRC is $D \cdot 2^r \text{ XOR } R$

Example (r=3)

$$D = 101110$$

$$G = 1001$$

$$2^r D = 101110000$$

$$D(x) = x^5 + x^3 + x^2 + x$$

$$G(x) = x^3 + 1$$

$$x^3 D(x) = x^8 + x^6 + x^5 + x^4$$

$$x^3 D(x) = G(x) (x^5 + x^3 + x + 1) + (x+1)$$

$$\text{So } R(x) = x+1 \text{ and } R = 011$$

CRC will transmit

$$D \cdot 2^r \text{ XOR } R = 101110011$$

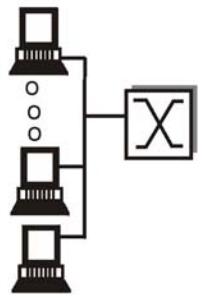
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Media Access Control (MAC) Protocols

Two types of "links":

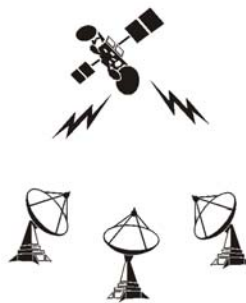
- ❑ point-to-point
 - PPP for dial-up access
 - point-to-point link between Ethernet switch and host
- ❑ **broadcast** (shared wire or medium)
 - traditional Ethernet
 - upstream HFC
 - 802.11 wireless LAN



shared wire
(e.g. Ethernet)



shared wireless
(e.g. Wavelan)



satellite



cocktail party

Media Access Control (MAC) protocols

- ❑ single shared communication channel
- ❑ two or more simultaneous transmissions by nodes: interference
 - only one node can send **successfully** at a time
- ❑ ***multiple access protocol:***
 - distributed algorithm that determines how stations share channel, i.e., determine when station can transmit
 - communication about channel sharing must use channel itself!
 - what to look for in multiple access protocols:
 - synchronous or asynchronous
 - information needed about other stations
 - robustness (e.g., to channel errors)
 - performance

Ideal Multiple Access Protocol

Broadcast channel of rate R bps

1. When one node wants to transmit, it can send at rate R .
2. When M nodes want to transmit, each can send at average rate R/M
3. Fully decentralized:
 - no special node to coordinate transmissions
 - no synchronization of clocks, slots
4. Simple

MAC Protocols: a taxonomy

Three broad classes:

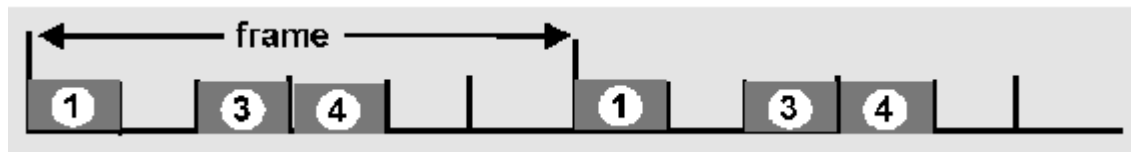
- ❑ **Channel Partitioning** TDMA, FDMA, CDMA
 - divide channel into smaller "pieces" (time slots, frequency)
 - allocate piece to node for exclusive use
- ❑ **Random Access** ALOHA, CSMA, CSMA/CD, CSMA/CA
 - allow collisions
 - "recover" from collisions
- ❑ **"Taking turns"** Polling, Token passing
 - tightly coordinate shared access to avoid collisions

Goal: efficient, fair, simple, decentralized

Channel Partitioning MAC protocols: TDMA

TDMA: time division multiple access

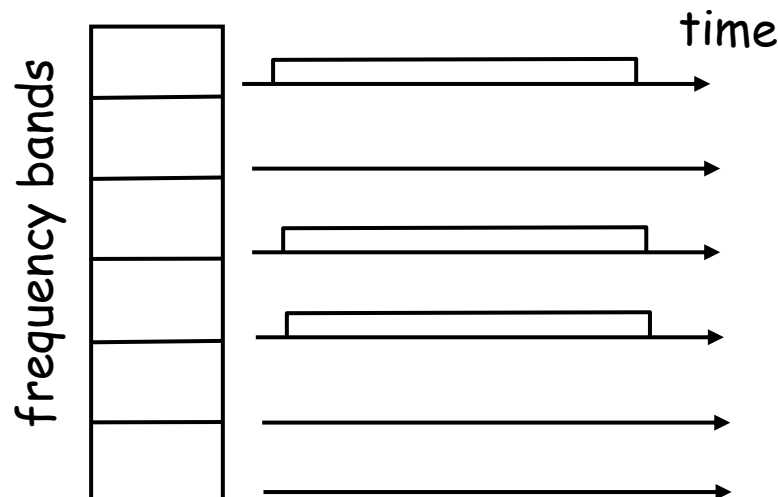
- ❑ access to channel in "rounds"
- ❑ each station gets fixed length slot (length = pkt trans time) in each round
- ❑ unused slots go idle
- ❑ example: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle



Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- ❑ channel spectrum divided into frequency bands
- ❑ each station assigned fixed frequency band
- ❑ unused transmission time in frequency bands go idle
- ❑ example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle

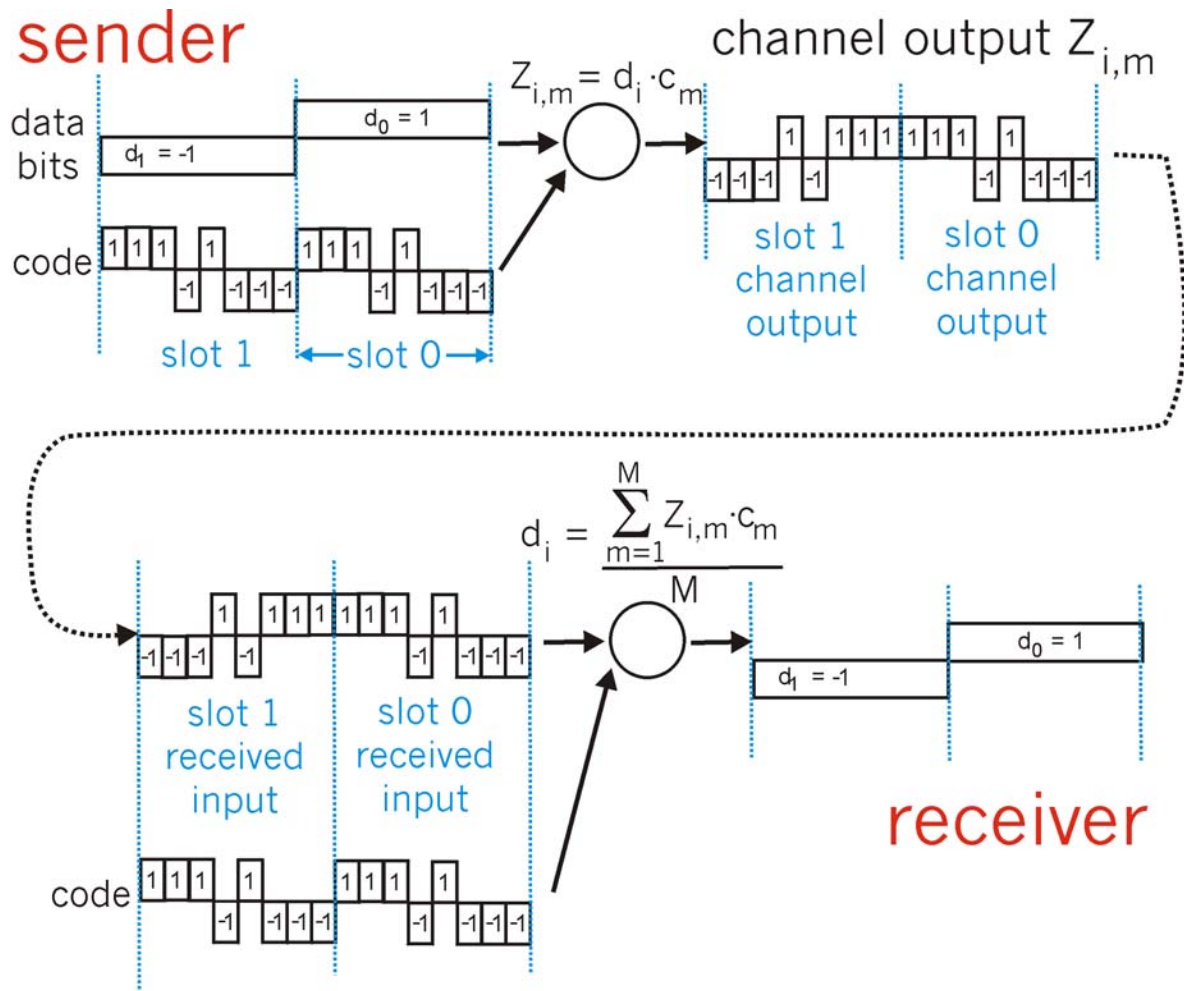


Channel Partitioning (CDMA)

CDMA (Code Division Multiple Access)

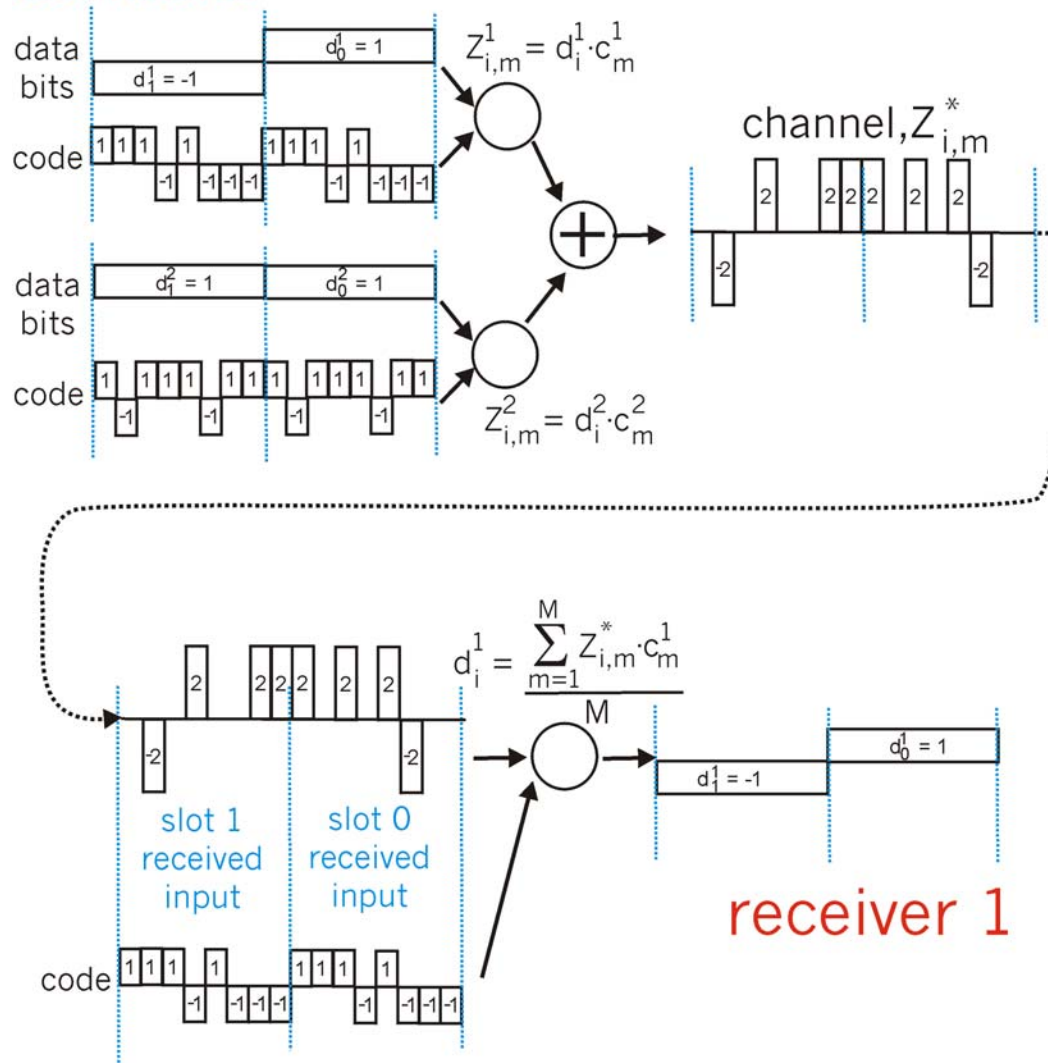
- ❑ unique “code” assigned to each user; i.e., code set partitioning
- ❑ used mostly in wireless broadcast channels (cellular, satellite, etc)
- ❑ all users share same frequency, but each user has own “chipping” sequence (i.e., code) to encode data
- ❑ *encoded signal* = (original data) X (chipping sequence)
- ❑ *decoding*: inner-product of encoded signal and chipping sequence
- ❑ allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)

CDMA Encode/Decode



CDMA: two-sender interference

senders

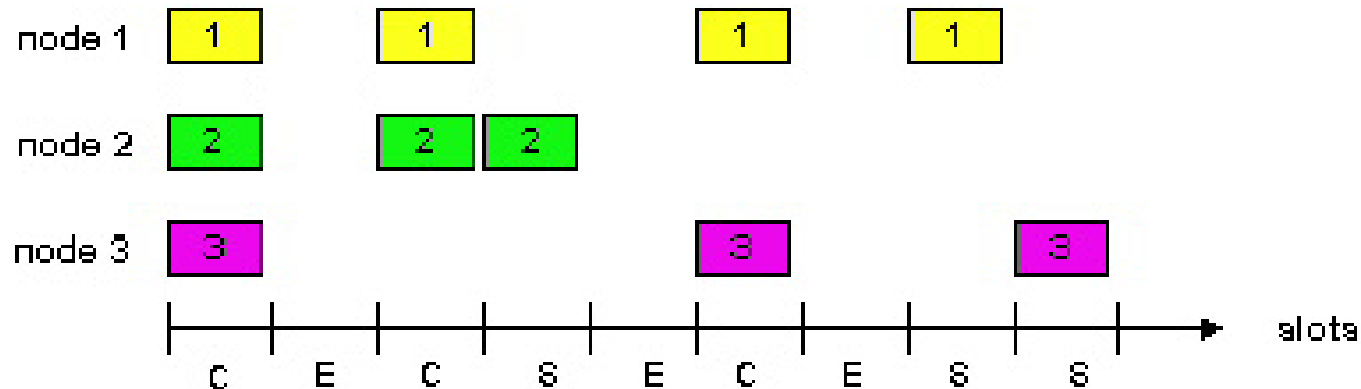


Random Access Protocols

- ❑ When node has packet to send
 - transmit at full channel data rate R .
 - no *a priori* coordination among nodes
- ❑ two or more transmitting nodes -> "collision",
- ❑ random access MAC protocol specifies:
 - how to detect collisions
 - how to recover from collisions (e.g., via delayed retransmissions)
- ❑ Examples of random access MAC protocols:
 - slotted ALOHA
 - ALOHA
 - CSMA, CSMA/CD, CSMA/CA

Slotted Aloha

- ❑ time is divided into equal size slots (= pkt trans. time)
- ❑ node with new arriving pkt: transmit at beginning of next slot
- ❑ if collision: retransmit pkt in future slots with probability p , until successful.



Success (S), Collision (C), Empty (E) slots

Slotted ALOHA

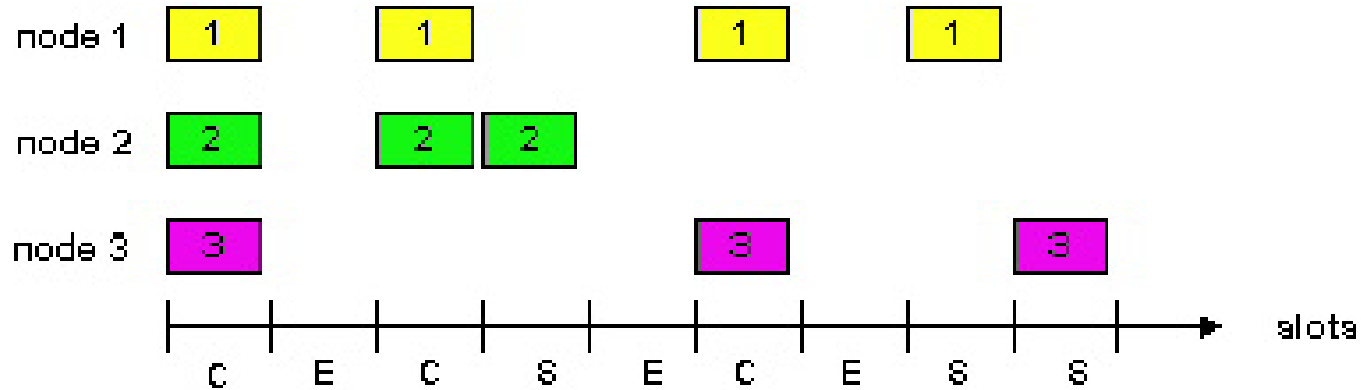
Assumptions

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

Operation

- ❑ when node obtains fresh frame, it transmits in next slot
- ❑ no collision, node can send new frame in next slot
- ❑ if collision, node retransmits frame in each subsequent slot with prob. p until success

Slotted ALOHA



Pros

- ❑ single active node can continuously transmit at full rate of channel
- ❑ highly decentralized: only slots in nodes need to be in sync
- ❑ simple

Cons

- ❑ collisions, wasting slots
- ❑ idle slots
- ❑ nodes may be able to detect collision in less than time to transmit packet

Slotted Aloha efficiency

Efficiency is the long-run fraction of successful slots when there's many nodes, each with many frames to send

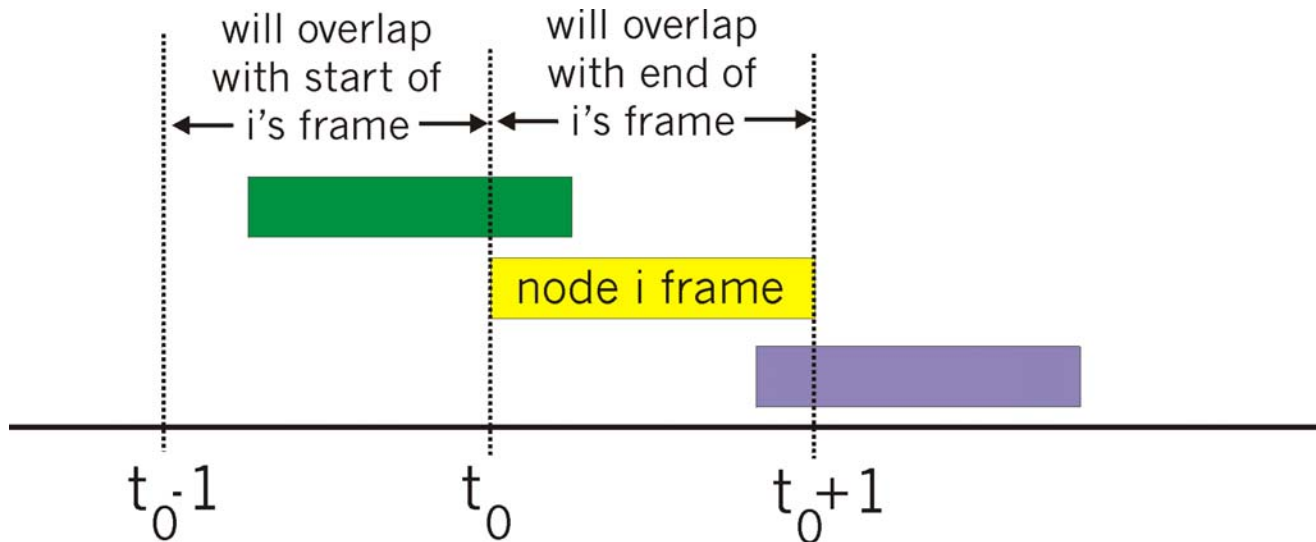
- Suppose N nodes with many frames to send, each transmits in slot with probability p
- prob that 1st node has success in a slot
 $= p(1-p)^{N-1}$
- prob that any node has a success $= Np(1-p)^{N-1}$

- For max efficiency with N nodes, find p^* that maximizes $Np(1-p)^{N-1}$
- For many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives $1/e = .37$

At best: channel used for useful transmissions 37% of time!

Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
 - transmit immediately
- collision probability increases:
 - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



Pure Aloha efficiency

$P(\text{success by given node}) = P(\text{node transmits}) \cdot$

$P(\text{no other node transmits in } [t_0-1, t_0] \cdot$

$P(\text{no other node transmits in } [t_0, t_0+1]$

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

$$= p \cdot (1-p)^{2(N-1)}$$

... choosing optimum p and then letting $n \rightarrow \infty$...

Even worse ! $= 1/(2e) = .18$

CSMA: (Carrier Sense Multiple Access)

- ❑ CSMA: Listen before transmitting
 - This is **Carrier Sensing**
 - If someone else is already transmitting then **back off** (wait) until channel is free
Wait how long?
 - If collision is detected during transmission then must retransmit the frame.
When is it retransmitted?

CSMA: (Carrier Sense Multiple Access)

□ 1-Persistent CSMA

- If channel sensed idle: transmit entire pkt
- If channel sensed busy, wait until channel becomes idle and then transmit right away.
- If collision occurs wait *random* time and then restart process

□ Non-persistent CSMA: (for nonslotted channels)

- If channel sensed idle: transmit entire pkt
- If channel sensed busy, wait *random* time before trying again.
- If collision occurs wait *random* time and then restart process

□ P-Persistent CSMA: (for slotted channels)

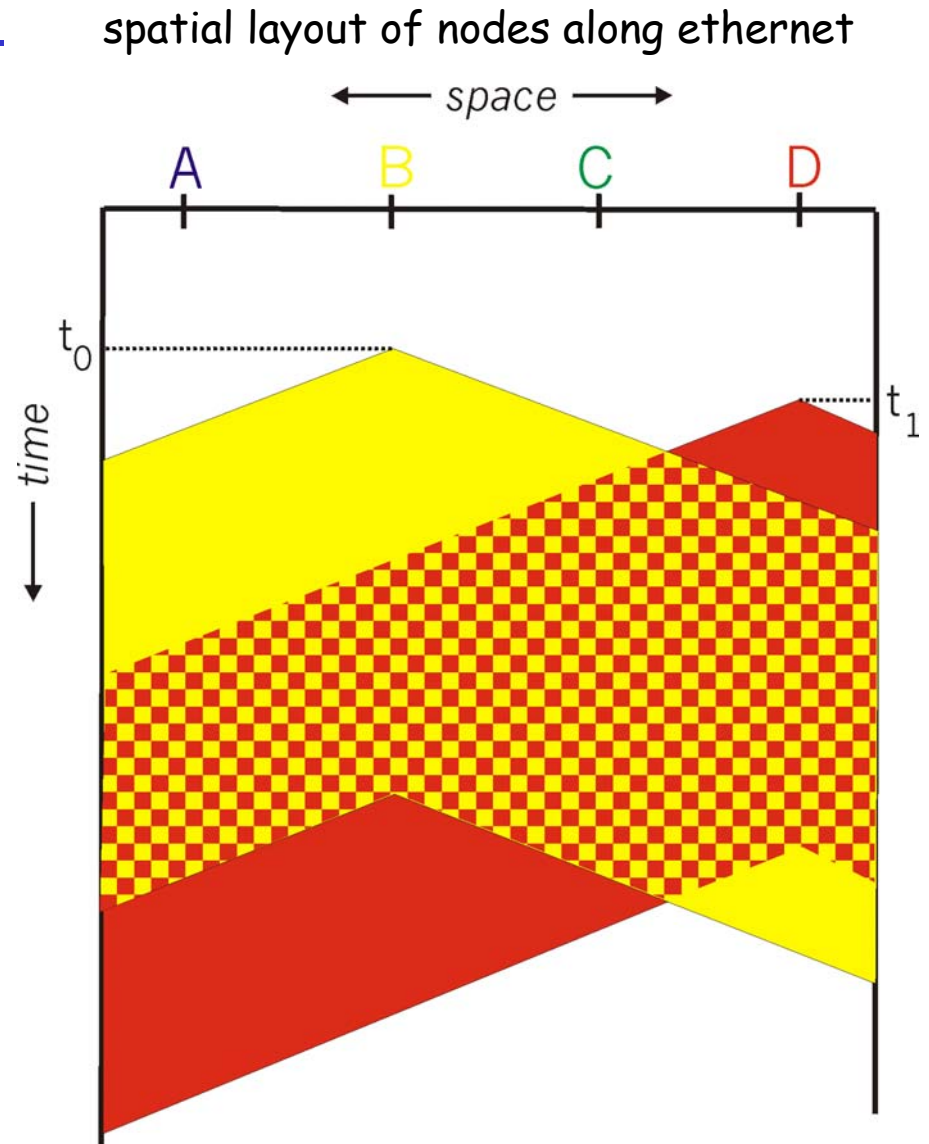
- If channel sensed idle then, with probability p , transmit in current slot. With probability $q=1-p$, wait until next slot and try again (with probability p)
- If channel sensed busy wait until next slot and try again
- If collision occurs, wait *random* time and then restart process

CSMA collisions

collisions can occur:
propagation delay means
two nodes may not hear
each other's transmission

collision:
entire packet transmission
time wasted

note:
role of distance and
propagation delay in
determining collision prob.



CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA

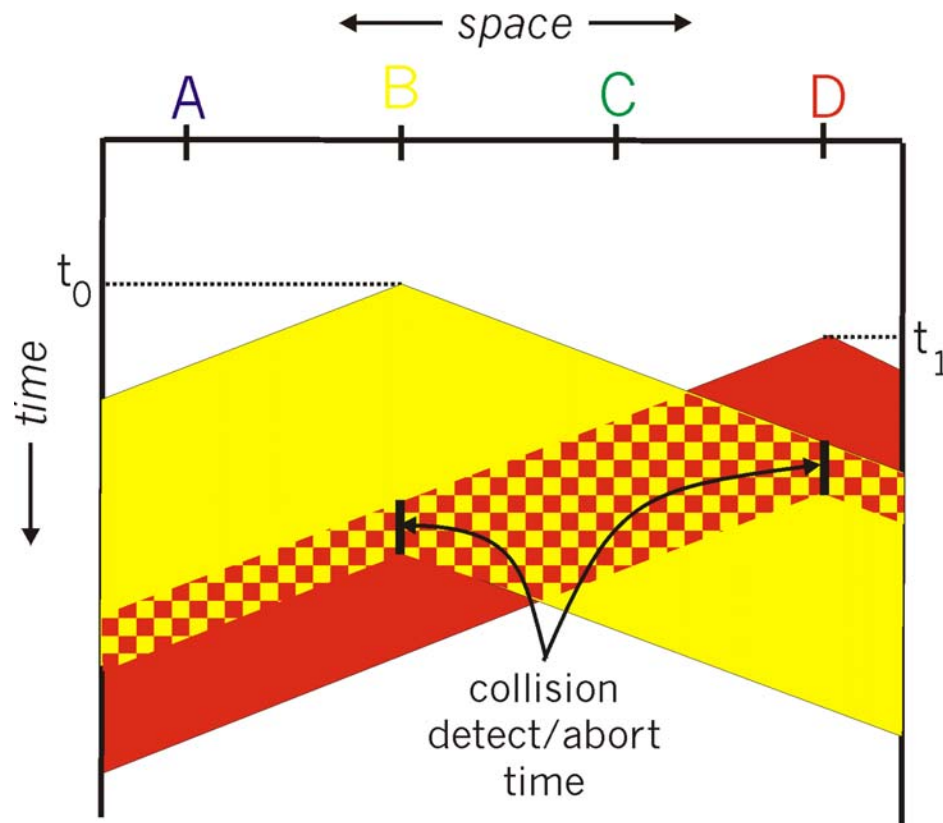
- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage

□ collision detection:

- easy in wired LANs: measure signal strengths, compare transmitted, received signals
- difficult in wireless LANs: receiver shut off while transmitting

□ human analogy: the polite conversationalist

CSMA/CD collision detection



"Taking Turns" MAC protocols

channel partitioning MAC protocols:

- share channel efficiently and fairly at high load
- inefficient at low load: delay in channel access, $1/N$ bandwidth allocated even if only 1 active node!

Random access MAC protocols

- efficient at low load: single node can fully utilize channel
- high load: collision overhead

"taking turns" protocols

look for best of both worlds!

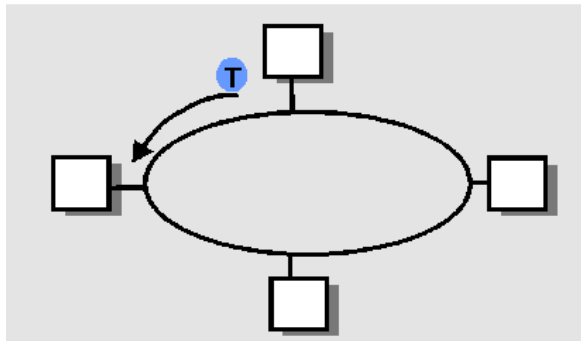
"Taking Turns" MAC protocols

Polling:

- ❑ master node
"invites" slave nodes
to transmit in turn
- ❑ concerns:
 - polling overhead
 - latency
 - single point of failure (master)

Token passing:

- ❑ control **token** passed from
one node to next
sequentially.
- ❑ token message
- ❑ concerns:
 - token overhead
 - latency
 - single point of failure (token)



Summary of MAC protocols

- ❑ What do you do with a shared media?
 - Channel Partitioning, by time, frequency or code
 - Time Division, Code Division, Frequency Division
 - Random partitioning (dynamic),
 - ALOHA, S-ALOHA, CSMA, CSMA/CD
 - carrier sensing: easy in some technologies (wire), hard in others (wireless)
 - CSMA/CD used in Ethernet
 - Taking Turns
 - polling from a central site, token passing

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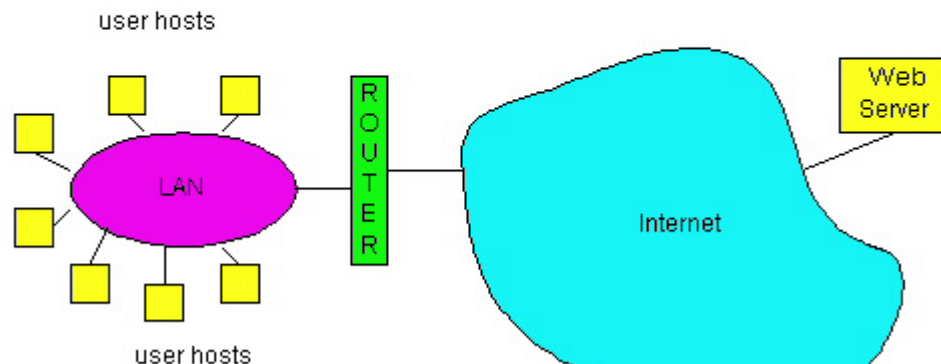
LAN technologies

Data link layer so far:

- services, error detection/correction, multiple access

Next: LAN technologies

- addressing
- Ethernet
- hubs, bridges, switches
- 802.11
- PPP
- ATM



LAN Addresses and ARP

32-bit IP address:

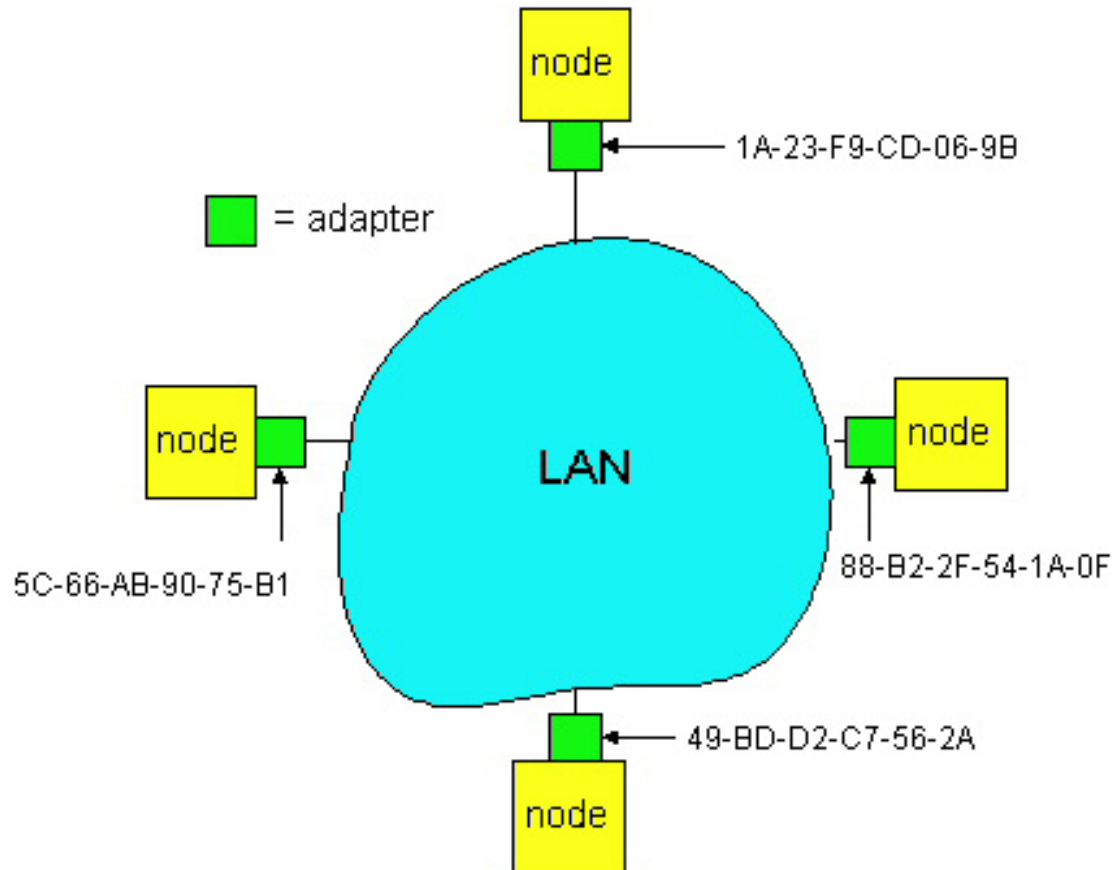
- ❑ *network-layer* address
- ❑ used to get datagram to destination IP network (recall IP network definition)

LAN (or MAC or physical or Ethernet) 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 Addresses and ARP

Each adapter on LAN has unique LAN address



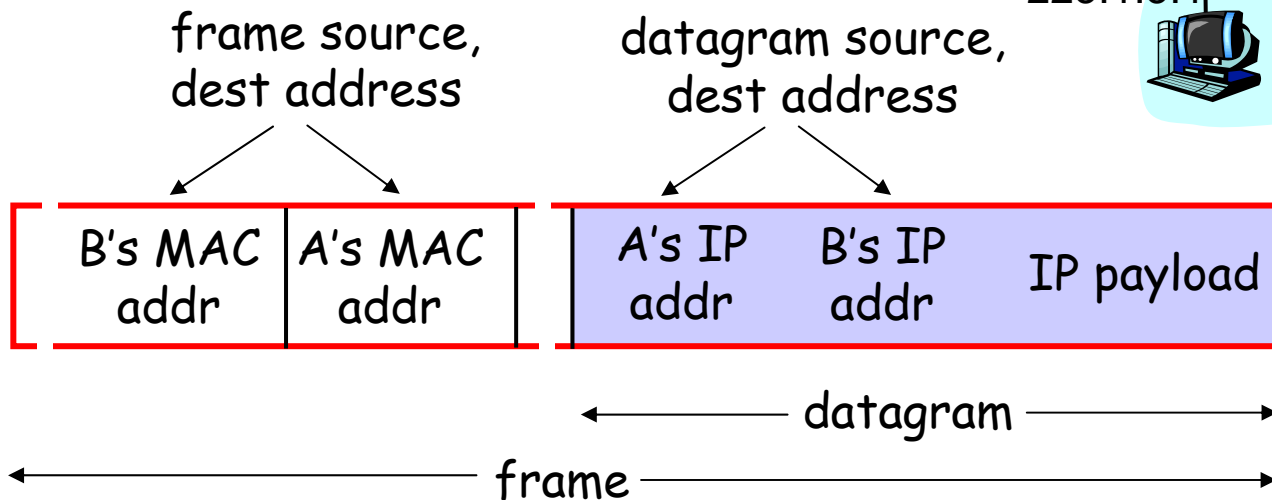
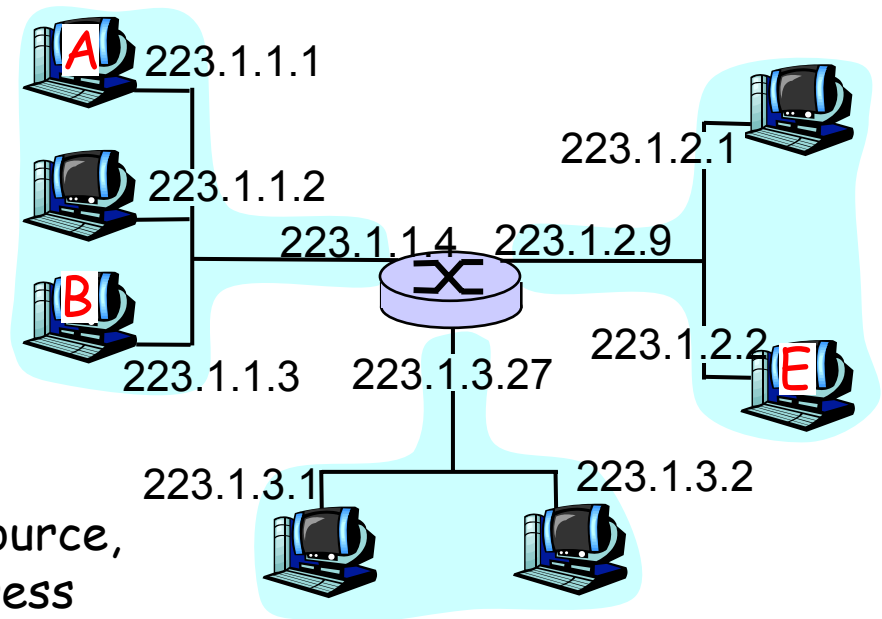
LAN Address (more)

- ❑ 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
 - depends on IP network to which node is attached

Recall earlier routing discussion

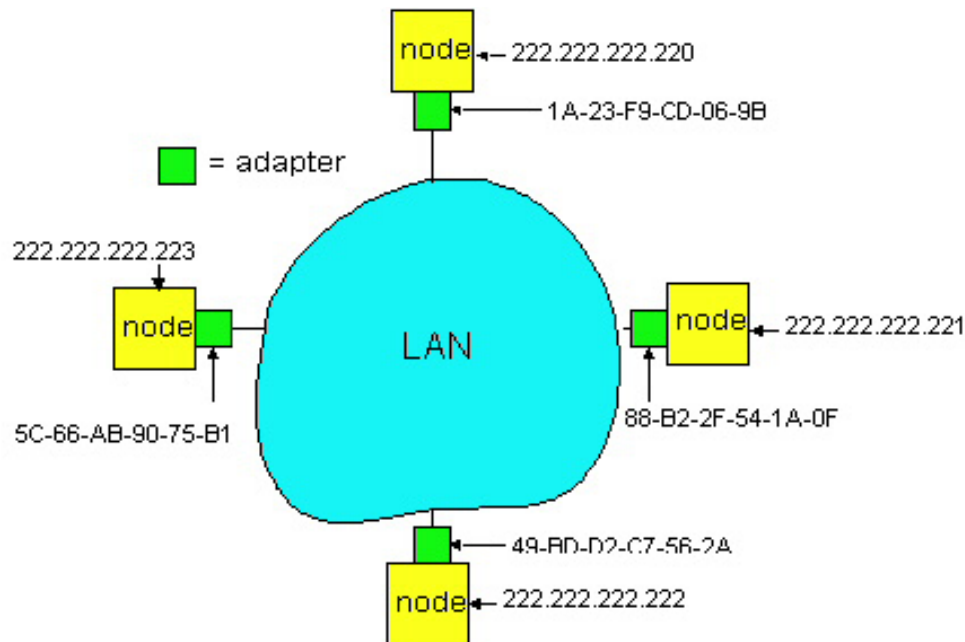
Starting at A, given IP datagram addressed to B:

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



ARP: Address Resolution Protocol

Question: how to determine MAC address of B knowing B's IP address?



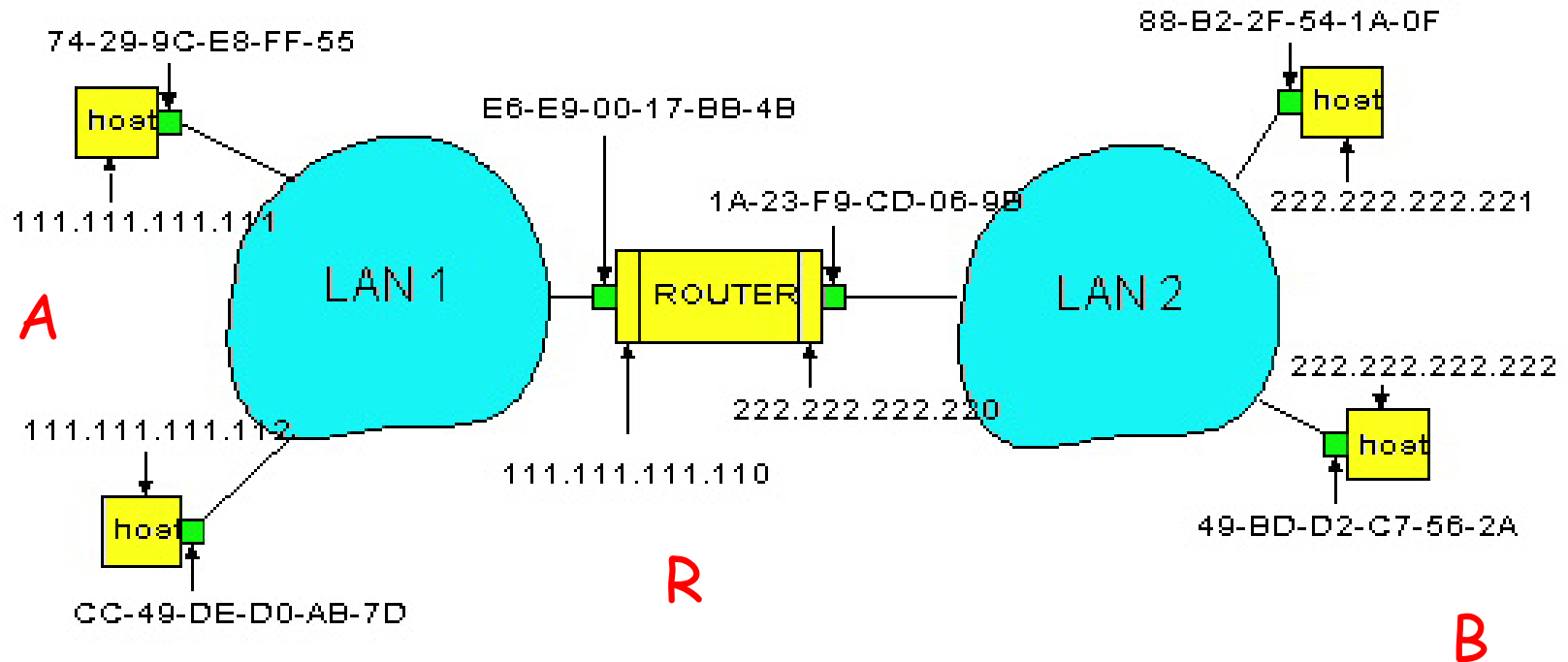
- ❑ Each IP node (Host, Router) on LAN has **ARP** table
- ❑ ARP Table: IP/MAC address mappings for some LAN nodes
 - < IP address; MAC address; TTL >
 - TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

ARP protocol

- ❑ A wants to send datagram to B, and A knows B's IP address.
- ❑ Suppose B's MAC address is not in A's ARP table.
- ❑ A **broadcasts** ARP query packet, containing B's IP address
 - 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

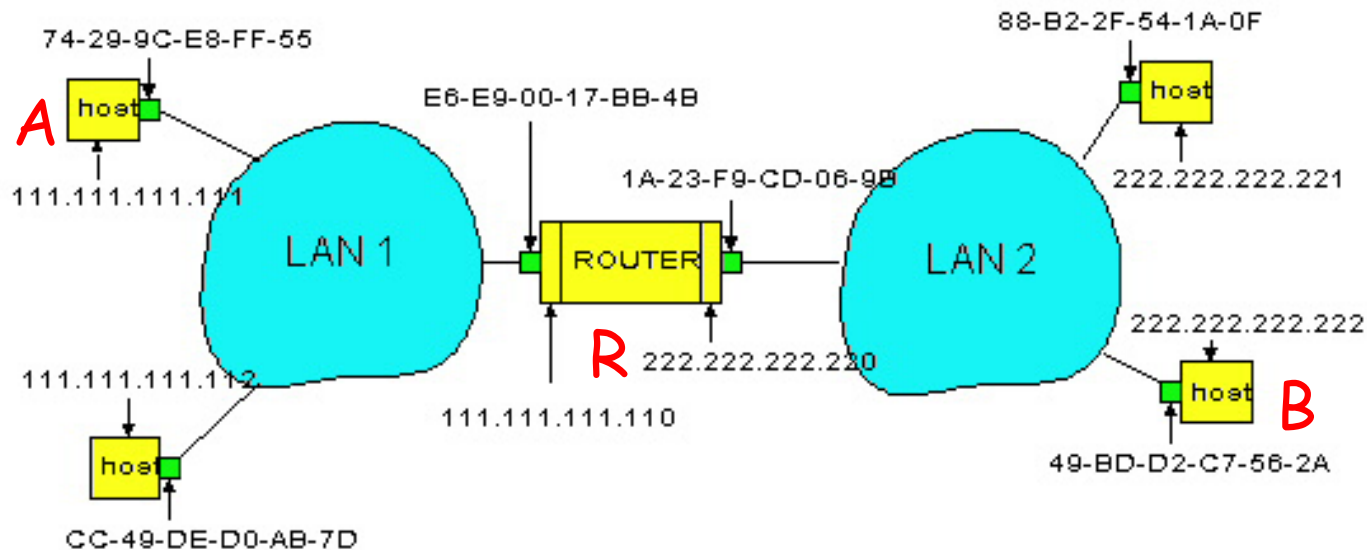
Routing to another LAN

walkthrough: **send datagram from A to B via R**
assume A knows B IP address



- Two ARP tables in router R, one for each IP network (LAN)

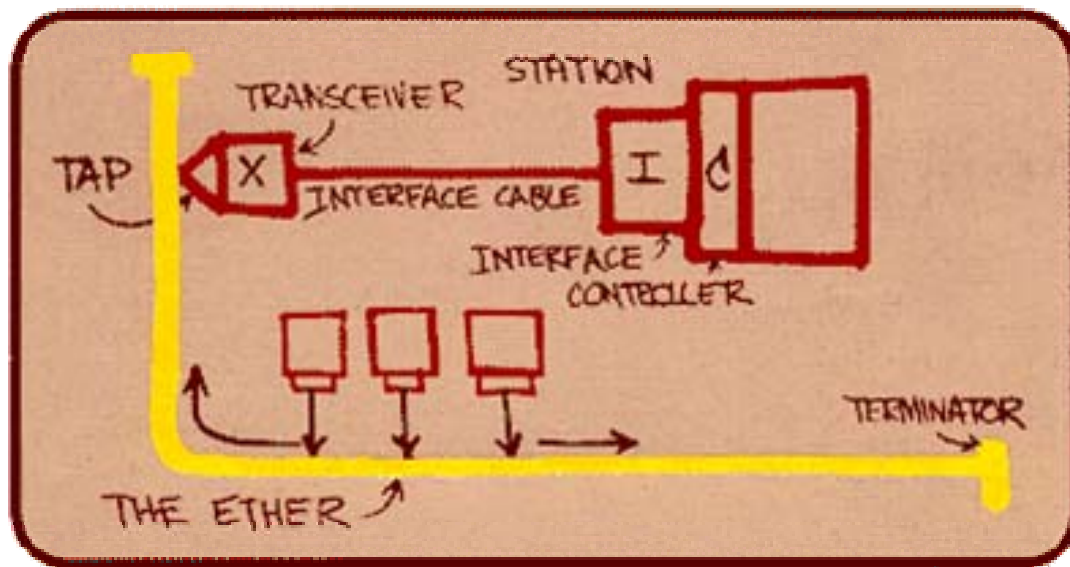
- ❑ A creates datagram with source A, destination B
- ❑ A uses ARP to get R's MAC address for 111.111.111.110
- ❑ A creates link-layer frame with R's MAC address as dest, frame contains A-to-B IP datagram
- ❑ A's data link layer sends frame
- ❑ R's data link layer receives frame
- ❑ R removes IP datagram 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



Ethernet

"dominant" LAN technology:

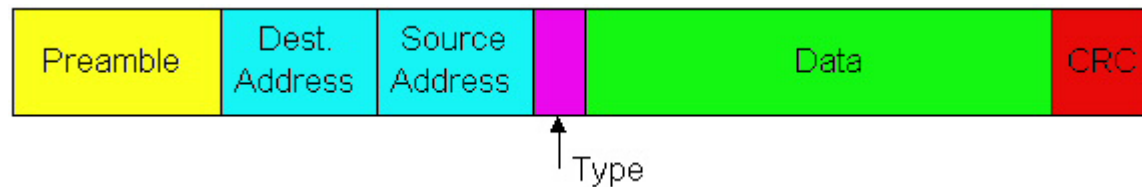
- ❑ cheap \$20 for 100Mbps!
- ❑ first widely used LAN technology
- ❑ Simpler, cheaper than token LANs and ATM
- ❑ Kept up with speed race: 10, 100, 1000 Mbps



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

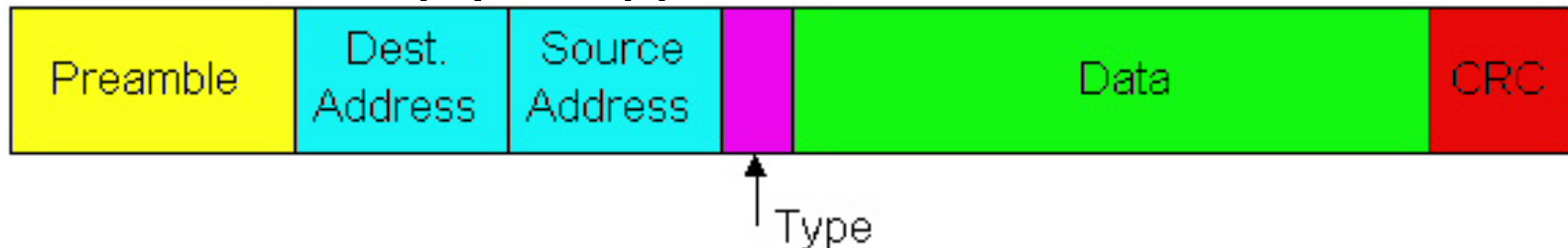
Ethernet Frame Structure (more)

❑ **Addresses:** 6 bytes

- if adapter receives frame with matching destination address, or with broadcast address (eg ARP packet), it passes data in frame to net-layer protocol
- otherwise, adapter discards frame

❑ **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



Unreliable, connectionless service

- ❑ **Connectionless:** No handshaking between sending and receiving adapter.
- ❑ **Unreliable:** receiving adapter doesn't send acks or nacks to sending adapter
 - stream of datagrams passed to network layer can have gaps
 - gaps will be filled if app is using TCP
 - otherwise, app will see the gaps

Ethernet uses CSMA/CD

- ❑ No slots
- ❑ adapter doesn't transmit if it senses that some other adapter is transmitting, that is, **carrier sense**
- ❑ transmitting adapter aborts when it senses that another adapter is transmitting, that is, **collision detection**
- ❑ Before attempting a retransmission, adapter waits a random time, that is, **random access**
random time depends upon # collisions so far

Ethernet CSMA/CD algorithm

1. Adaptor gets datagram from link and creates frame
2. If adapter senses channel idle, it starts to transmit frame. If it senses channel busy, waits until channel idle and then transmits
3. If adapter transmits entire frame without detecting another transmission, the adapter is done with frame !
4. If adapter detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, adapter enters **exponential backoff**: after the m th collision, adapter chooses a K at random from $\{0, 1, 2, \dots, 2^m - 1\}$. Adapter waits $K \times 512$ bit times and returns to Step 2

Ethernet: slotless, uses CSMA/CD

create frame from datagram

A: sense channel; if idle

then {

transmit frame 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 $K \times 512$ bit transmission times (btt = .1 microsec for 10Mbps Ethernet)
- ❑ after second collision: choose K from $\{0,1,2,3\}$...
- ❑ after ten or more collisions, choose K from $\{0,1,2,3,4,...,1023\}$

CSMA/CD efficiency

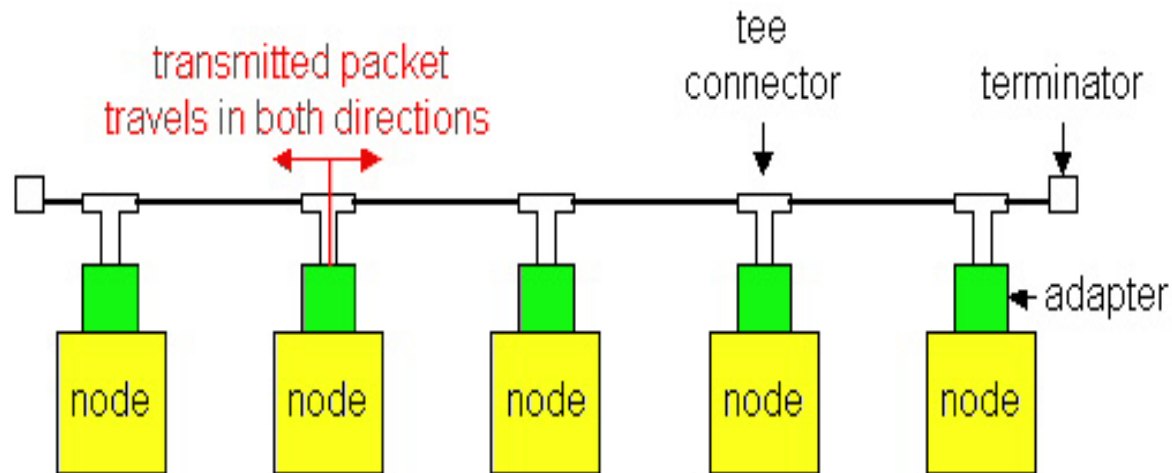
- T_{prop} = max prop between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame

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

- Efficiency goes to 1 as t_{prop} goes to 0
- Goes to 1 as t_{trans} goes to infinity
- Much better than ALOHA, but still decentralized, simple, and cheap

Ethernet Technologies: 10Base2

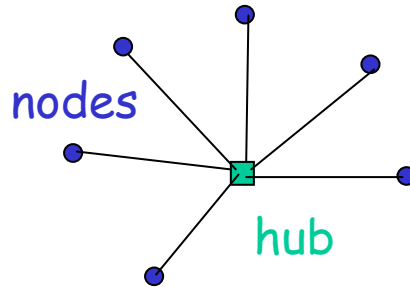
- ❑ 10: 10Mbps; 2: under 200 meters max cable length
- ❑ thin coaxial cable in a bus topology



- ❑ repeaters used to connect up to 5 multiple segments
- ❑ repeater repeats bits it hears on one interface to its other interfaces: physical layer device only!
- ❑ has become a legacy technology

10BaseT and 100BaseT

- ❑ 10/100 Mbps rate; latter called "fast ethernet"
- ❑ T stands for Twisted Pair
- ❑ Nodes connect to a hub: "star topology"; 100 m max distance between nodes and hub



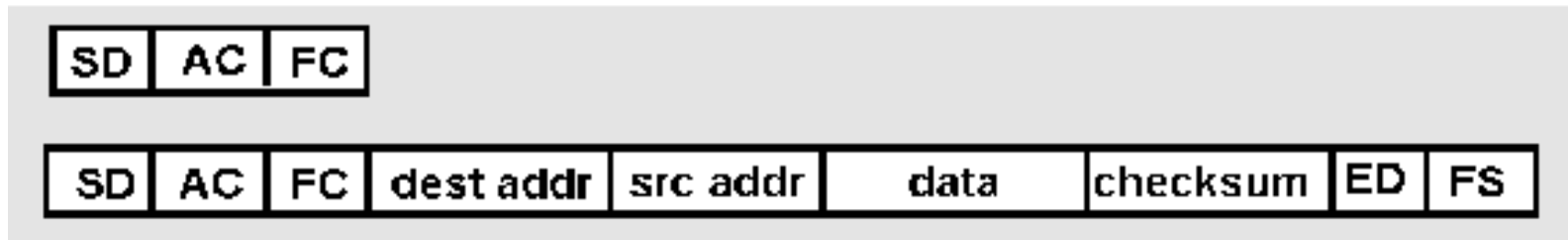
- ❑ Hubs are essentially physical-layer repeaters:
 - bits coming in one link go out all other links
 - no frame buffering
 - no CSMA/CD at hub: adapters detect collisions
 - provides net management functionality

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
- ❑ 10 Gbps now !

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
 - DLC-level ACKing

Chapter 5 outline

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- ❑ 5.2 Error detection and correction
- ❑ 5.3 Multiple access protocols
- ❑ 5.4 LAN addresses and ARP
- ❑ 5.5 Ethernet
- ❑ 5.6 Hubs, bridges, and switches
- ❑ 5.7 Wireless links and LANs
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- ❑ 5.9 ATM
- ❑ 5.10 Frame Relay

Interconnecting LANs

Q: Why not just one big LAN?

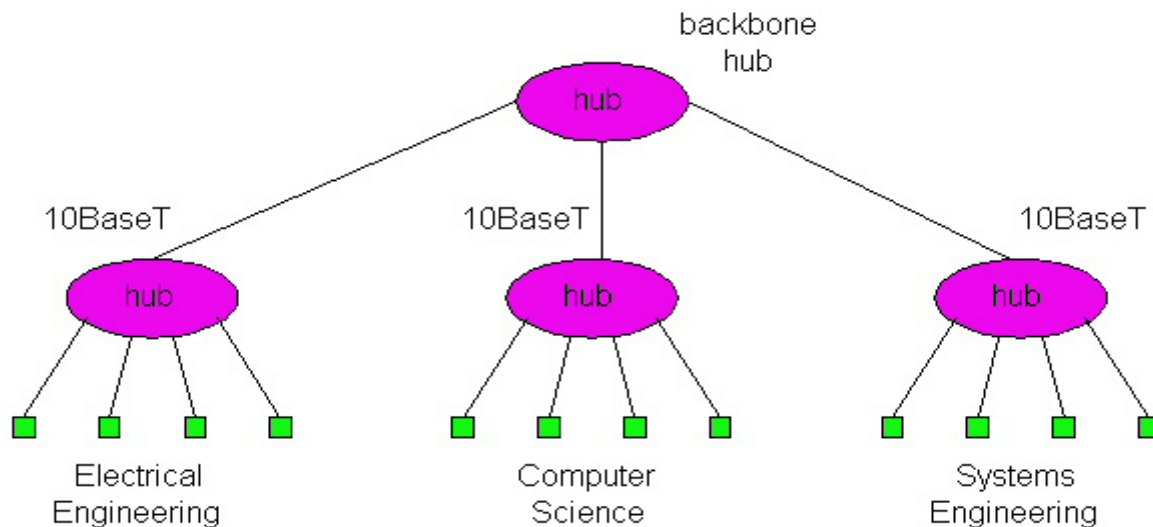
- ❑ Limited amount of supportable traffic: on single LAN, all stations must share bandwidth
- ❑ limited length: 802.3 specifies maximum cable length
- ❑ large "collision domain" (can collide with many stations)
- ❑ limited number of stations: 802.5 have token passing delays at each station

Interconnecting LAN segments

- ❑ Hubs
- ❑ Bridges
- ❑ Switches
 - Remark: switches are essentially multi-port bridges.
 - What we say about bridges also holds for switches!

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

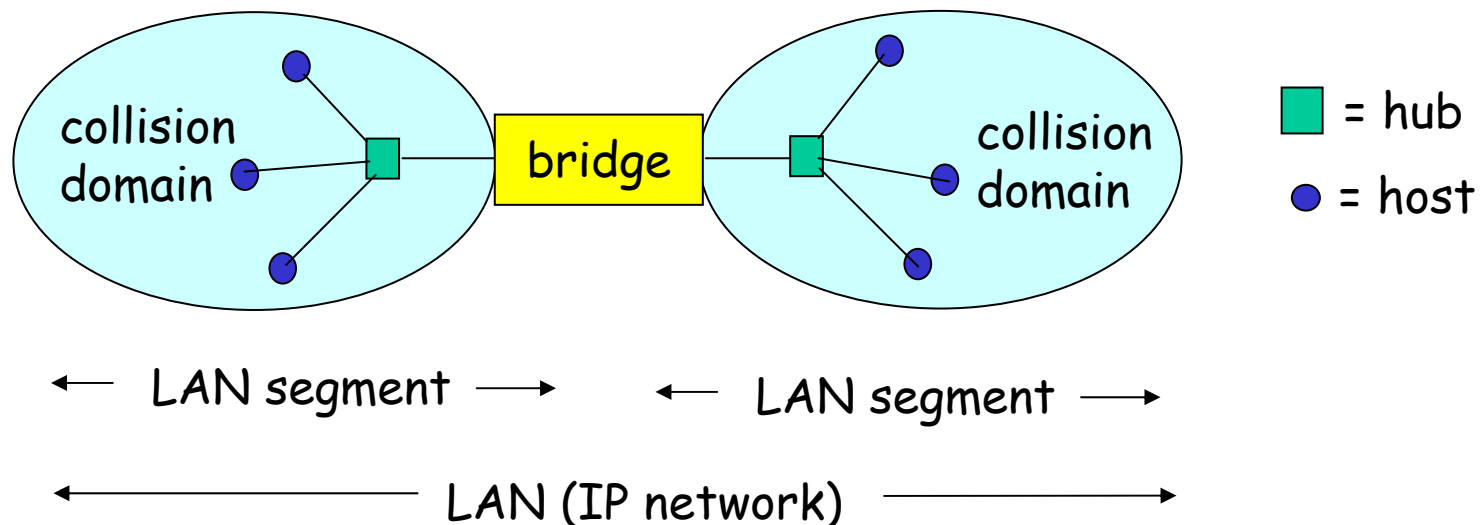
- ❑ single collision domain results in no increase in max throughput
 - multi-tier throughput same as single segment throughput
- ❑ individual LAN restrictions pose limits on number of nodes in same collision domain and on total allowed geographical coverage
- ❑ cannot connect different Ethernet types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

Bridges

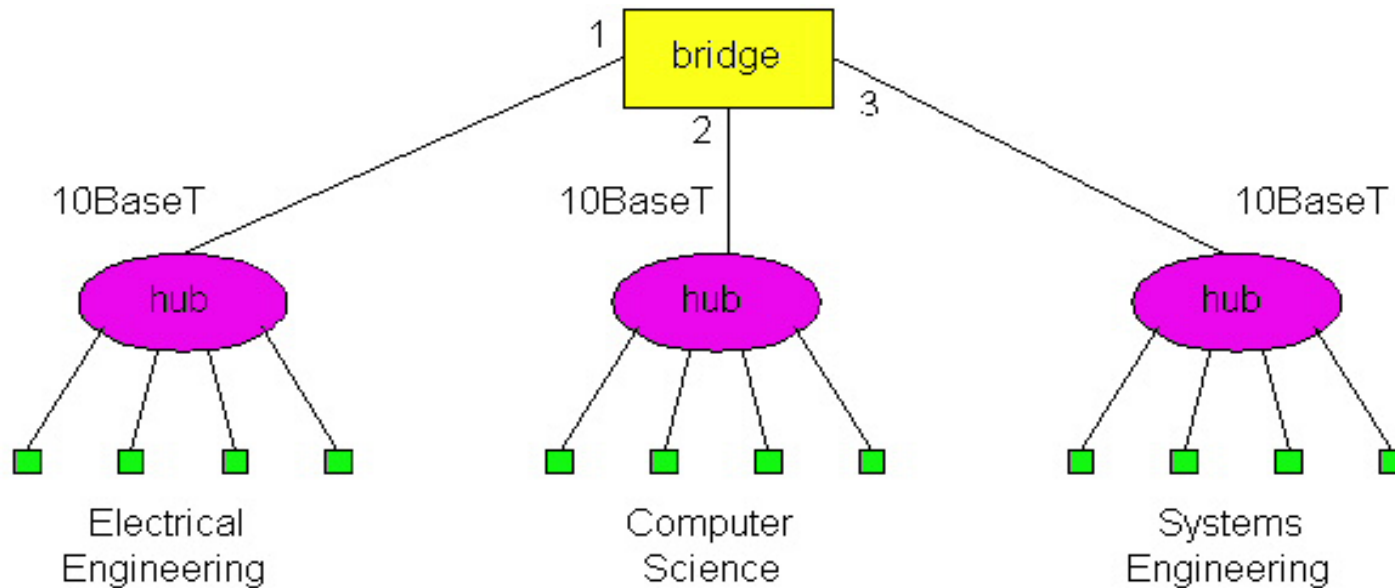
- ❑ Link layer device
 - stores and forwards Ethernet frames
 - examines frame header and **selectively** forwards frame based on MAC dest address
 - when frame is to be forwarded on segment, uses CSMA/CD to access segment
- ❑ transparent
 - hosts are unaware of presence of bridges
- ❑ plug-and-play, self-learning
 - bridges do not need to be configured

Bridges: traffic isolation

- ❑ Bridge installation breaks LAN into LAN segments
- ❑ bridges **filter** packets:
 - same-LAN-segment frames not usually forwarded onto other LAN segments
 - segments become separate **collision domains**



Bridges: Forwarding



How do determine to which LAN segment to forward frame?

- Looks like a routing problem...

Bridges: Self learning

- ❑ A bridge has a **bridge table**
- ❑ entry in bridge table:
 - (Node LAN Address, Bridge Interface, Time Stamp)
 - stale entries in table dropped (TTL can be 60 min)
- ❑ bridges **learn** which hosts can be reached through which interfaces
 - when frame received, bridge “learns” location of sender: incoming LAN segment
 - records sender/location pair in bridge table

Bridges: Filtering/Forwarding

When bridge receives a frame:

index bridge table using MAC dest address

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

}

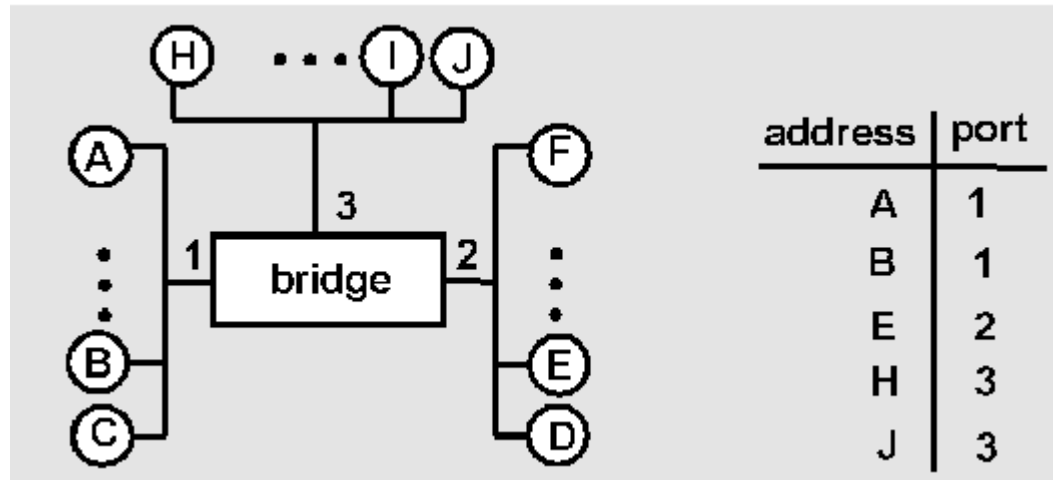
else flood



*forward on all but the interface
on which the frame arrived*

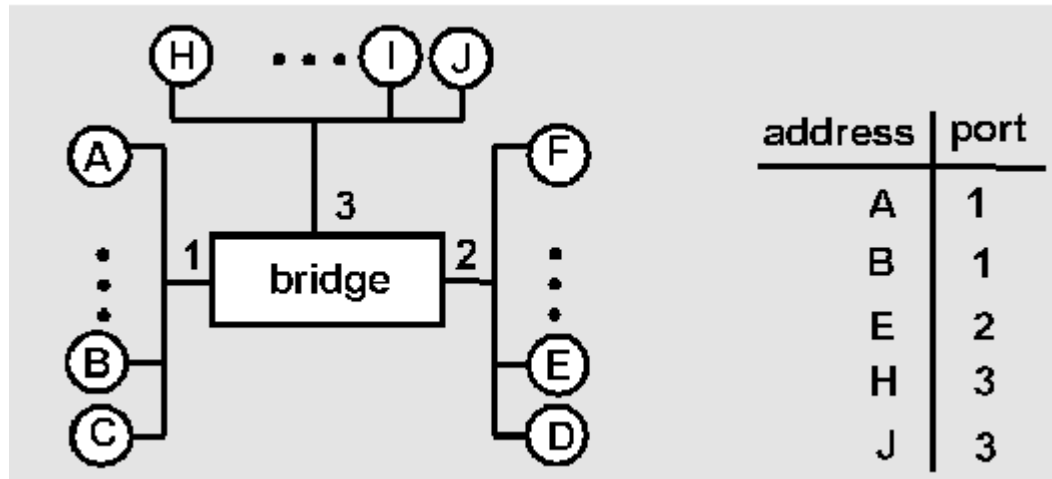
Bridge example

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



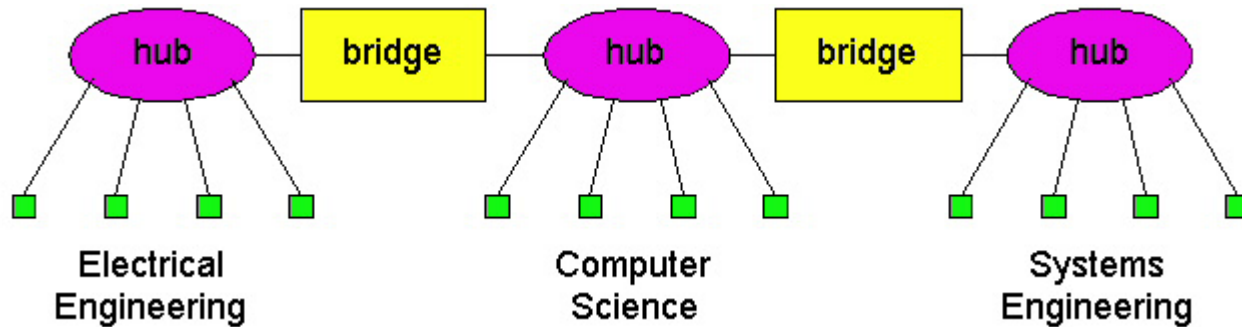
- ❑ Bridge receives frame from from C
 - notes in bridge table that C is on interface 1
 - because D is not in table, bridge sends frame into interfaces 2 and 3
- ❑ frame received by D

Bridge Learning: example



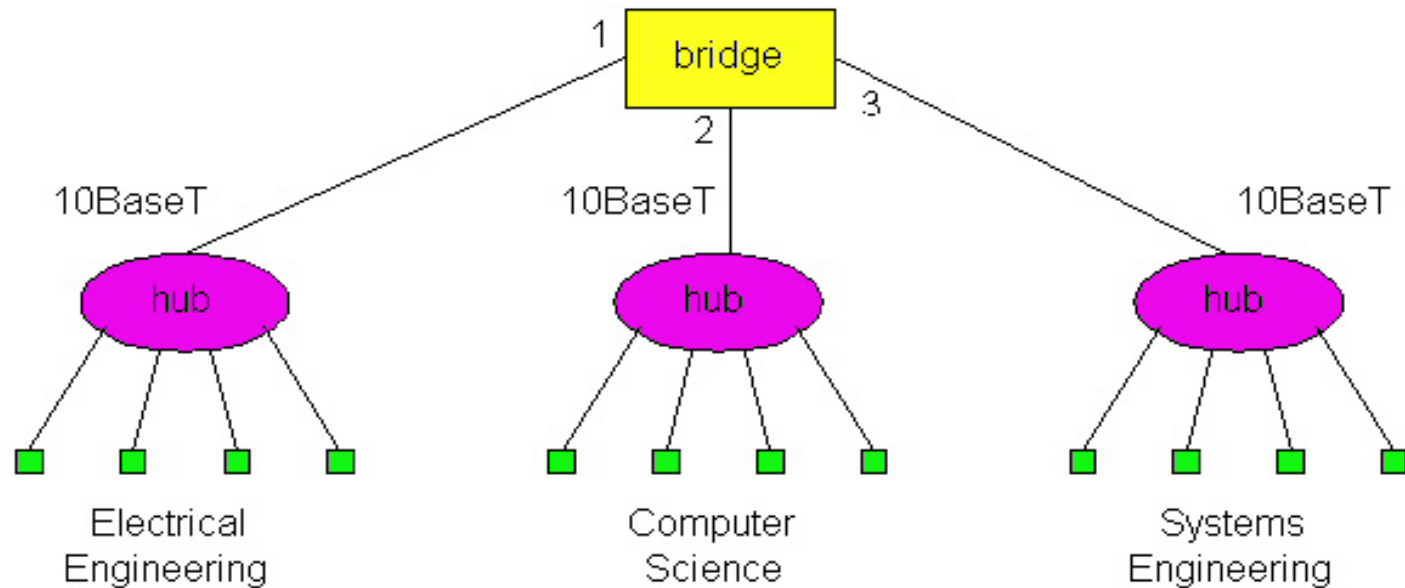
- ❑ D generates frame for C, sends
- ❑ bridge receives frame
 - notes in bridge table that D is on interface 2
 - bridge knows C is on interface 1, so *selectively* forwards frame to interface 1

Bridges: 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

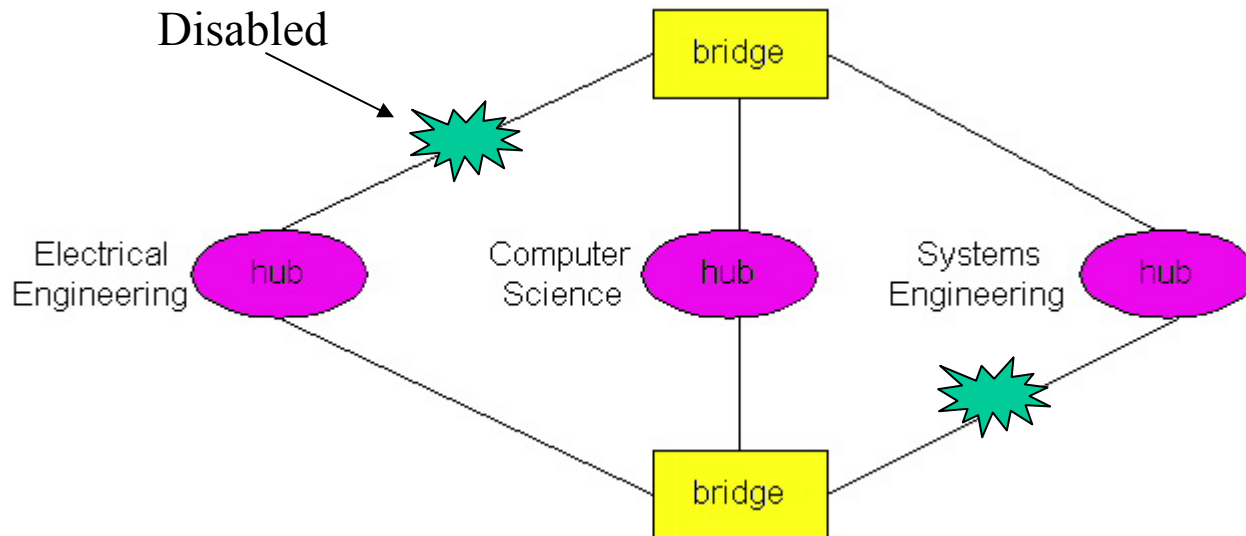
Bridges: Backbone configuration



Recommended !

Bridges Spanning Tree

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

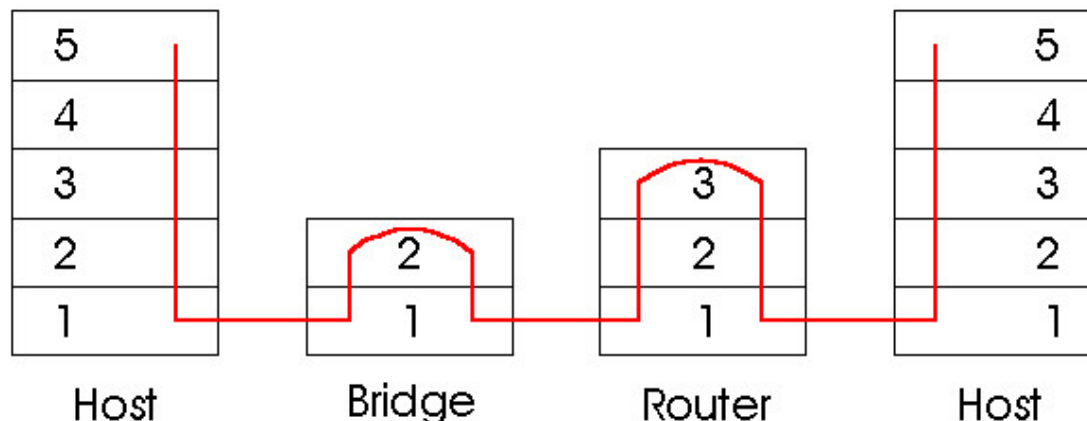


Some bridge features

- ❑ Isolates collision domains resulting in higher total max throughput
- ❑ limitless number of nodes and geographical coverage
- ❑ Can connect different Ethernet types
- ❑ Transparent ("plug-and-play"): no configuration necessary

Bridges vs. Routers

- ❑ both store-and-forward devices
 - routers: network layer devices (examine network layer headers)
 - bridges are link layer devices
- ❑ routers maintain routing tables, implement routing algorithms
- ❑ bridges maintain bridge tables, implement filtering, learning and spanning tree algorithms



Routers vs. Bridges

Bridges + and -

- + Bridge operation is simpler requiring less packet processing
- + Bridge tables are self learning
- All traffic confined to spanning tree, even when alternative bandwidth is available
- Bridges do not offer protection from broadcast storms

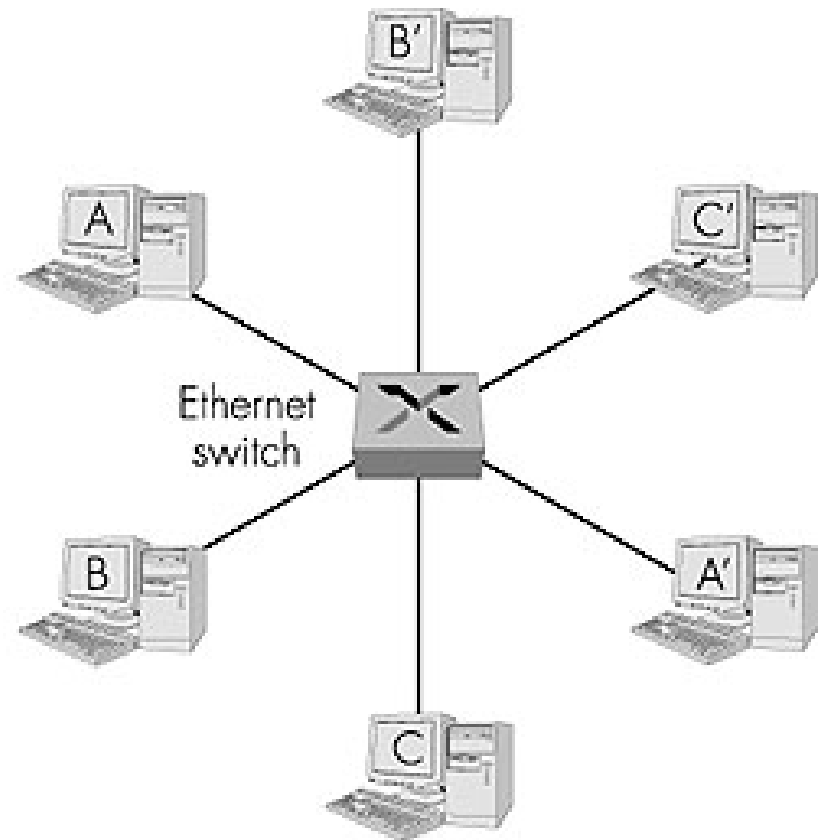
Routers vs. Bridges

Routers + and -

- + arbitrary topologies can be supported, cycling is limited by TTL counters (and good routing protocols)
 - + provide protection against broadcast storms
 - require IP address configuration (not plug and play)
 - require higher packet processing
- bridges do well in small (few hundred hosts) while routers used in large networks (thousands of hosts)

Ethernet Switches

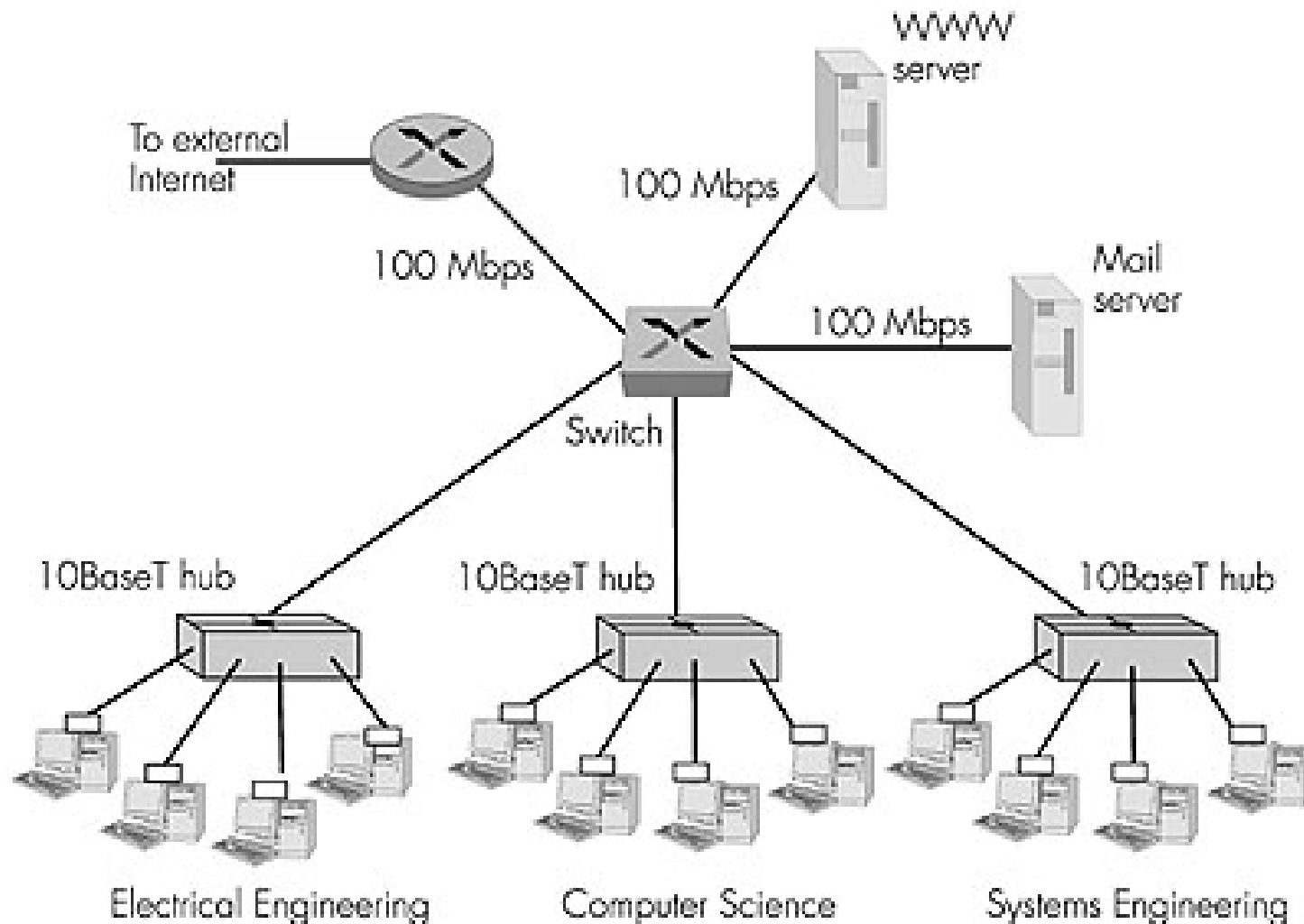
- ❑ Essentially a multi-interface bridge
- ❑ layer 2 (frame) forwarding, filtering using LAN addresses
- ❑ **Switching:** A-to-A' and B-to-B' simultaneously, no collisions
- ❑ large number of interfaces
- ❑ often: individual hosts, star-connected into switch
 - Ethernet, but no collisions!



Ethernet Switches

- ❑ **cut-through switching:** frame forwarded from input to output port without awaiting for assembly of entire frame
 - slight reduction in latency
- ❑ combinations of shared/dedicated, 10/100/1000 Mbps interfaces

Not an atypical LAN (IP network)



Summary comparison

	<u>hubs</u>	<u>bridges</u>	<u>routers</u>	<u>switches</u>
traffic isolation	no	yes	yes	yes
plug & play	yes	yes	no	yes
optimal routing	no	no	yes	no
cut through	yes	no	no	yes

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IEEE 802.11 Wireless LAN

❑ 802.11b

- 2.4-5 GHz unlicensed radio spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
 - all hosts use same chipping code
- widely deployed, using base stations

❑ 802.11a

- 5-6 GHz range
- up to 54 Mbps

❑ 802.11g

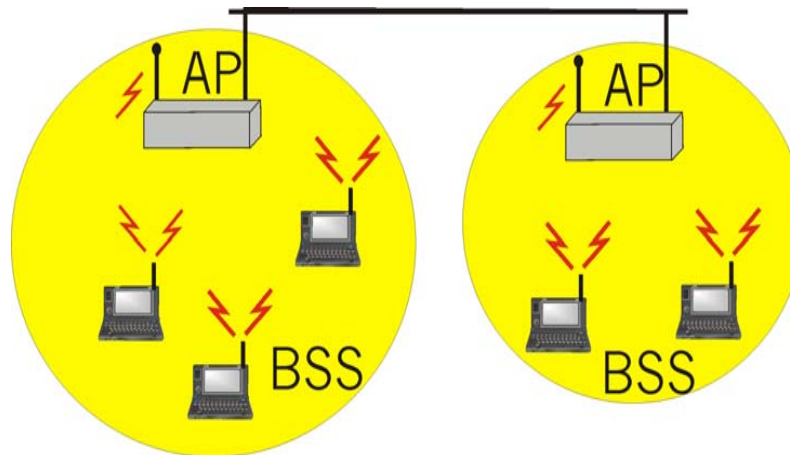
- 2.4-5 GHz range
- up to 54 Mbps

❑ All use CSMA/CA for multiple access

❑ All have base-station and ad-hoc network versions

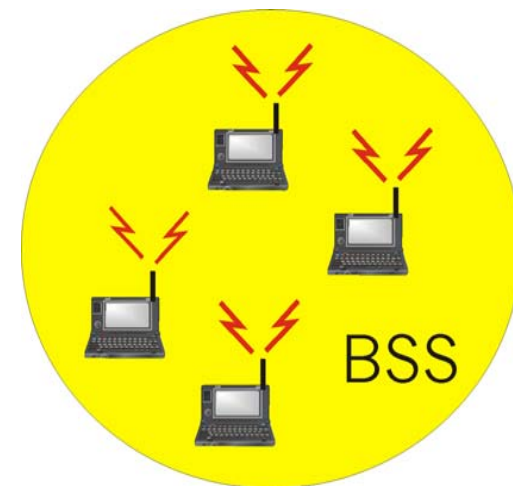
Base station approach

- ❑ Wireless host communicates with a base station
 - base station = access point (AP)
- ❑ **Basic Service Set (BSS)** (a.k.a. "cell") contains:
 - wireless hosts
 - access point (AP): base station
- ❑ BSSs combined to form distribution system (DS)



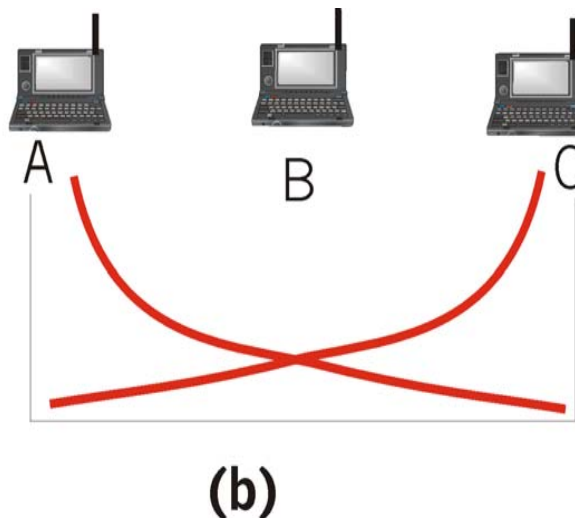
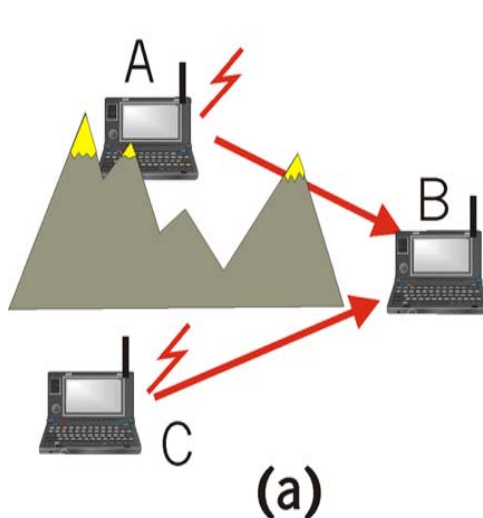
Ad Hoc Network approach

- ❑ No AP (i.e., base station)
- ❑ wireless hosts communicate with each other
 - to get packet from wireless host A to B may need to route through wireless hosts X,Y,Z
- ❑ Applications:
 - "laptop" meeting in conference room, car
 - interconnection of "personal" devices
 - battlefield
- ❑ IETF MANET (Mobile Ad hoc Networks) working group



IEEE 802.11: multiple access

- ❑ Collision if 2 or more nodes transmit at same time
- ❑ CSMA makes sense:
 - get all the bandwidth if you're the only one transmitting
 - shouldn't cause a collision if you sense another transmission
- ❑ Collision detection doesn't work: **hidden terminal problem**



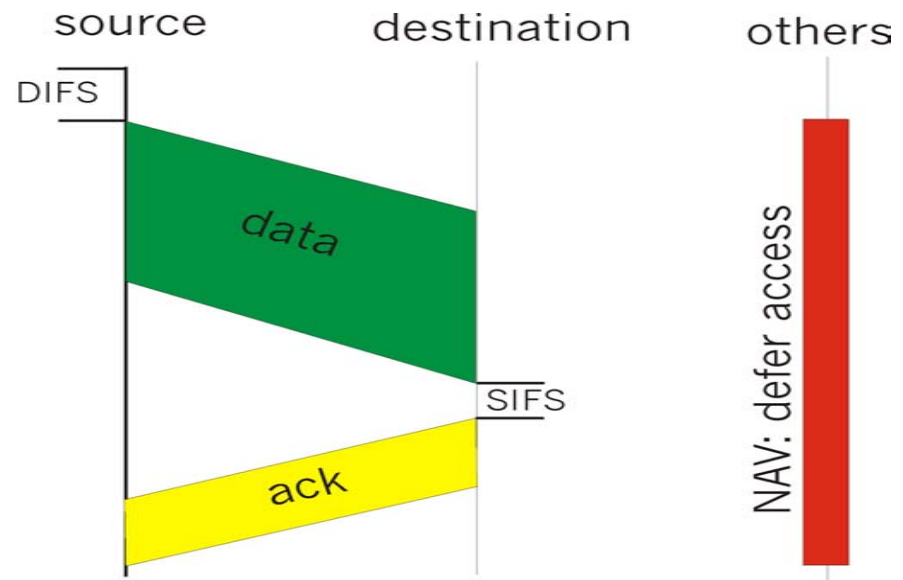
IEEE 802.11 MAC Protocol: CSMA/CA

802.11 CSMA: sender

- if sense channel idle for **DIFS** 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**
(ACK is needed due to hidden terminal problem)



Collision avoidance mechanisms

❑ Problem:

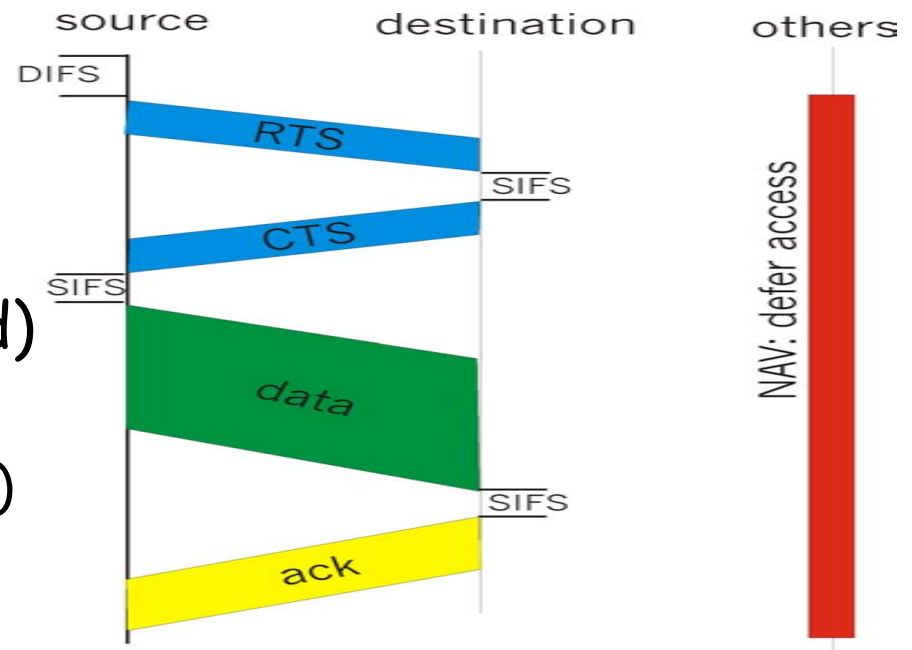
- two nodes, hidden from each other, transmit complete frames to base station
- wasted bandwidth for long duration !

❑ Solution:

- small reservation packets
- nodes track reservation interval with internal "network allocation vector" (NAV)

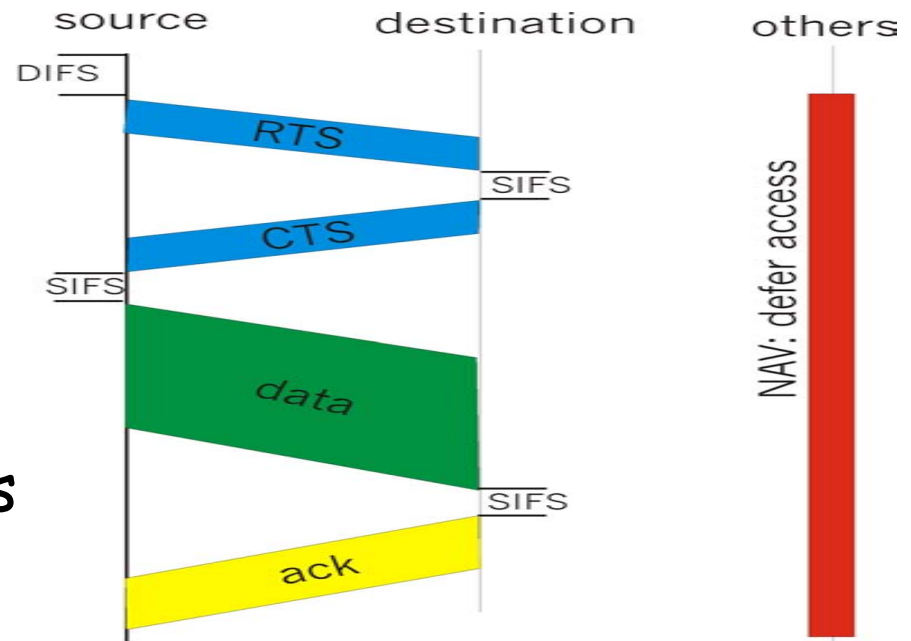
Collision Avoidance: RTS-CTS exchange

- sender transmits short RTS (request to send) packet: indicates duration of transmission
- receiver replies with short CTS (clear to send) packet
 - notifying (possibly hidden) nodes
- hidden nodes will not transmit for specified duration: NAV



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



A word about Bluetooth

- ❑ Low-power, small radius, wireless networking technology
 - 10-100 meters
- ❑ omnidirectional
 - not line-of-sight infrared
- ❑ Interconnects gadgets
- ❑ 2.4-2.5 GHz unlicensed radio band
- ❑ up to 721 kbps
- ❑ Interference from wireless LANs, digital cordless phones, microwave ovens:
 - frequency hopping helps
- ❑ MAC protocol supports:
 - error correction
 - ARQ
- ❑ Each node has a 12-bit address

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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 (Data link used to be considered “high layer” in protocol stack!)

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 liveness:** detect, signal link failure to network layer
- ❑ **network layer address negotiation:** endpoint can learn/configure each other's network address

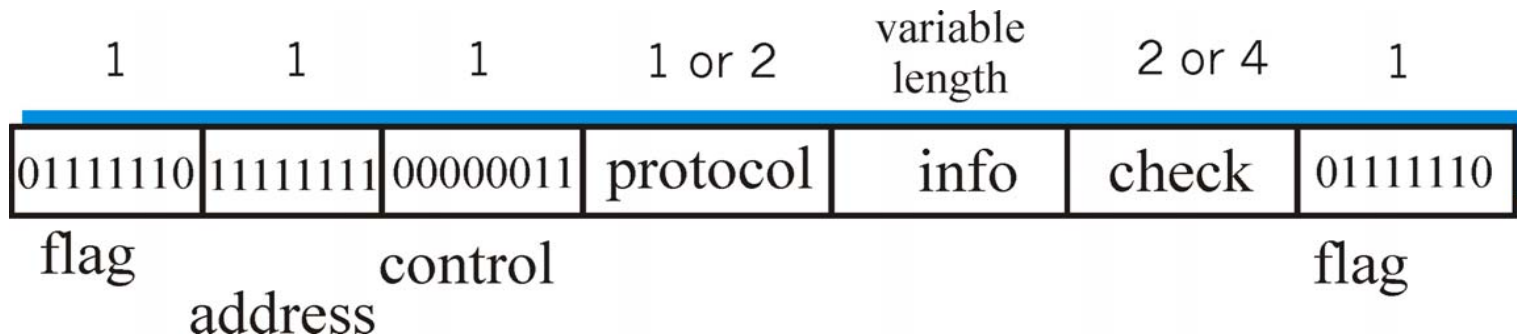
PPP non-requirements

- ❑ 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!

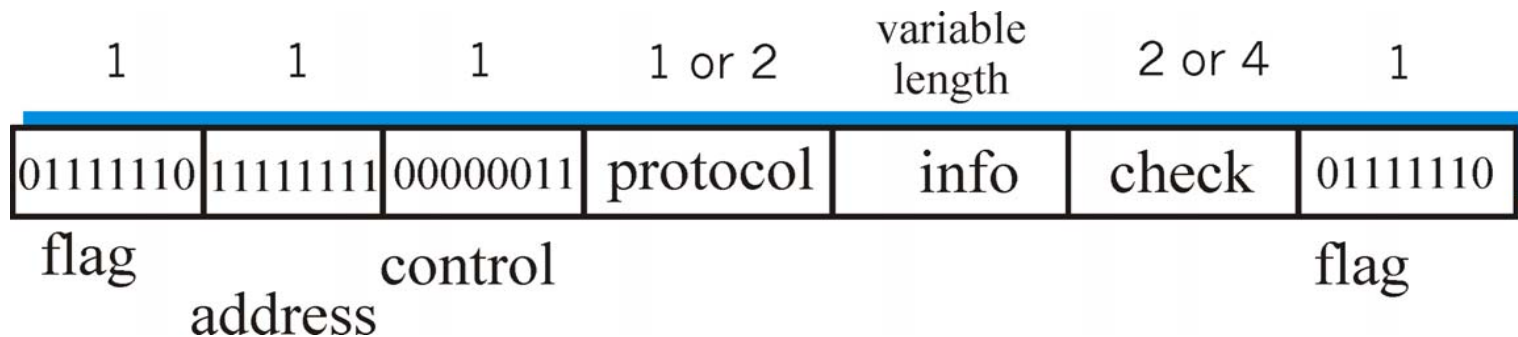
PPP Data Frame

- ❑ **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

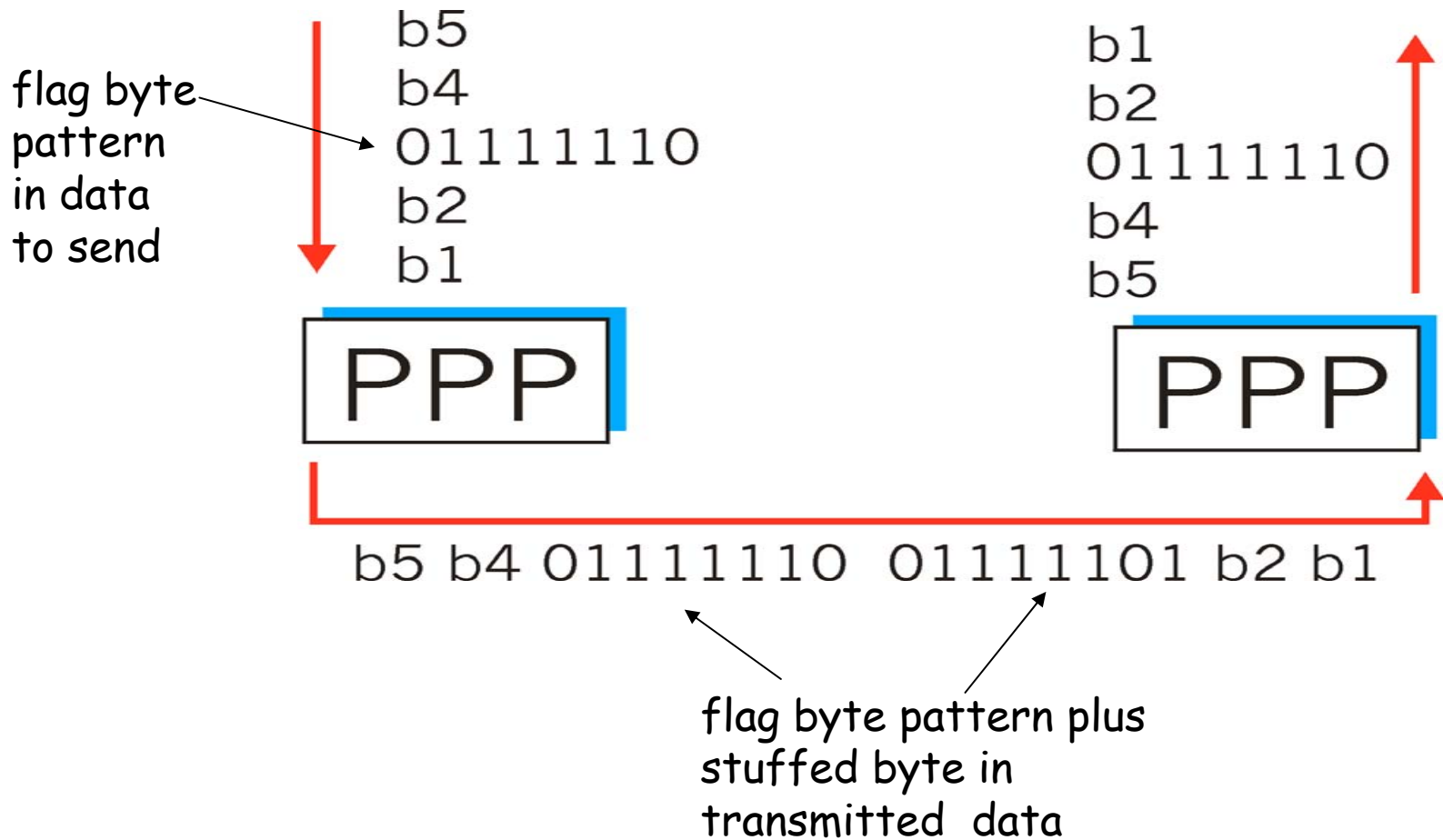
- **info**: upper layer data being carried
- **check**: cyclic redundancy check for error detection



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

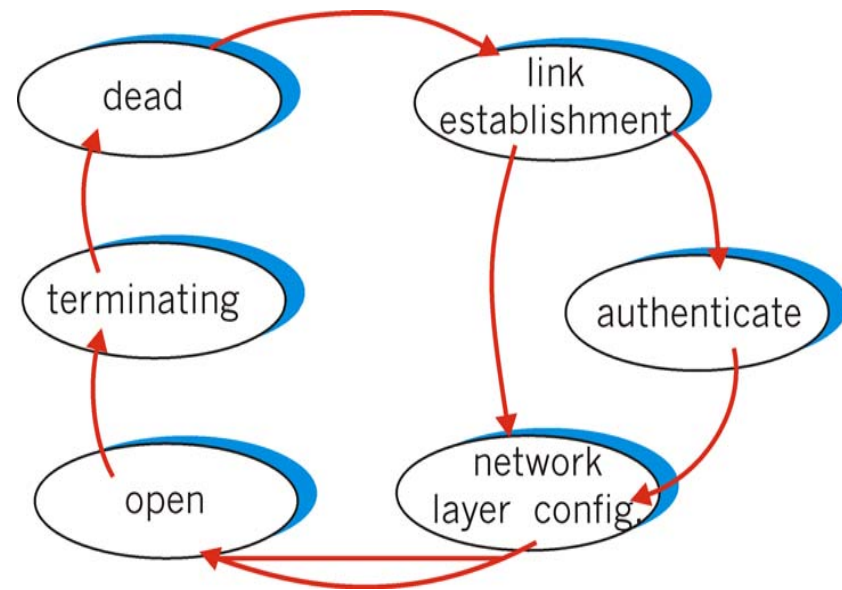
Byte Stuffing



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



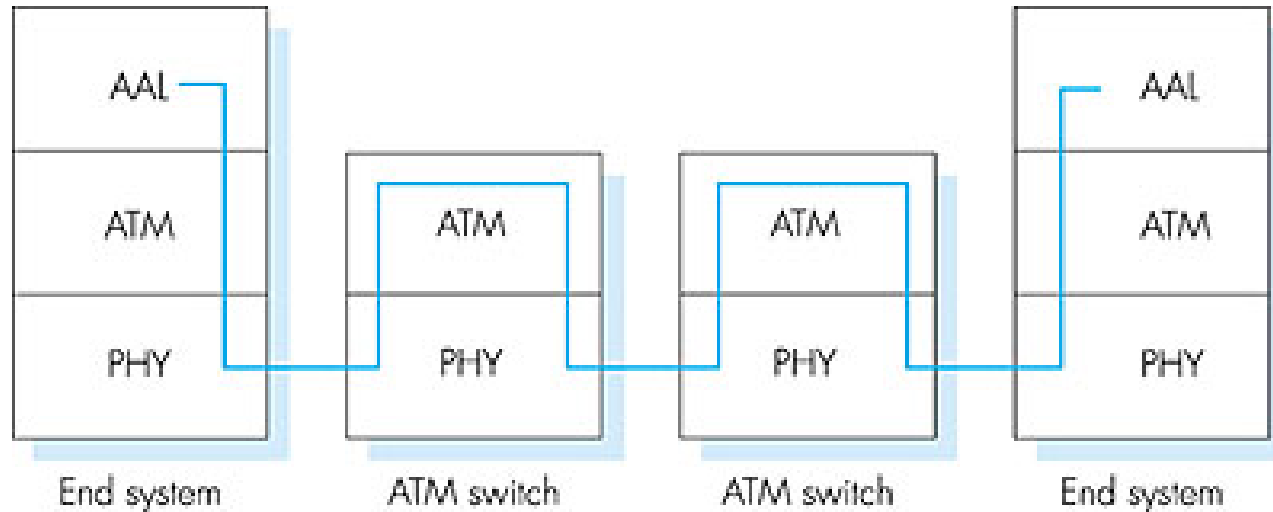
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Asynchronous Transfer Mode: ATM

- ❑ 1990's/00 standard for high-speed (155Mbps to 622 Mbps and higher) *Broadband Integrated Service Digital Network* architecture
- ❑ Goal: *integrated, end-end transport of carry voice, video, data*
 - meeting timing/QoS requirements of voice, video (versus Internet best-effort model)
 - "next generation" telephony: technical roots in telephone world
 - packet-switching (fixed length packets, called "cells") using virtual circuits

ATM architecture



- ❑ **adaptation layer:** only at edge of ATM network
 - data segmentation/reassembly
 - roughly analogous to Internet transport layer
- ❑ **ATM layer:** “network” layer
 - cell switching, routing
- ❑ **physical layer**

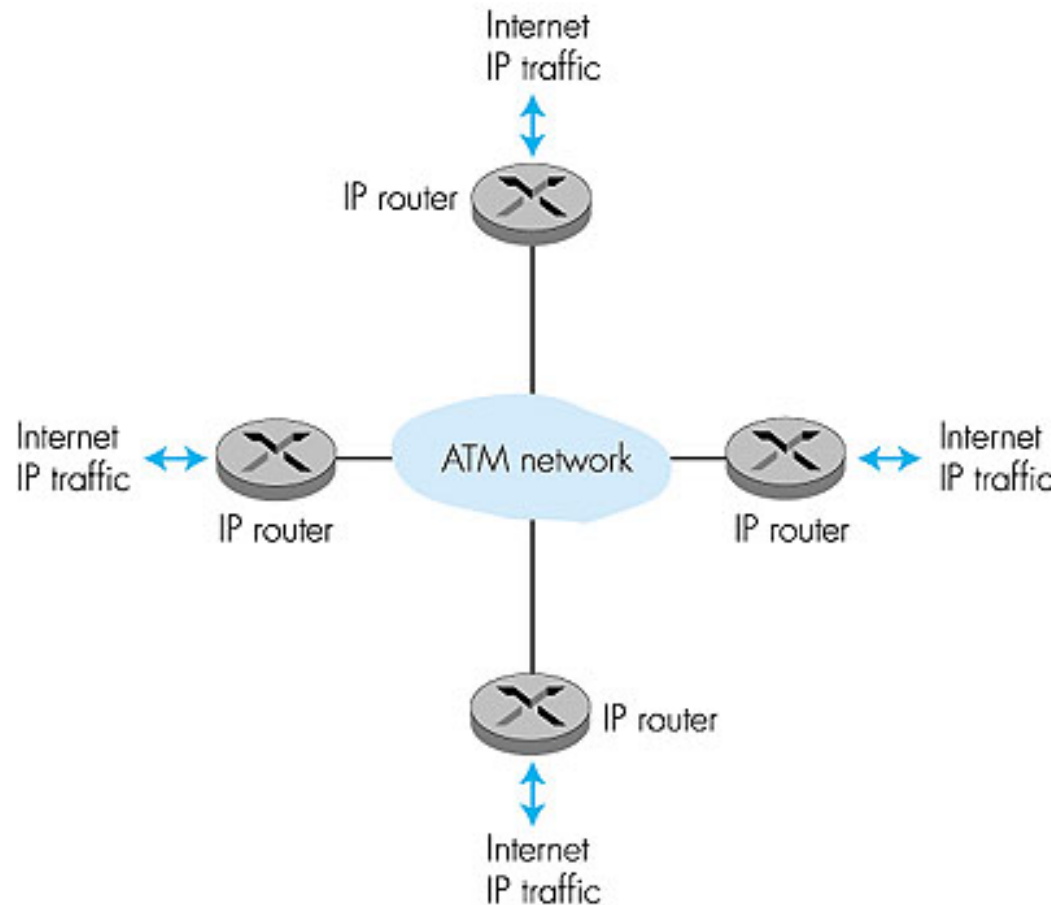
ATM: network or link layer?

Vision: end-to-end
transport: "ATM from
desktop to desktop"

- *ATM is a network technology*

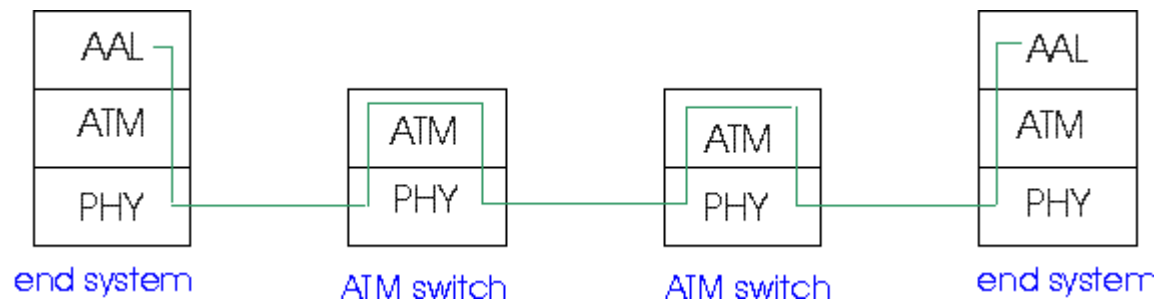
Reality: used to connect
IP backbone routers

- "IP over ATM"
- ATM as switched link layer, connecting IP routers



ATM Adaptation Layer (AAL)

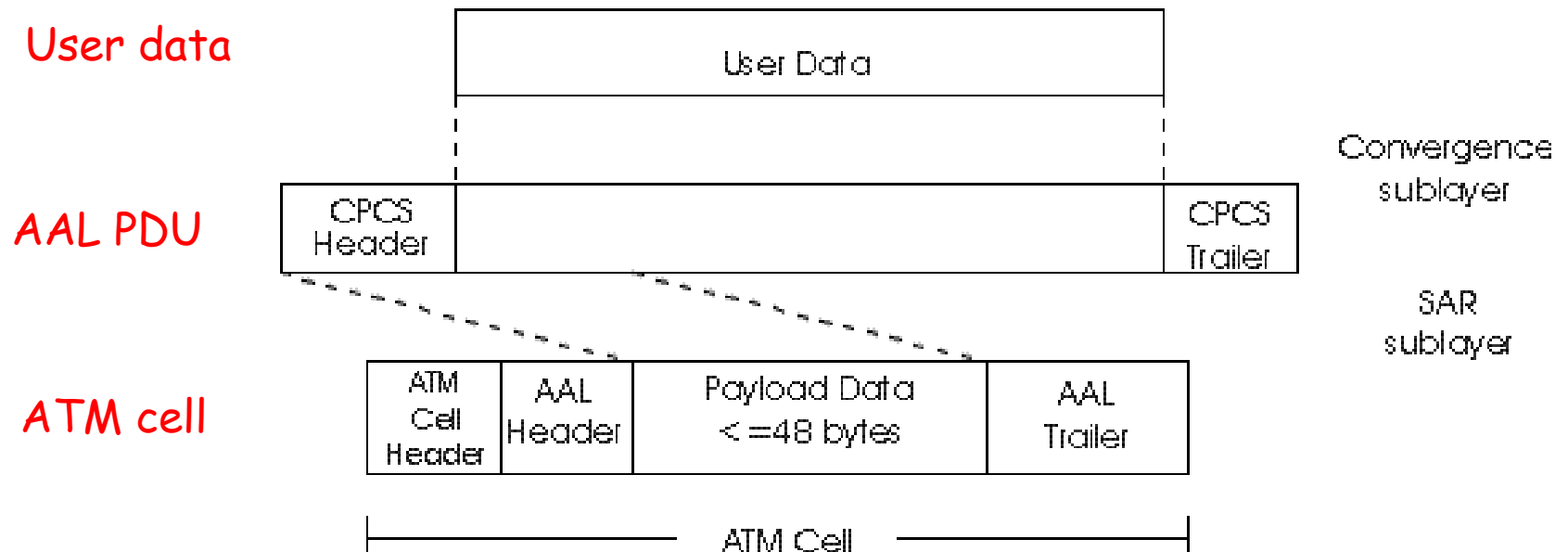
- ❑ **ATM Adaptation Layer (AAL):** “adapts” upper layers (IP or native ATM applications) to ATM layer below
- ❑ **AAL present only in end systems**, not in switches
- ❑ **AAL layer segment** (header/trailer fields, data) fragmented across multiple ATM cells
 - analogy: TCP segment in many IP packets



ATM Adaptation Layer (AAL) [more]

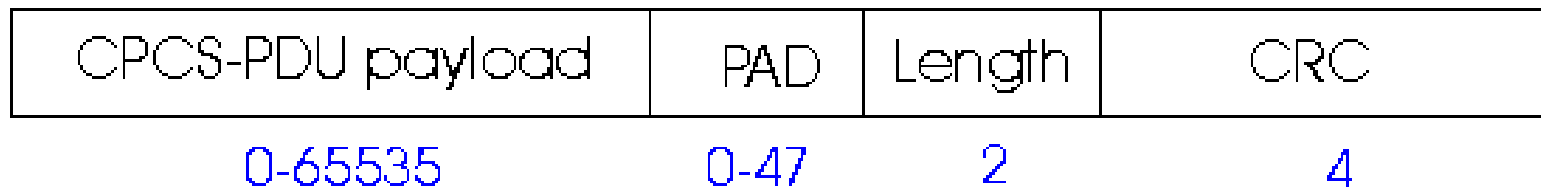
Different versions of AAL layers, depending on ATM service class:

- ❑ **AAL1:** for CBR (Constant Bit Rate) services, e.g. circuit emulation
- ❑ **AAL2:** for VBR (Variable Bit Rate) services, e.g., MPEG video
- ❑ **AAL5:** for data (e.g., IP datagrams)



AAL5 - Simple And Efficient AL (SEAL)

- ❑ **AAL5: low overhead AAL used to carry IP datagrams**
 - 4 byte cyclic redundancy check
 - PAD ensures payload multiple of 48bytes
 - large AAL5 data unit to be fragmented into 48-byte ATM cells



ATM Layer

Service: transport cells across ATM network

- analogous to IP network layer
- very different services than IP network layer

Network Architecture	Service Model	Guarantees ?				Congestion feedback
		Bandwidth	Loss	Order	Timing	
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR	constant rate	yes	yes	yes	no congestion
ATM	VBR	guaranteed rate	yes	yes	yes	no congestion
ATM	ABR	guaranteed minimum	no	yes	no	yes
ATM	UBR	none	no	yes	no	no

ATM Layer: Virtual Circuits

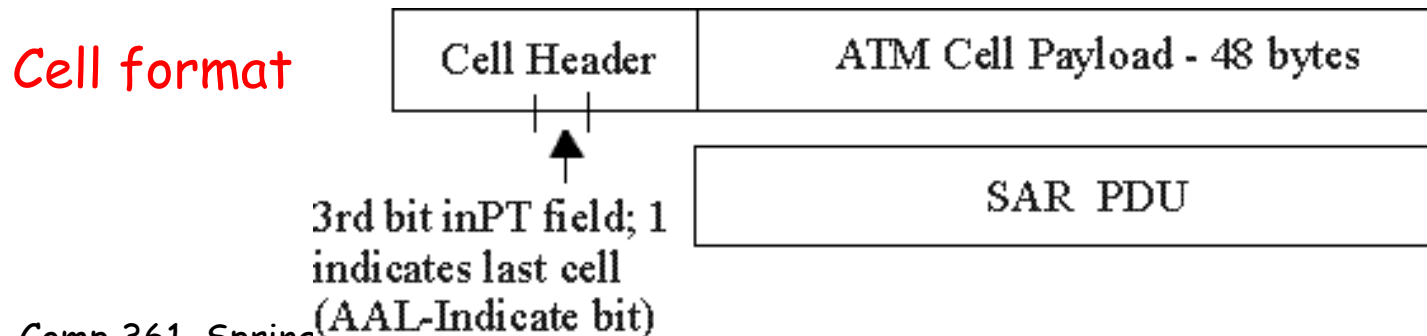
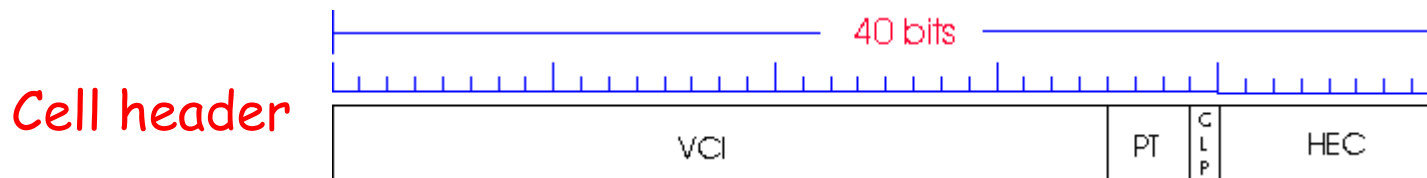
- ❑ **VC transport:** cells carried on VC from source to dest
 - call setup, teardown for each call *before* data can flow
 - each packet carries VC identifier (not destination ID)
 - *every* switch on source-dest path maintain "state" for each passing connection
 - link, switch resources (bandwidth, buffers) may be *allocated* to VC: to get circuit-like perf.
- ❑ **Permanent VCs (PVCs)**
 - long lasting connections
 - typically: "permanent" route between to IP routers
- ❑ **Switched VCs (SVC):**
 - dynamically set up on per-call basis

ATM VCs

- ❑ Advantages of ATM VC approach:
 - QoS performance guarantee for connection mapped to VC (bandwidth, delay, delay jitter)
- ❑ Drawbacks of ATM VC approach:
 - Inefficient support of datagram traffic
 - one PVC between each source/dest pair) does not scale (N^2 connections needed)
 - SVC introduces call setup latency, processing overhead for short lived connections

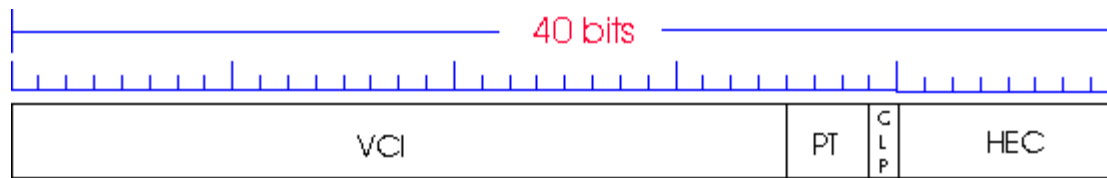
ATM Layer: ATM cell

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



ATM cell header

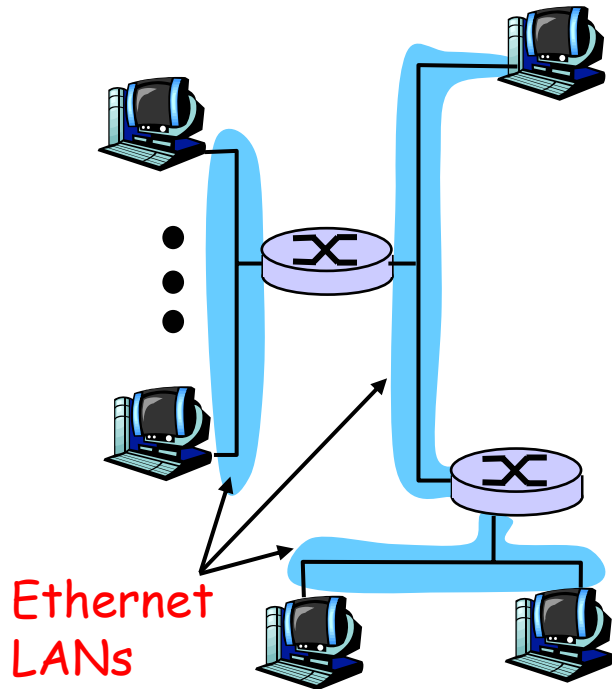
- **VCI:** virtual channel ID
 - will *change* from link to link thru net
- **PT:** Payload type (e.g. RM cell versus data cell)
- **CLP:** Cell Loss Priority bit
 - CLP = 1 implies low priority cell, can be discarded if congestion
- **HEC:** Header Error Checksum
 - cyclic redundancy check



IP-Over-ATM

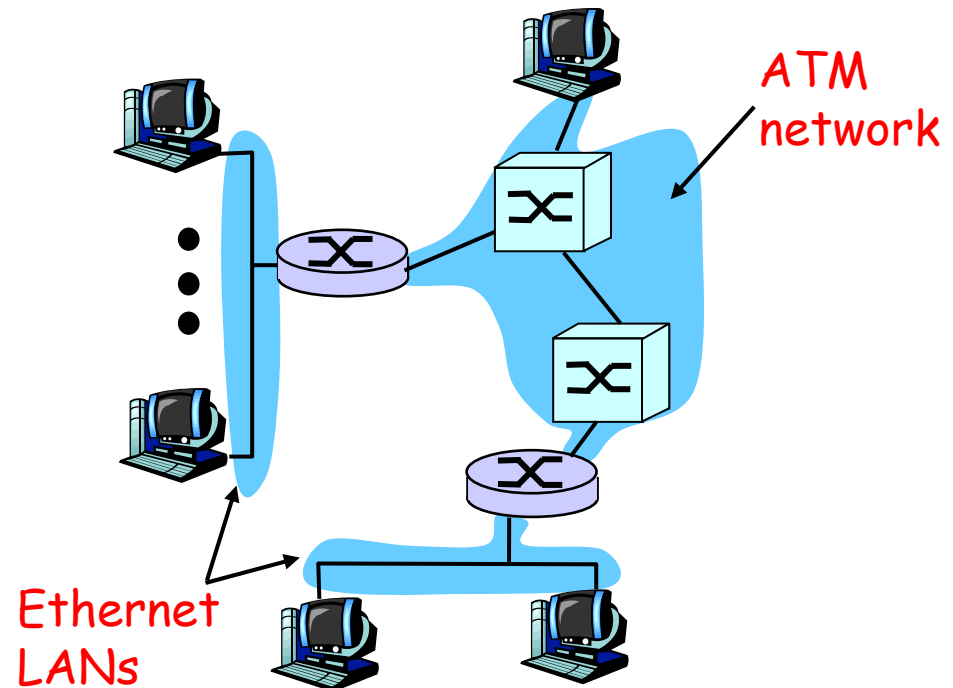
Classic IP only

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



IP over ATM

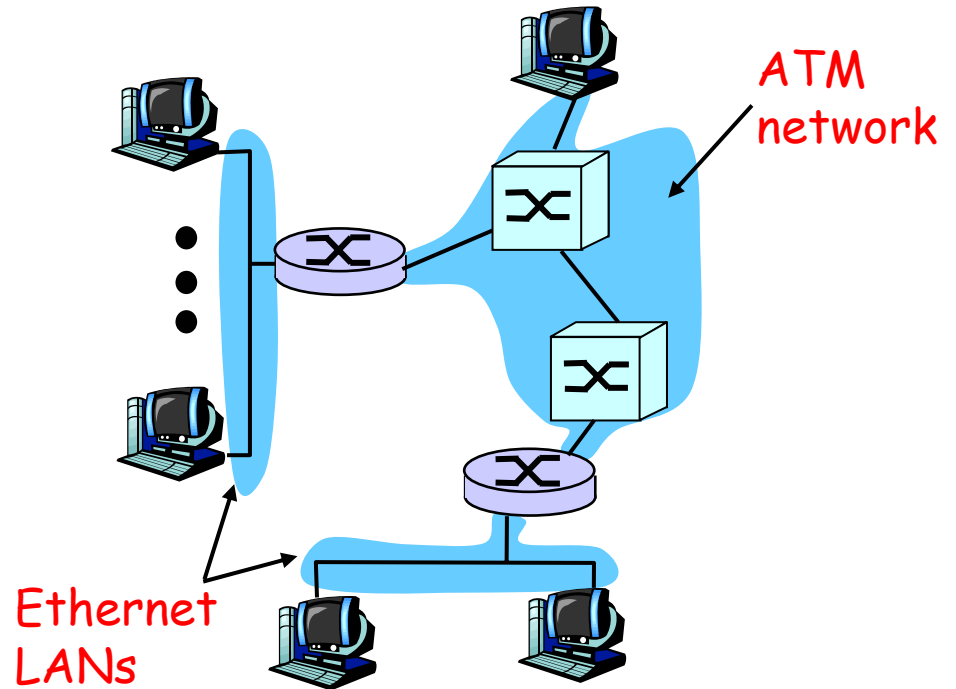
- ❑ replace "network" (e.g., LAN segment) with ATM network
- ❑ ATM addresses, IP addresses



IP-Over-ATM

Issues:

- ❑ IP datagrams into ATM AAL5 PDUs
- ❑ from IP addresses to ATM addresses
 - just like IP addresses to 802.3 MAC addresses!



Chapter 5 outline

- ❑ 5.1 Introduction and services
- ❑ 5.2 Error detection and correction
- ❑ 5.3 Multiple access protocols
- ❑ 5.4 LAN addresses and ARP
- ❑ 5.5 Ethernet
- ❑ 5.6 Hubs, bridges, and switches
- ❑ 5.7 Wireless links and LANs
- ❑ 5.8 PPP
- ❑ 5.9 ATM
- ❑ 5.10 Frame Relay

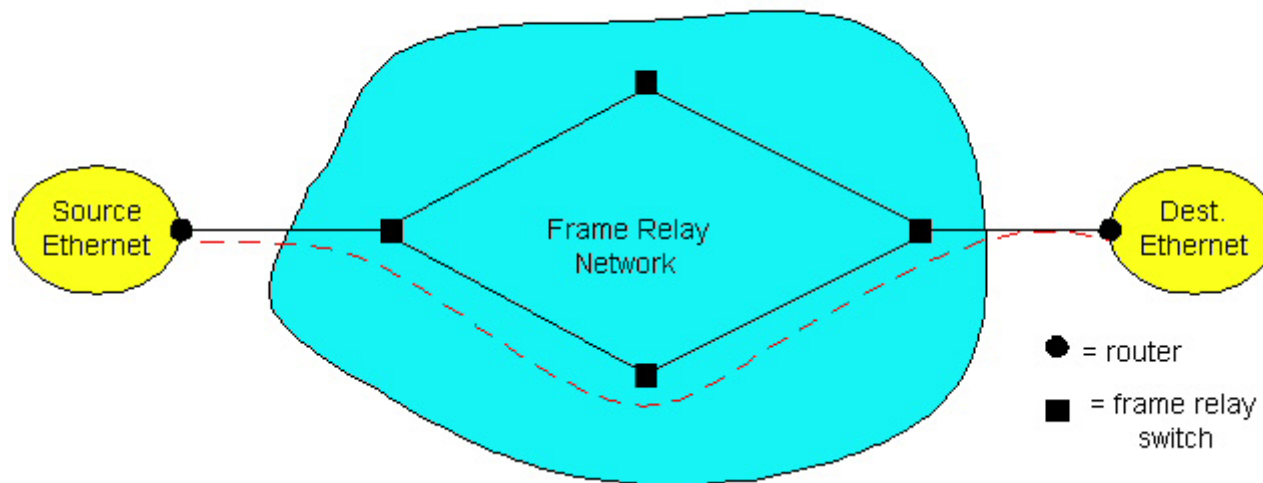
Frame Relay

Like ATM:

- ❑ wide area network technologies
- ❑ Virtual-circuit oriented
- ❑ origins in telephony world
- ❑ can be used to carry IP datagrams
 - can thus be viewed as link layers by IP protocol

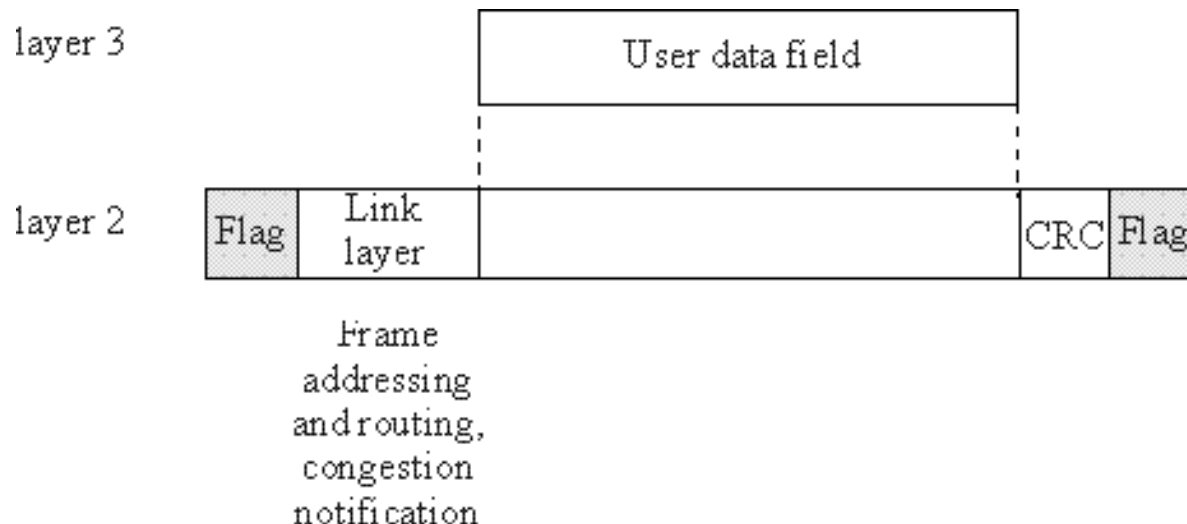
Frame Relay

- ❑ 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 (e.g., Sprint, ATT)



Frame Relay (more)



- ❑ Flag bits, 01111110, delimit frame
- ❑ address:
 - 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 congestion discard

Frame Relay - CIR & Frame Marking

- ❑ **Access Rate**: rate **R** of the access link between **source router** (customer) and **edge FR switch** (provider); $64\text{Kbps} < R < 1,544\text{Kbps}$
- ❑ Typically, **many VCs** (one per destination router) multiplexed on the same access trunk; each VC has own **CIR**
- ❑ Edge FR switch **measures** traffic rate for each VC; it **marks** (i.e. DE = 1) frames which **exceed CIR** (these may be later dropped)
- ❑ Internet's more recent **differentiated service** uses similar ideas

Chapter 5: Summary

- ❑ **principles** behind data link layer services:
 - error detection, correction
 - sharing a broadcast channel: multiple access
 - link layer addressing, ARP
- ❑ **link layer technologies:** Ethernet, hubs, bridges, switches, IEEE 802.11 LANs, PPP, ATM, Frame Relay
- ❑ journey down the protocol stack now **OVER!**
- ❑ for continuation, e.g., multicasting, multimedia, enroll in **comp362!**