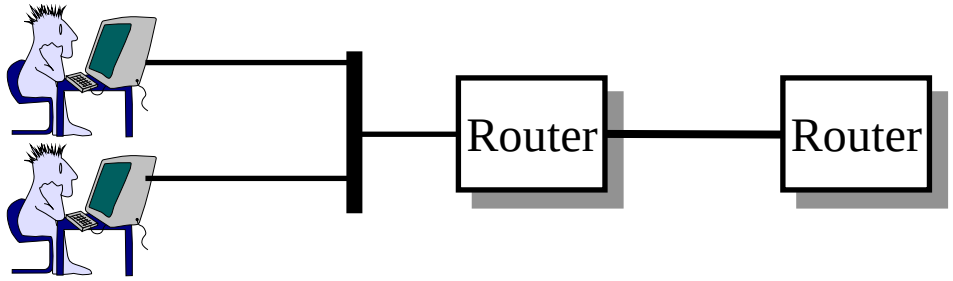
The Link Layer and LANs



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Audio/Video recordings of this lecture are available online at:

http://www.cse.wustl.edu/~jain/cse4703-26/

Student Questions

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Overview

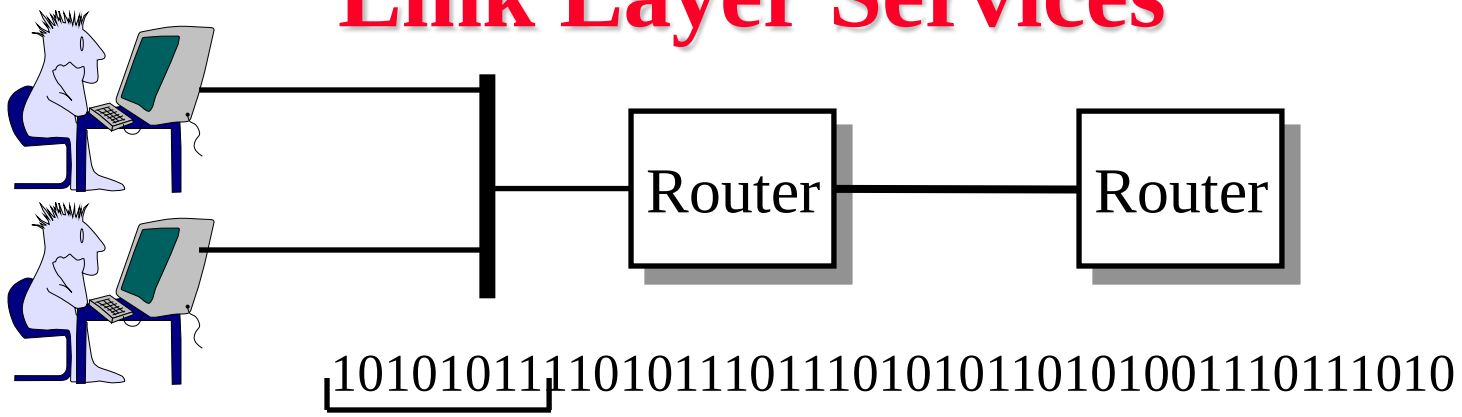
1. Datalink Services
2. Error Detection
3. Multiple Access
4. Bridging
5. MPLS

Note: This class lecture is based on Chapter 6 of the textbook (Kurose and Ross) and the figures provided by the authors.

Student Questions

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Link Layer Services



- Link = One hop
- Framing: Bit patterns at the beginning/end of a frame
- Multiple Access: Multiple users sharing a wire
- Optional (On Lossy wireless links)
  - Flow Control
  - Error Detection/Correction
  - Reliable Delivery
- Duplex Operation

Student Questions

- Is the framing bit sequence universal? Is it possible for a bit sequence of some data to match that of the frame?

Many Layer 2 protocols use bit stuffing. For example, HDLC uses 01111110 as framing. Whenever 5 one's appear in the data, the sender inserts a 0. Whenever receiver sees 5 one's followed by 0, it removes the 0. Ethernet does not use bit stuffing. Each new Ethernet frame starts and ends with an idle. It starts with 7-byte preamble 10101010x7, followed by Start Frame Delimiter (SFD) of 10101011. This sets the exact bit where the frame starts. If the sequence appears in the data, nothing is done.

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Line Duplexity

- Simplex: Transmit or receive,
  e.g., Television



- Full Duplex: Transmit and receive simultaneously,
  e.g., Telephone



- Half-Duplex: Transmit and receive alternately,
  e.g., Police Radio



Ref: Section 6.1, Review question R1

Student Questions

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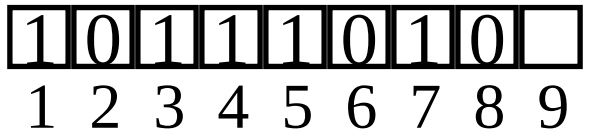
Error Detection

- Parity Checks
- Check Digit Method
- Modulo 2 Arithmetic
- Cyclic Redundancy Check (CRC)
- Popular CRC Polynomials

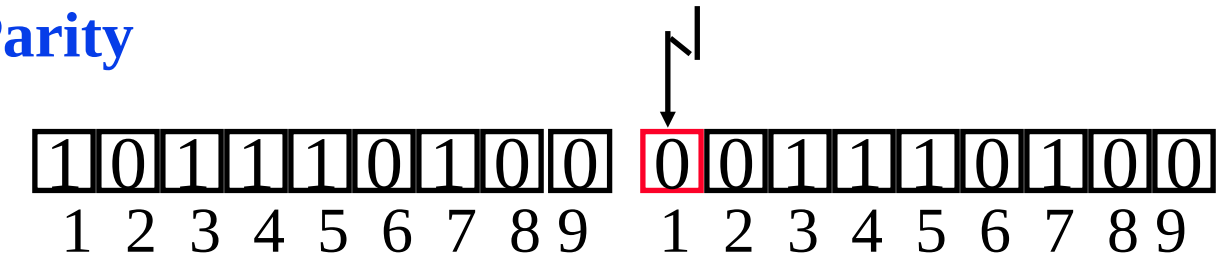
Student Questions

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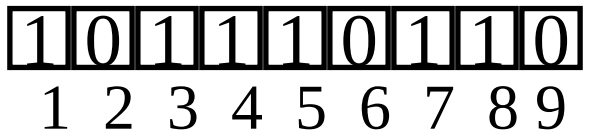
Parity Checks



- **Odd Parity**



- **Even Parity**

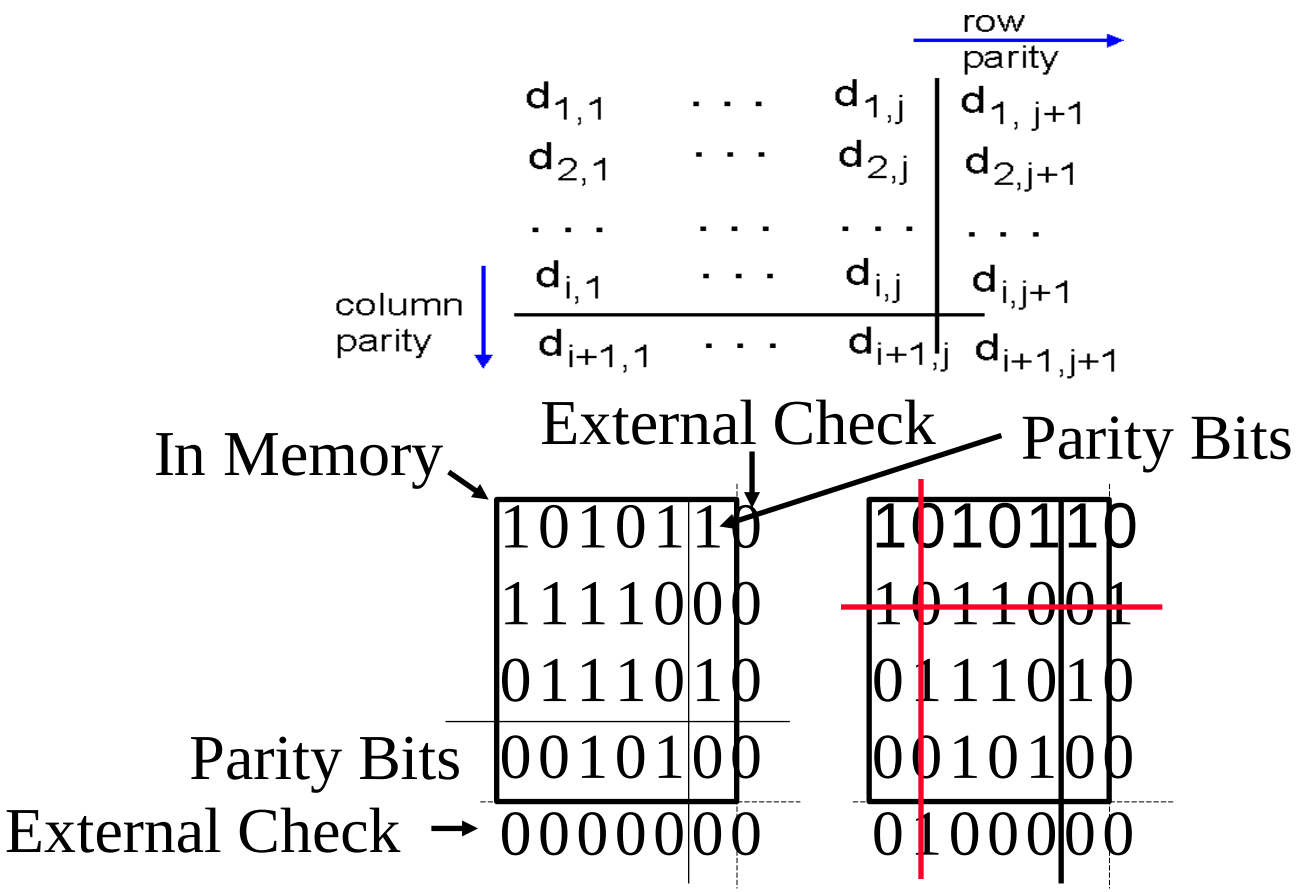


Student Questions

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Two-Dimensional Parity

- Detect and correct single bit errors



Student Questions

- How can two-dimensional parity correct a single-bit error?

All frames are transmitted with column and row parity bit set so that the parity check is zero. At the receiver, a mismatched parity check indicates the column and the row where errors may have occurred. If there is only one bit error, it can be corrected.
Note that three bit errors in a row or a column may be misinterpreted as a single bit error.

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Check Digit Method

- Make a number divisible by 9

Example: 823 is to be sent

1. Left-shift: 8230
2. Divide by 9, and find the remainder: 4
3. Subtract the remainder from 9: 9-4=5
4. Add the result of step 3 to step 1: 8235
5. Check that the result is divisible by 9.

Detects all single-digit errors except 0-9 substitutions: 7235, 8335, 8255, 8237

Detects several multiple-digit errors: 8765, 7346

It does not detect some errors, such as 7335, 8775, etc.

Does not detect transpositions: 2835

Credit card numbers are protected via a similar method called the "Luhn Algorithm," which detects most transpositions.

Ref: http://en.wikipedia.org/wiki/Luhn_algorithm

Student Questions

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Modulo 2 Arithmetic

```
 1111        11001        110
+1010      ×    11     11  | 1010
-------    --------        /  11 |
 0101       11001             ----------
           11001              x11
           ---------           11
           101011             --------
                               x00
                                00
                               -----
                                x0
```

010	2	
011	3	
---	--	
001	1	Mod 2
101	5	Binary

Student Questions

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Modulo 2 Arithmetic: More Examples

Addition:

1-bit				2-bit				3-bit
1	0	0	1	00	01	10	11	110
+1	+0	+1	+0	+11	+11	+11	+11	+101
0	0	1	?	11	10	01	??	???

Multiplication:

1-bit				2-bit				3-bit
1	0	0	1	00	01	10	11	110
×1	×0	×1	×0	×11	×11	×11	×11	×101
1	0	0	?	00	01	10	??	???
				00	01	10	??	???
				000	011	110	???	????

Student Questions

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Cyclic Redundancy Check (CRC)

- **Binary Check Digit Method**
- Make a number divisible by P=110101 (n+1=6 bits)

Example: M=1010001101 is to be sent

1. Left-shift M by n bits 2^nM= 101000110100000
2. Divide 2^nM by P, find remainder: R=01110
3. ~~Subtract the remainder from P~~ ← Not required in Mod 2
4. Add the result of step 2 to step 1: T=101000110101110
5. Check that the result T is divisible by P.

Student Questions

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Modulo 2 Division

Q=1101010110

P=110101)1010001101**00000**=2^nM

110101

111011

110101

011101

000000

111010

110101

011111

000000

111110

110101

010110

000000

101100

110101

110010

110101

001110

000000

01110 = R

Student Questions

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Checking At The Receiver

```
          1101010110
110101)101000110101110
       110101
         111011
         110101
          011101
          000000
           111010
           110101
            011111
            000000
             111110
             110101
```

```
010111
000000
 101111
 110101
  110101
  110101
   00000
```

Student Questions

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Modulo 2 Division: More Examples

Long Division:

Decimal Arithmetic

```
13) 1514( 116
    13
    ---
    021
     13
     --
     084
      78
      --
      06 ← Remainder
```

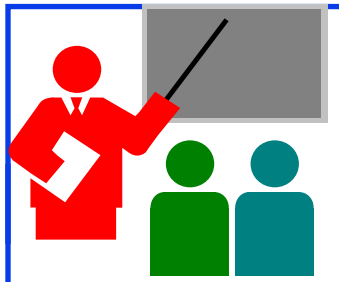
Mod-2 Arithmetic

```
10) 1101( 110
    10
    --
    010
     10
     --
     001
      00
      --
      01 ← Remainder
```

```
10) 11011( 101?
    10
    --
    010
     10
     --
     001
      00
      --
      01?
       ??
       --
       ??
```

Student Questions

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Error Detection: Review

1. **Parity bits** can help detect/correct errors
2. Remainder obtained by dividing by a **prime** number provides good error detection
3. **CRC** uses mod 2 division

Student Questions

Ref: Section 6.2, Review questions R2, R3

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Homework 6A: CRC

- [4 points] Find the CRC of 1001100 using a generator *1011*. *Use mod 2 division. Show all steps, including the checking at the receiver.*

Student Questions

End of Part 1



Multiple Access Links and Protocols

1. Multiple Access
2. CSMA/CD
3. IEEE 802.3 CSMA/CD
4. CSMA/CD Performance
5. Cable Modem Access

Student Questions

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Multiple Access



(a) Aloha Multiple Access



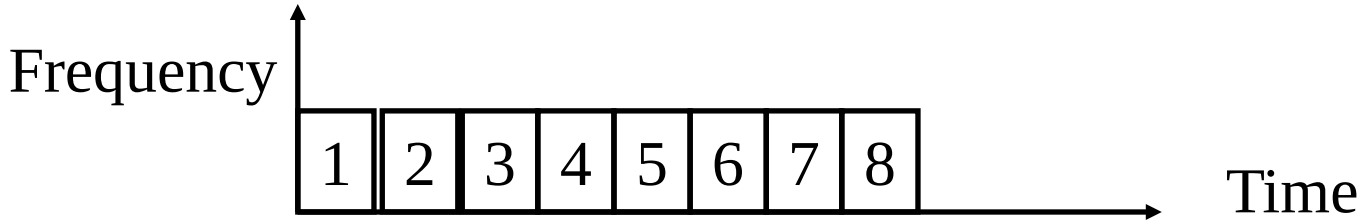
(b) Carrier-Sense Multiple Access with Collision Detection

Student Questions

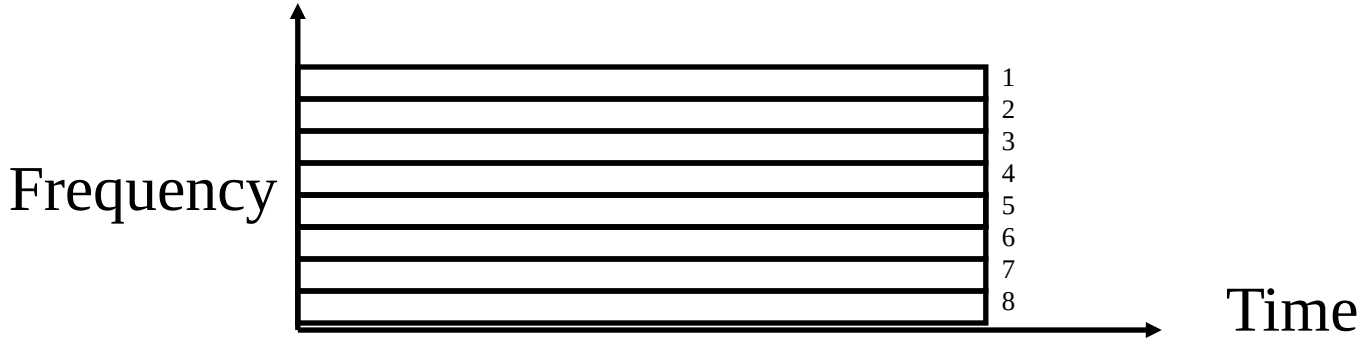
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Multiple Access

- How multiple users can share a link?
- **Time Division Multiple Access**



- **Frequency Division Multiple Access**



Student Questions

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CSMA/CD



- **Aloha** at Univ of Hawaii:
  Transmit whenever you like
  Worst case utilization = 1/(2e) =18%
- **Slotted Aloha**: Fixed-size transmission slots
  Worst case utilization = 1/e = 37%
- **CSMA**: Carrier Sense Multiple Access
  Listen before you transmit
- **p-Persistent CSMA**: If idle, transmit with probability p. Delay by one time unit with probability 1-p
- **CSMA/CD**: CSMA with Collision Detection
  Listen while transmitting. Stop if you hear someone else.

Student Questions

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IEEE 802.3 CSMA/CD

- If the medium is idle, transmit (1-persistent).
- If the medium is busy, wait until it is idle and transmit immediately.
- If a collision is detected while transmitting,
  - Transmit a **jam** signal for one slot (= 51.2 μs = 64-byte times)
  - Wait for a random time and reattempt (up to **16** times)
  - Random time = Uniform[0,$2^{\min(k,10)}$-1] slots
    Truncated Binary Backoff
- Collision detected by monitoring the voltage
  High voltage ⇒ two or more transmitters ⇒ Collision
  ⇒ The cable length is limited to 2.5 km.

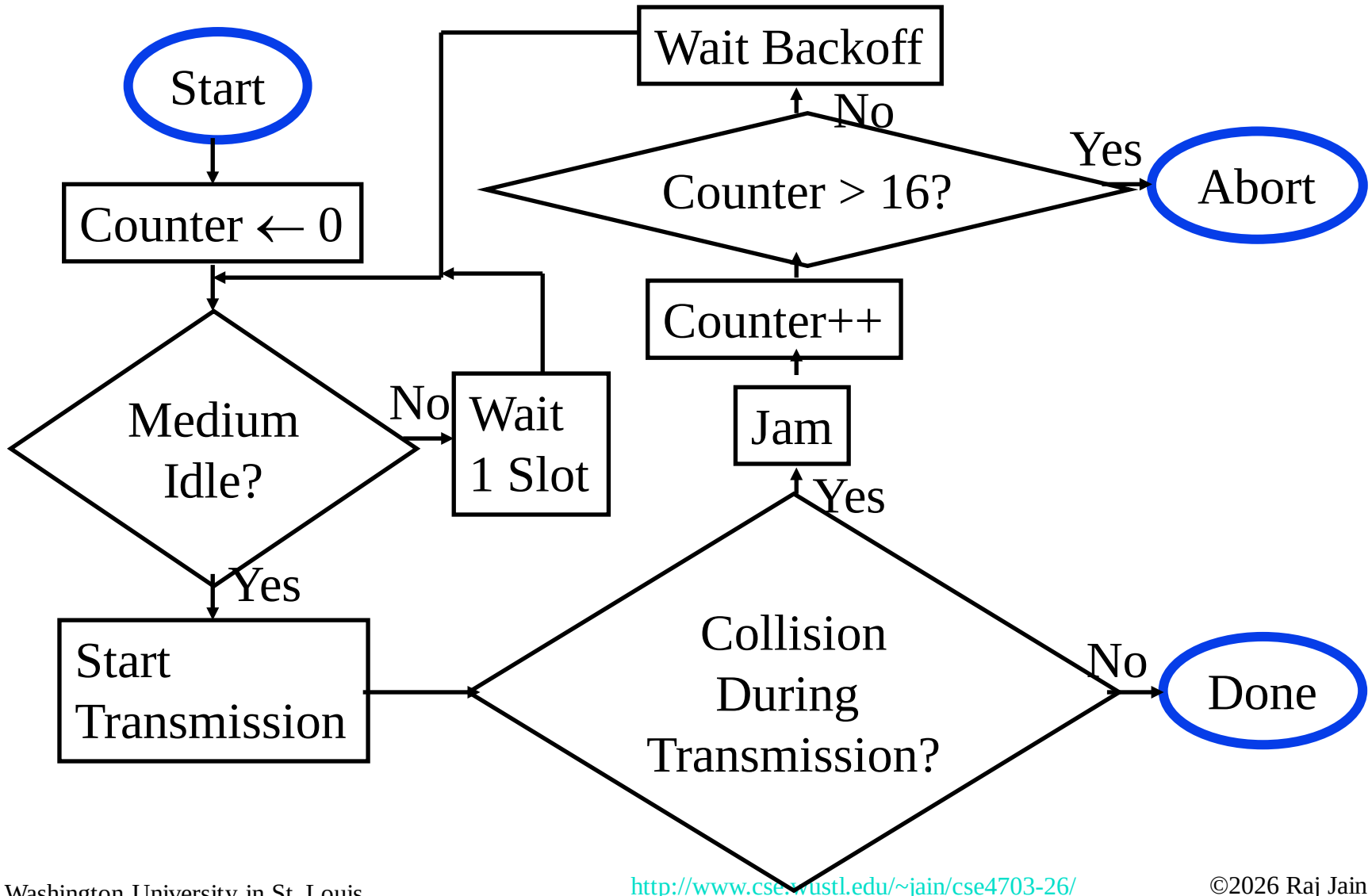
Student Questions

- Why is the exponent capped at 10 instead of continuing to grow up to the maximum of 16 attempts? Wouldn't a larger backoff window at higher collision counts further reduce the probability of repeated collisions?

n^{th} backoff helps resolve collision among 2^n nodes. The number of nodes on a single Ethernet is limited to 1024. So simulations showed that it does not help to keep increasing the back off beyond 2^{10}. 16 attempts are allowed before giving up since there are no retransmissions.

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IEEE 802.3 CSMA/CD Flow Chart

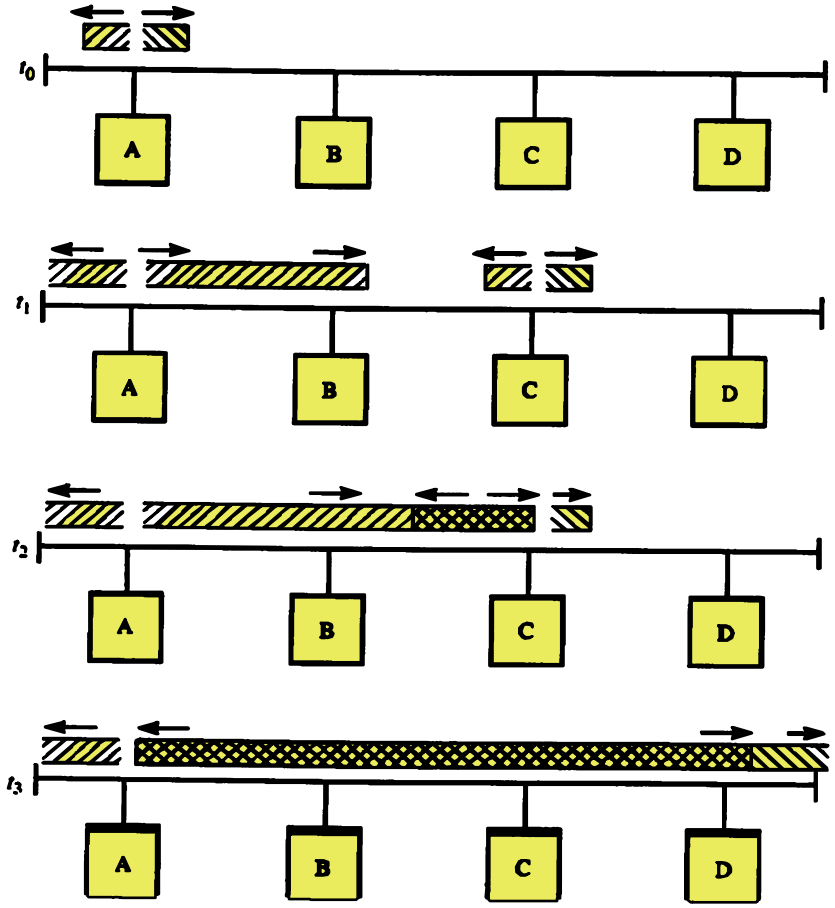


Student Questions

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CSMA/CD Operation

- **Collision window** = 2 × One-way Propagation delay = 51.2 μs



One way delay = 25.6 μs
Max Distance <2.5 km

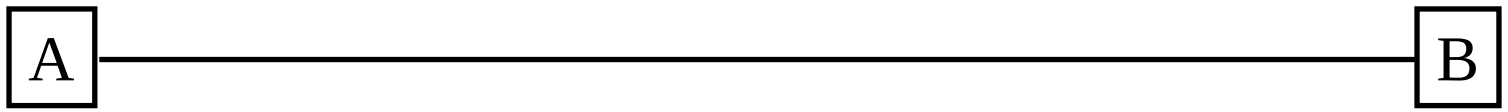
T_x = Time x starts transmitting.
D_{xy} = Time for the signal to travel from x to y
F = Frame time
C sees collision after T_A+D_{AC}
A sees a collision after $T_C+D_{AC.}$
IF A's transmission ends before T_C+D_{AC}, it will not detect a collision.
$T_C+ D_{AC} < T_A+F$
$F>T_C-T_A+ D_{AC}$
In the worst case :
T_C-T_A=full wire length
= One-way Propagation delay,
D_{AC} = One-way Propagation delay
F>2× One-way propagation delay

Student Questions

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Homework 6B: Collision Detection

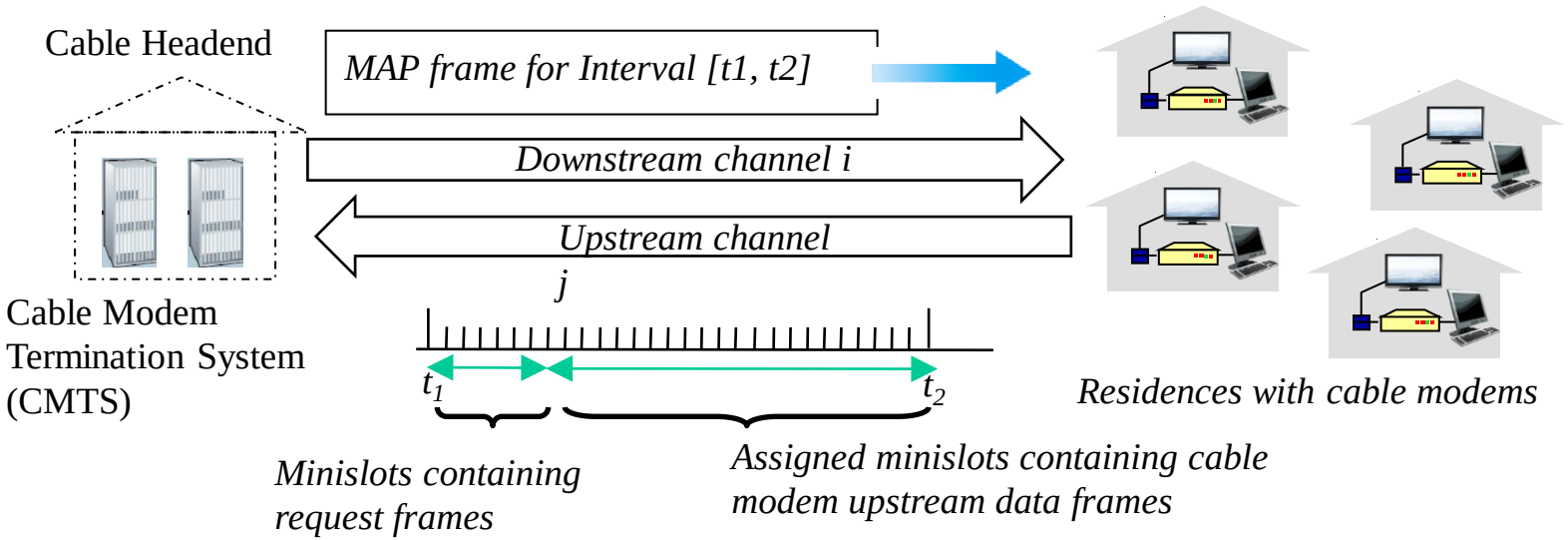
- [6 Points] Suppose nodes A and B are on the same 10 Mbps Ethernet bus, and the propagation delay between the two nodes is 325-bit times. Node A begins transmitting a frame, and node B begins transmitting a frame before it finishes. Can A finish transmitting before it detects that B has transmitted? Why or why not? In the worst case, when does B's signal reach A? (Minimum frame size is 512+64 bits).



Student Questions

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Cable Access Network



- **DOCSIS**: Data Over Cable Service Interface Specification
- Frequency Division Multiplexed (**FDM**) channels over upstream and downstream
- Time Division Multiplexed (**TDM**) slots in each upstream channel:
  - Some slots are assigned, and some have contention
  - Downstream **MAP** frame: Assigns upstream slots
  - Request for upstream slots (and data) transmitted using random access (binary backoff) in selected slots

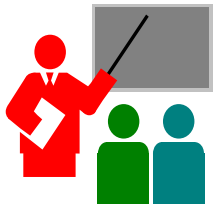
Student Questions

- As I understand, the upstream channel is divided into TDM slots. Are each of these slots also FDM? And I am confused about the "Minislots containing request frames" part of the upstream channel on the slide?

Yes, FDM is used to divide the media in to channels. On each upstream channel, first few slots are reserved for requests. If a request is received the head-end will allocate appropriate number of upstream slots in the next cycle. Two nodes collide they retry after a timeout.

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Multiple Access Links and Protocols: Review



1. Multiple users can share using **TDMA** or **FDMA**
2. Random access is better for data traffic.
3. Aloha has an efficiency of **1/2e**. Slotted Aloha makes it **1/e**.
4. Carrier sense and collision detection improve the efficiency further.
5. IEEE 802.3 uses **CSMA/CD** with **truncated** binary exponential backoff
6. DOCSIS used in cable access networks has **frequency-division-multiplexed** channels. Each channel time division is multiplexed, with some slots reserved for random access.

Student Questions

Ref: Section 6.3, Review question R4-R8

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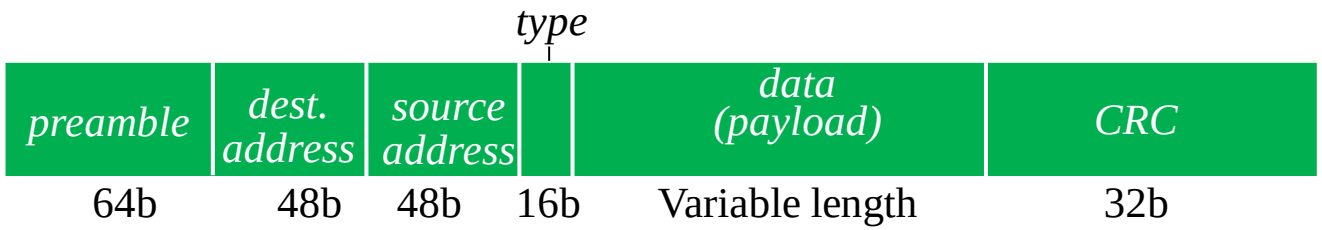
Switched Local Area Networks

1. Ethernet Standards
2. IEEE 802 Address Format
3. Address Resolution Protocol
4. Bridging
5. Virtual LANs

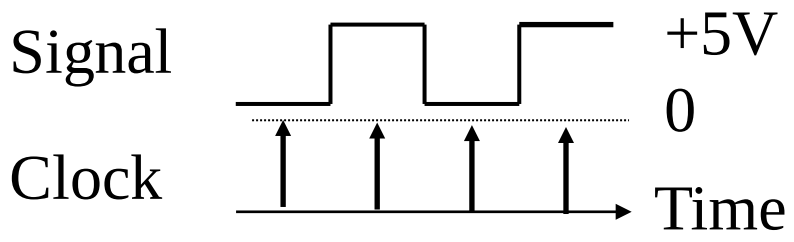
Student Questions

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Ethernet Frame Structure



- ***Preamble:*** 7 bytes with pattern 10101010 followed by one byte with pattern 10101011. To synchronize the receiver, the sender clocks
- ***Addresses:*** 6-byte source, destination MAC addresses
- ***Type:*** indicates higher-layer protocol
  - IP: 0x0800
  - ARP: 0x0806



- ***CRC:*** Cyclic Redundancy Check
  - If an error is detected, the frame is silently dropped at the receiver
- ***Connectionless***: No need to ask the receiver
- ***Unreliable***: No ack, nack, or retransmissions

Student Questions

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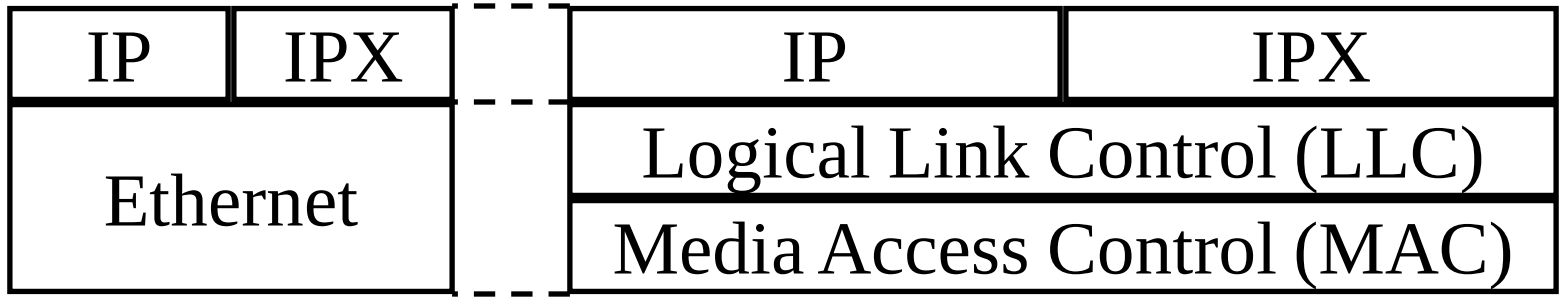
Ethernet Standards

- **10BASE5**: 10 Mb/s over coaxial cable (ThickWire)
- **10BROAD36**: 10 Mb/s over broadband cable, 3600 m max segments
- **1BASE5**: 1 Mb/s over two pairs of UTP
- **10BASE2**: 10 Mb/s over thin RG58 coaxial cable (ThinWire), 185 m max segments
- **10BASE-T**: 10 Mb/s over two pairs of UTP
- **100BASE-T4**: 100 Mb/s over four pairs of CAT-3, 4, 5 UTP
- **100BASE-TX**: 100 Mb/s over **two** pairs of CAT-5 UTP or STP
- **1000BASE-T**: 1 Gbps (Gigabit Ethernet)
- **10GBASE-T**: 10 Gbps
- **40GBASE-T**: 40 Gbps

Student Questions

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Ethernet vs. IEEE 802.3



- In 802.3, the data link layer was divided into two sublayers: LLC and MAC
- **LLC** provides protocol multiplexing. MAC does not.
- **MAC** does not need a protocol-type field.

Student Questions

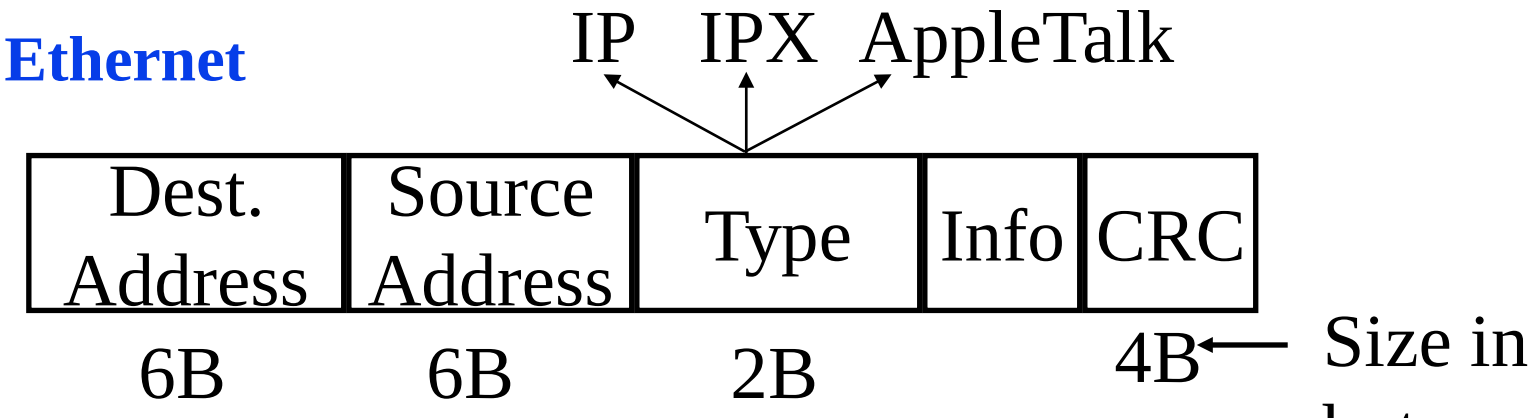
- I know that MAC *addresses* don't need a protocol-type field, but what are they used for in the first place? What is a MAC address?

*We need to distinguish between MAC frame and MAC address. MAC frame is the whole packet. MAC address is where the packet is going or coming from. MAC. Protocol type field is in the frame not in the address. The addresses are 48-bit long and are permanent like Social Security Numbers. In IEEE 802.3, the protocol type field was moved to the LLC **sublayer**.*

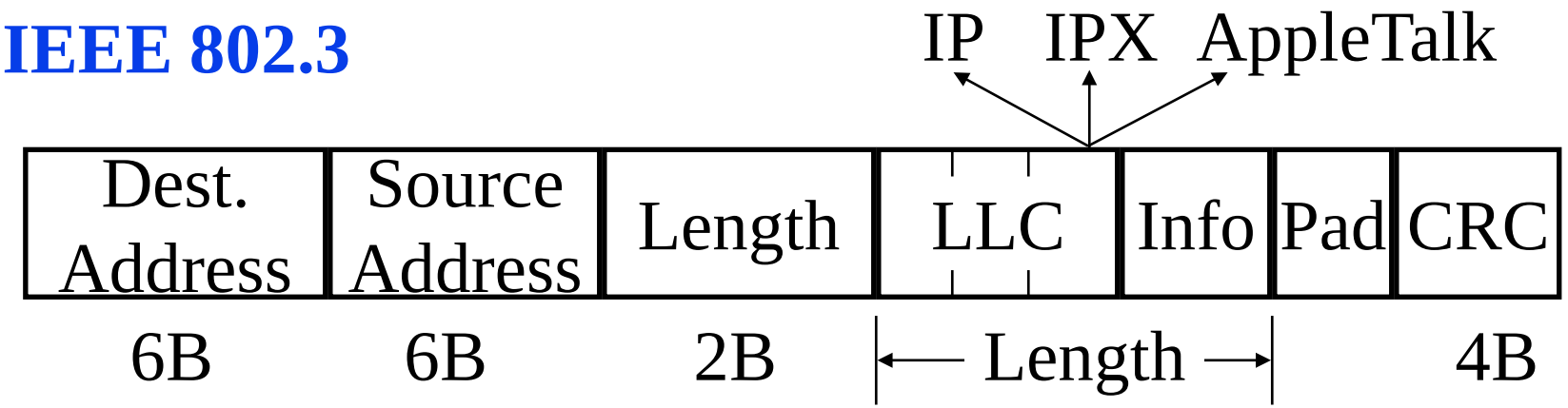
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Ethernet and 802.3 Frame Formats

- **Ethernet**



- **IEEE 802.3**



- Length > 1518B ⇒ It is a protocol type ⇒ Ethernet

Student Questions

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IEEE 802 Address Format

- 48-bit:1000 0000 : 0000 0001 : 0100 0011 : 0000 0000 : 1000 0000 : 0000 1100
  = 80:01:43:00:80:0C

Organizationally Unique Identifier (**OUI**)		24 bits assigned by OUI Owner
Individual/ Group	Universal/ Local	
1	1	22	24

- Multicast = "To all bridges on this LAN"
- Broadcast = "To all stations"
  = 111111....111 = FF:FF:FF:FF:FF:FF

Student Questions

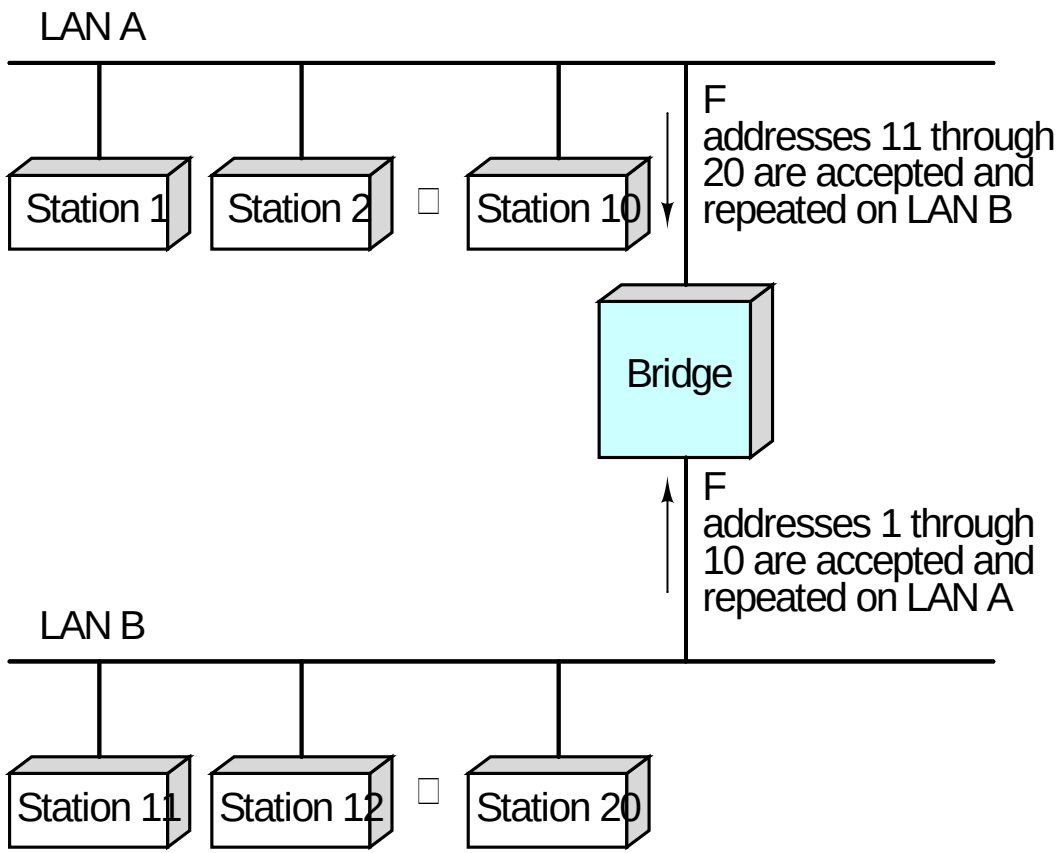
- Can you give a few examples of IEEE 802 address formats? Specifically cases where the individual/group bit is set and the universal/local bit is set?

$0ABC\ DEF1\ 2345_{16}$
$=0000\ 1010\ 1011\ 1100$
$1101\ 1110\ 1111\ 0001$
$0010\ 0011\ 0100\ 0101_2$
I/G bit is 0 => Individual
U/L Bit is 0 => Universal

$8ABC\ DEF1\ 2345_{16}$
$=1000\ 1010\ 1011\ 1100\ldots_2$
I/G bit is 1 => Group
U/L Bit is 0 => Universal

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Bridges



Student Questions

- For 2 LANs connected with a bridge, is there anyway for a station on one side of the bridge to broadcast to the stations on the other side of the bridge?

All Broadcasts, Unknowns, and Multicasts (BUMs) are forwarded to the other sides by the bridges.

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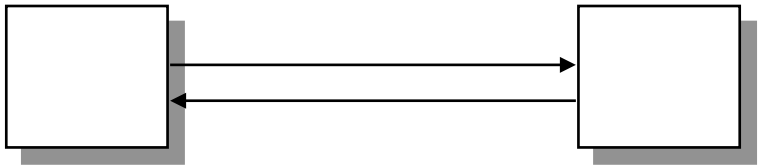
Bridge: Functions

- Monitor all frames on LAN A
- Pick up frames that are for stations on the other side
- Retransmit the frames on the other side
- Knows or learns about stations on various sides
  Learns by looking at source addresses ⇒ **Self-learning**
- Does not modify the content of the frames
  ⇒ **Transparent**
  May change headers.
- Provides storage for frames to be forwarded
- Improves reliability (fewer nodes per LAN)
- Improves performance (more bandwidth per node)
- Security (Keeps different traffic from entering a LAN)
- May provide flow and congestion control (in Token Rings)

Student Questions

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Full-Duplex Ethernet



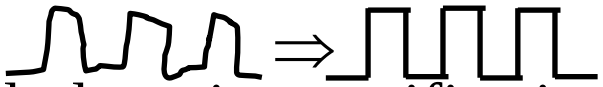
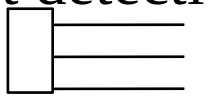
- Uses point-to-point links between TWO nodes
- Full-duplex bi-directional transmission ⇒ Transmit any time
- Standardized in IEEE 802.3-2018
- All vendors are shipping switch/bridge/NICs with full duplex
- No collisions ⇒ 50+ km on fiber.
- Between servers and switches or between switches
- CSMA/CD is no longer used (except in old 10/100 hubs)
- 1G Ethernet standard allows CSMA/CD but is not implemented.
- 10G and higher speed Ethernet standards do not allow CSMA/CD

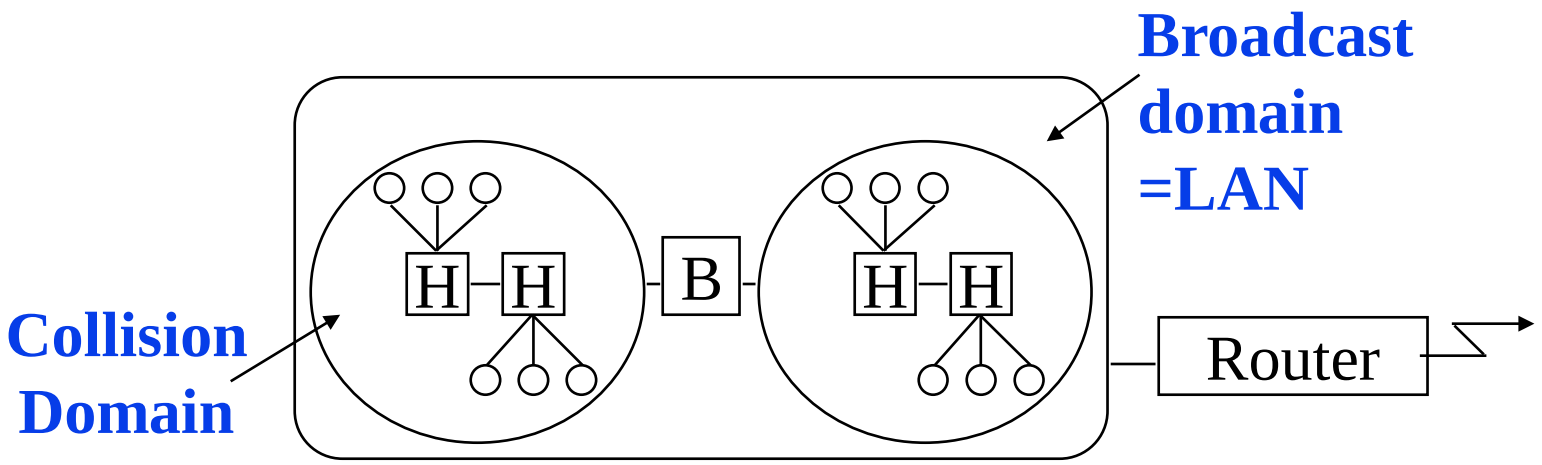
Student Questions

End of Part 2

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Interconnection Devices

- **Repeater**: A PHY device that restores data and collision signals
  Repeater = Digital Amplifier 
- **Hub:** Multiport repeater + fault detection, notification, and signal broadcast 
- **Bridge:** A data link layer device connecting two or more collision domains
- **Router:** Network layer device (does not propagate MAC multicasts)



Student Questions

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Address Resolution Protocol

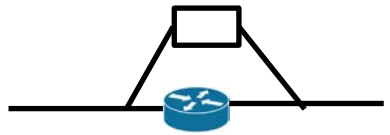
- Problem: Given an IP address, find the MAC address
- Solution: Address Resolution Protocol (**ARP**)
- The host broadcasts a request (Dest MAC=FFFFFFFF): "What is the MAC address of 127.123.115.08?"
- The host, whose IP address is 127.123.115.08, replies: "The MAC address for 127.123.115.08 is $8A:5F:3C:23:45:56_{16}$"
- Nodes cache the MAC-IP mapping in an "ARP table." You can list the ARP table using the "arp –a" command
- Frame Format: Hardware (HW): 0x0001 = Ethernet,
  - Protocol (Prot): 0x0800 = IP,
  - Operation: 1 = Request, 2=Response

HW Type	Prot Type	HW Addr Length	Prot Addr Length	Oper-ation	Sender HW Addr	Sender Prot Addr	Target HW Addr	Target Prot Addr
16b	16b	8b	8b	16b	48b	32b	48b	32b

Student Questions

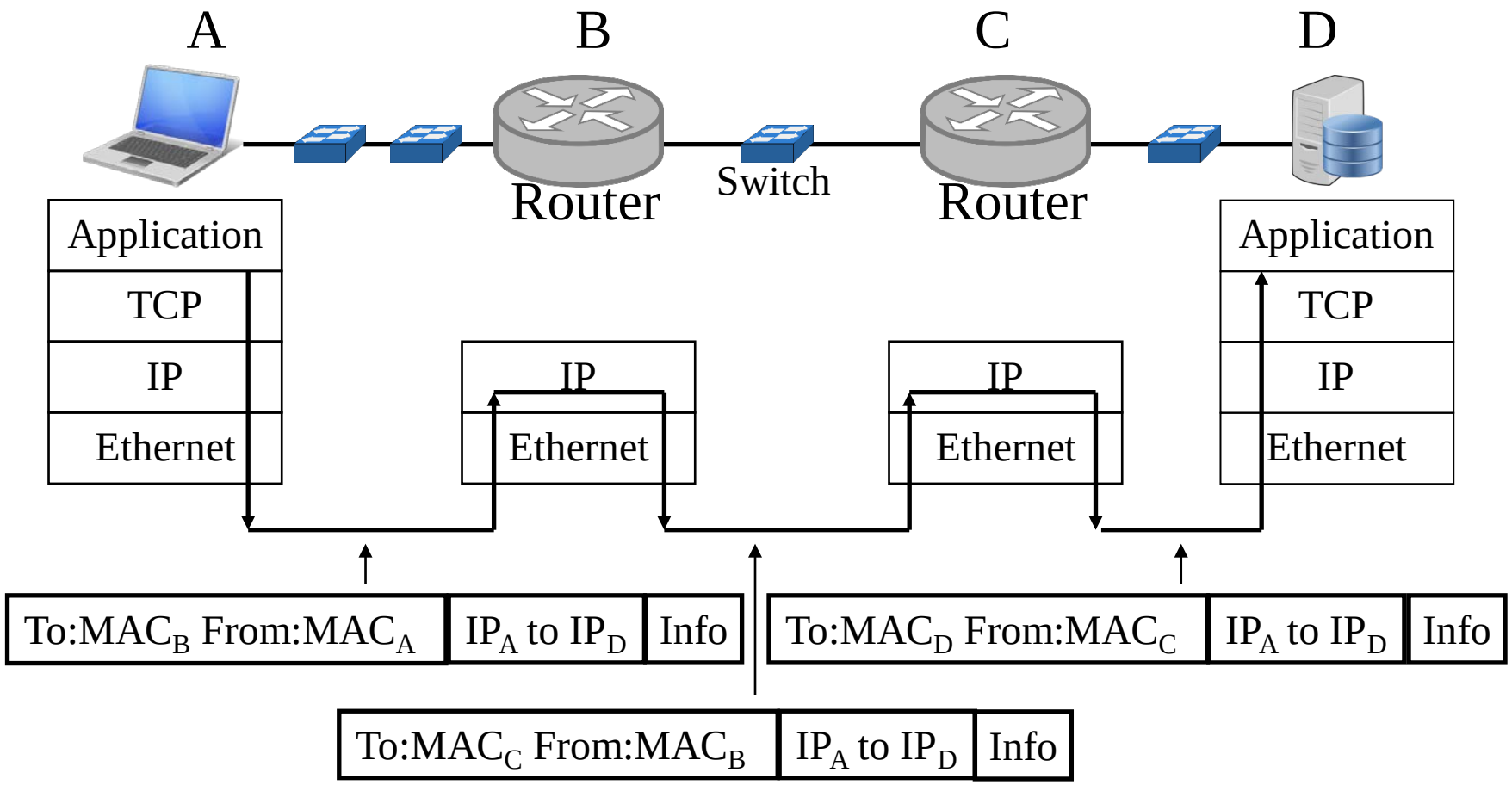
- If a router has two ARP modules, each with its own ARP table, is it possible that the same MAC address appears in both tables?

No, MAC addresses are unique for each interface. A node may be dual-ported and will be reachable from multiple router ports but each will have its own MAC address and IP address since routers connect different subnets.



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IP over Multiple Hops



- Switches = Transparent Bridges ⇒ No changes to frames
- ARP required only for nodes on the same "subnet."

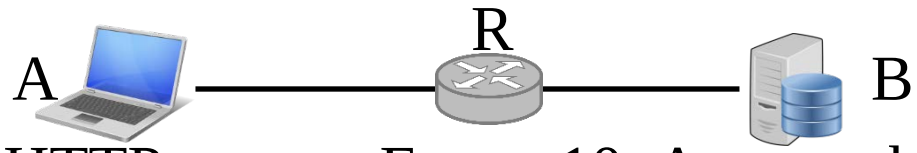
Student Questions

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Lab 6: Ethernet and ARP

[32 points] Download the Wireshark traces from http://gaia.cs.umass.edu/wireshark-labs/wireshark-traces.zip

Open *Ethernet--ethereal-trace-1* in Wireshark. Select **View → Expand All**. This trace shows an HTTP exchange between end host A and Server B via Router R, as shown below:



1. Examine the HTTP request Frame 10. Answer the following questions.
   A. What is the 48-bit Ethernet source address? To whom does it belong: A, B, or R?
   B. What is the 48-bit Ethernet destination address? To whom does it belong: A, B, or R?
   C. What is the hexadecimal value for the two-byte Frame type field? What upper-layer protocol does this correspond to?

Student Questions

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Lab 6 (Cont)

D. How many bytes from the start of the Ethernet frame does the ASCII "G" in "GET" appear in the Ethernet frame? How many bytes are used up in the Ethernet header, IP header, and TCP header before this first byte of the HTTP message?

2. Examine the HTTP OK response. (Frame **12 … 16**).

A. What is the Ethernet source address? To whom does it belong: A, B, or R?

B. What is the destination address in the Ethernet frame? To whom does it belong: A, B, or R?

C. What is the hexadecimal value for the two-byte Frame type field? What upper-layer protocol does this correspond to?

D. How many bytes from the start of the Ethernet frame does the ASCII "O" in "OK" appear in the Ethernet frame? How many bytes are used up in the Ethernet header, IP header, and TCP header before the first byte of the HTTP message?

Student Questions

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Lab 6 (Cont)

3. Examine Frame 1. This is an ARP request.
   A. A. at are the hexadecimal values for the source and destination addresses in the Ethernet frame containing the ARP request message?
   B. What is the hexadecimal value for the two-byte Frame type field? What upper-layer protocol does this correspond to?
   C. How many bytes from the very beginning of the Ethernet frame does the ARP opcode field begin?
   D. What is the value of the opcode field within the ARP payload?
   E. What is the IP address of the sender?
   F. What are the target MAC and IP addresses in the ARP "question"?

Student Questions

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Lab 6 (Cont)

4. Examine Frame 2. This is the ARP response.

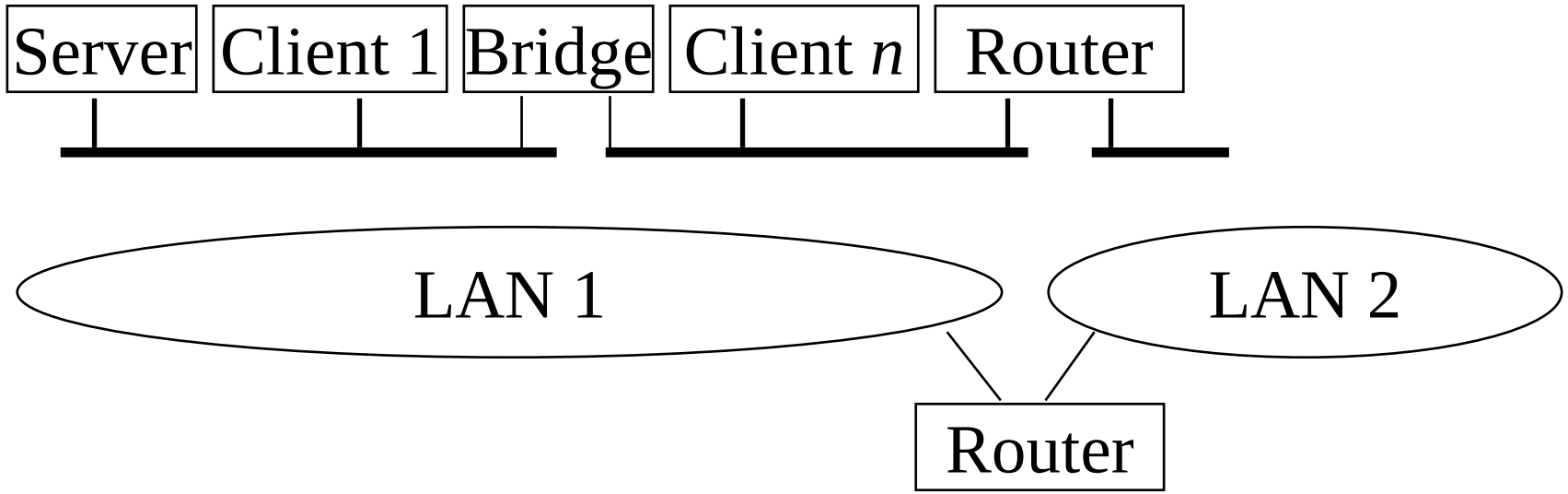
A. What are the hexadecimal values for the source and destination addresses in the Ethernet frame containing the ARP response message?
B. What is the hexadecimal value for the two-byte Frame type field? What upper-layer protocol does this correspond to?
C. How many bytes from the very beginning of the Ethernet frame does the ARP opcode field begin?
D. at is the value of the opcode field within the ARP payload?
E. What is the IP address of the sender?
F. What are the target MAC and IP addresses in the ARP "answer"?

For all questions of this lab, please provide numerical answers only. There is no need to add screen captures.

Student Questions

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What is a LAN?



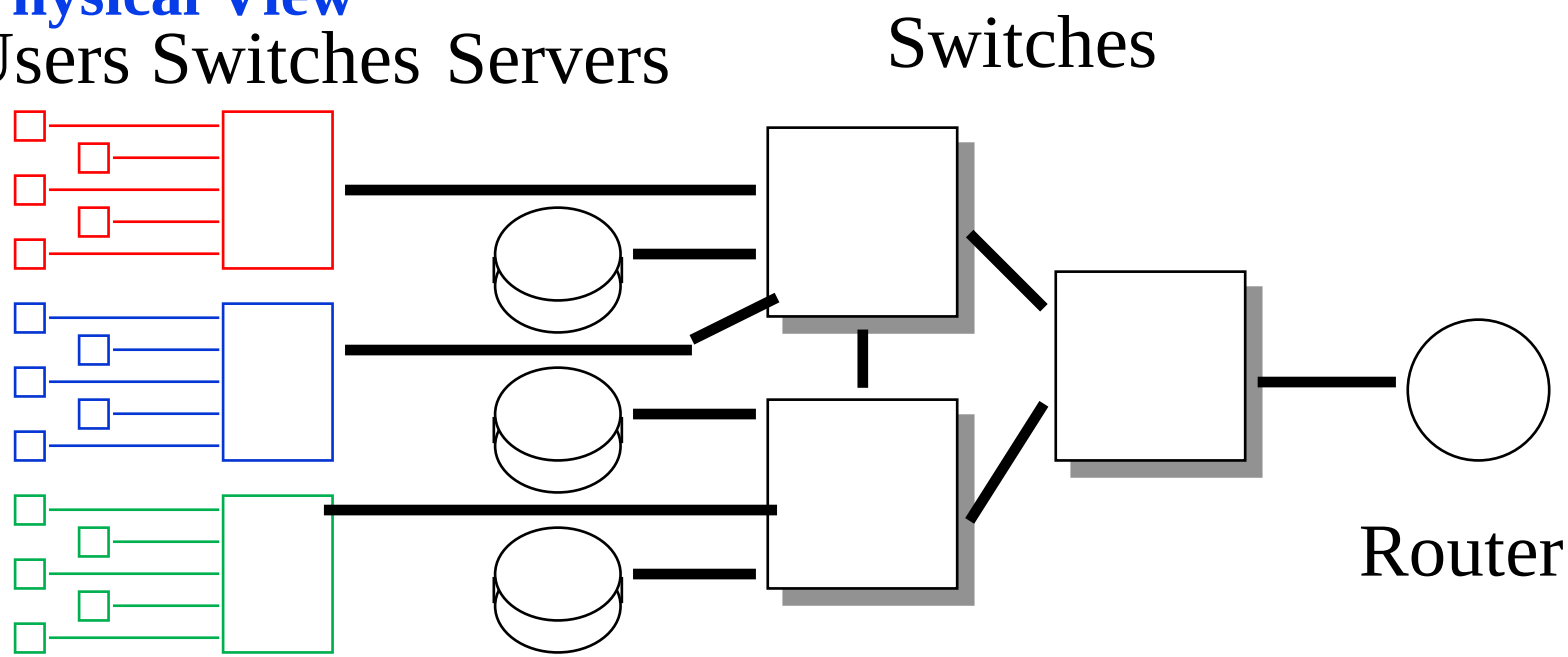
- LAN = **Single broadcast domain** = Subnet
- No routing between members of a LAN
- Routing required between LANs

Student Questions

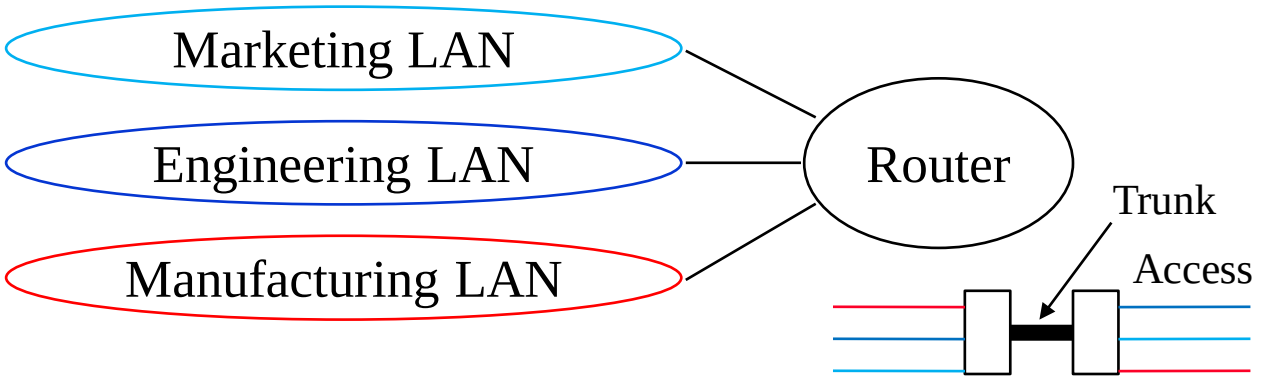
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What is a Virtual LAN

- **Physical View**



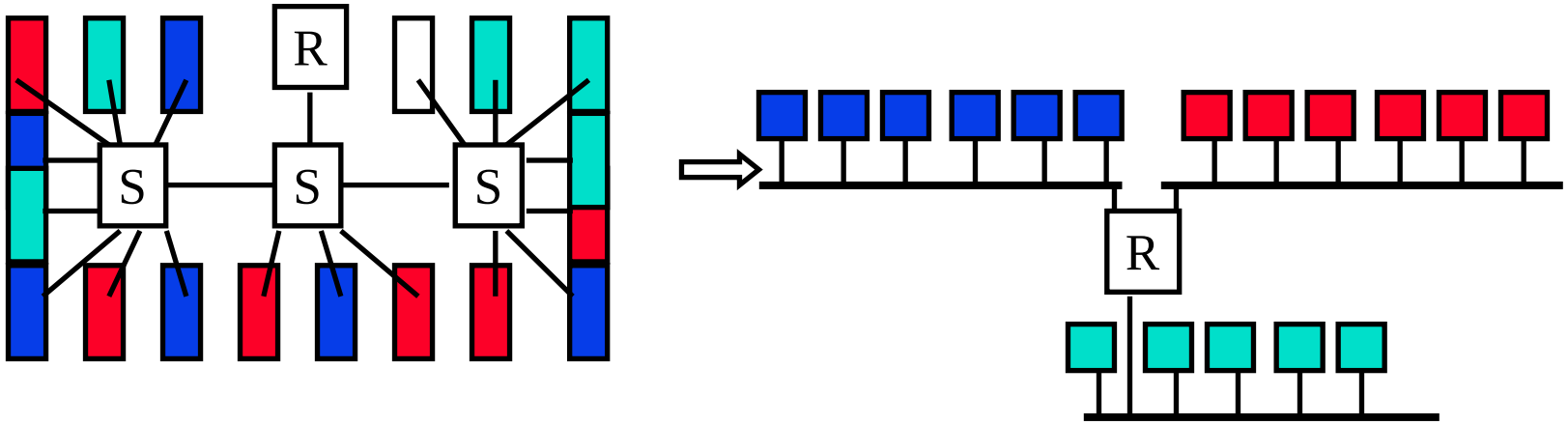
- **Logical View**



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Virtual LAN



- Virtual LAN = Broadcasts and multicasts go only to the nodes in the virtual LAN
- The network manager defines LAN membership
  ⇒ Virtual

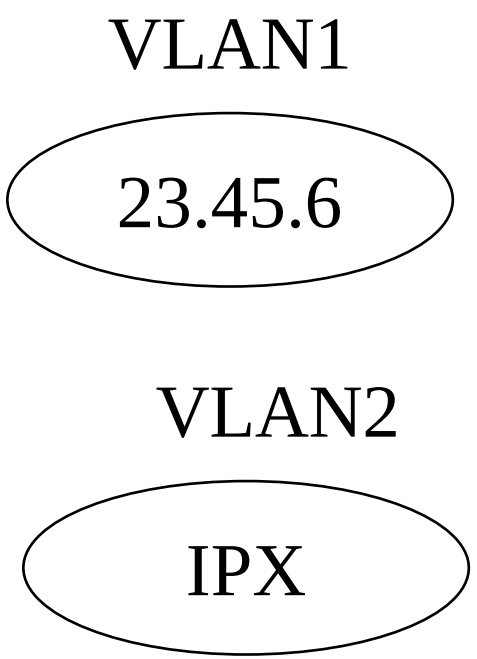
Student Questions

Types of Virtual LANs

- Layer-1 VLAN = Group of Physical ports
- Layer-2 VLAN = Group of MAC addresses
- Layer-3 VLAN = IP subnet

Switch Port	VLAN 1	VLAN 2
A1	√	
A2		√
A3	√	
B1		√
B2	√	

VLAN1	VLAN2
A1B234565600	21B234565600
D34578923434	634578923434
1345678903333	8345678903333
34384703450555	94384703450555
4387434304343	5387434304343
4780357056135	6780357056135
4153953470641	9153953470641
34703436374133	04703436374133
34038470333412	84038470333412
3483434343143	8483434343143
4343134134234	0343134134234



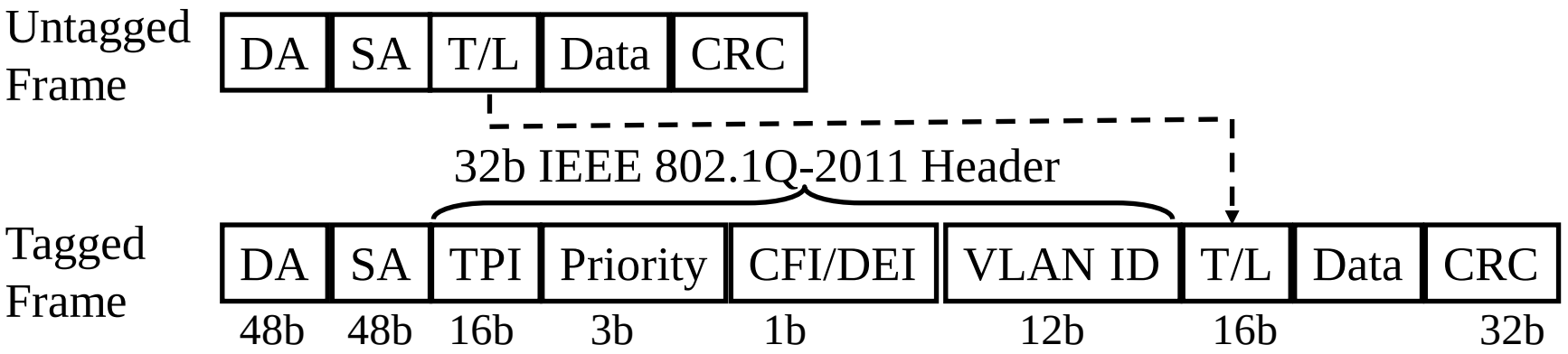
Student Questions

- Why we need different type of VLAN?

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IEEE 802.1Q-2011 Tag

- **Tag Protocol Identifier** (**TPI**)
- **Priority Code Point** (**PCP**): 3 bits = 8 priorities 0..7 (High)
- **Canonical Format Indicator** (**CFI**): 0 ⇒ Standard Ethernet, 1 ⇒ IBM Token Ring format (non-canonical or non-standard)
- CFI is now replaced by the Drop Eligibility Indicator (**DEI**)
- VLAN Identifier (12 bits ⇒ 4095 VLANs)
- Switches forward based on MAC address + VLAN ID
  Unknown addresses are flooded.



Ref: Canonical vs. MSB Addresses, http://support.lexmark.com/index?page=content&id=HO1299&locale=en&userlocale=EN_US

Ref: G. Santana, "Data Center Virtualization Fundamentals," Cisco Press, 2014, ISBN:1587143240

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Student Questions



Switched Local Area Networks : Review

1. IEEE 802.3 uses a *truncated binary exponential backoff*.
2. Ethernet uses 48-bit addresses, of which the first bit is the unicast/multicast, 2nd bit is universal/local, and 22-bits are OUI (Organizationally unique identifier).
3. Ethernet bridges are transparent and self-learning, using source addresses in the frame.
4. Bridges are layer-2 devices, while routers are layer-3 devices and do not forward layer-2 broadcasts.
5. Address Resolution Protocol (ARP) is used to find the MAC address for a given IP address and vice versa.
6. The IEEE 802.1Q tag in Ethernet frames allows a LAN to be divided into multiple VLANs. Broadcasts are limited to each VLAN; you need a router to go from one VLAN to another.

Student Questions

Ref: Section 6.4, Review Questions R9-R16

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Multiprotocol Label Switching

Connection-oriented IP: Paths set up in advance

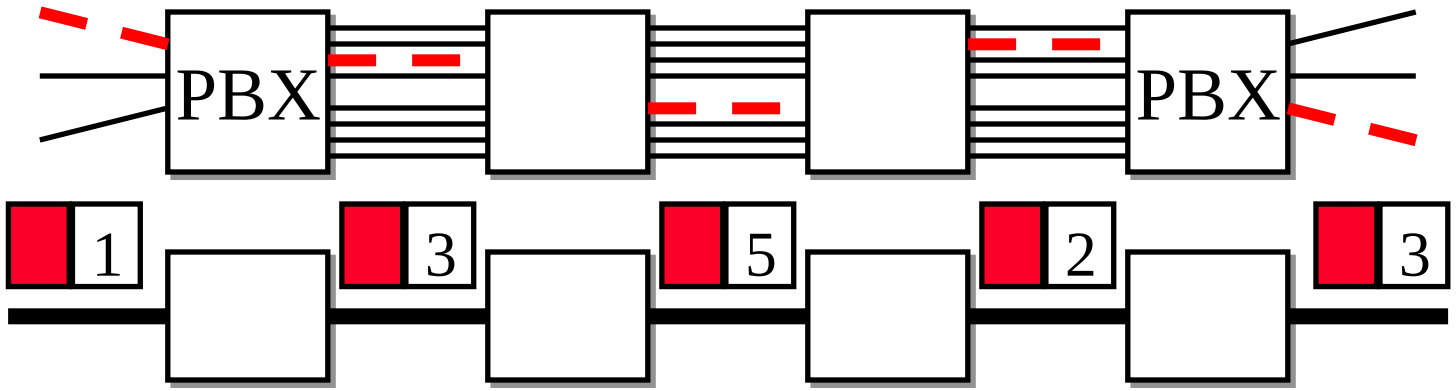
Borrowed from the Telephone networks

- Multiprotocol Label Switching (MPLS)
- Label Switching Example
- MPLS Forwarding Tables
- MPLS versus IP Paths
- MPLS Label Format

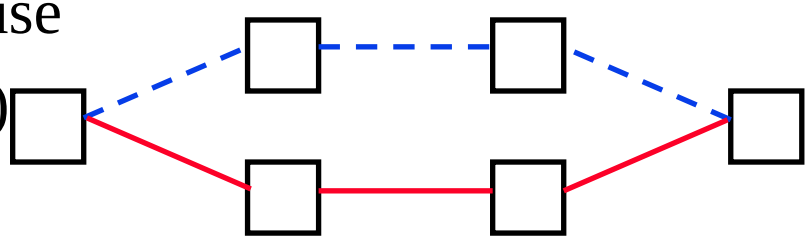
Student Questions

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Multiprotocol Label Switching (MPLS)



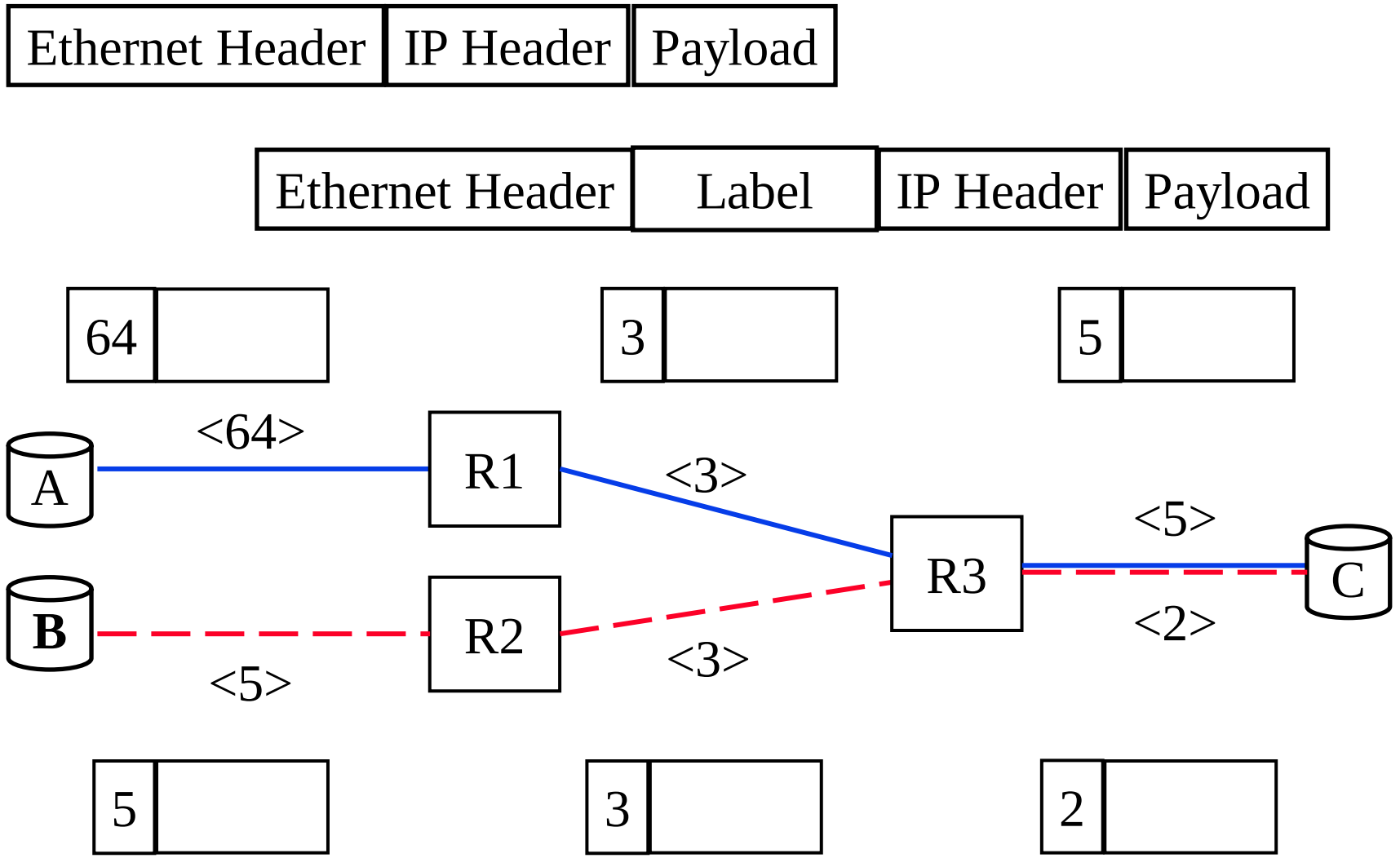
- Allows virtual circuits in IP Networks (May 1996)
- Each packet has a virtual circuit ID called 'label.'
- Label determines the packet's queuing and forwarding
- Circuits are called Label-Switched Paths (LSPs)
- LSPs have to be set up before use
- Label-switching routers (LSRs) allows traffic engineering



Student Questions

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Label Switching Example



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MPLS Forwarding Tables

- Interface numbers are in circles. Label IDs are in rectangles.

R6

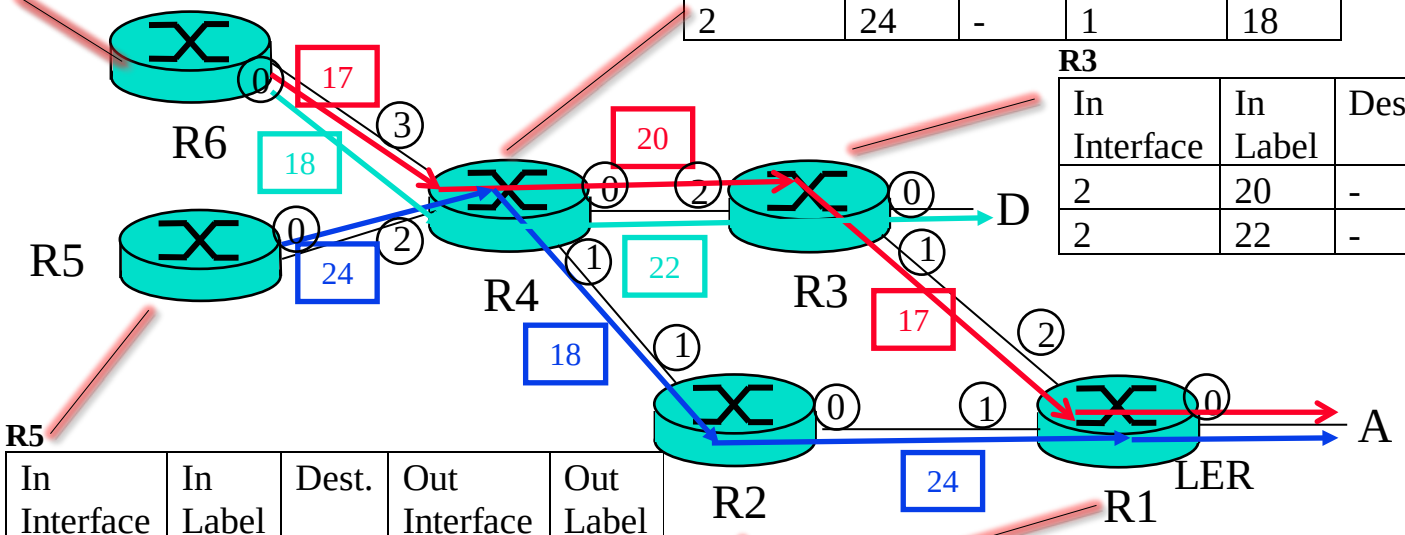
In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	17
-	None	D	0	18

R4

In Interface	In Label	Dest.	Out Interface	Out Label
3	17	-	0	20
3	18	-	0	22
2	24	-	1	18

R3

In Interface	In Label	Dest.	Out Interface	Out Label
2	20	-	1	17
2	22	-	0	None



R5

In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	24

R2

In Interface	In Label	Dest.	Out Interface	Out Label
1	18	-	0	24

R1

In Interface	In Label	Dest.	Out Interface	Out Label
2	17	-	0	None
1	24	-	0	None

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Notes

- **Error in the Book:**
  - The tables are per interface, not per router.
  - For compatibility, we have kept the table per router but added the input interface column.
  - The book lists no input interface in the table.
  - The same label #s can be used in different interfaces of the same router. For example, See Router R3 in the "Label Switching Example" slide.
  - The textbook notation will not allow this possibility.
- Only one direction of circuits is shown for clarity.
  - There is an equal number of reverse circuits that have their own labels unrelated to forward labels.
- Out Label=None ⇒ MPLS Tag is removed.
  In Label=None ⇒ Packet arrives with no MPLS tag.

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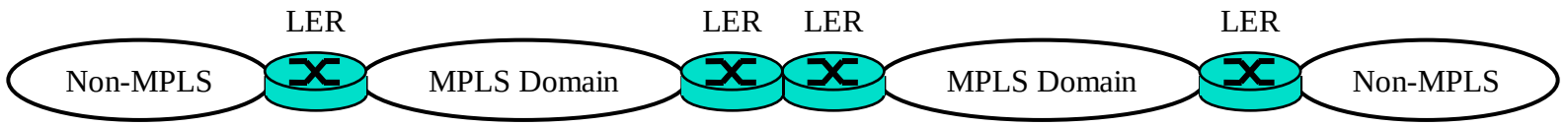
MPLS Label Switched Paths (LSPs)

- Label-switched paths (LSPs) are set up before use.
  ⇒ Connection-oriented
- During setup, each router tells the previous router what label it should put on the frames of that LSP.
- The label is an index in the MPLS forwarding table.
- Indexing in an MPLS table is much faster than searching in IP tables.
- Although speed was one reason for using MPLS, the main reason is that the bandwidth can be reserved along the path.
- Labels are local. Different routers may use the same label ID for different LSPs.
- The label ID changes along various links of the same LSP.
- Label IDs are 20-bit long ⇒ 2^{20}-1 Labels.
  Labels 0-15 are reserved.

Student Questions

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Label Edge Routers (LERs)

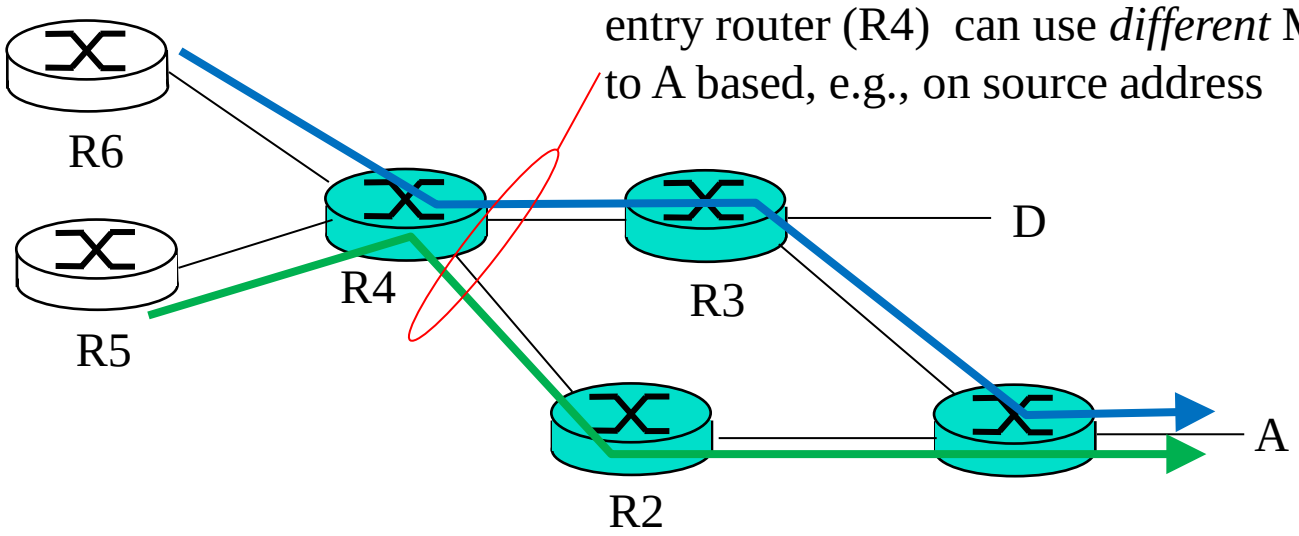


- Routers connected to non-MPLS routers or nodes or routers of other MPLS domains are called Label Edge Routers (**LERs**)
- LERs add labels to frames from non-MPLS nodes or remove their labels if forwarding to non-MPLS nodes or other domains.
- The labels added by LERs **may be** based on destination address and other considerations, such as source address, QoS, etc.
- Other LSRs forward based solely on the label and the frame's incoming interface. They **do not** look at the destination address field.

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MPLS versus IP Paths



- **IP Routing**: Path determined by destination address alone
- **MPLS Routing**: Path can be based on source and destination address, flow type, …
  - **Fast reroute**: Precompute backup routes in case of link failure



IP-only router



MPLS and IP router

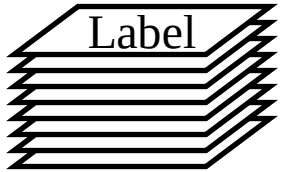
Student Questions

- How does a switch experience a link failure between it and another switch?

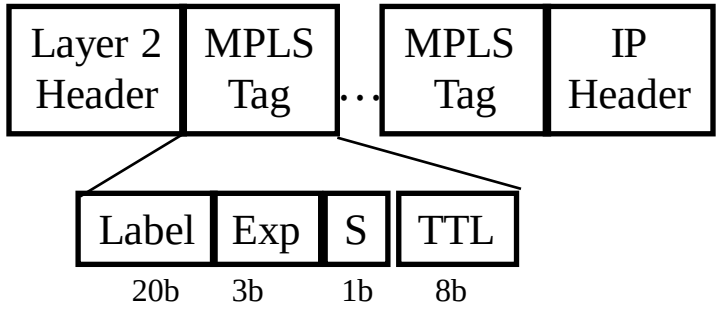
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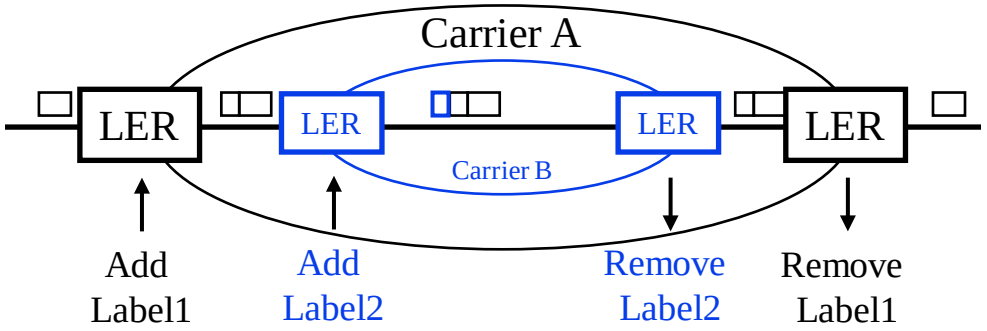
MPLS Label Format

- MPLS label is inserted after the layer-2 header but before the layer-3 header ⇒ MPLS is **Layer-2.5**
  - 20-bit label
  - 3-bit Experimental: Class of Service
  - 1-bit end-of-stack. A packet may have a stack of labels to allow carrier nesting.



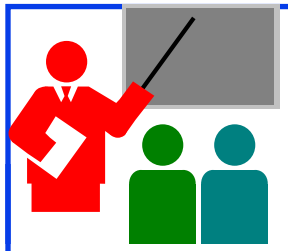
- TTL field is decremented for all forwarded packets.
  When adding a label, the TTL field from the IP header is copied to the MPLS tag.
  When removing a label, the TTL field from the MPLS tag is copied to the IP Header.
- MPLS Signaling:
  - OSPF has been extended to help prepare label tables
  - There are several other "*Label Distribution Protocols.*"





Student Questions

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MPLS: Review

1. Multiprotocol Label Switching (MPLS) allows virtual circuits called "Label Switched Paths (LSPs)" in IP
2. Each packet has a Layer 2.5 MPLS tag, which includes a 20-bit label ID
3. Label-switching routers (LSRs) forward based on the input interface and the label
4. The label table is prepared using a "Label Distribution Protocol." OSPF is one example of an LDP.
5. MPLS tags can be stacked to allow network nesting

Ref: Section 6.5

Student Questions

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Homework 6C: MPLS

- [6 points] Consider the MPLS network in the "MPLS Forwarding Tables" slide. Suppose we want to perform traffic engineering so that packets from R6 destined for A are switched via R6-R4-R2-R1, and packets from R5 destined for A are switched via R5-R4-R3-R1. Show the updated MPLS table in R4 that would enable this. For simplicity, use the same label values as shown currently. Only LSP paths change, and the table at Router R4.

Student Questions

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Homework 6C (Cont)

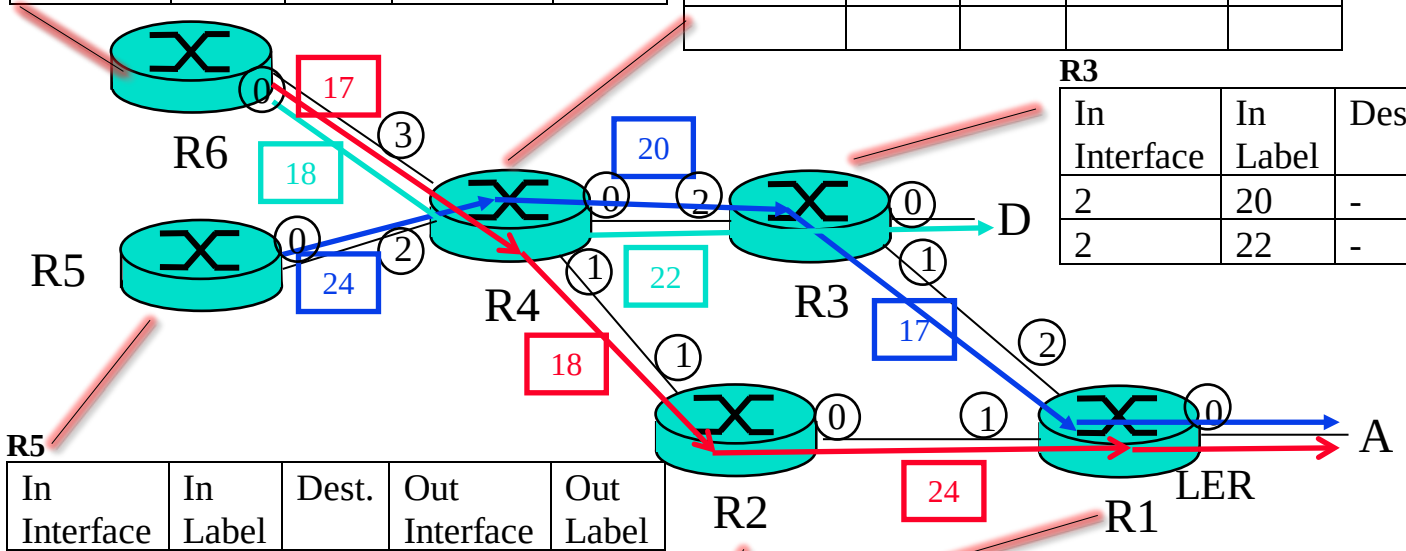
- Interface numbers are in circles. Label IDs are in rectangles.

R6

In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	17
-	None	D	0	18

R4

In Interface	In Label	Dest.	Out Interface	Out Label



R3

In Interface	In Label	Dest.	Out Interface	Out Label
2	20	-	1	17
2	22	-	0	None

R5

In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	24

R2

In Interface	In Label	Dest.	Out Interface	Out Label
1	18	-	0	24

R1

In Interface	In Label	Dest.	Out Interface	Out Label
2	17	-	0	None
1	24	-	0	None

Student Questions

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Homework 6D: MPLS

- [28 points] The figure on the next slide shows the flows on an MPLS network with the reverse direction flows. Using the Labels shown, fill in all the tables.

Student Questions

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Homework 6D (Cont)

- Interface numbers are in circles. Label IDs are in rectangles.

R6

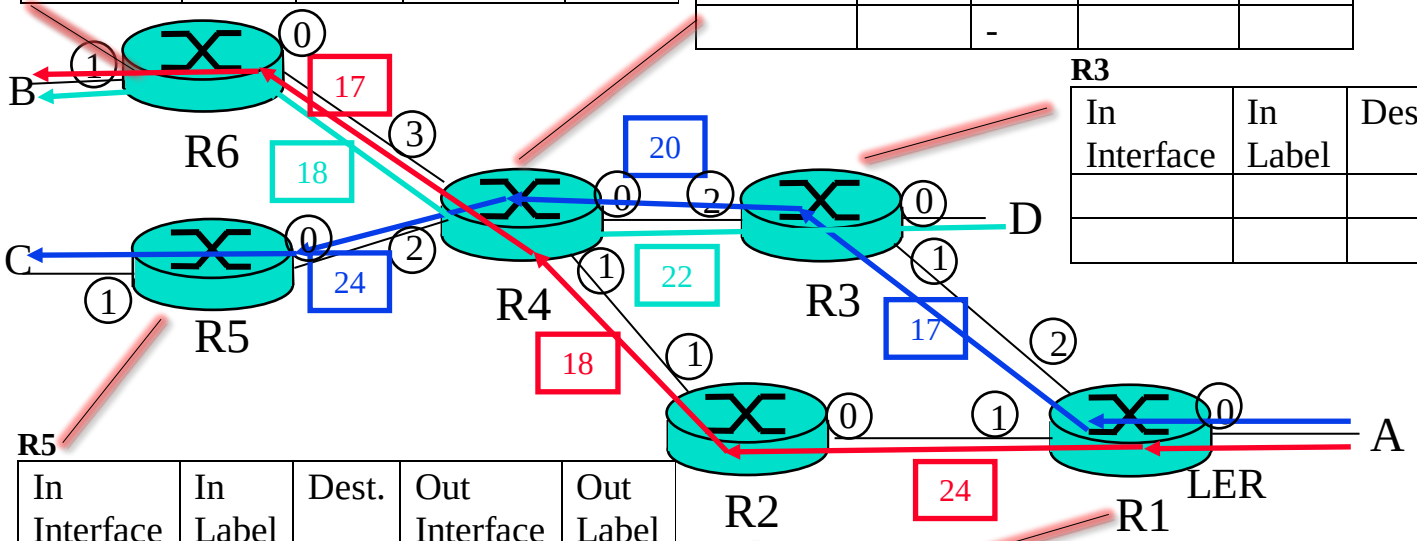
In Interface	In Label	Dest.	Out Interface	Out Label

R4

In Interface	In Label	Dest.	Out Interface	Out Label
		-		

R3

In Interface	In Label	Dest.	Out Interface	Out Label



R5

In Interface	In Label	Dest.	Out Interface	Out Label

R2

In Interface	In Label	Dest.	Out Interface	Out Label

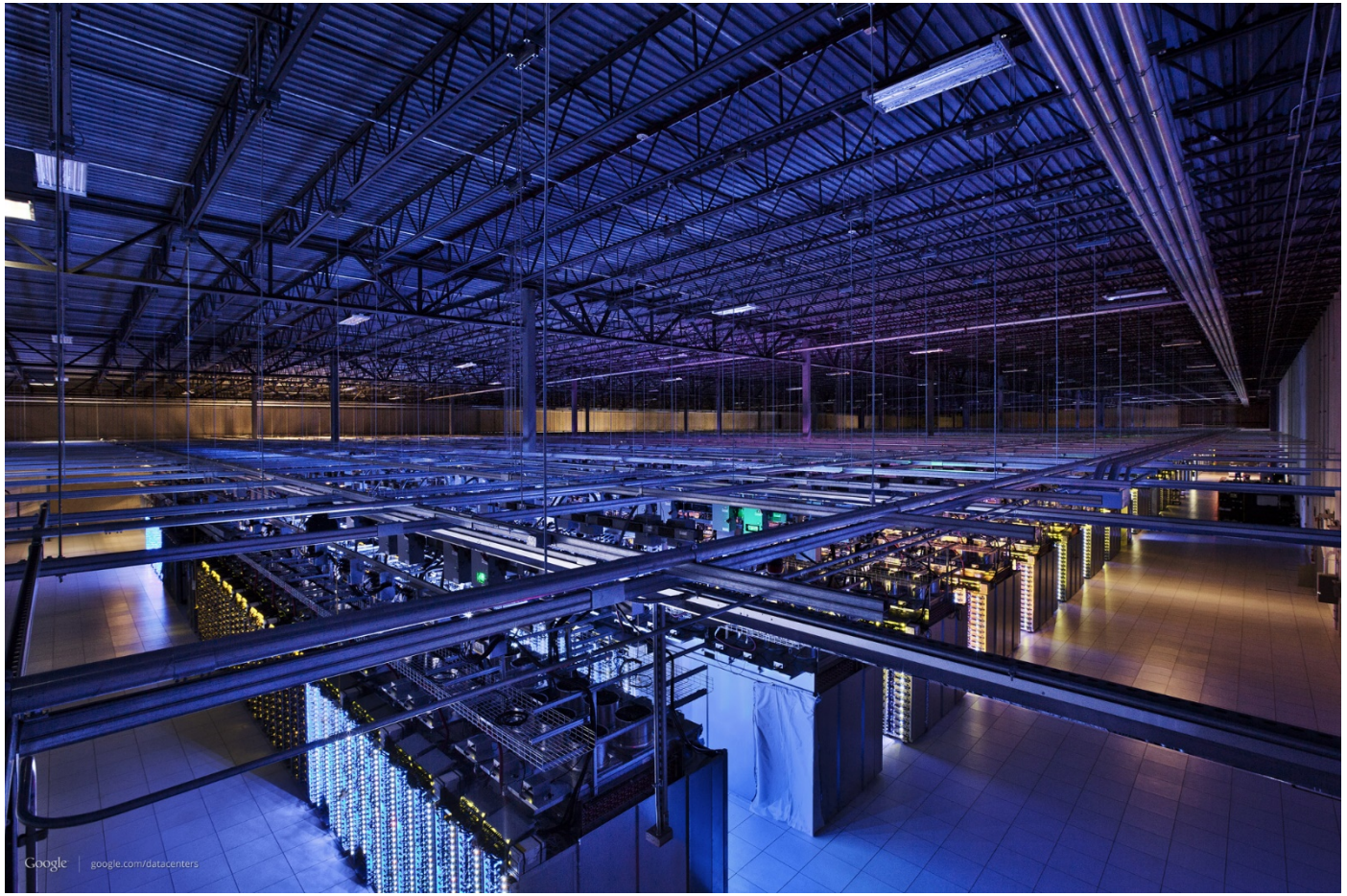
R1

In Interface	In Label	Dest.	Out Interface	Out Label

Student Questions

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Google's Data Center



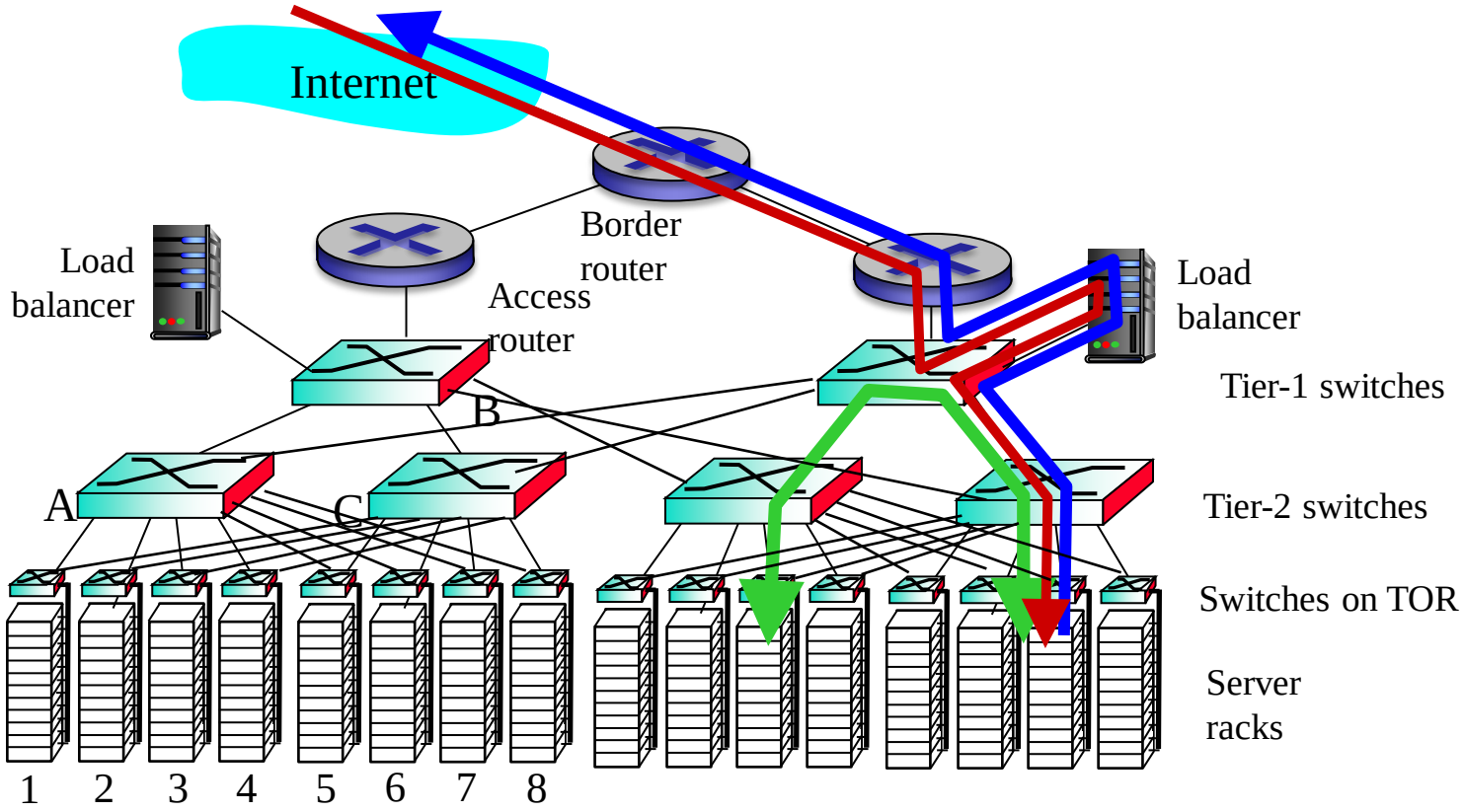
Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Student Questions

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Data Center Networks Topology

- **3-Tier Architecture**: Server switches, Aggregation, Core
- **Middleboxes**: Load balancer, Firewall, Intrusion detection, …
- Rich Interconnection between switches
- Server switches on "top of rack" (TOR) or "end of rack" (EOR)



Student Questions

- End-to-end argument, p362 of the textbook, what is that?

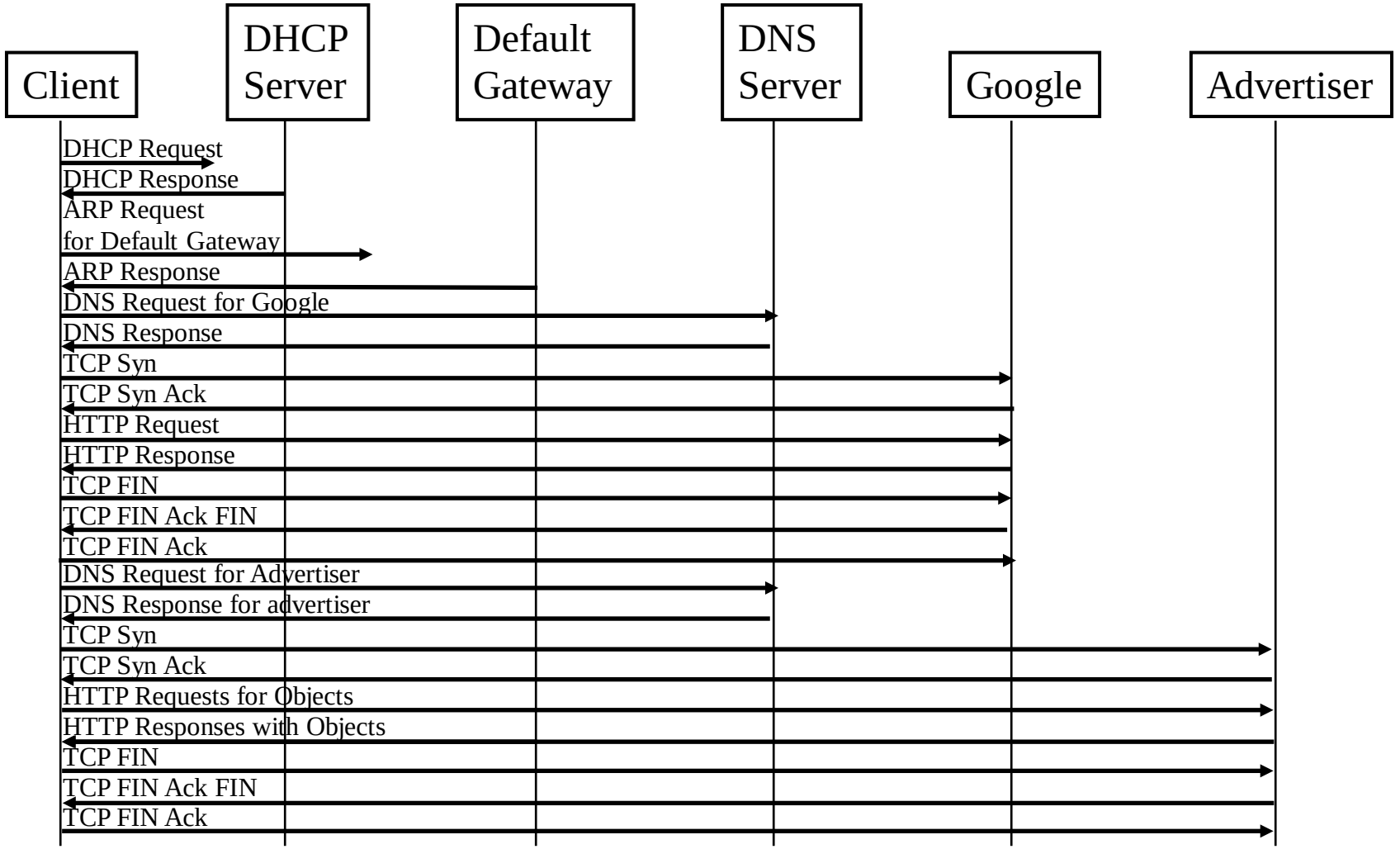
Before middle-boxes, network provided only forwarding service. All other services were done at the edge.

Ref: Section 6.6

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Protocols: Complete Picture

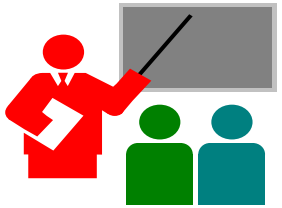
Task: Connect and search in www.google.com



Student Questions

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Summary



1. CRC uses mod-2 division using specially selected numbers
2. IEEE 802.3 uses a *truncated binary exponential backoff*.
3. Ethernet uses 48-bit universal addresses.
4. Ethernet bridges are transparent and self-learning
5. 802.1Q allows several virtual LANs inside a LAN.
6. Address Resolution Protocol (ARP) is used to find the MAC address for a given IP address and vice versa.
7. MPLS allows virtual circuits (LSPs) on IP networks.
8. Data centers use a multi-tier switching architecture with redundancy.

Student Questions

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Acronyms

- ARP Address Resolution Protocol
- ASCII American Standard Code for Information Exchange
- CAT Category
- CD Collision Detection
- CRC Cyclic Redundancy Check
- CSMA Carrier Sense Multiple Access
- DA Destination Address
- DEI Drop Eligibility Indicator
- DHCP Dynamic Host Control Protocol
- DNS Domain Name Server
- DOCSIS Data over Cable Service Interface Specification
- FDMA Frequency Division Multiple Access
- HTTP Hypertext Transfer Protocol
- ID Identifier
- IEEE Institution of Electrical and Electronics Engineers

Student Questions

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Acronyms (Cont)

- IP Internet Protocol
- IPX Internetwork Packet Exchange
- LAN Local Area Network
- LDP Label Distribution Protocol
- LLC Logical Link Control
- LSP Label Switched Path
- MAC Media Access Control
- MAP Map
- MPLS Multiprotocol Label Switching
- MSB Most Significant Byte First
- NIC Network Interface Card
- OSPF Open Shortest Path First
- OUI Organizationally Unique Identifier
- PBX Private Branch Exchange
- PCP Priority Code Point
- PHY Physical Layer

Student Questions

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Acronyms (Cont)

- SA Source Address
- STP Shielded Twisted Pair
- TCP Transmission Control Protocol
- TDMA Time Division Multiple Access
- TOR Top of the Rack
- TPI Tag Protocol Identifier
- TTL Time to live
- TX Transmit
- UTP Unshielded Twisted Pair
- VLAN Virtual Local Area Network

Student Questions

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