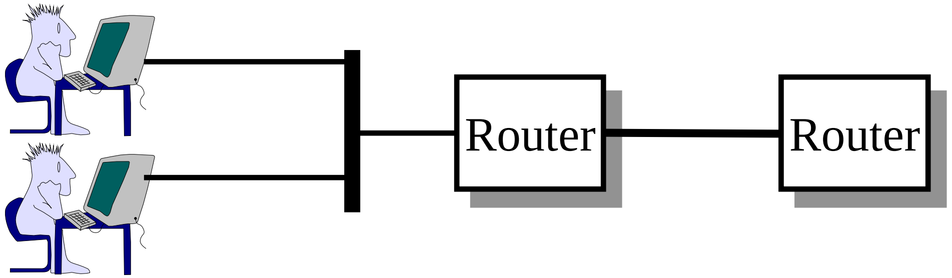
The Link Layer and LANs



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

http://www.cse.wustl.edu/~jain/cse473-25/

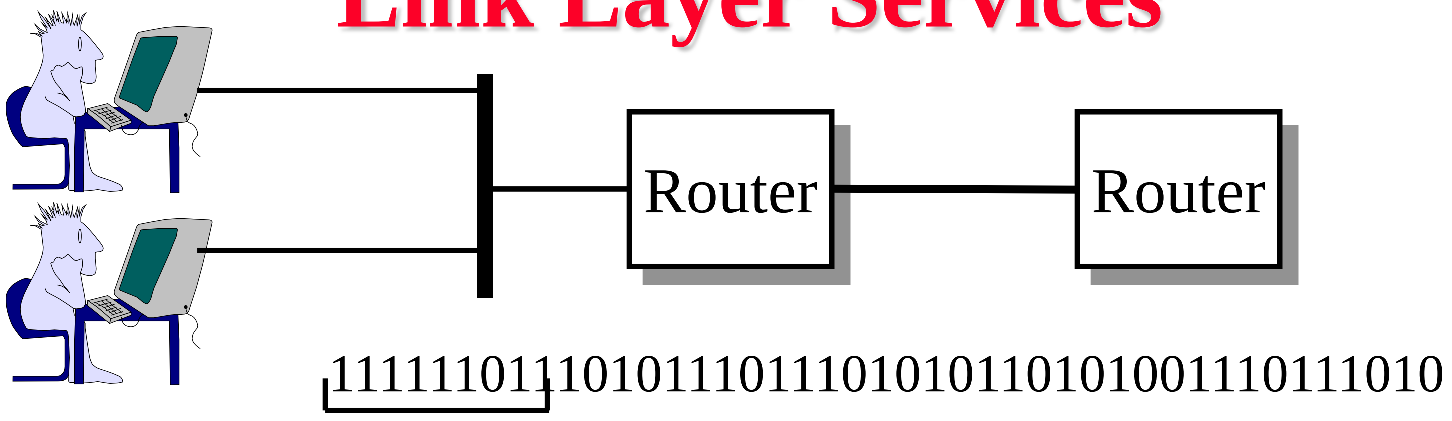
Student Questions

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

Link Layer Services



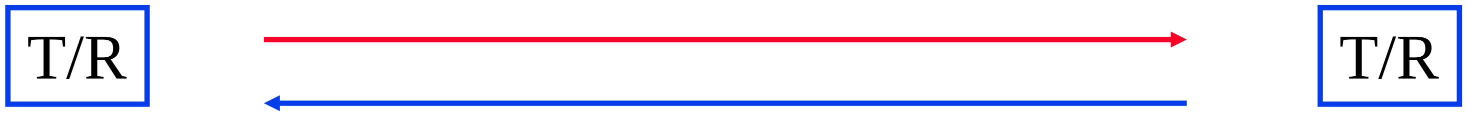
- Link = One hop
- Framing: Bit patterns at the begin/end of a frame
- Multiple Access: Multiple users sharing a wire
- Optional (On Lossy wireless links)
  - Flow Control
  - Error Detection/Correction
  - Reliable Delivery
- Duplex Operation

Student Questions

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

Error Detection

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

Student Questions

Parity Checks

1	2	3	4	5	6	7	8	9
1	0	1	1	1	0	1	0	

- **Odd Parity**

1	2	3	4	5	6	7	8	9
1	0	1	1	1	0	1	0	0

1	2	3	4	5	6	7	8	9
0	0	1	1	1	0	1	0	0

1-bit error

1	2	3	4	5	6	7	8	9
0	0	0	1	0	0	1	0	0

3-bit error

1	2	3	4	5	6	7	8	9
0	0	0	1	1	0	1	0	0

2-bit error

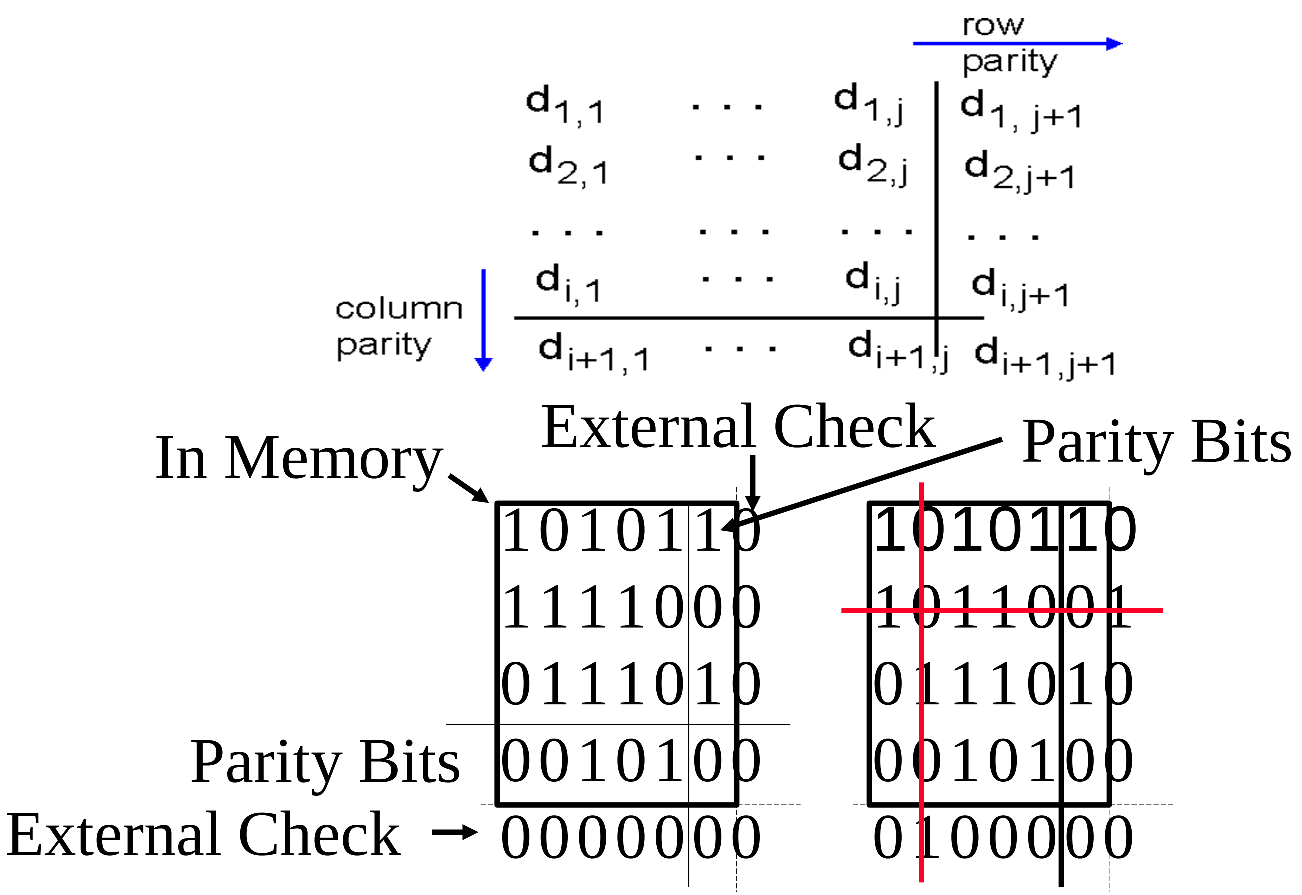
- **Even Parity**

1	2	3	4	5	6	7	8	9
1	0	1	1	1	0	1	1	0

Student Questions

Two-Dimensional Parity

- Detect and correct single bit errors



Student Questions

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: 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

Modulo 2 Arithmetic

```
  1111        11001          110
+1010       ×      11      11 | 1010
--------    --------          /  11
 0101         11001           ---------     010    2
             11001               x11        011    3
             ---------            11        ----   --
             101011              ---------  001    1  Mod 2
                                   x00      101    5  Binary
                                    00
                                  -----
                                    x0
```

See Slides 6.70 and 6.71 for more Mod-2 examples.

Student Questions

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

Modulo 2 Division

Q=1101010110

P=110101)101000110100000=2^nM

110101

111011

110101

011101

000000

111010

110101

011111

000000

111110

110101

010110

000000

101100

110101

110010

110101

001110

000000

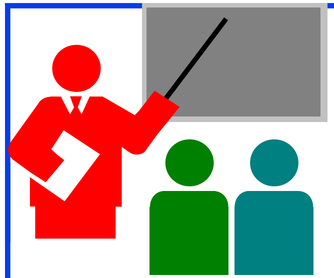
01110 = R

Student Questions

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



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

Ref: Section 6.2, Review questions R2, R3

Student Questions

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

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

Multiple Access

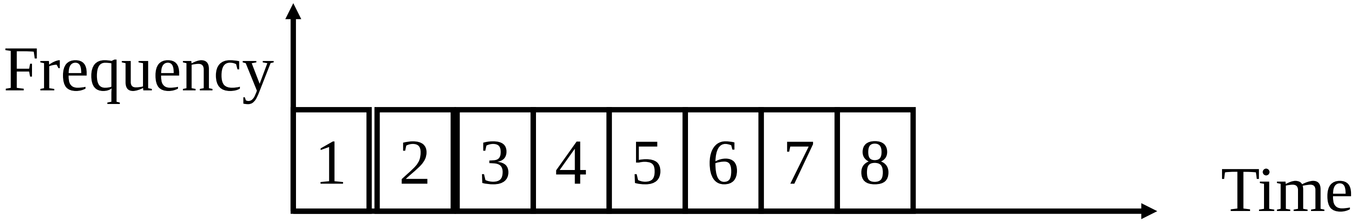
(a) Aloha Multiple Access

(b) Carrier-Sense Multiple Access with Collision Detection

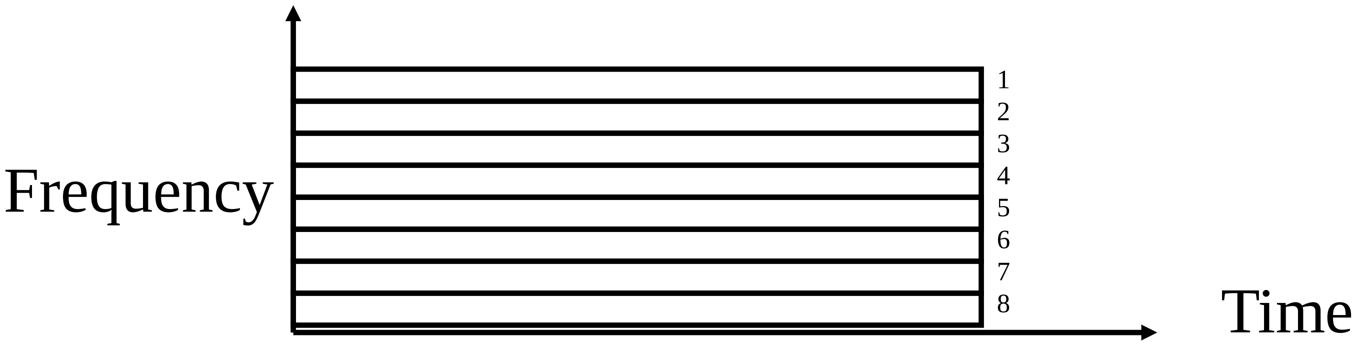
Student Questions

Multiple Access

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



- **Frequency Division Multiple Access**



Student Questions

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.

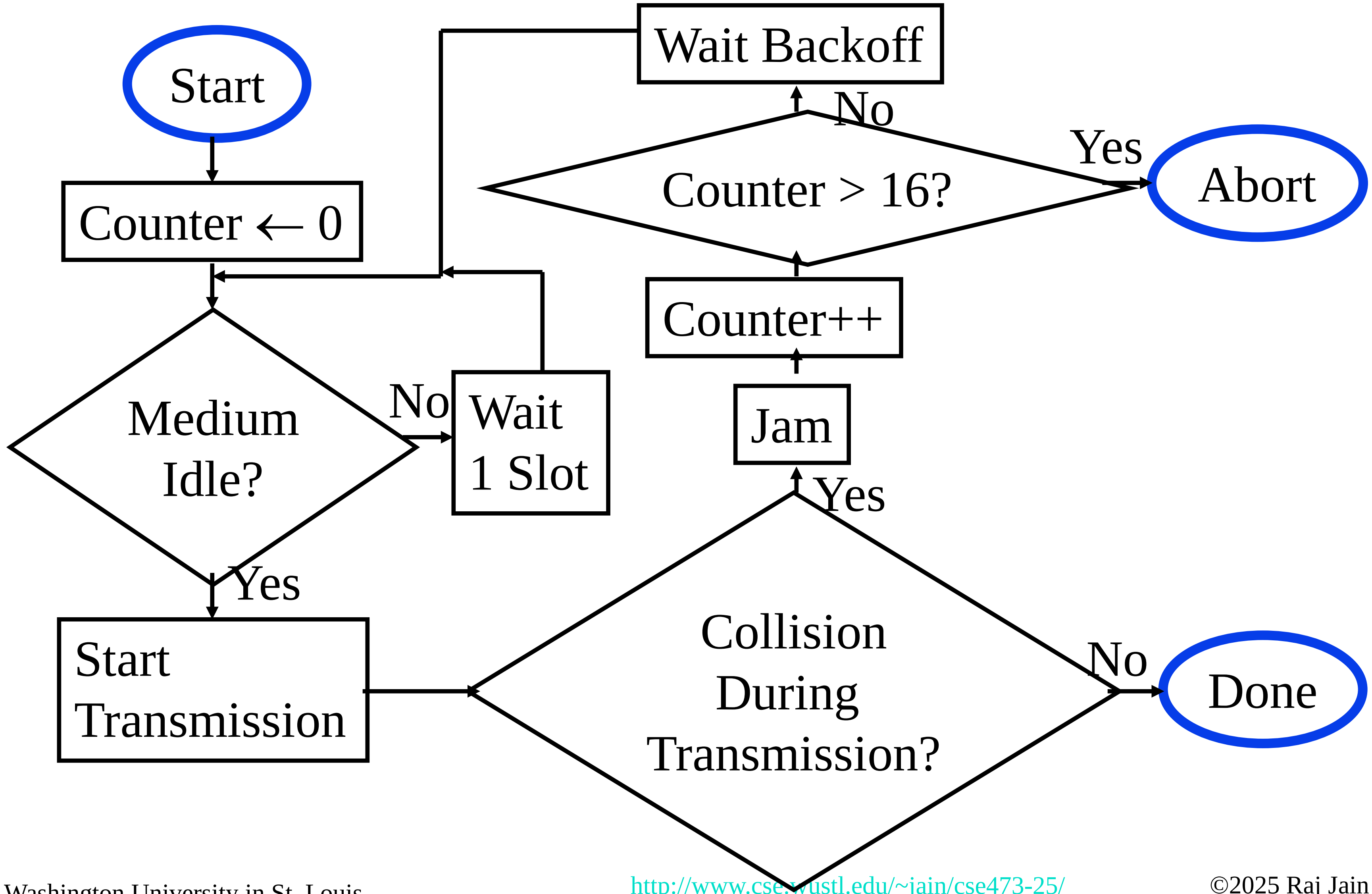
Student Questions

IEEE 802.3 CSMA/CD

- If the medium is idle, transmit (1-persistent).
- If the medium is busy, wait until 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 length of the cable is limited to 2.5 km.

Student Questions

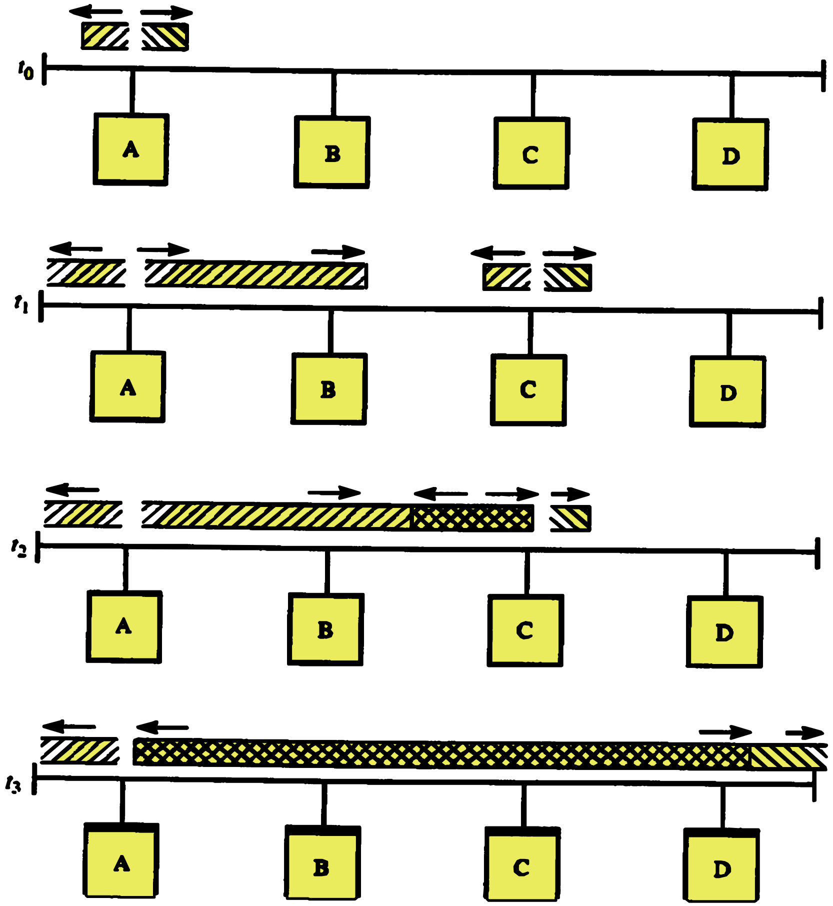
IEEE 802.3 CSMA/CD Flow Chart



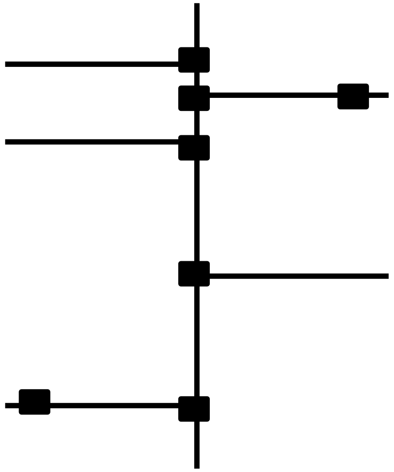
Student Questions

CSMA/CD Operation

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



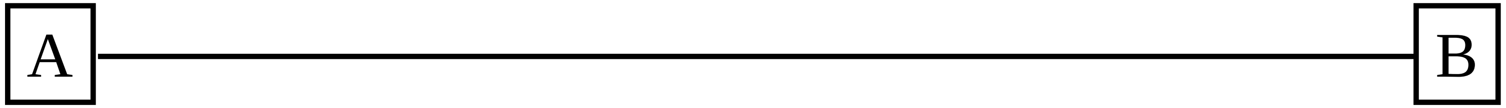
One way delay
= 25.6 μs
Max Distance
<2.5 km



Student Questions

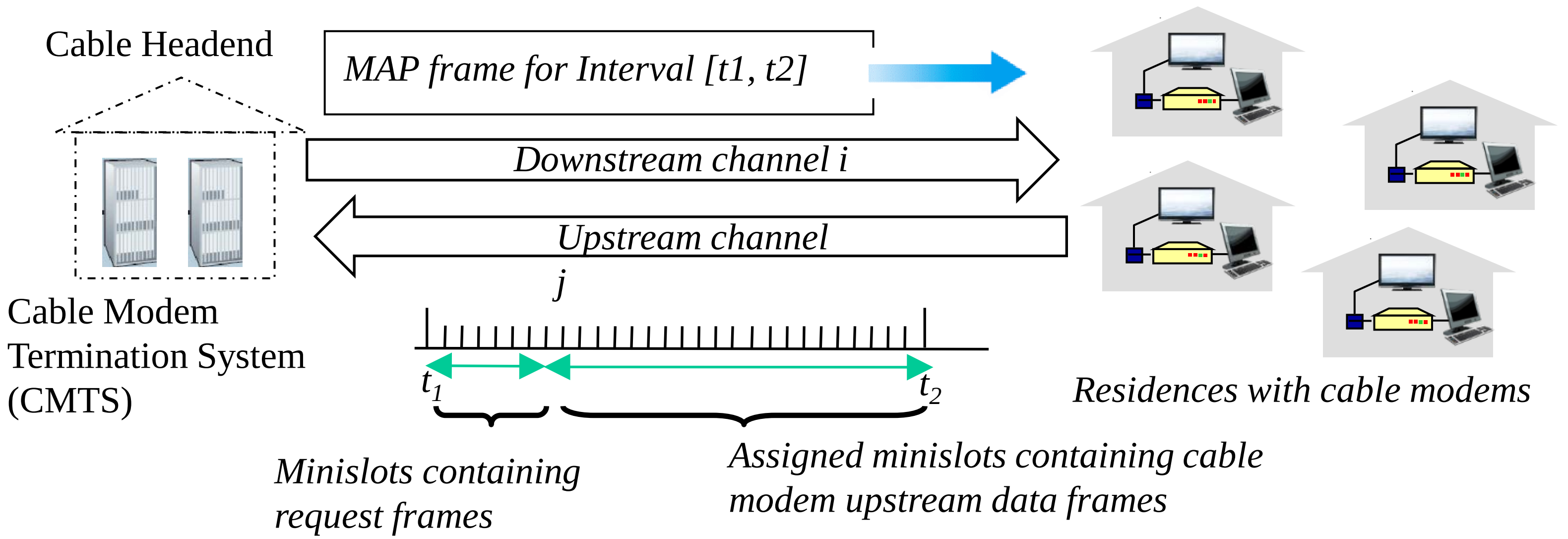
Homework 6B: Collision Detection

- [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

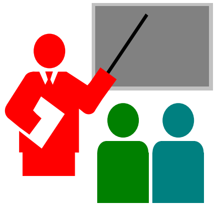
Cable Access Network



- **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 random access (binary backoff) in selected slots

Student Questions

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.

Ref: Section 6.3, Review question R4-R8

Student Questions

End of Part 1

Switched Local Area Networks

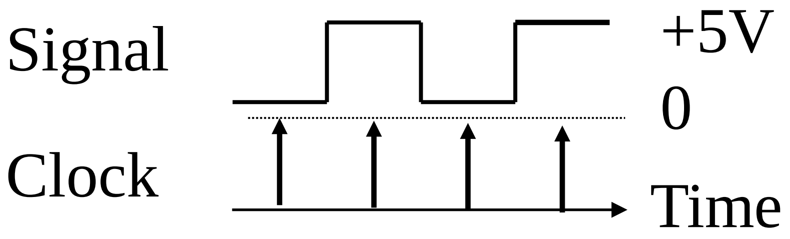
1. Ethernet Standards
2. IEEE 802 Address Format
3. Address Resolution Protocol
4. Bridging
5. Virtual LANs

Student Questions

Ethernet Frame Structure

preamble	dest. address	source address	type	data (payload)	CRC
64b	48b	48b	16b	Variable length	32b

- ***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

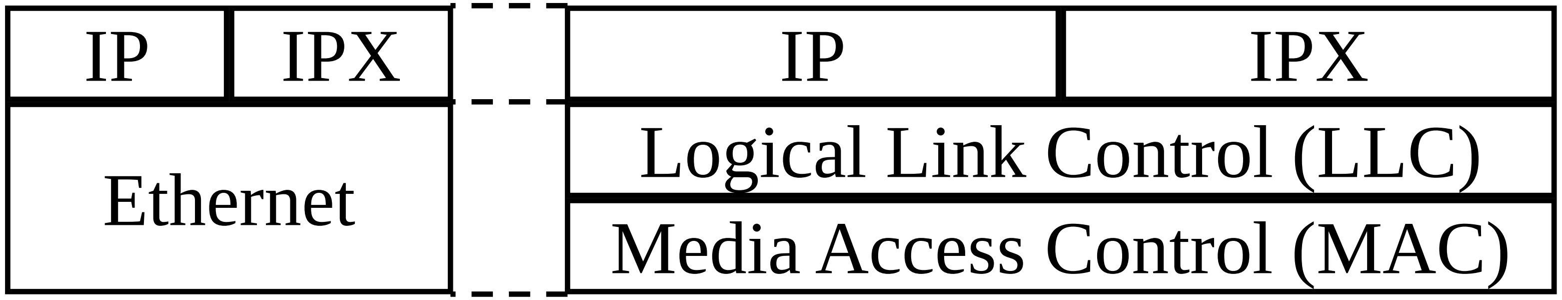
Student Questions

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

Ethernet vs. IEEE 802.3

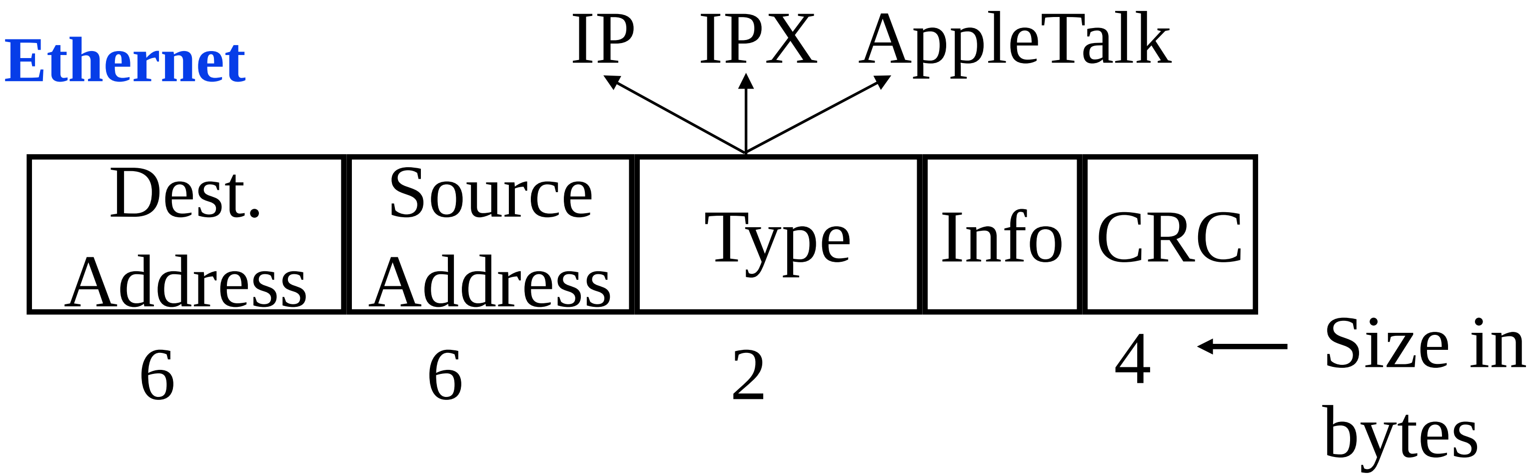


- In 802.3, datalink was divided into two sublayers: LLC and MAC
- **LLC** provides protocol multiplexing. MAC does not.
- **MAC** does not need a protocol-type field.

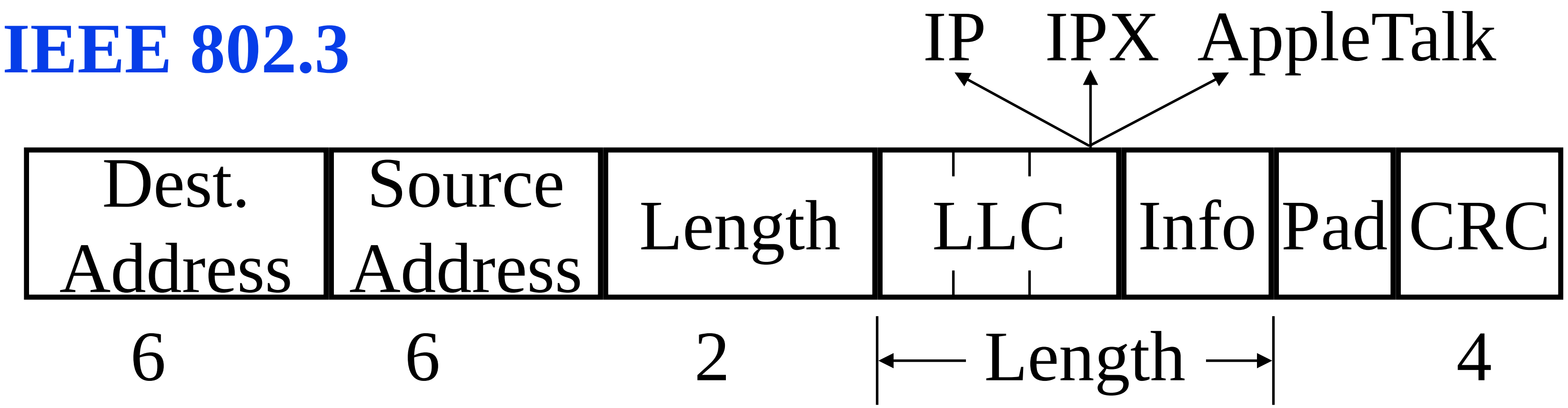
Student Questions

Ethernet and 802.3 Frame Formats

- Ethernet



- IEEE 802.3



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

Student Questions

IEEE 802 Address Format

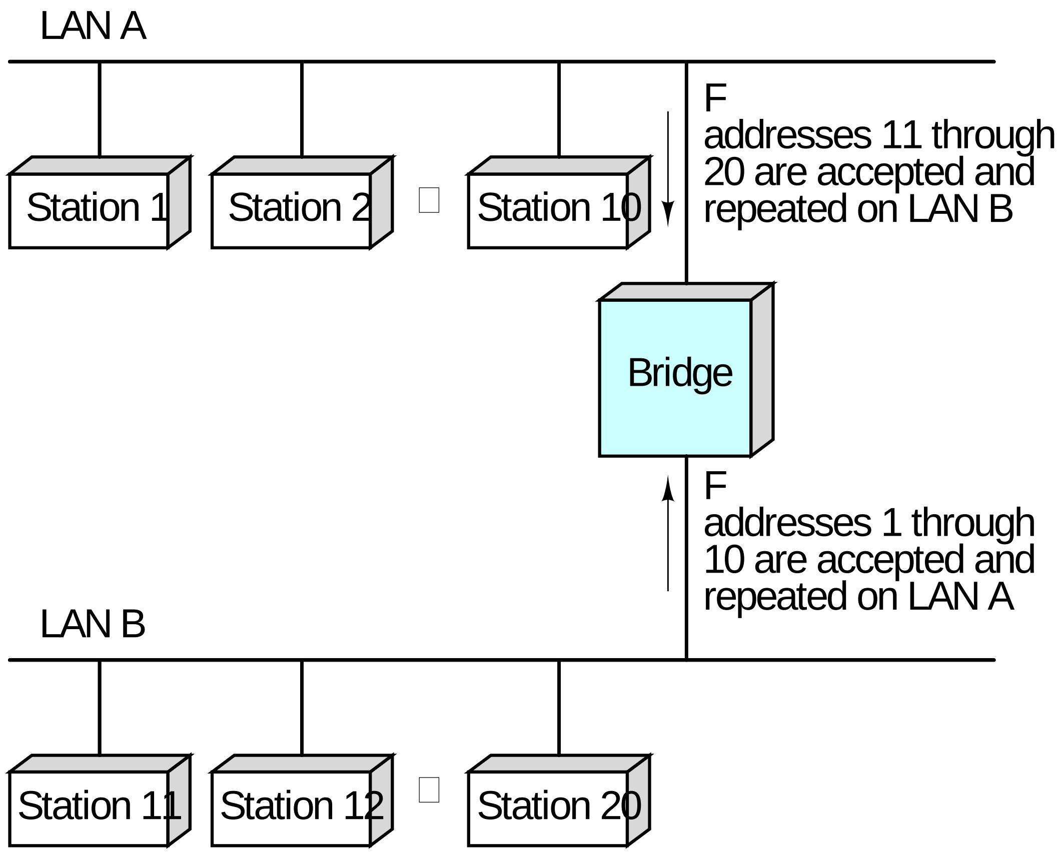
- 48-bit:1000 0000 : 0000 0001 : 0100 0011 : 0000 0000 : 1000 0000 : 0000 1100 = 80:01:43:00:80:0C

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

Bridges



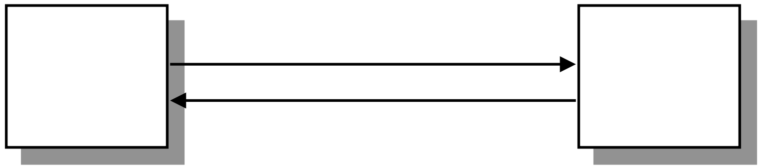
Student Questions

Bridge: Functions

- Monitor all frames on LAN A
- Pickup 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

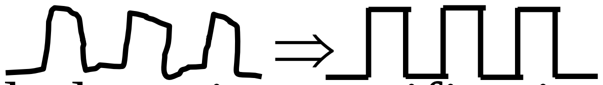
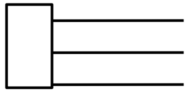
Full-Duplex Ethernet

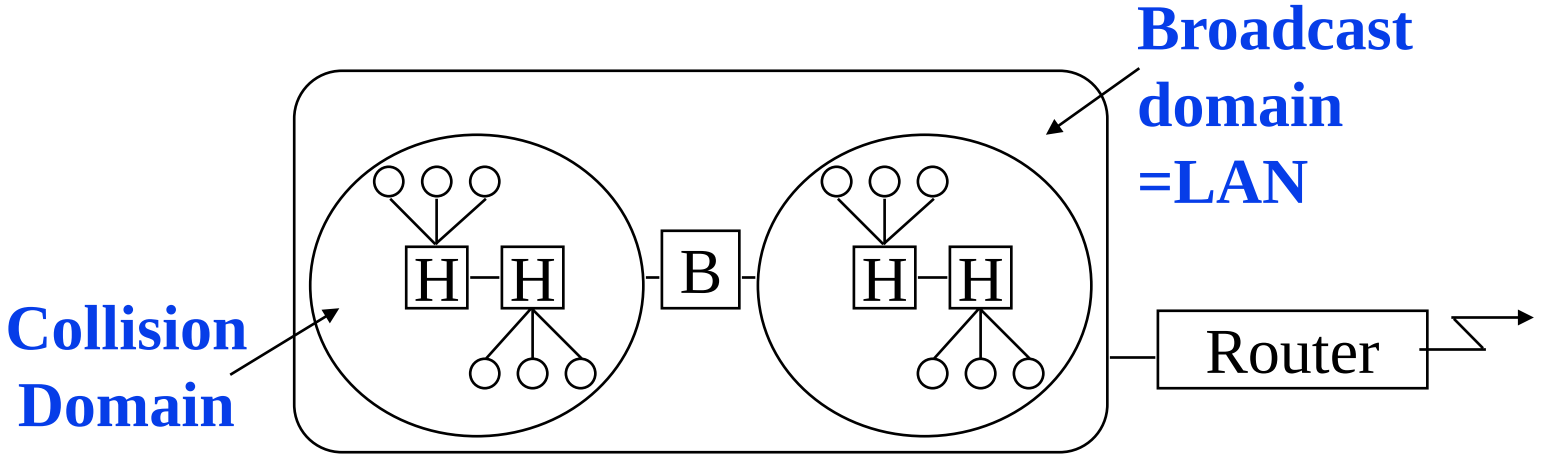


- Uses point-to-point links between TWO nodes
- Full-duplex bi-directional transmission ⇒ Transmit any time
- Standardized in IEEE 802.3-2018
- All vendors are shipping switch/bridge/NICs with full duplex
- No collisions ⇒ 50+ km on fiber.
- Between servers and switches or between switches
- CSMA/CD 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

Interconnection Devices

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



Student Questions

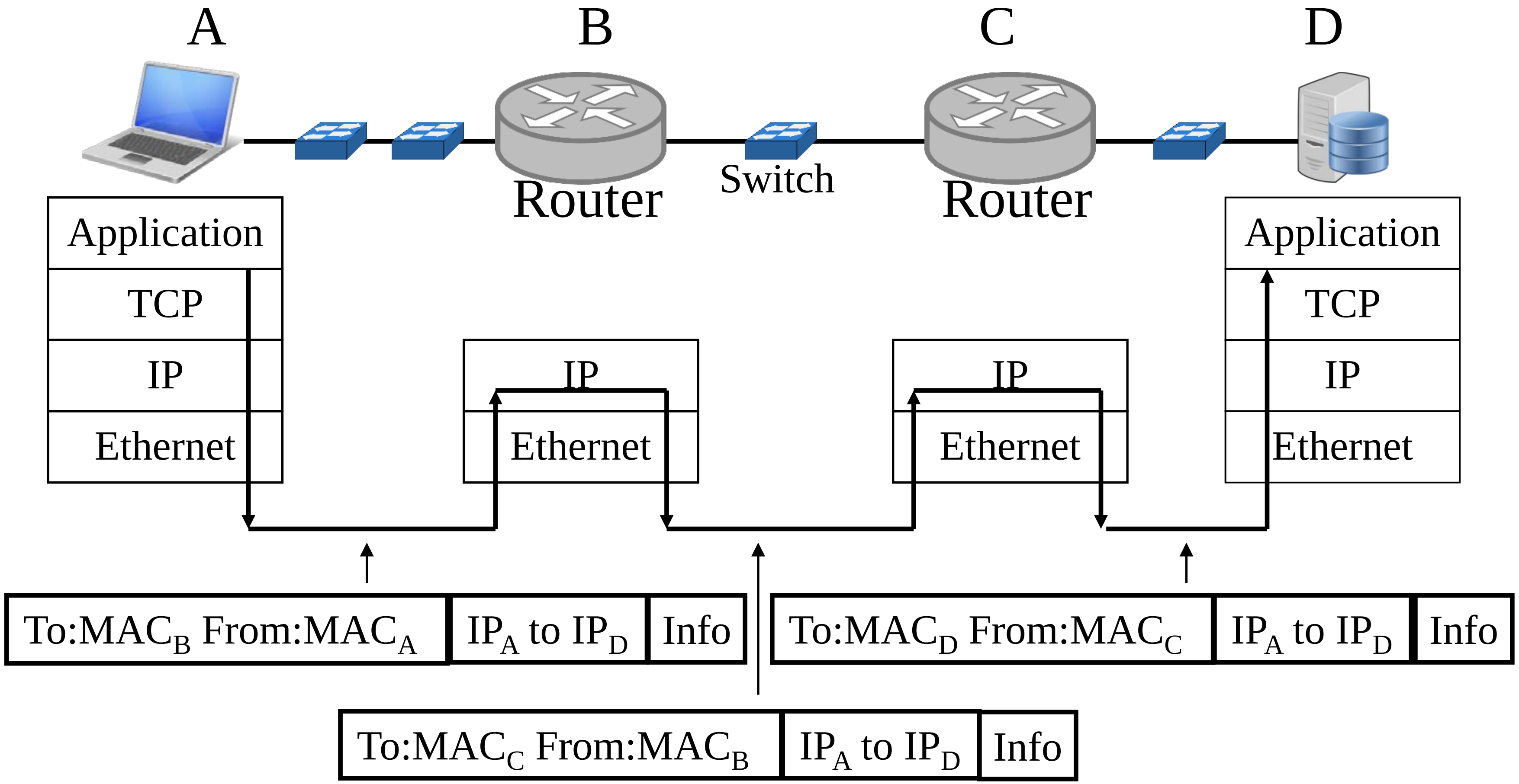
Address Resolution Protocol

- 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 back: "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

IP over Multiple Hops



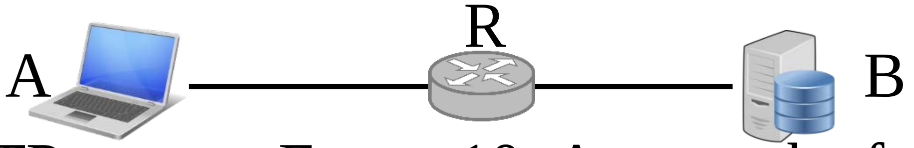
- Switches = Transparent Bridges ⟹ No changes to frames
- ARP required only for nodes on the same "subnet."

Student Questions

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 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

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

Lab 6 (Cont)

3. Examine Frame 1. This is an ARP request.

   A. What 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

Lab 6 (Cont)

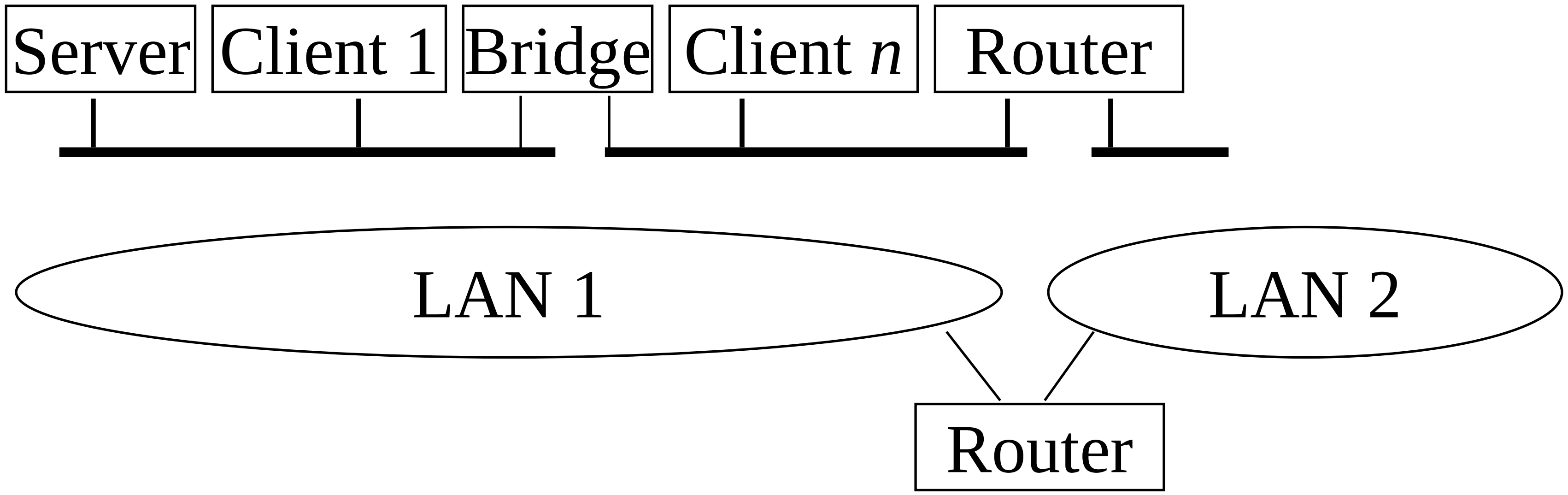
4. Examine Frame 2. This is the ARP response.

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. What is the value of the opcode field within the ARP payload?
E. What is the IP address of the sender?
F. What is 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

What is a LAN?

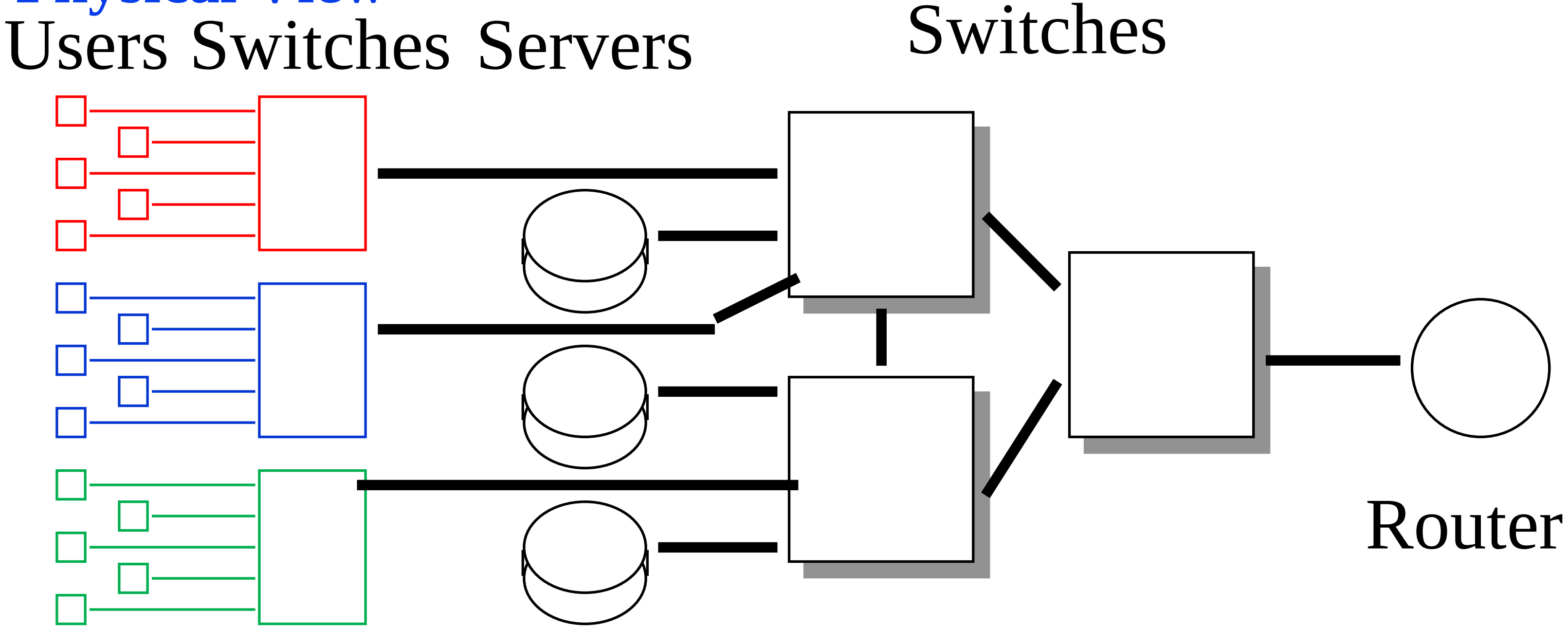


- LAN = **Single broadcast domain** = Subnet
- No routing between members of a LAN
- Routing required between LANs

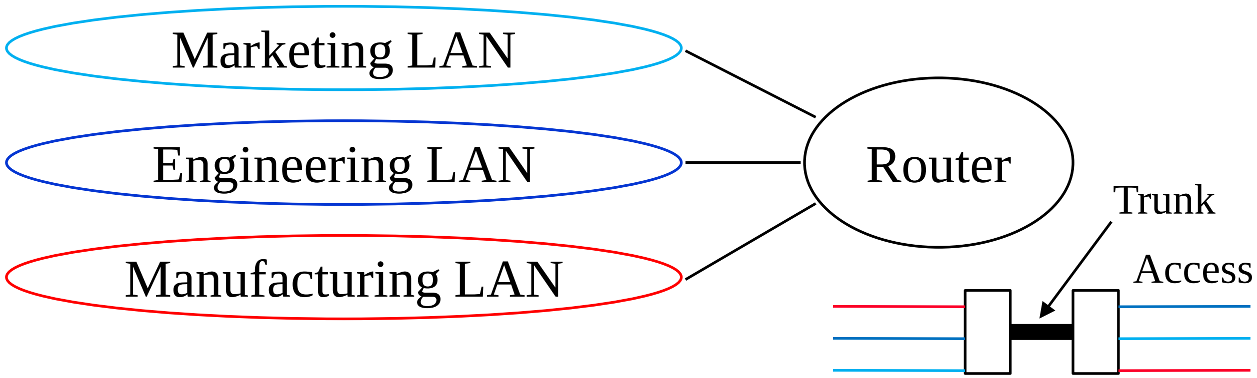
Student Questions

What is a Virtual LAN

- **Physical View**

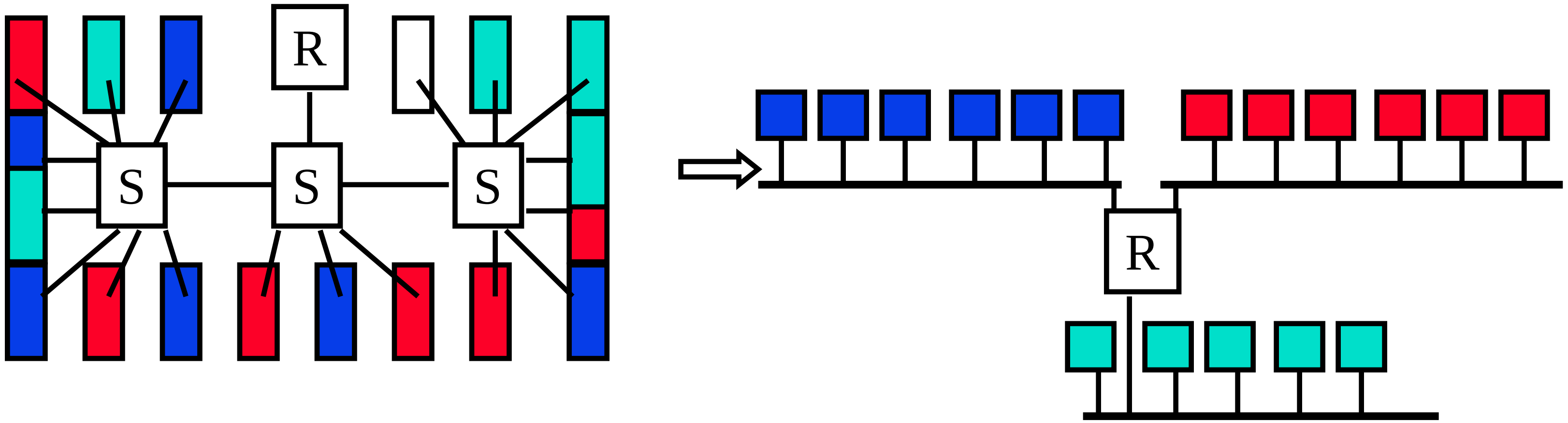


- **Logical View**



Student Questions

Virtual LAN



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

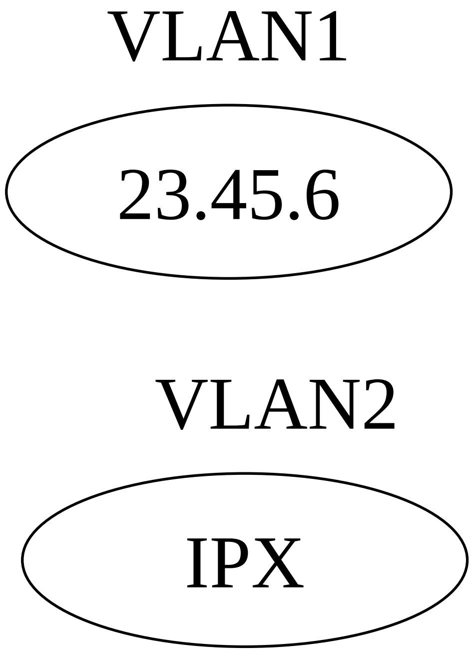
Student Questions

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	√	

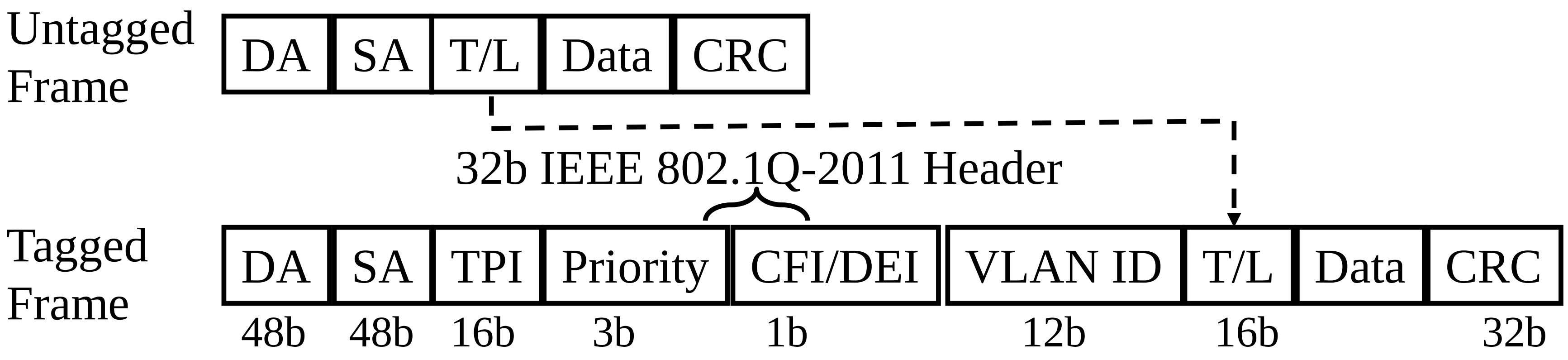
VLAN1	VLAN2
A1B234565600	21B234565600
D34578923434	634578923434
1345678903333	8345678903333
3438473450555	9438473450555
4387434304343	5387434304343
4780357056135	6780357056135
4153953470641	9153953470641
3473436374133	0473436374133
3403847333412	8403847333412
3483434343143	8483434343143
4343134134234	0343134134234



Student Questions

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 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

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.

Ref: Section 6.4, Review Questions R9-R16

Student Questions

Multiprotocol Label Switching

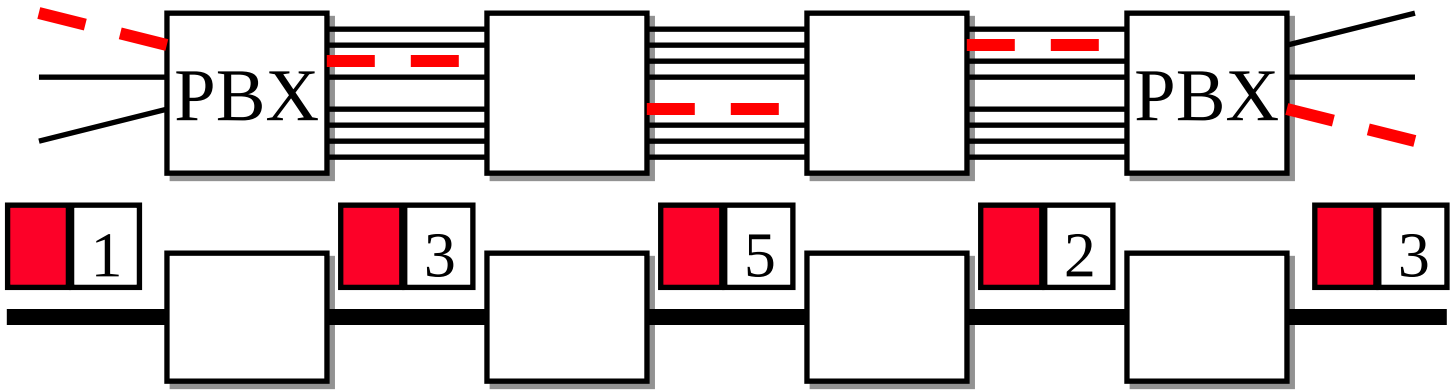
Connection-oriented IP: Paths set up in advance

Borrowed from the Telephone networks

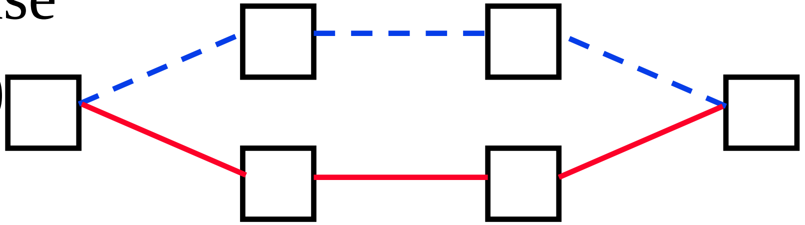
- Multiprotocol Label Switching (MPLS)
- Label Switching Example
- MPLS Forwarding Tables
- MPLS versus IP Paths
- MPLS Label Format

Student Questions

Multiprotocol Label Switching (MPLS)

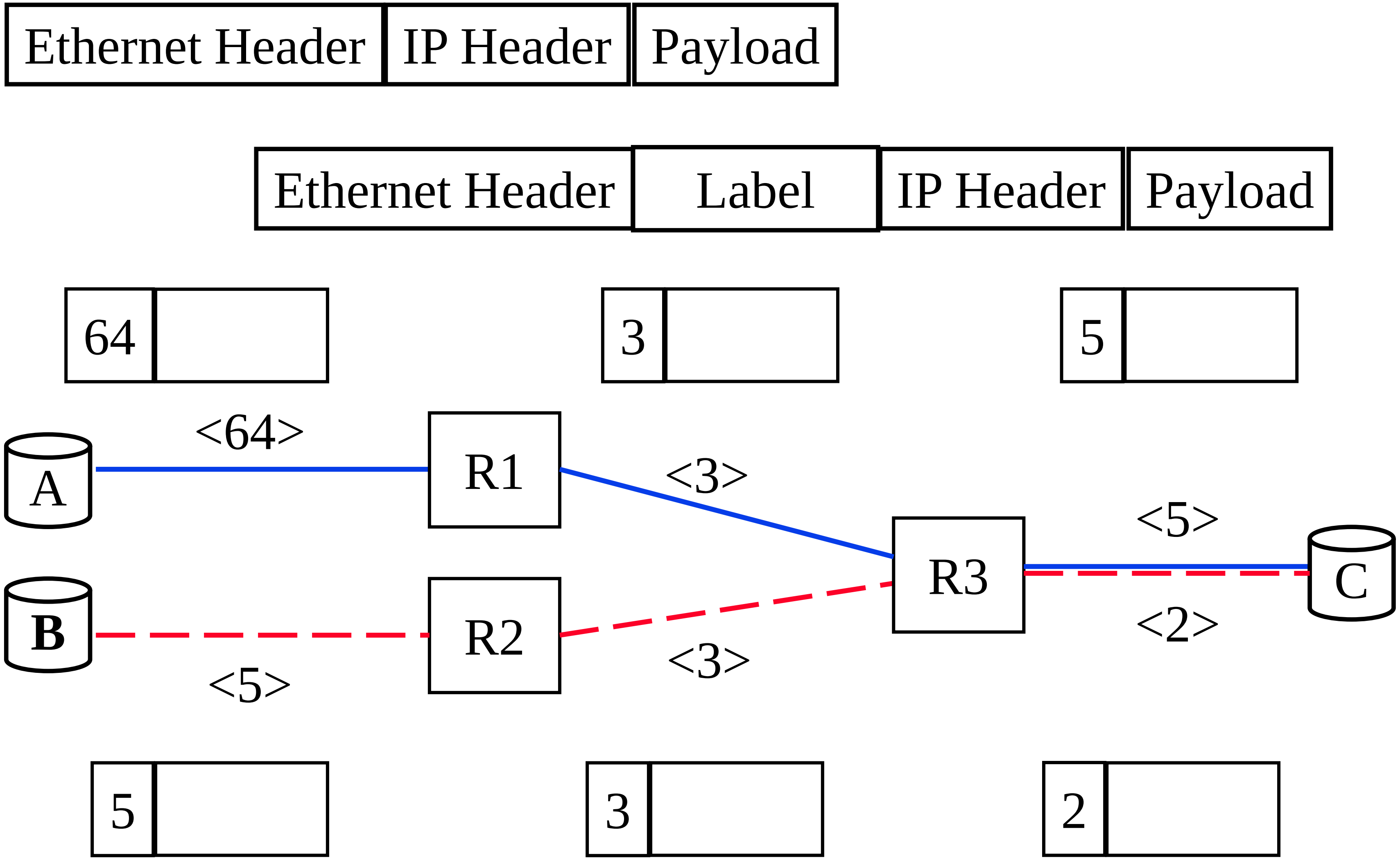


- Allows virtual circuits in IP Networks (May 1996)
- Each packet has a virtual circuit ID called 'label.'
- Label determines the packet's queuing and forwarding
- Circuits are called Label-Switched Paths (LSPs)
- LSPs have to be set up before use
- Label-switching routers (LSRs) allows traffic engineering



Student Questions

Label Switching Example



Student Questions

MPLS Forwarding Tables

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

R6

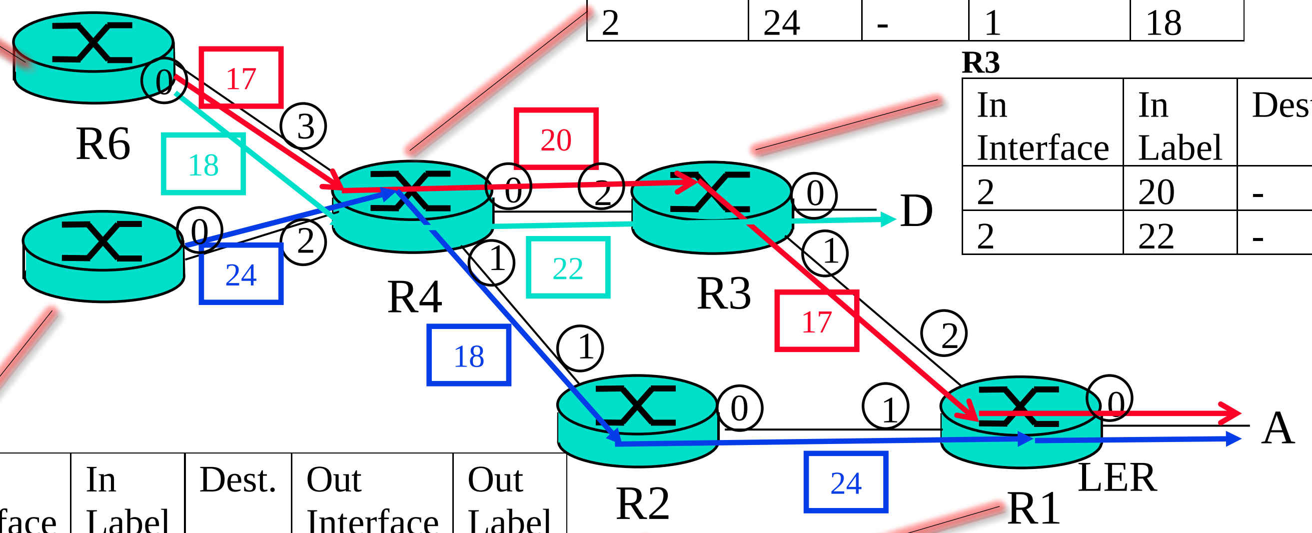
In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	17
-	None	D	0	18

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

Student Questions

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 $\Rightarrow$ MPLS Tag is removed.
  In Label=None $\Rightarrow$ Packet arrives with no MPLS tag.

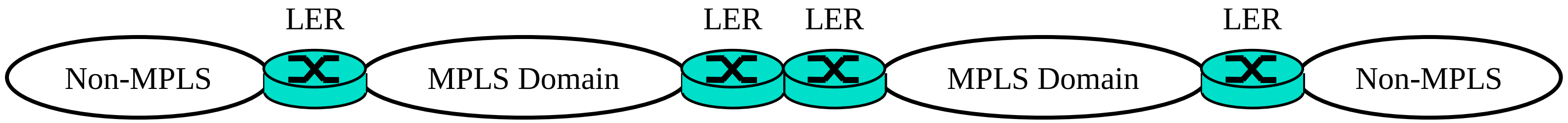
Student Questions

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

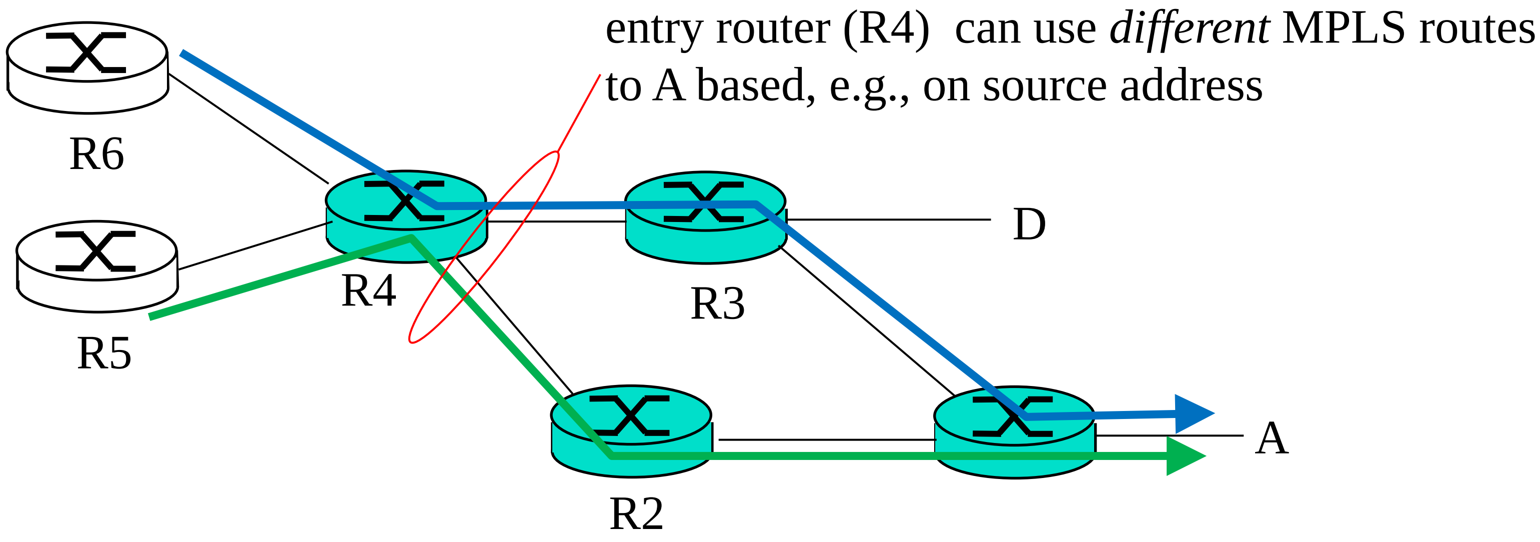
Label Edge Routers (LERs)



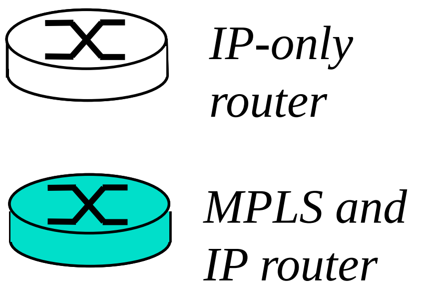
- Routers connected to non-MPLS routers or nodes or routers of other MPLS domains are called Label Edge Routers (**LERs**)
- LERs add labels to frames from non-MPLS nodes or remove their labels if forwarding to non-MPLS nodes or other domains.
- The labels added by LERs **may be** based on destination 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.

Student Questions

MPLS versus IP Paths



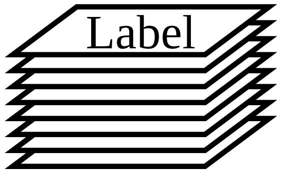
- **IP Routing**: Path determined by destination address alone
- **MPLS Routing**: Path can be based on source and destination address, flow type, …
  - **Fast reroute**: Precompute backup routes in case of link failure



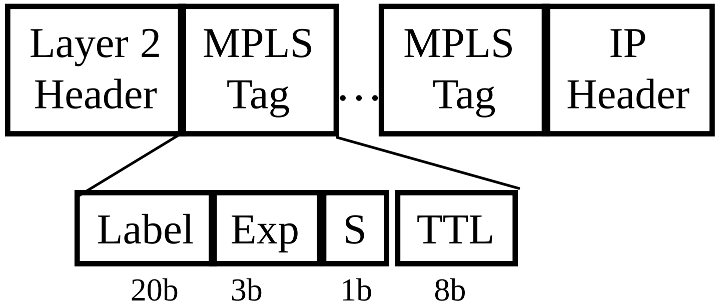
Student Questions

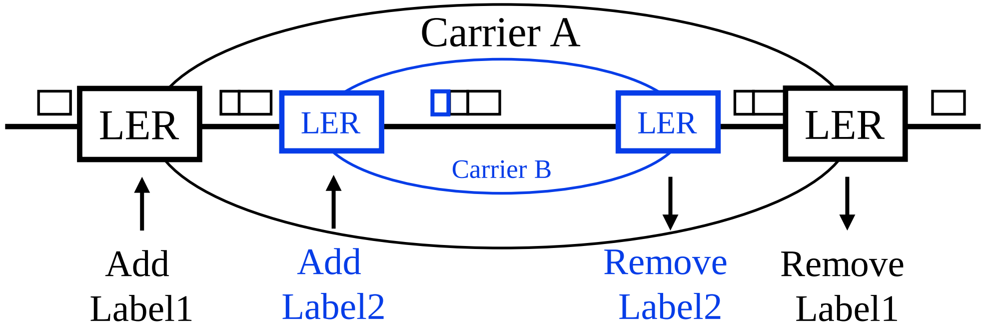
MPLS Label Format

- 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.

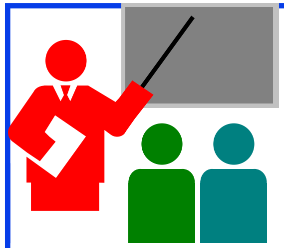


- TTL field is decremented for all forwarded packets.
  When adding a label, the TTL field from the IP header is copied to the MPLS tag.
  When removing a label, the TTL field from the MPLS tag is copied to the IP Header.
- MPLS Signaling:
  - OSPF has been extended to help prepare label tables
  - There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





Student Questions



MPLS: Review

Student Questions

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 a LDP.
5. MPLS tags can be stacked to allow network nesting

Ref: Section 6.5

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 to A 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 make this possible. For simplicity, use the same label values as shown currently. Only LSP paths change, and the table at Router R4.

Student Questions

Homework 6C (Cont)

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

R6

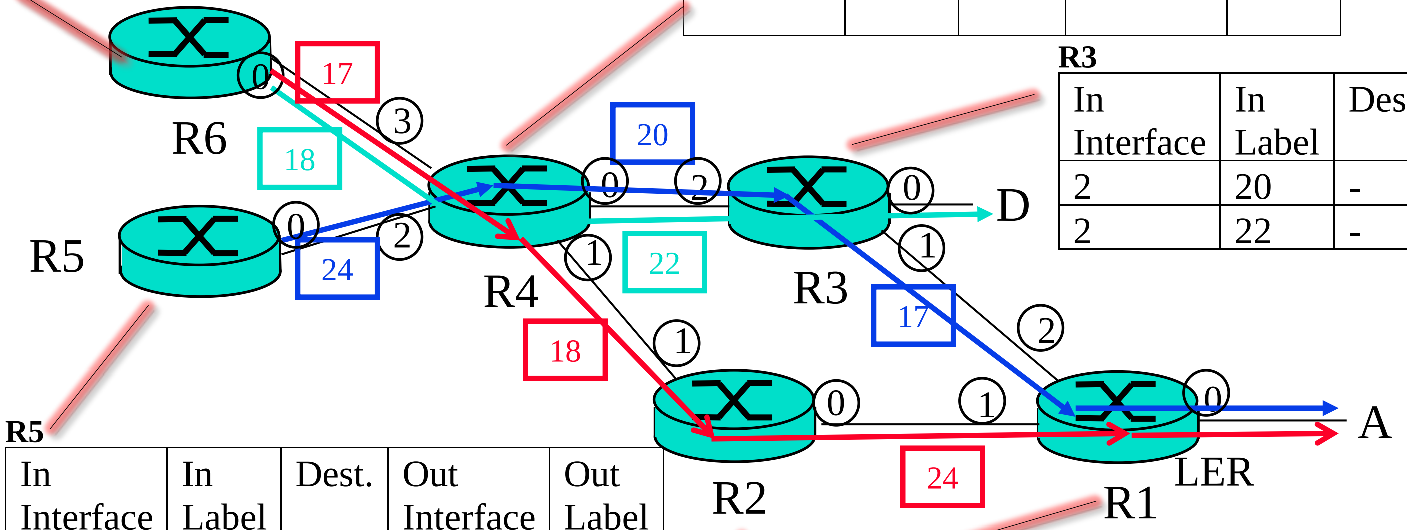
In Interface	In Label	Dest.	Out Interface	Out Label
-	None	A	0	17
-	None	D	0	18

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

Homework 6D: MPLS

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

Student Questions

Homework 6D (Cont)

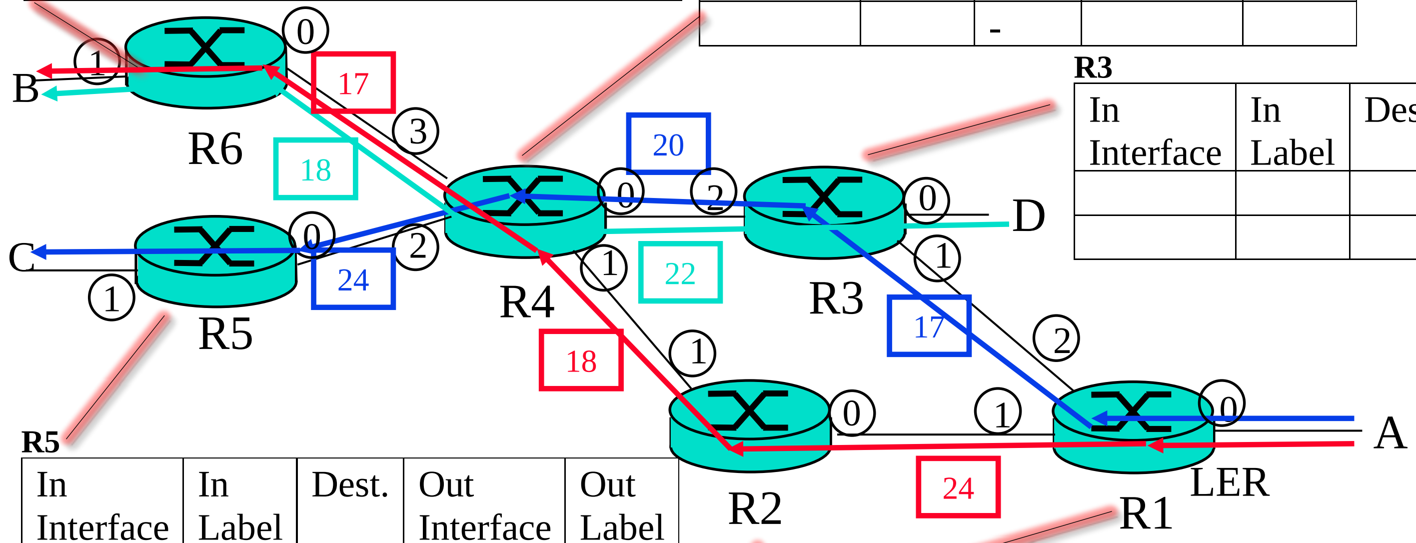
- Interface numbers are in circles. Label IDs are in rectangles.

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

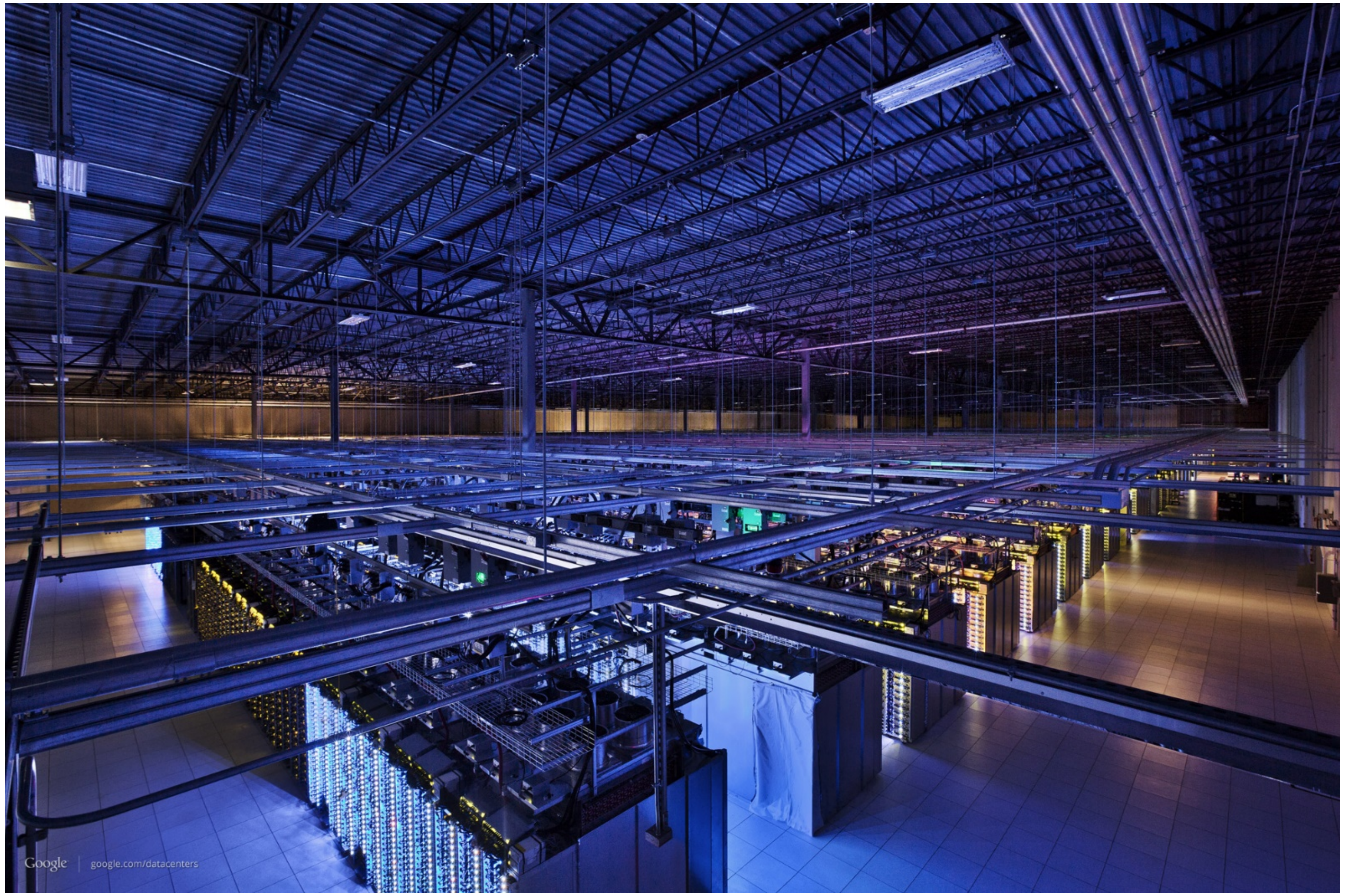
In Interface	In Label	Dest.	Out Interface	Out Label

R1

In Interface	In Label	Dest.	Out Interface	Out Label

Student Questions

Google's Data Center

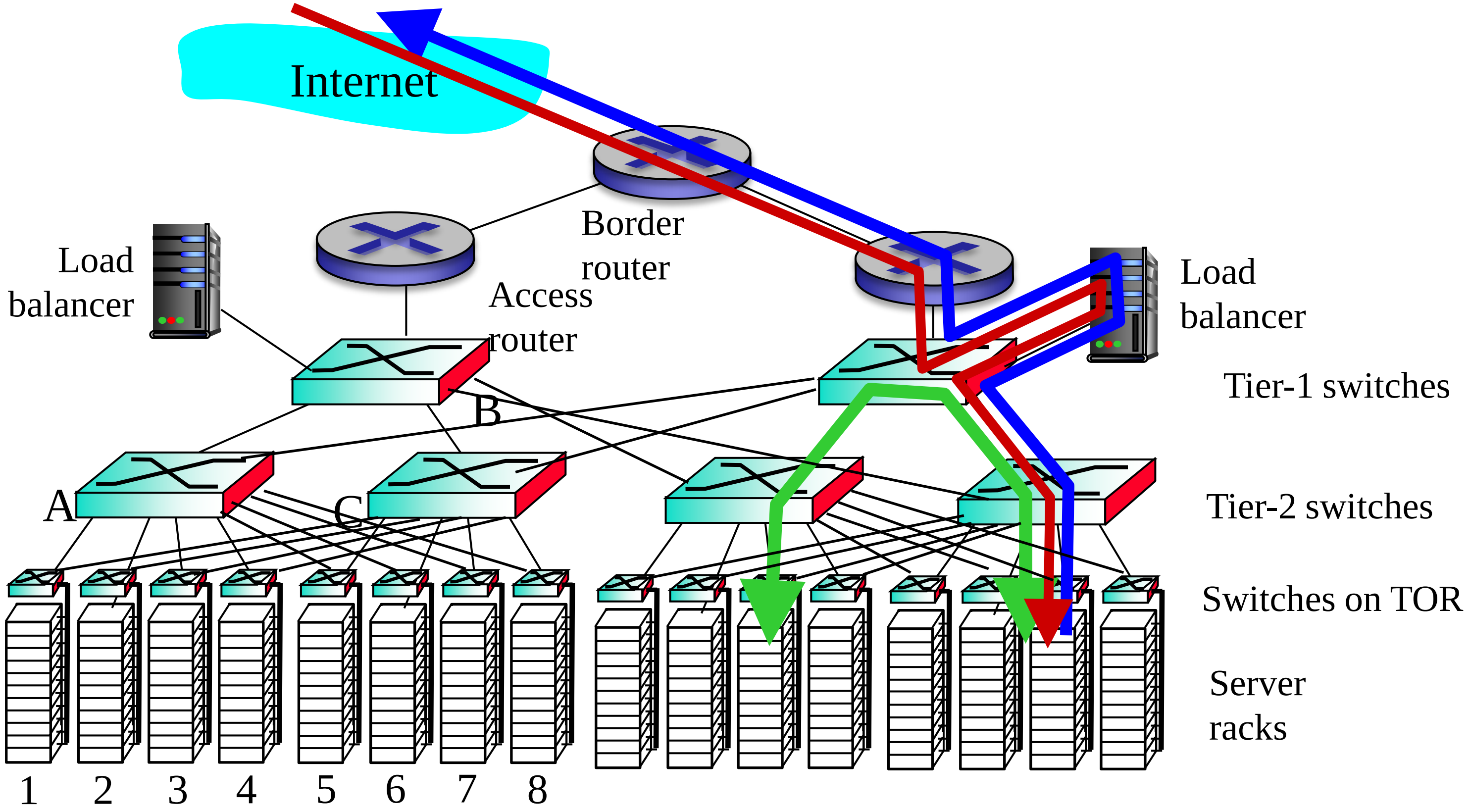


Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Student Questions

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)

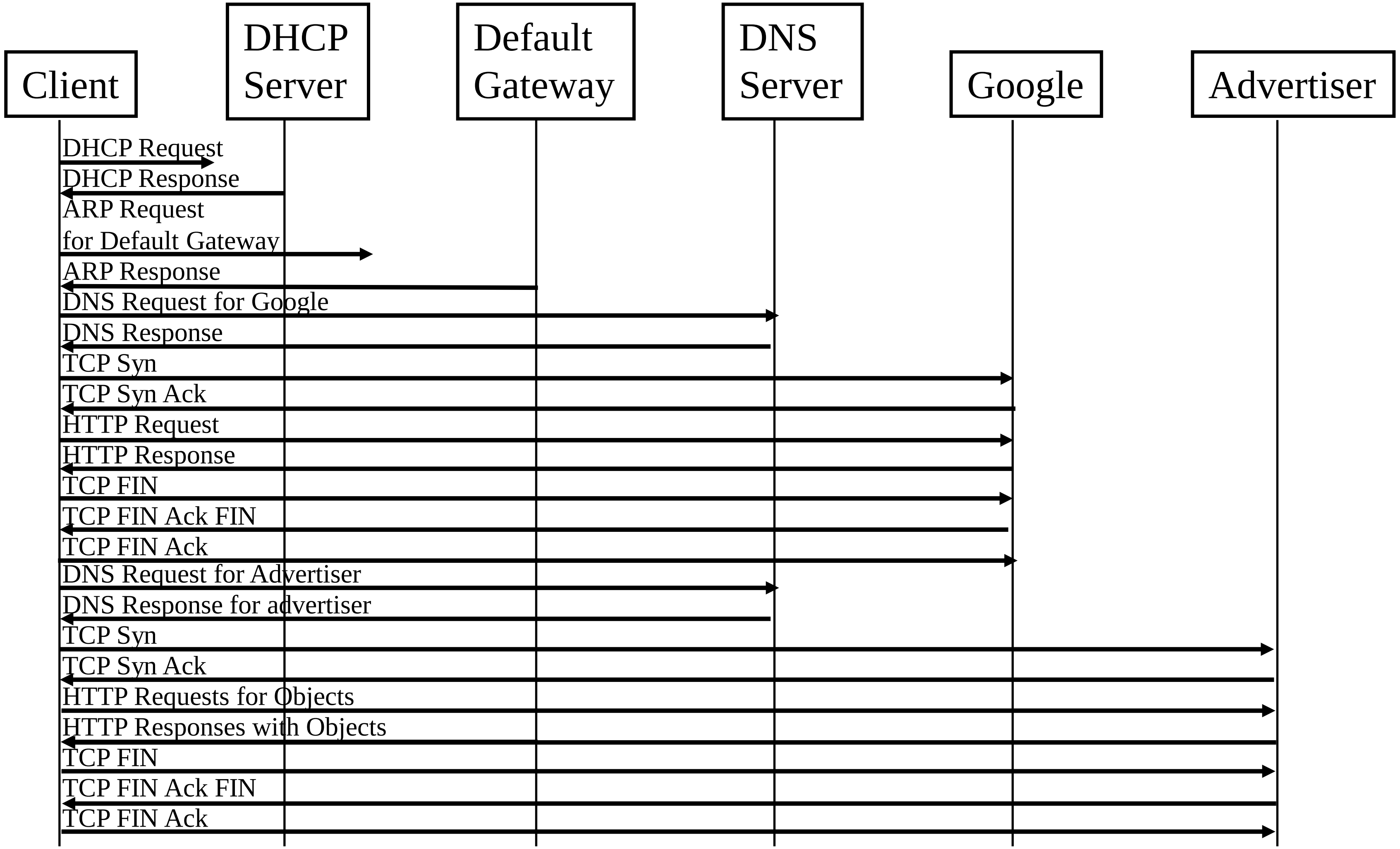


Ref: Section 6.6

Student Questions

Protocols: Complete Picture

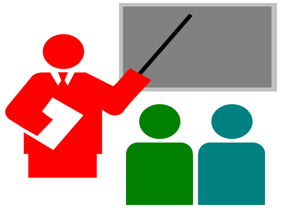
Task: Connect and search in www.google.com



Ref: Section 6.7

Student Questions

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

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 Electronic Engineers

Student Questions

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

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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Raj Jain

http://rajjain.com

http://www.cse.wustl.edu/~jain/cse473-25/i_6lan.htm

Student Questions

Modulo 2 Arithmetic: More Examples

Addition:

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

Multiplication:

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

Student Questions

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