# Networks, Security, and Privacy

## 158.235



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# Data Link Layer



*Reading: Chapter 4 in the prescribed textbook*

# Introduction

- **Layer 2 in the Internet model**
- **Responsible for moving messages (datagram) from one device (node) to another physically adjacent node over a link**
- **Major functions of a data link layer protocol**
  - **Error Control**
  - **Flow Control**
  - **Link layer addressing**

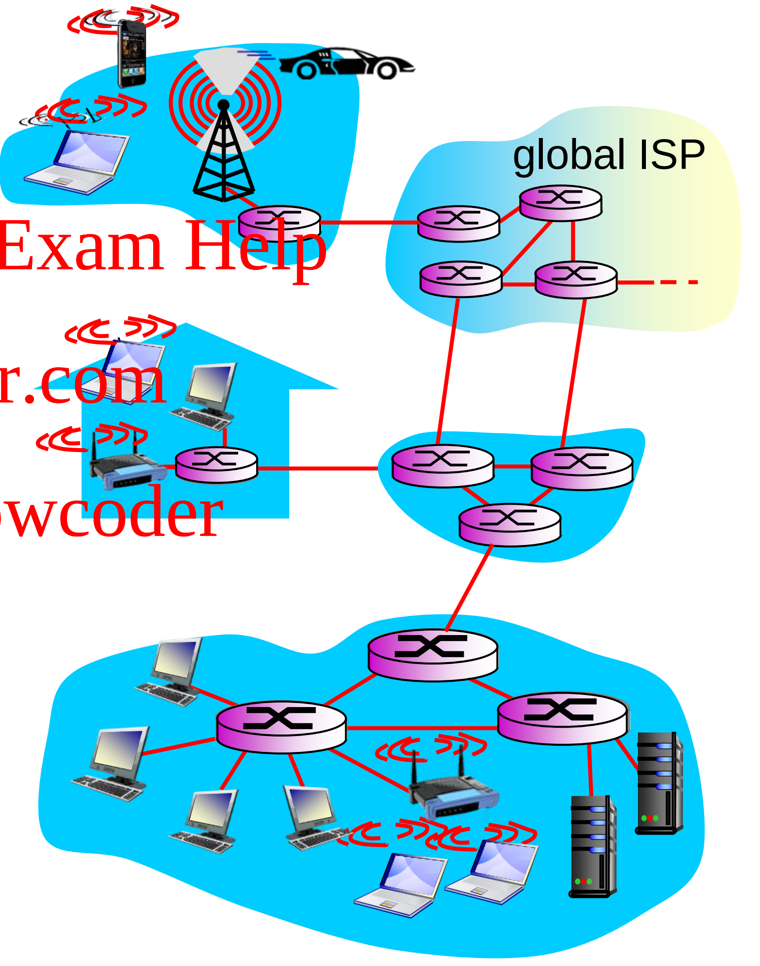
**Internet Model**

| |
|---|
| Application |
| Transport |
| Network |
| **Data Link** |
| Physical |

# Introduction

***terminology:***

- **hosts and routers: nodes**
- **communication channels that connect adjacent nodes along communication path: links**
  - **wired links**
  - **wireless links**
  - **LANs**
- **layer-2 packet: frame, encapsulates datagram**



# Introduction

- 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 reliable data transfer over link

*transportation analogy:*

- trip from Palmerston North to Disney Land, LA
  - Taxi: City center to PN airport
  - Plane: PN to Auckland
  - Plane: Auckland to LAX
  - Bus: LAX to Disney Land
- tourist = datagram
- transport segment = communication link
- transportation mode = link layer protocol
- travel agent = routing algorithm

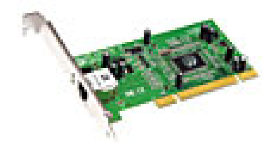
# Link layer services

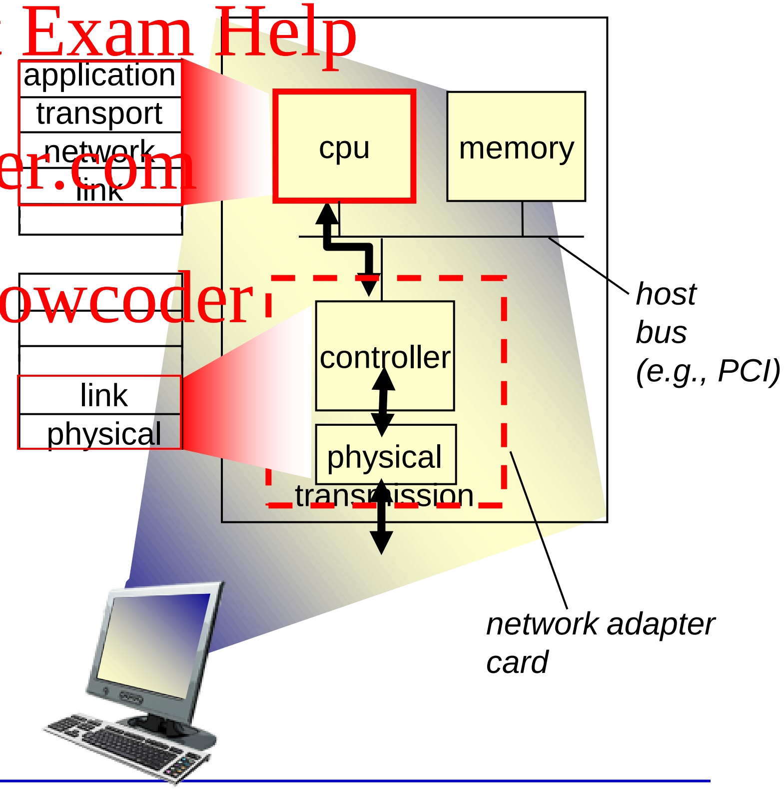
- ***framing, link access:***
  - •encapsulate datagram into frame, adding header, trailer
  - •“MAC” addresses used in frame headers to identify source, dest (different from IP address!)
- ***flow control:***
  - – pacing between adjacent sending and receiving nodes
- ***error detection*:**
  - – errors caused by signal attenuation, noise.
  - – receiver detects presence of errors:
- ***error correction:***
  - – receiver identifies ***and corrects*** bit error(s) without resorting to retransmission

# Where is the link layer implemented?

- in each and every host
- link layer implemented in “adaptor” (aka *network interface card* NIC) or on a chip
  - Ethernet card, 802.11 card; Ethernet chipset
  - implements link, physical layer
- attaches into host’s system buses
- combination of hardware, software, firmware







# Data Link Layer

- **Error Control**
- **Flow Control**
- **Link Addressing**

# Error Control

- Network errors
  - Types
    - Corrupted data
    - Lost data
  - Caused by problems in transmission (not humans)
- Networks should be designed with:
  - Error prevention
  - Error detection
  - Error correction

# Sources of Network Errors

- **Line noise and distortion**
  - **Major reason for errors and caused by several sources**
  - **More likely on electrical media and lower-end cables (e.g. twisted pair)**
  - **Undesirable electrical signal**
  - **Degrades performance of a circuit**
  - **Manifestation**
    - Extra bits
    - Flipped bits
    - Missing bits

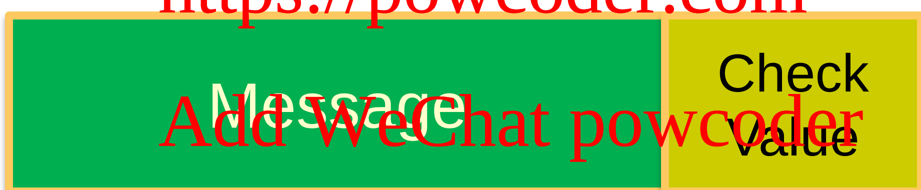
# Sources of Errors and Prevention

| Source of Error | What Causes It | How to Prevent or Fix |
|---|---|---|
| White Noise | Movement of electrons | Increase signal strength |
| Impulse Noise | Sudden increases in electricity (e.g., lightning) | Shield or move the wires |
| Cross-talk | Multiplexer guardbands too small or wires too close together | Increase the guardbands or move or shield the wires |
| Echo | Poor (misaligned) connections | Fix the connections or tune equipment |
| Attenuation | Gradual decrease in signal over distance | Use repeaters |
| Intermodulation noise | Signals from several circuits combine | Move or shield the wires |

# Error Detection

- Receivers need to know when the data transmitted is not correct
- Add “check value” (error detection value) to message



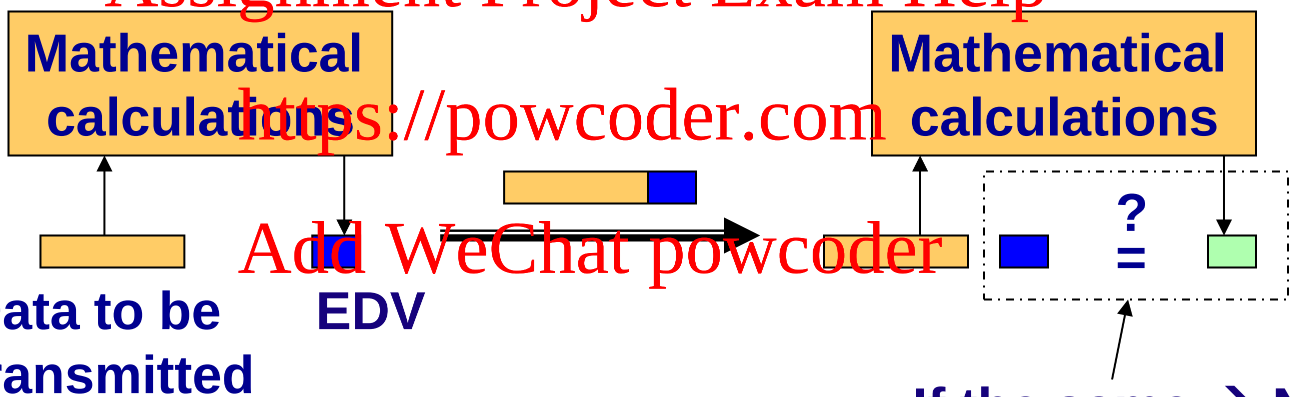



- Check value produced by mathematical formula

# Error Detection

Sender calculates an Error Detection Value (EDV) and transmits it along with data

Receiver recalculates EDV and checks it against the received EDV






– If the same → No errors in transmission

– If different → Error(s) in transmission

# Error Detection Techniques

- Parity checks
- Checksum
- Cyclic Redundancy Check (CRC)

# Parity Checking

- One of the oldest and simplest
- A single bit added to each character
  - Even parity: number of 1's remains even
  - Odd parity: number of 1's remains odd
- Receiving end recalculates parity bit
  - If one bit has been transmitted in error the received parity bit will differ from the recalculated one
- Simple, but doesn't catch all errors
  - If two (or an even number of) bits have been transmitted in error at the same time, the parity check appears to be correct
  - Detects about 50% of errors

# Examples of Using Parity

**To be sent: Letter V in 7-bit ASCII: 0110101**

**EVEN parity**

sender → 01101010 → receiver

parity

Add a bit so that the number of all transmitted 1's is EVEN

**ODD parity**

sender → 01101011 → receiver

parity

Add a bit so that the number of all transmitted 1's is ODD

# Checksum

- A checksum (usually 1 byte) is added to the end of the message
- It is 95% effective



- Method:



  - Add decimal values of each character in the message
  - Divide the sum by 255



  - The remainder is the checksum value

# CRC

- Cyclic redundancy check (CRC)
  - Treats message as a single binary number
  - Divides by a preset number
  - Uses remainder as the check value
- Preset number is chosen so that remainder is the correct number of bits
- Modes:
  - CRC-16 (~99.998% error detection rate)
  - CRC-32 (>99.99999% error detection rate)

# Cyclic Redundancy Check (CRC)

$$P / G = Q + R / G$$

Example:
P = 58
G = 8
Q = 7
R = 2

Message (treated as one long binary number)



Quotient (whole number)



A fixed number (divisor) which determines the length of the R



Remainder:
- added to the message as EDV
- could be 8 bits, 16 bits, 24 bits, or 32 bits long
- CRC16 has R of 16 bits

- Most powerful and most common
- Detects 100% of errors (if number of errors <= size of R)
  - Otherwise: CRC-16 (99.998%) and CRC-32 (99.9999%)

# Error Correction

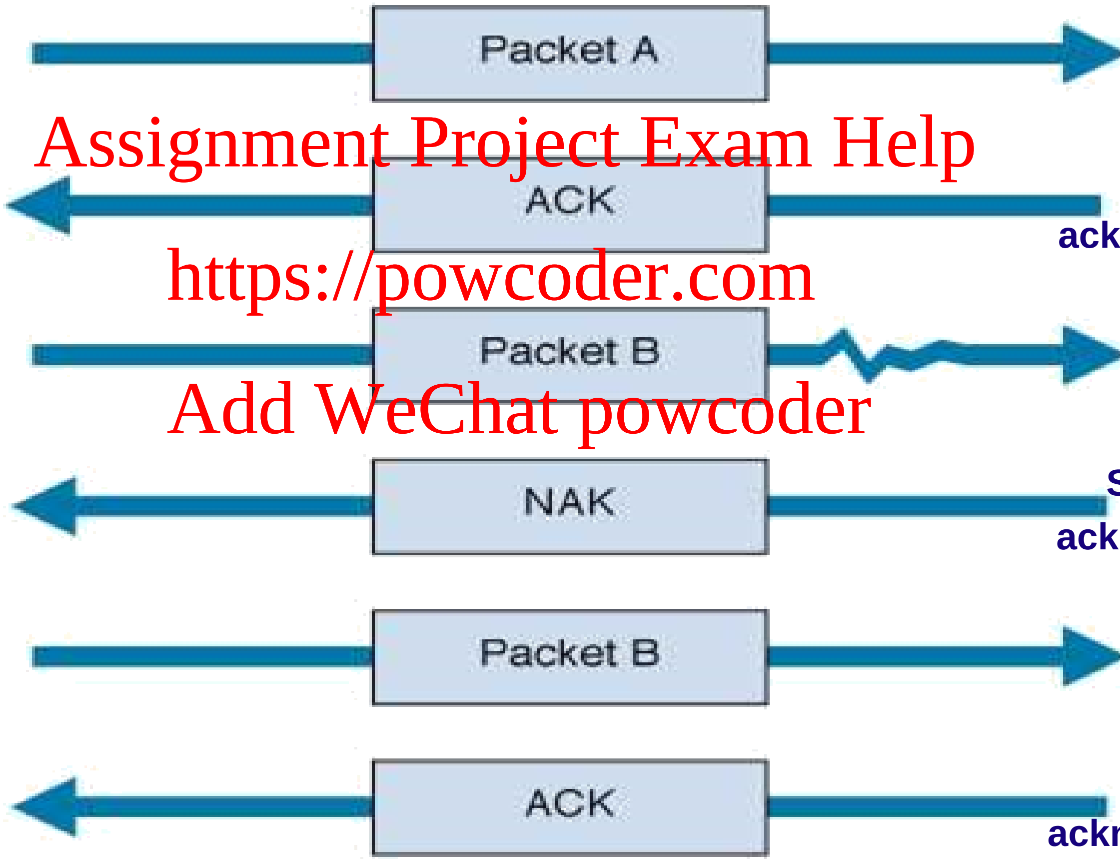
- Once detected, the error must be corrected
- Error correction techniques
  - Retransmission (or, backward error correction)
    - Simple and most common
    - Automatic Repeat reQuest (ARQ)
    - This can also provide flow control by limiting the number of messages sent
  - Forward Error Correction
    - Receiving device can correct incoming messages without retransmission

# Automatic Repeat reQuest (ARQ)

- Process of requesting a data transmission be resent
- Main ARQ protocols
  - Stop and Wait ARQ (A half duplex technique)
    - Sender sends a message and waits for acknowledgment, then sends the next message
    - Receiver receives the message and sends an acknowledgement, then waits for the next message
  - Continuous ARQ (A full duplex technique)
    - Sender continues sending packets without waiting for the receiver to acknowledge
    - Receiver continues receiving messages without acknowledging them right away

# Stop and Wait ARQ

**Sender** | **Receiver**




Sends Packet A, then waits to hear from receiver.

No errors detected

Sends acknowledgement

Sends the next packet (B)

Errors detected

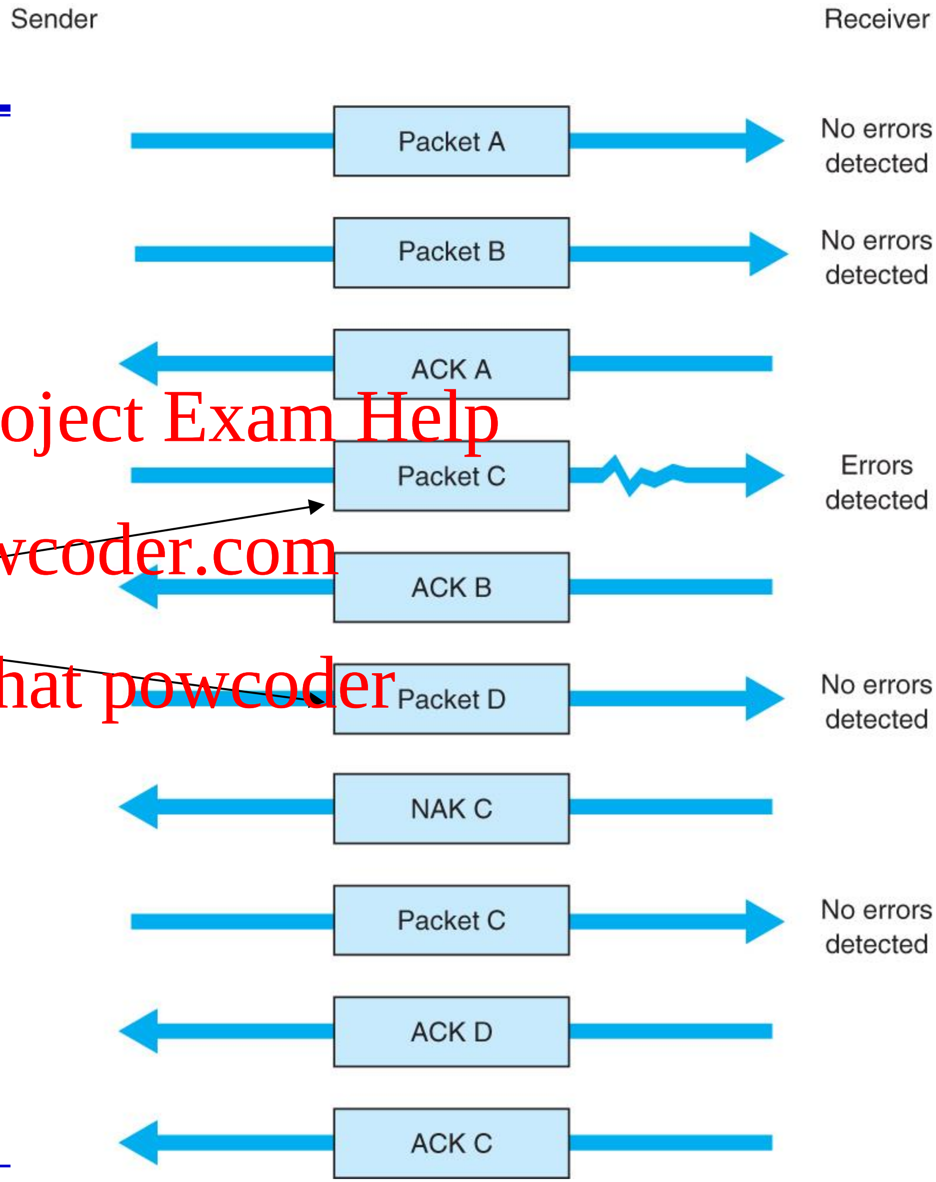
Sends negative acknowledgement

Resends the packet again

No errors detected

Sends acknowledgement

# Continuous ARQ




Sender sends packets continuously without waiting for receiver to acknowledge

Notice that acknowledgments now identify the packet being acknowledged.

Receiver sends back a NAK for a specific packet to be resent.

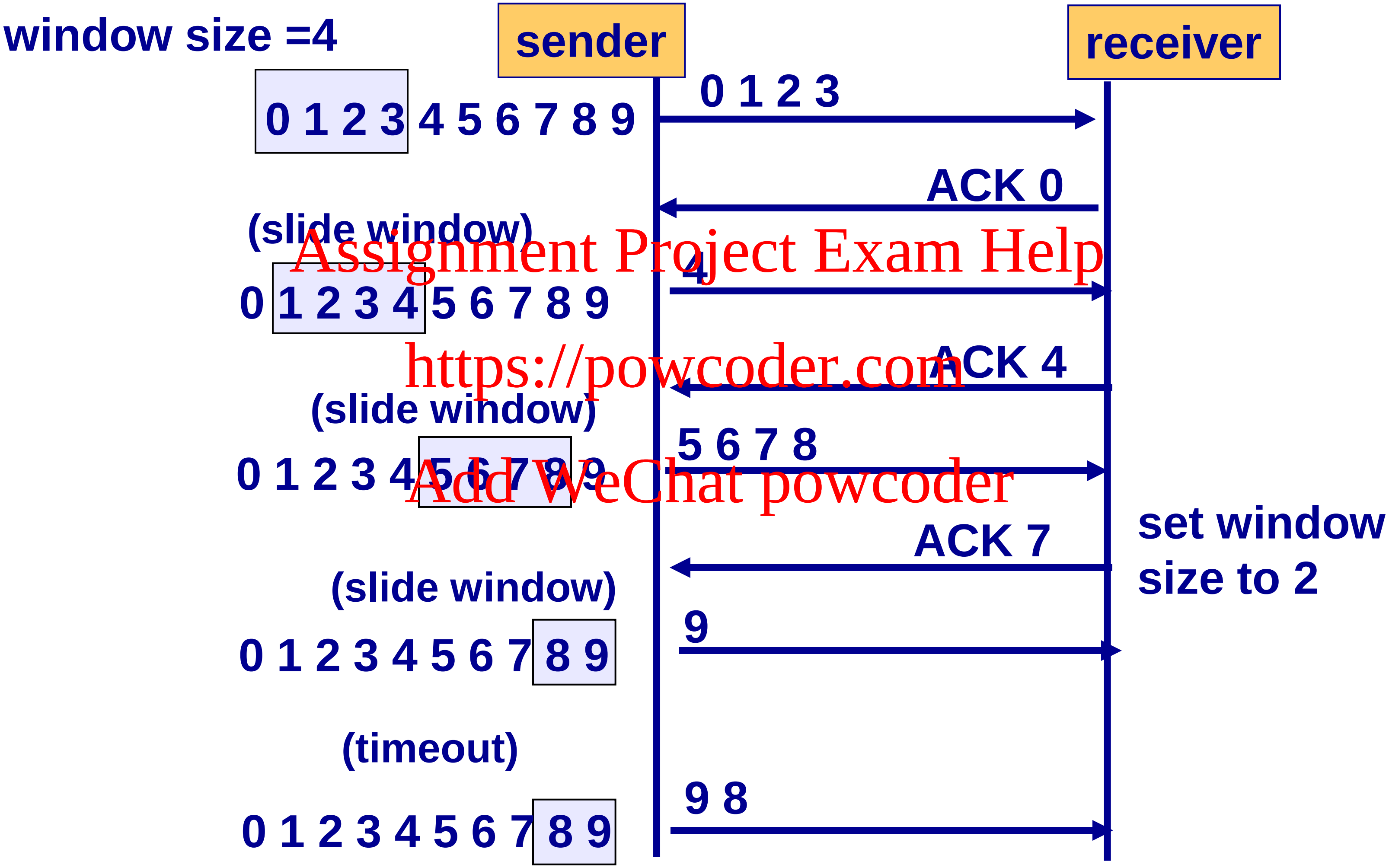
# Data Link Layer

- Error Control
- Flow Control
- Link Addressing

# Flow Control with ARQ

- Ensuring that sender is not transmitting too quickly for the receiver
  - Stop-and-wait ARQ
    - Receiver sends an ACK or NAK when it is ready to receive more packets
  - Continuous ARQ:
    - Both sides agree on the size of the "**sliding window**"
      - Number of messages that can be handled by the receiver without causing significant delays

# Flow Control Example



# Forward Error Correction

- Receiving device can correct incoming messages itself (without retransmission)
- Requires extra corrective information
  - Sent along with the data
  - Allows data to be checked and corrected by the receiver
  - Amount of extra information:  usually 50-100% of the data
- Used in the following situations:
  - One way transmissions (retransmission not possible)
  - Transmission times are very long (satellite)
  - In this situation, relatively insignificant cost of FEC

# Hamming Code – An FEC Example

- A scheme by adding parity bit intelligently such that *one* erroneous bit can be detected and corrected
- Bit position is split into 'parity bit' position and 'data bit' position:
  
  - parity bit occupies position 1, 2, 4, 8, 16, 32, …
  
  - data bit occupies the remaining positions (3, 5, 6, 7, 9,…)
  - parity bit value calculation:
  
    - position 1 → check 1 bit, skip 1 bit, and so forth (1, 3, 5, …)
    - position 2 → check 2 bits, skip 2 bits (2, 3, 6, 7, 10, 11,…)
    - position 4 → check 4 bits, skip 4 bits ( 4-7, 12-15, …)

# Hamming Code – Example

Data: 11011010

Even Parity



| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| | P1 | P2 | | P4 | | | | P8 | | | | |





P1: data at position 3, 5, 7, 9, 11 → 11111 (odd 1s) → Parity bit: 1
P2: data at position 3, 6, 7, 10, 11 → 10101 (odd 1s) → Parity bit: 1
P4: data at position 5, 6, 7, 12 →1010 (even 1s) → Parity bit: 0
P8: data at position 9, 10, 11, 12 → 1010 (even 1s) → Parity bit: 0

Data sent: 111010101010

# Hamming Code – Example

Data Received: 111010101110

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| | P1 | P2 | | P4 | | | | P8 | | | | |







Check P1: data at position 3, 5, 7, 9, 11 → 11111 (odd 1s) → Parity bit: 1 - OK

Check P2: data at position 3, 6, 7, 10, 11 → 10111 (even 1s) → Parity bit: 0 – Not OK

Check P4: data at position 5, 6, 7, 12 →1010 (even 1s) → Parity bit: 0 - OK

Check P8: data at position 9, 10, 11, 12 → 1110 (odd 1s) → Parity bit: 1 - Not OK

Parity bit at position 2 and 8 are incorrect.

**The erroneous bit is placed at bit position 2+8 = 10**

# Data Link Layer

- Error Control
- Flow Control
- Link Addressing

# Address Resolution

- Addresses exist at different layers

| Address Type | Example | Example Address |
|---|---|---|
| Application layer | Web address (URL) | www.indiana.edu |
| Network layer | IP address | 129.79.78.193 (4 bytes) |
| Data link layer | MAC address | 1C-6F-65-F8-33-8A (6 bytes) |



- Addresses may be translated (resolved) from one layer to another

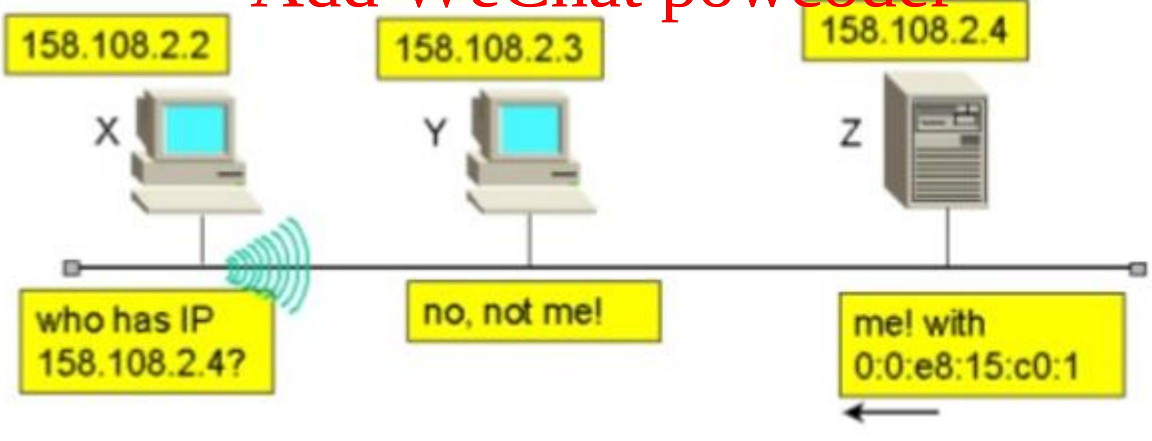
# Address Resolution

- **Data Link Layer Address Resolution**
  - **Identifying the MAC address of the next node (that packet must be forwarded)**
  - **Uses Address Resolution Protocol (ARP)**

# ARP name resolution

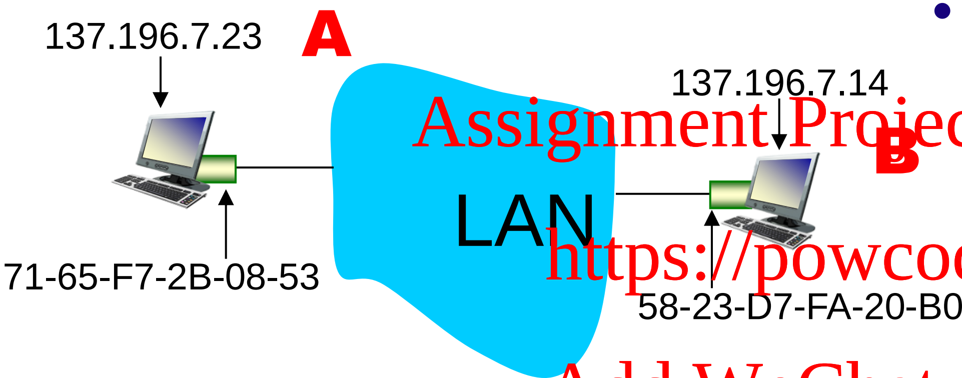
- Identifying the MAC address by IP address
- Operation
  - Broadcast an ARP message to all nodes on a LAN asking which node has a certain IP address
  - Host with that IP address then responds by sending back its MAC address
  - Store this MAC address in its address table
  - Send the message to the destination node





# ARP: same LAN

*Question:* how to determine a MAC address knowing its IP address?






| | ARP query | ARP reply |
|---|---|---|
| Src IP address | 137.196.7.23 | 137.196.7.14 |
| Dest IP address | 137.196.7.14 | 137.196.7.23 |
| Src MAC address | 71-65-F7-2B-08-53 | 58-23-D7-FA-20-B0 |
| Dest MAC address | FF-FF-FF-FF-FF-FF | 71-65-F7-2B-08-53 |

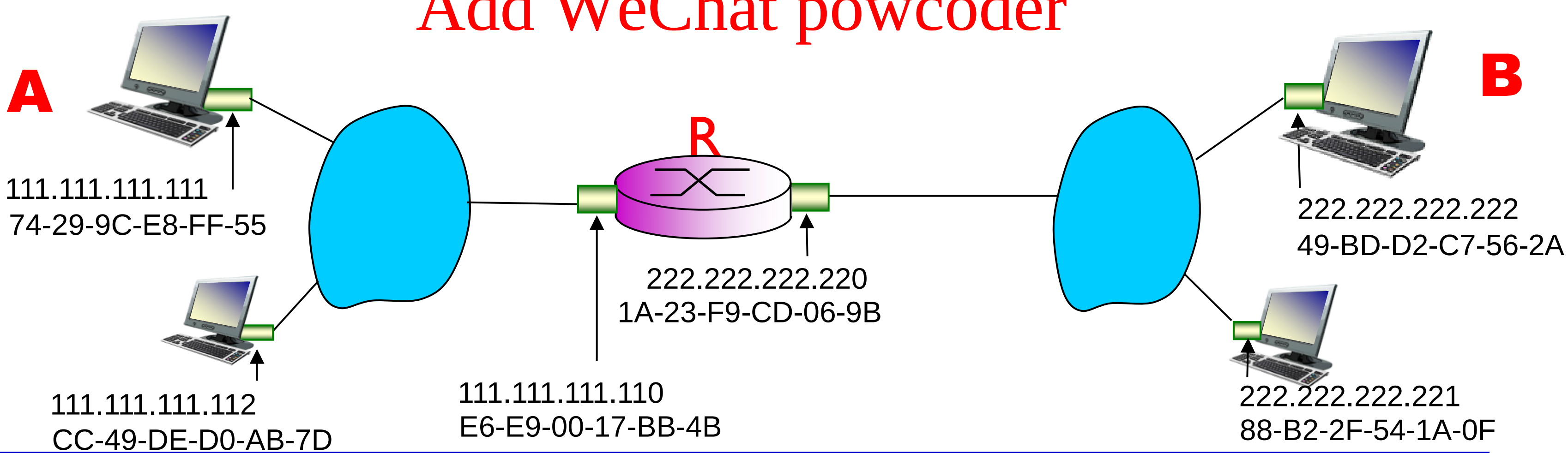
- A broadcasts ARP query packet, containing B's IP address
  - dest MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query (broadcast)
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's MAC address (unicast)

# Addressing: routing to another LAN

walkthrough: **send datagram from A to B via R**

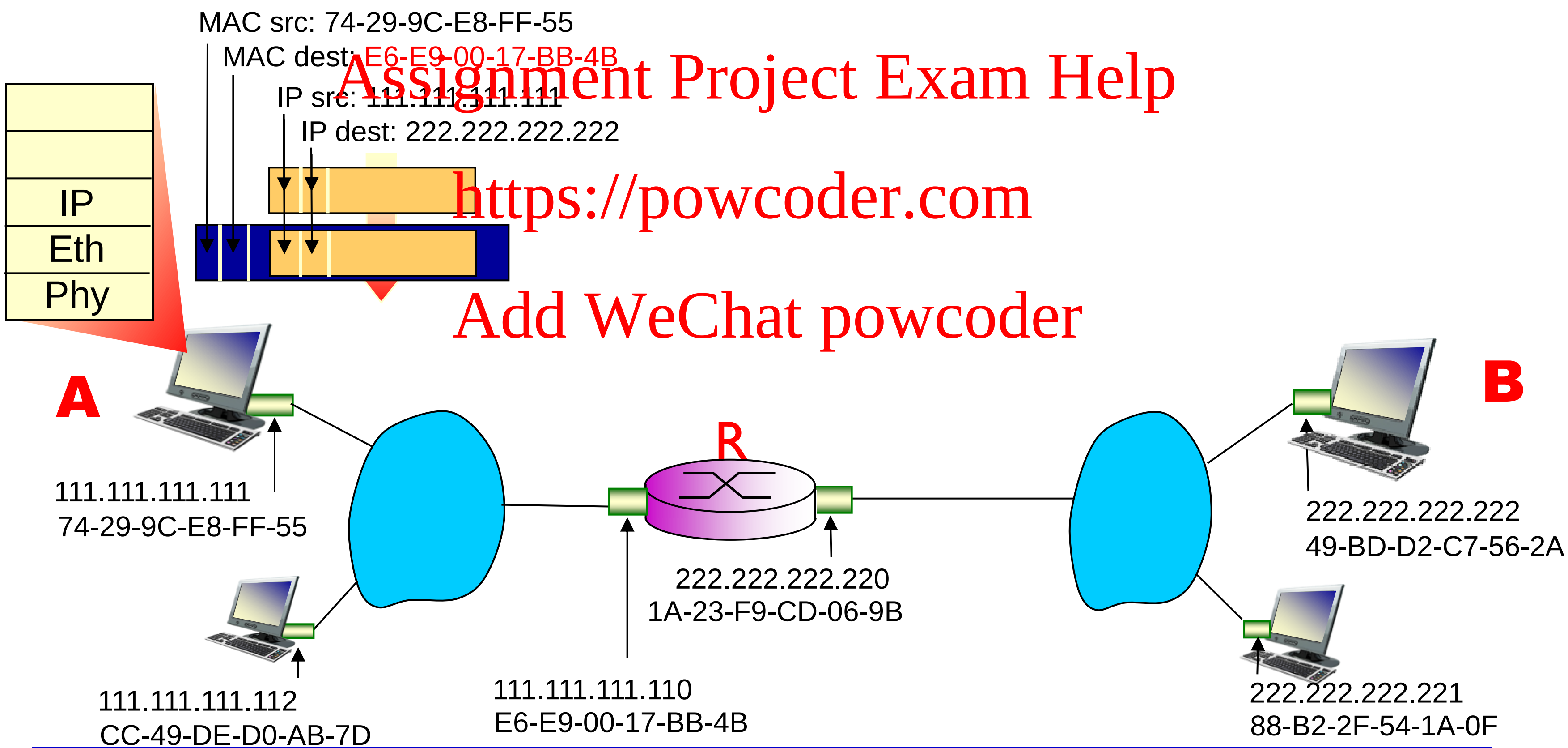
- focus on addressing – at IP (datagram) and MAC layer (frame)
- assume A knows B's IP address
- assume A knows IP address of first hop router, R
- assume A knows R's MAC address





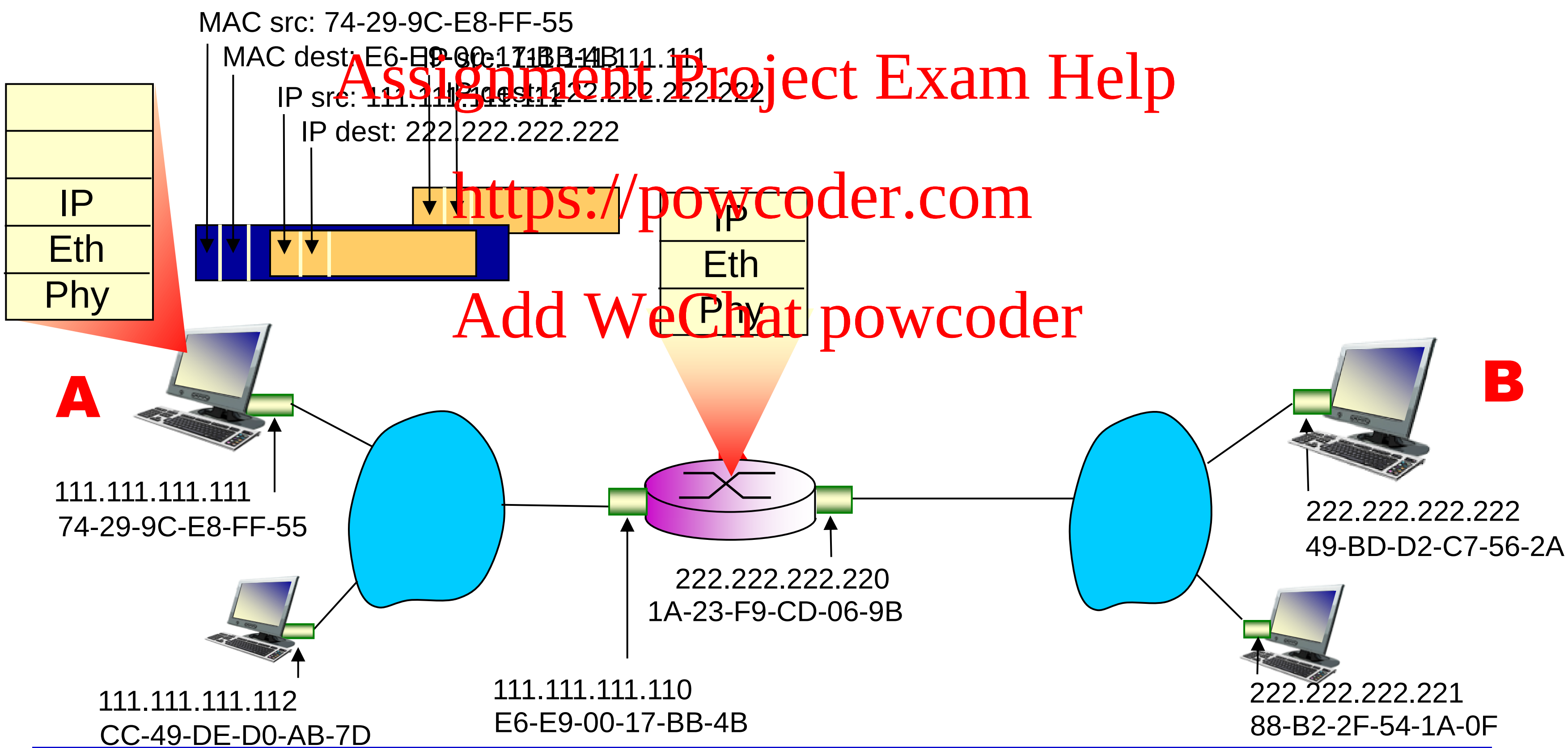
# Addressing: routing to another LAN

- A creates IP datagram with IP source A, destination B
- A creates link-layer frame with R's MAC address as dest, frame contains A-to-B IP datagram



# Addressing: routing to another LAN

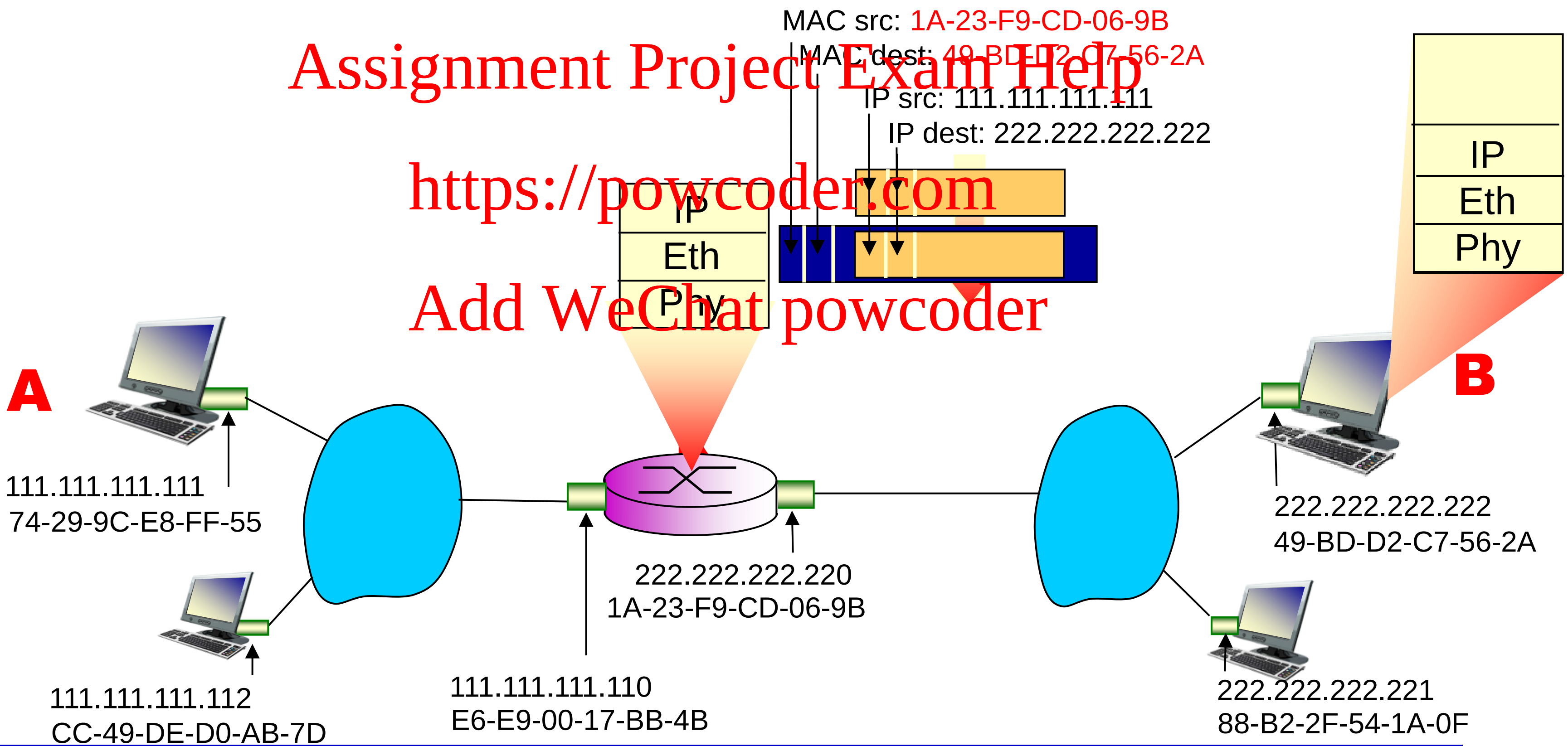
- frame sent from A to R
- frame received at R, datagram removed, passed up to IP



# Addressing: routing to another LAN

- R forwards datagram with IP source A, destination B
- R creates link-layer frame with B's MAC address as dest, frame contains A-to-B IP datagram





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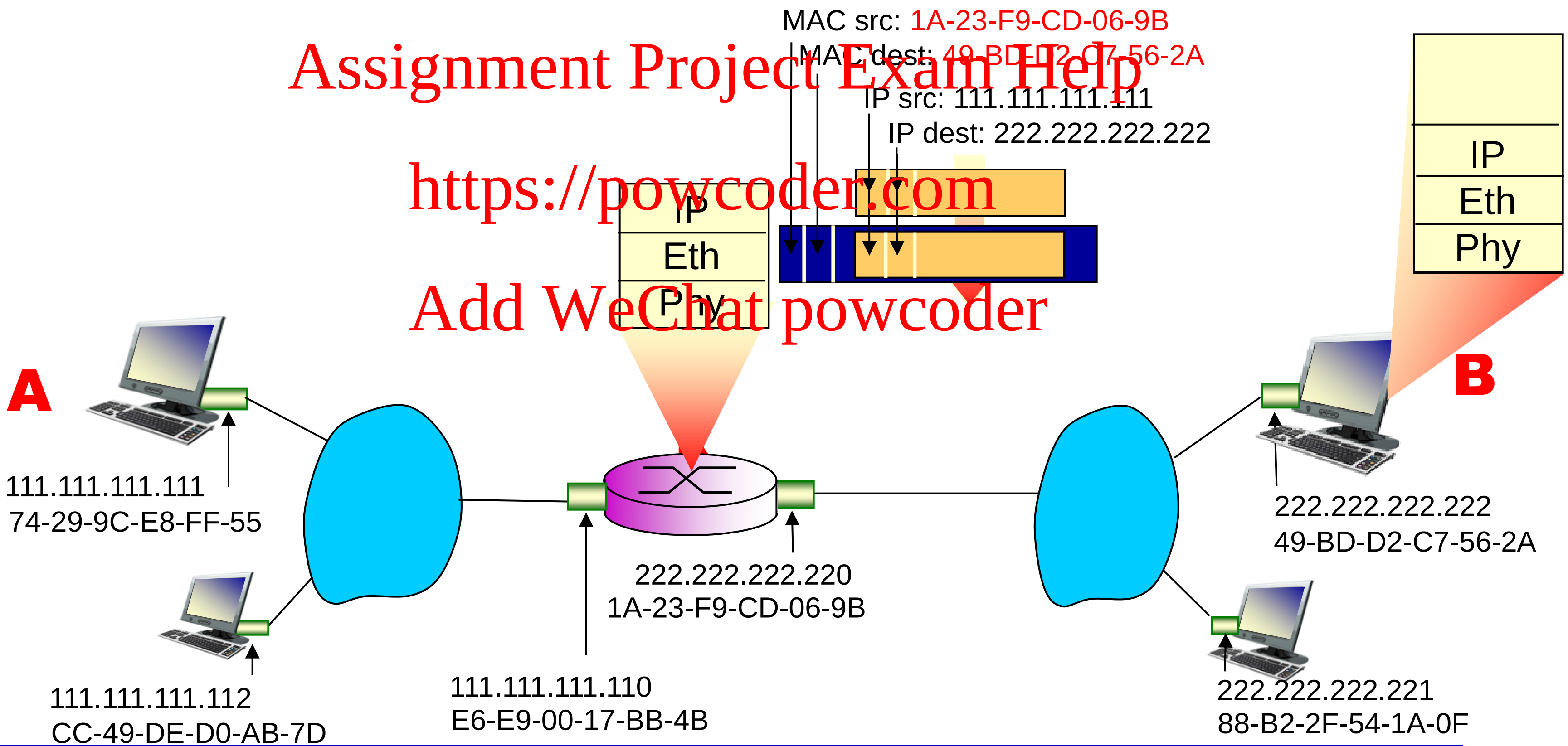

# Addressing: routing to another LAN

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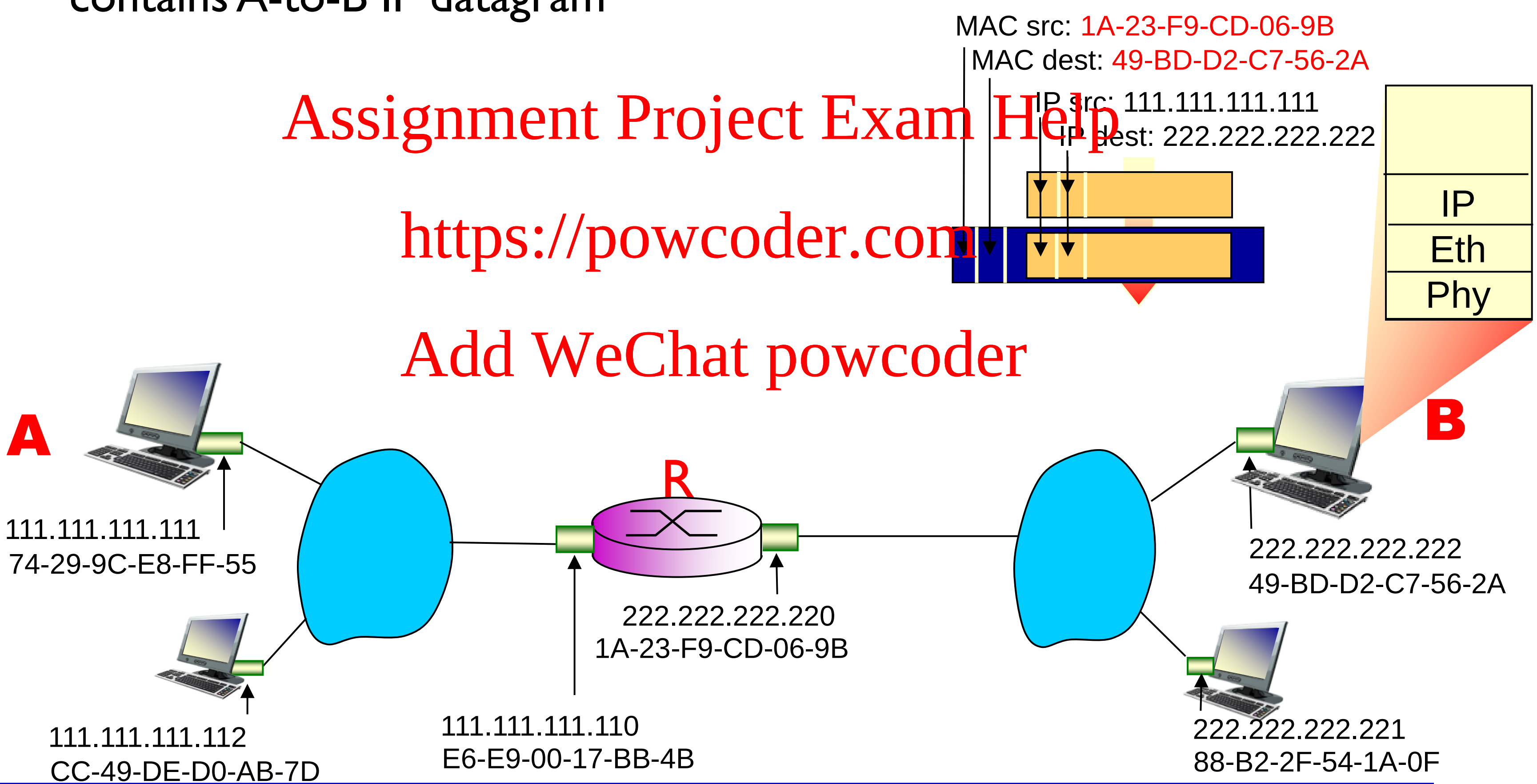
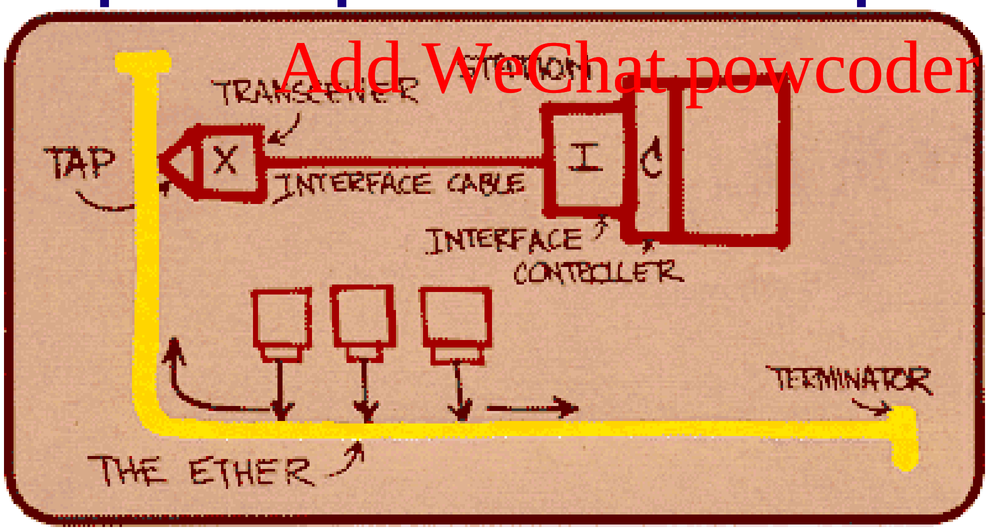


# Ethernet

"dominant" wired LAN technology:

- cheap $20 for NIC
- first widely used LAN technology
- simpler, cheaper than token LANs and ATM
- kept up with speed race: 10 Mbps – 10 Gbps

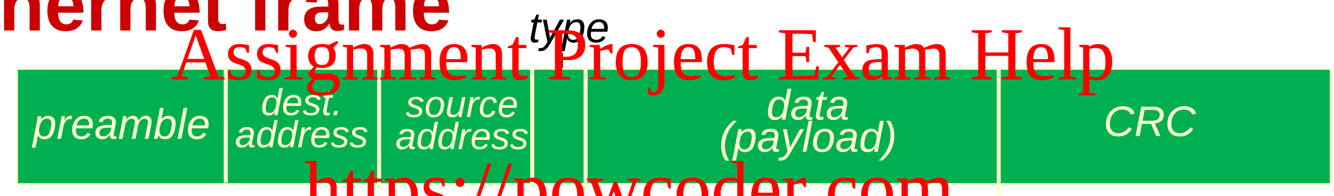





*Metcalfe's Ethernet sketch*

# Ethernet frame structure

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



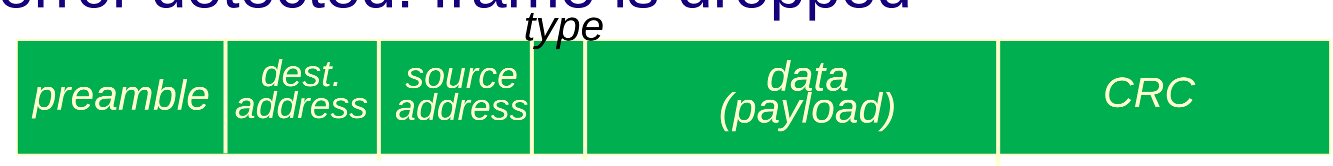



***preamble:***

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

# Ethernet frame structure

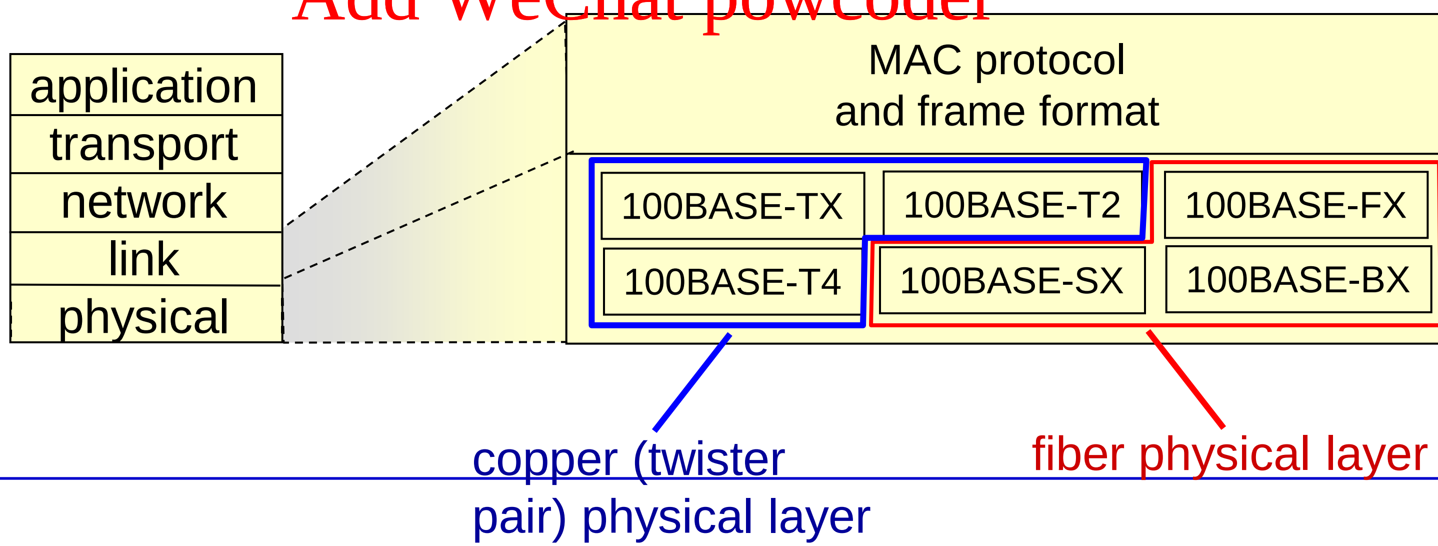
- *addresses:* 6 byte source, destination MAC addresses
  - if adapter receives frame with matching destination address, or with broadcast address (e.g. ARP packet), it passes data in frame to network layer protocol
  - otherwise, adapter discards frame
- *type:* indicates higher layer protocol (mostly IP but others possible, e.g., Novell IPX, AppleTalk)
- *CRC:* cyclic redundancy check at receiver
  - error detected: frame is dropped



# 802.3 Ethernet standards: link & physical layers

- ***many*** **different Ethernet standards**
  - **common MAC protocol and frame format**
  - **different speeds: 2 Mbps, 10 Mbps, 100 Mbps, 1Gbps, 10G bps**
  - **different physical layer media: fiber, cable**



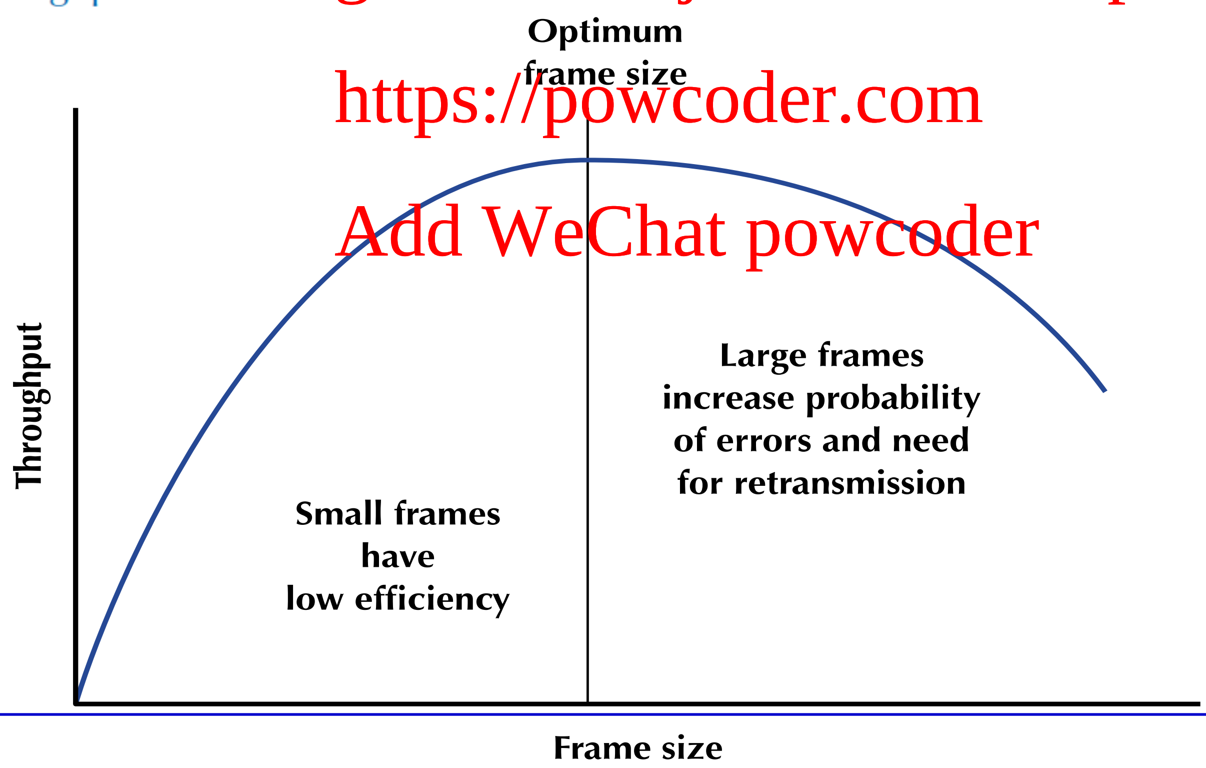


# Transmission Efficiency

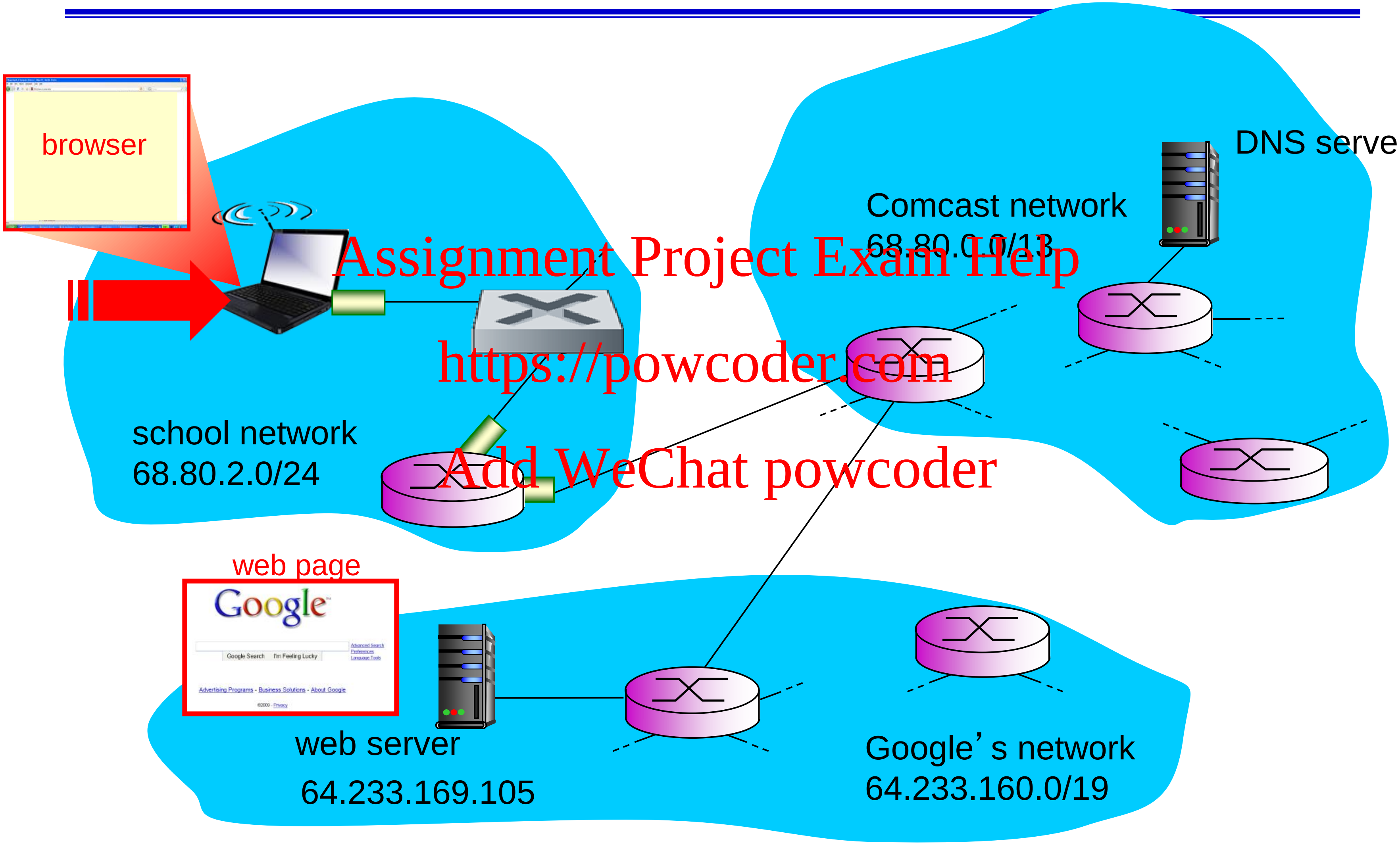
$$\text{Transmission efficiency} = \frac{\text{\# of information bits}}{\text{\# of information + overhead bits}}$$

**FIGURE 4-12**
Frame size effects on throughput

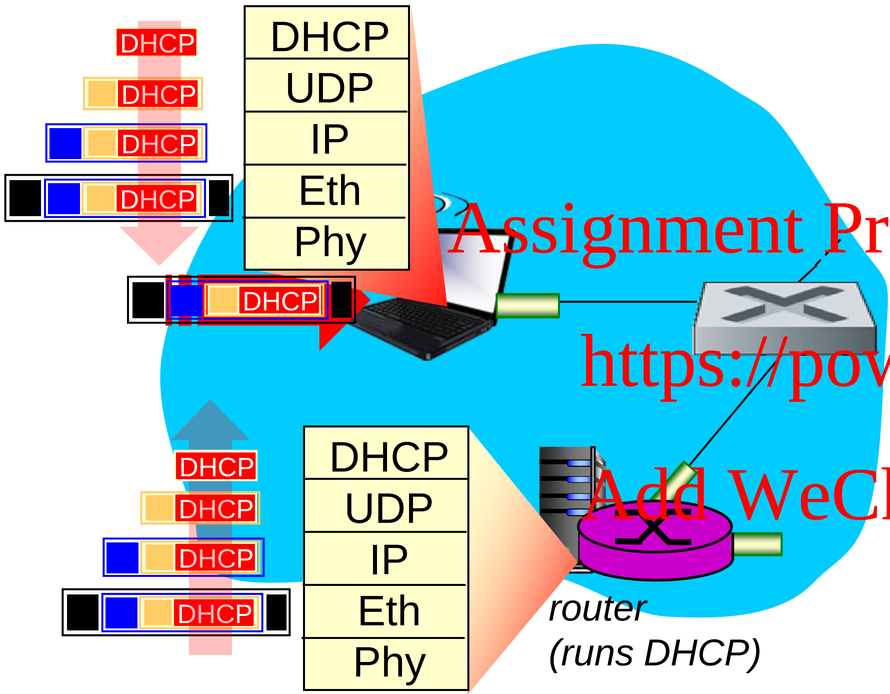




# A day in the life: scenario

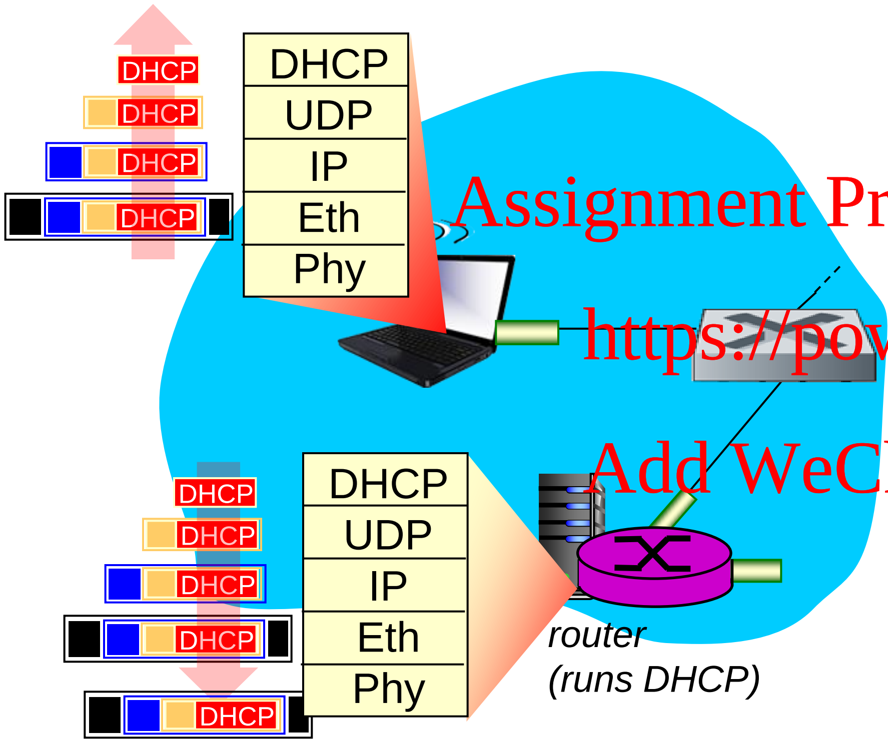


# A day in the life... connecting to the Internet




- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use *DHCP*
- DHCP request *encapsulated* in *UDP*, encapsulated in *IP*, encapsulated in *802.3* Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

# A day in the life... connecting to the Internet

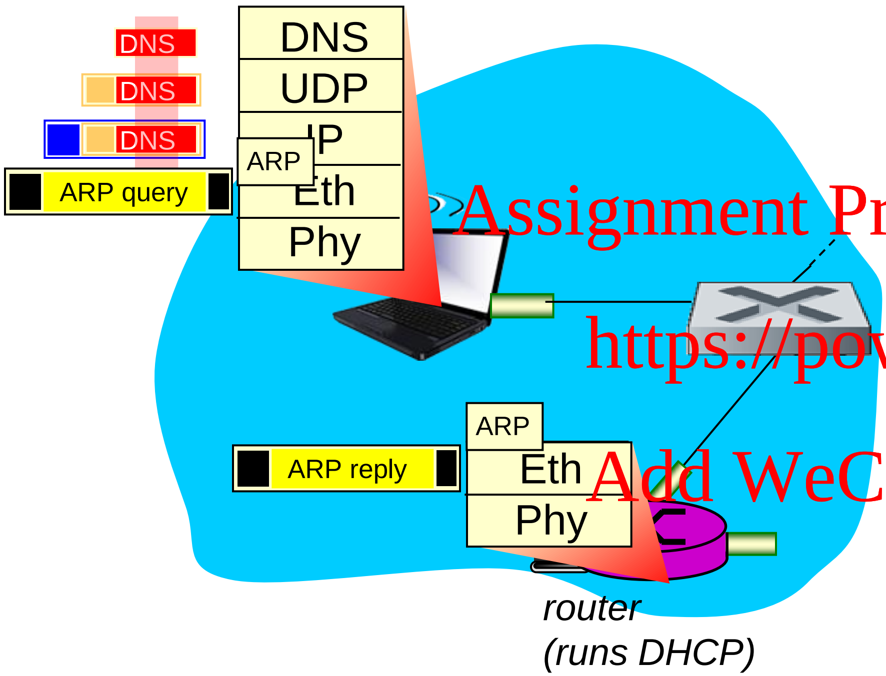



- DHCP server formulates DHCP ACK containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (*switch learning*) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply



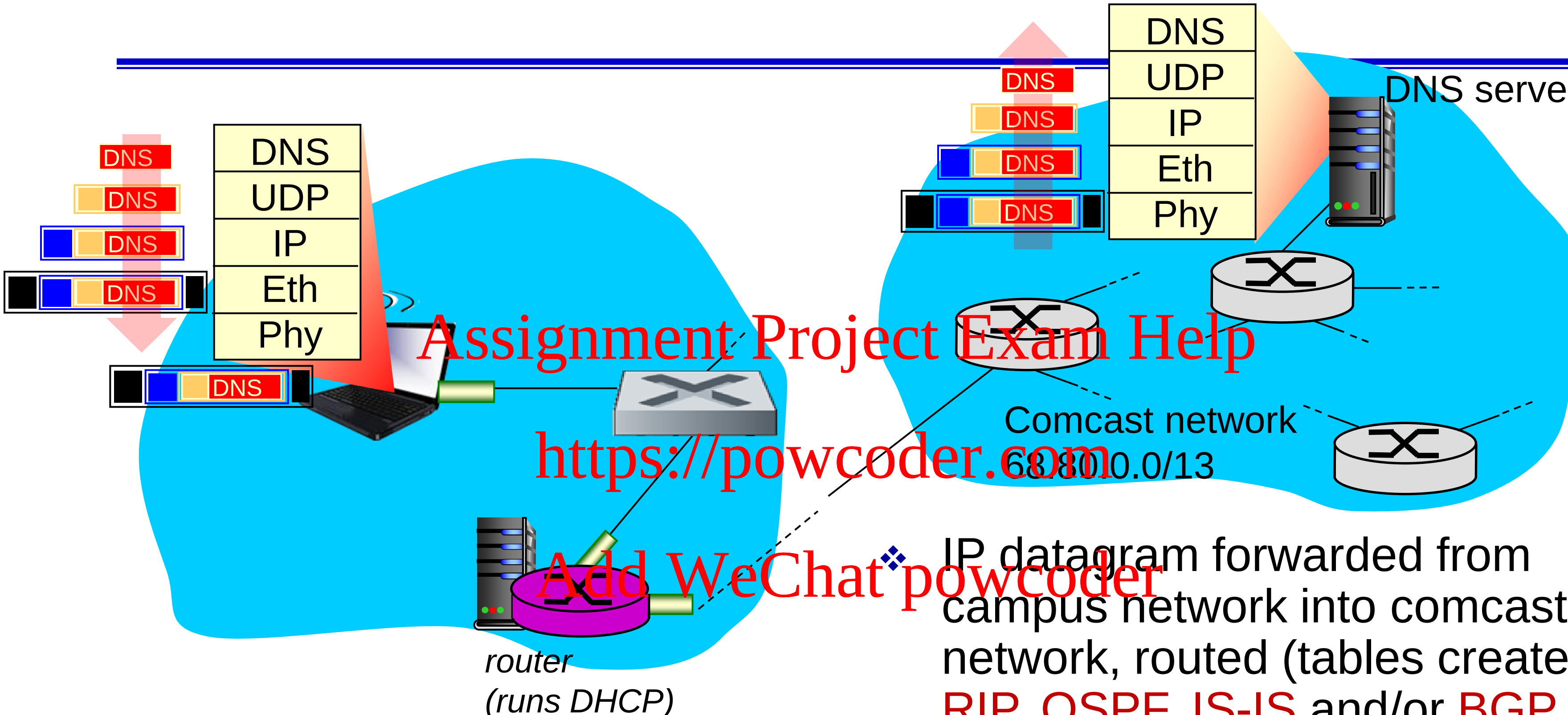
*Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router*

# A day in the life... ARP (before DNS, before HTTP)




- before sending HTTP request, need IP address of www.google.com: DNS
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: *ARP*
- ARP query broadcast, received by router, which replies with ARP reply giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

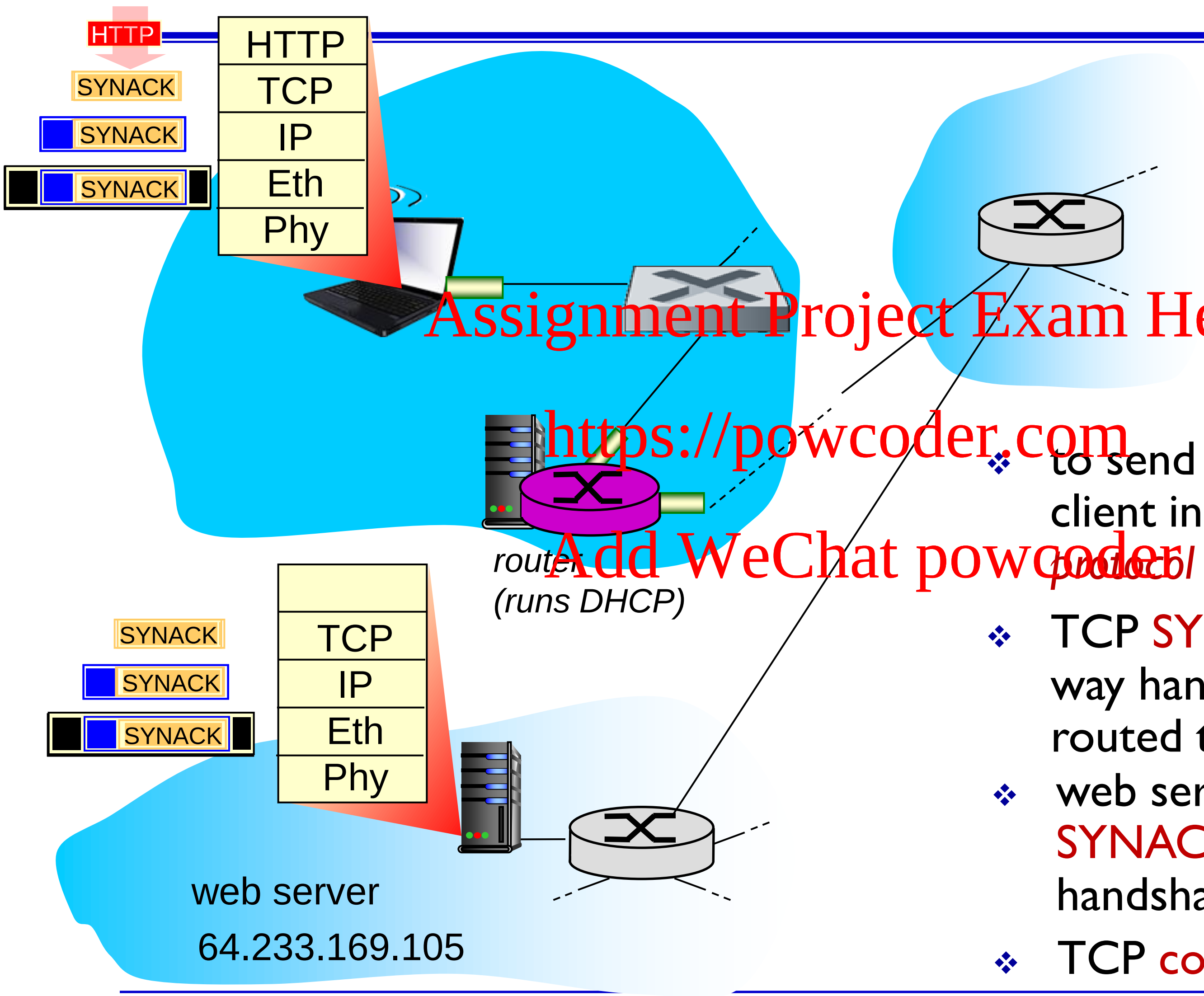
# A day in the life… using DNS






- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router
- IP datagram forwarded from campus network into comcast network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server
- demux'ed to DNS server
- DNS server replies to client with IP address of www.google.com

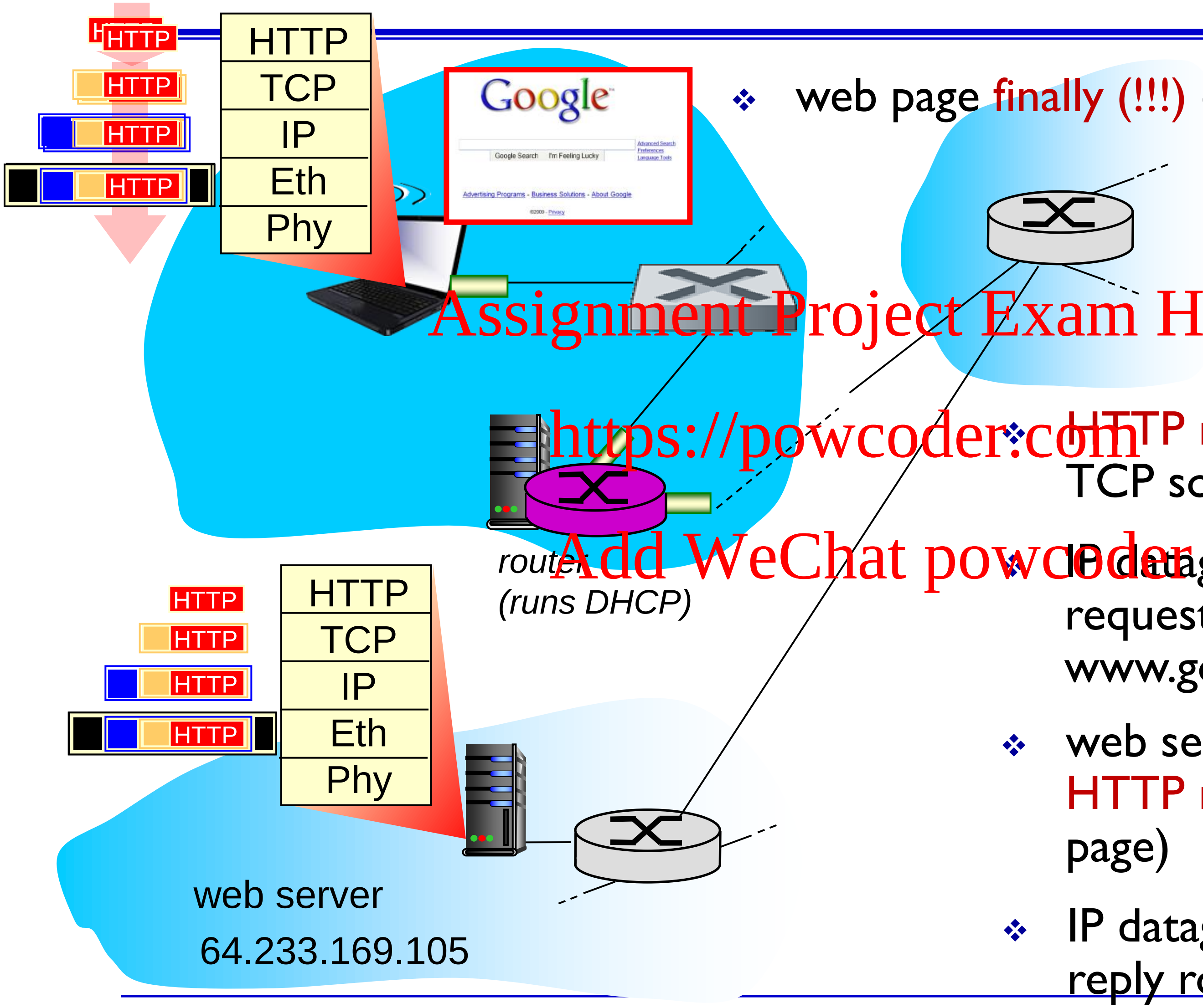
# A day in the life…TCP connection carrying HTTP






- to send HTTP request, client initiate *TCP handshake protocol*
- TCP SYN segment (step 1 in 3-way handshake) inter-domain routed to web server
- web server responds with TCP SYNACK (step 2 in 3-way handshake)
- TCP connection established!

# A day in the life... HTTP request/reply




- web page finally (!!!) displayed
- HTTP request sent into TCP socket
- IP datagram containing HTTP request routed to www.google.com
- web server responds with HTTP reply (containing web page)
- IP datagram containing HTTP reply routed back to client

# END