COS 461: Computer Networks
Lecture 2: Link Layer

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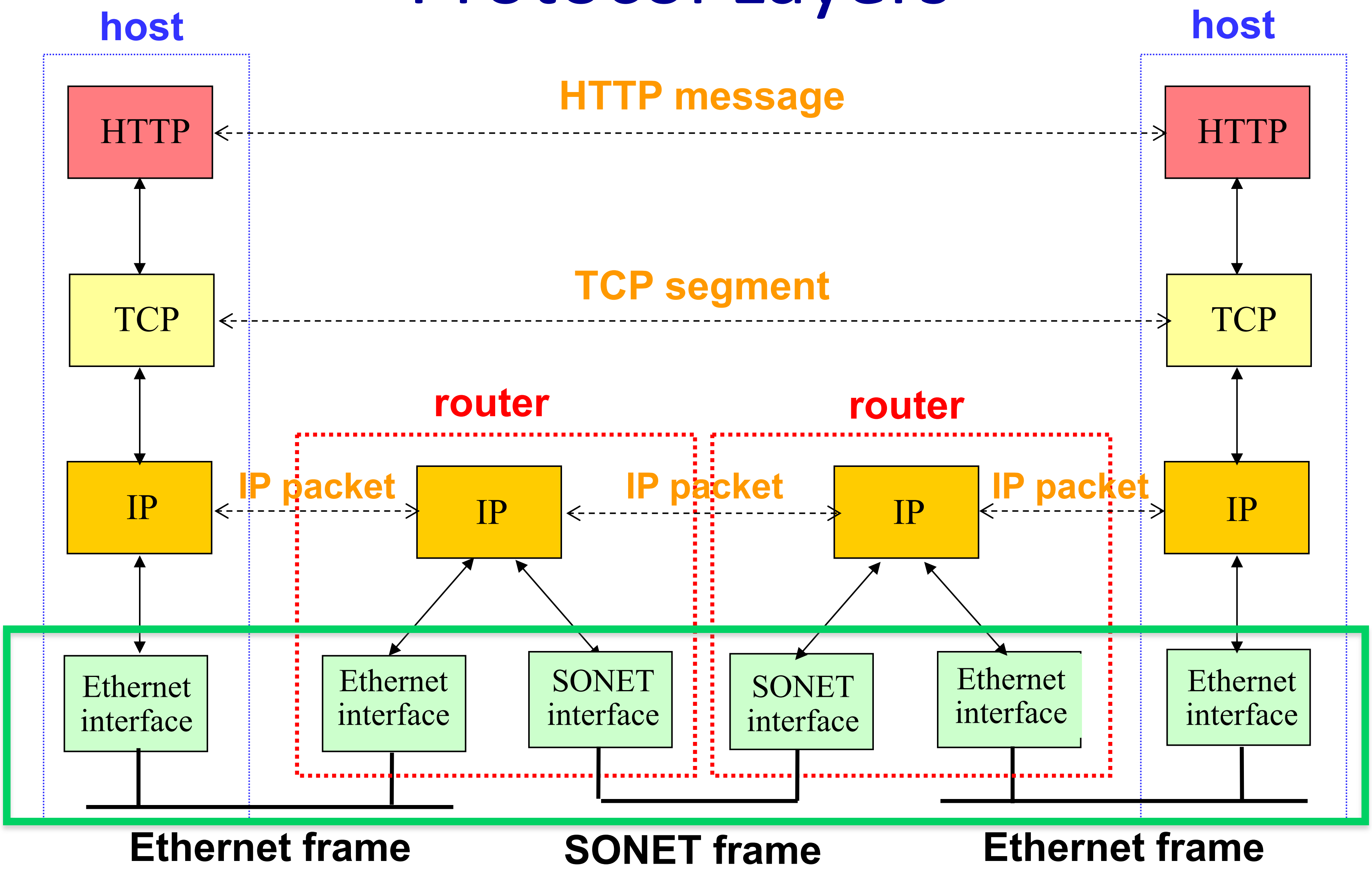
http://www.cs.princeton.edu/courses/archive/fall21/cos461/

Protocol Layers



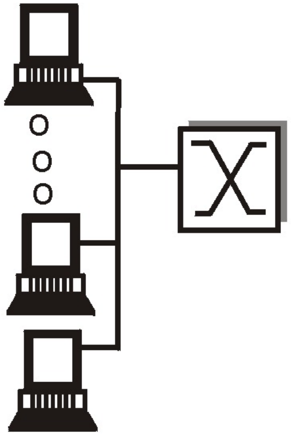
Link = Medium + Adapters

What is a Link?

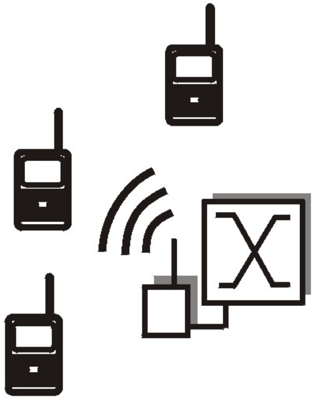
Communication Medium

Network Adapter

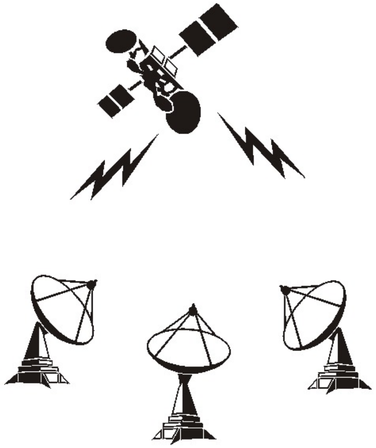
Broadcast Links: Shared Media



shared wire
(e.g. Ethernet)



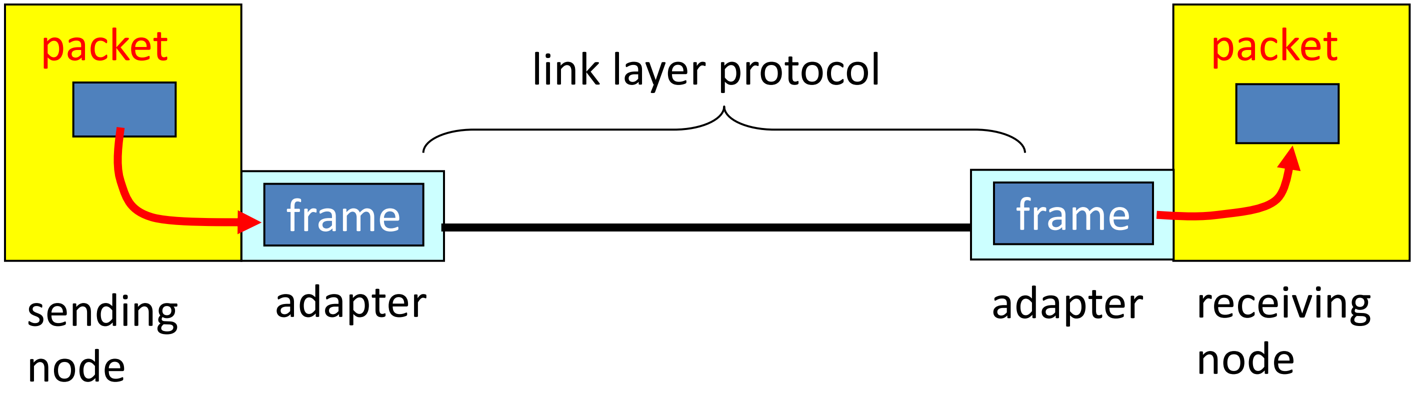
shared wireless
(e.g. Wavelan)



satellite

cocktail party

Adaptors Communicating



- Sending side
  - Encapsulates packet in a frame
  - Adds error checking bits, flow control, etc.

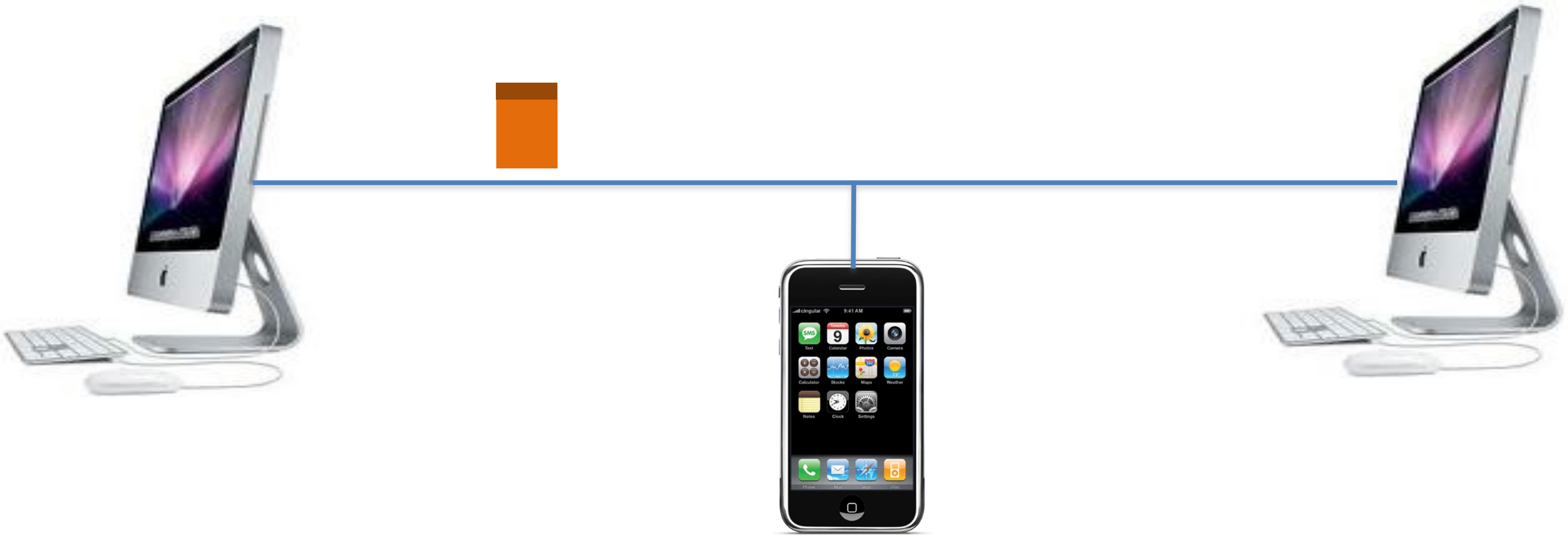
- Receiving side
  - Looks for errors, flow control, etc.
  - Extracts datagram and passes to receiving node

Link-Layer Services

- Encoding
  - Represent the 0s and 1s
- Framing
  - Encapsulate packet into frame, adding header/trailer
- Error detection
  - Receiver detecting errors with checksums
- Error correction
  - Receiver optionally correcting errors
- Flow control
  - Pacing between sending and receiving nodes

Addresses

Medium Access Control Address



- Identify the sending and receiving adapter
  - Unique identifier for each network adapter
  - Identifies the intended receiver(s) of the frame
  - … and the sender who sent the frame

Medium Access Control Address

- MAC address (e.g., 00-15-C5-49-04-A9)
  - Numerical address used within a link
  - Unique, hard-coded in the adapter when it is built
  - Flat name space of 48 bits
- Hierarchical allocation: Global uniqueness!
  - Blocks: assigned to vendors (e.g., Dell) by the IEEE
  - Adapters: assigned by the vendor from its block
- Broadcast address (i.e., FF-FF-FF-FF-FF-FF)
  - Send the frame to *all* adapters

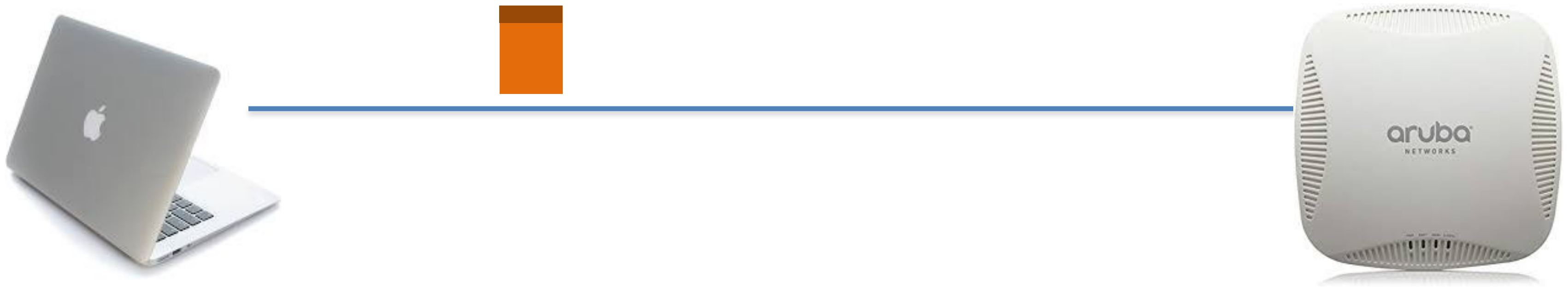
As an Aside: Promiscuous Mode

- Normal adapter: receives frames sent to
  - The local MAC address
  - Broadcast address FF-FF-FF-FF-FF-FF
- Promiscuous mode
  - Receive *everything*, independent of destination MAC
- Useful for packet sniffing
  - Network monitoring
  - E.g., wireshark, tcpdump

Why Not Just Use IP Addresses?

- Links can support *any* network protocol
  - Not just for IP (e.g., IPX, Appletalk, X.25, …)
  - Different addresses on different kinds of links
- An adapter may move to a new location
  - So, cannot simply assign a static IP address
  - Instead, must reconfigure the adapter's IP address
- Must identify the adapter during bootstrap
  - Need to talk to the adapter to assign it an IP address

Who Am I: Acquiring an IP Address



71-65-F7-2B-08-53

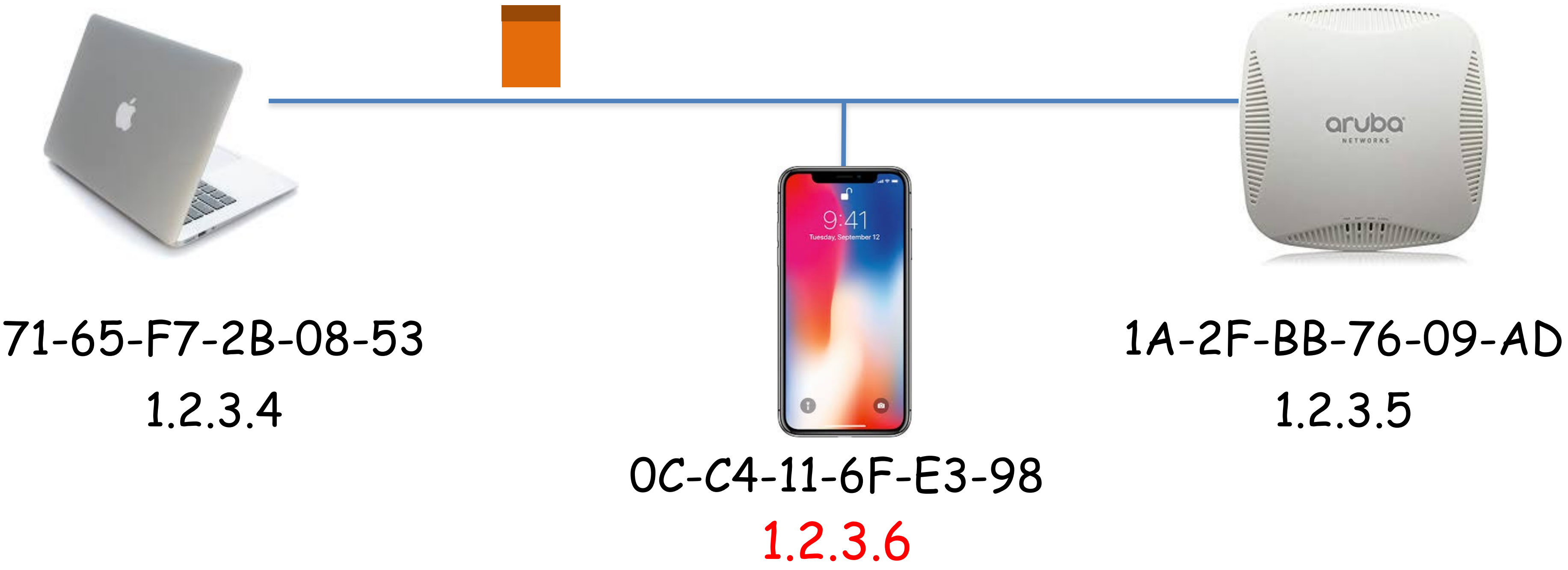
????

1A-2F-BB-76-09-AD

DHCP server

- Dynamic Host Configuration Protocol (DHCP)
  - Broadcast “I need an IP address, please!”
  - Response “You can have IP address 1.2.3.4.”

Who Are You: Discovering the Receiver



71-65-F7-2B-08-53
1.2.3.4

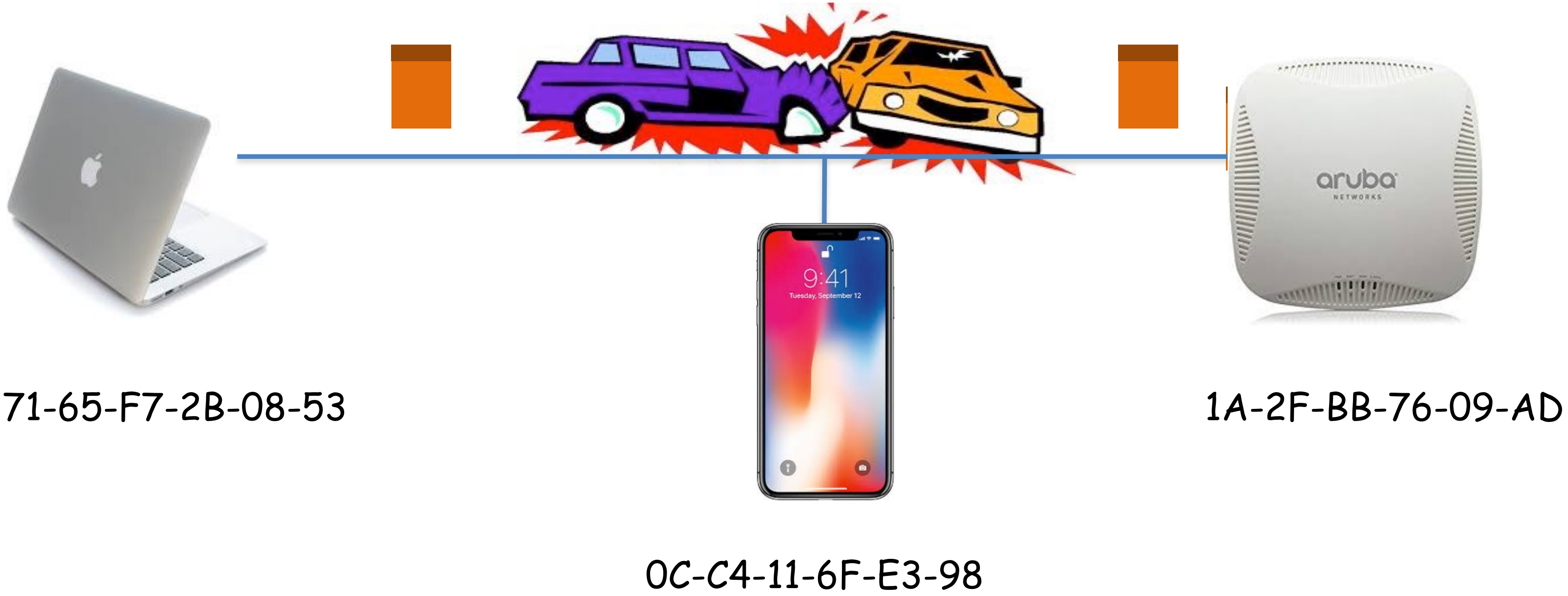
0C-C4-11-6F-E3-98
1.2.3.6

1A-2F-BB-76-09-AD
1.2.3.5

- Address Resolution Protocol (ARP)
  - Broadcast “who has IP address 1.2.3.6?”
  - Response “0C-C4-11-6F-E3-98 has 1.2.3.6!”

Sharing the Medium

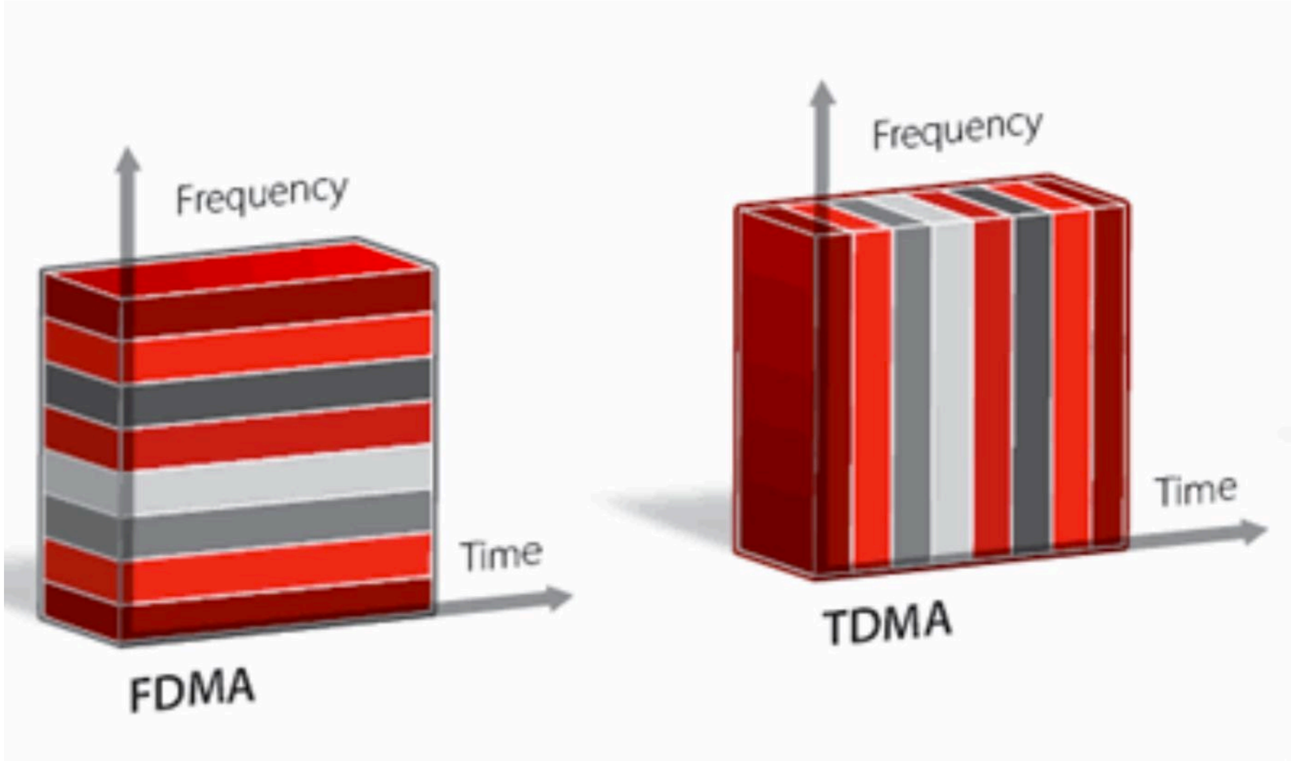
Collisions



- Single shared broadcast channel
  - Avoid having multiple nodes speaking at once
  - Otherwise, collisions lead to garbled data

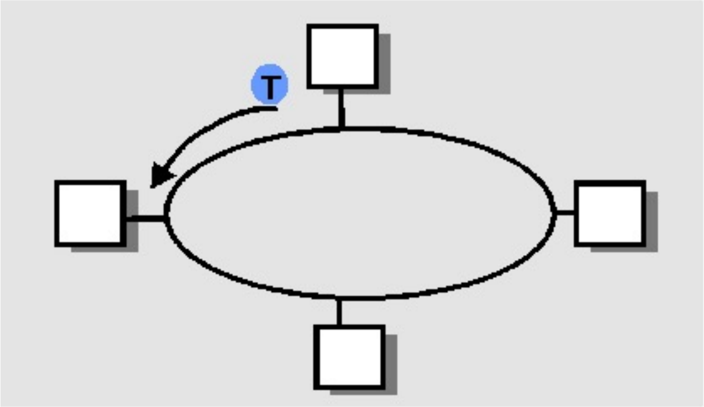
Multi-Access Protocol

- Divide the channel into pieces
  - in frequency vs. in time



Multi-Access Protocol

- Take turns
  - Do not transmit w/o token
  - With token, transmit for up to some max time/length
  - Pass token to right



- Punt
  - Let collisions happen
  - … and detect and recover from them

Like Human Conversation…

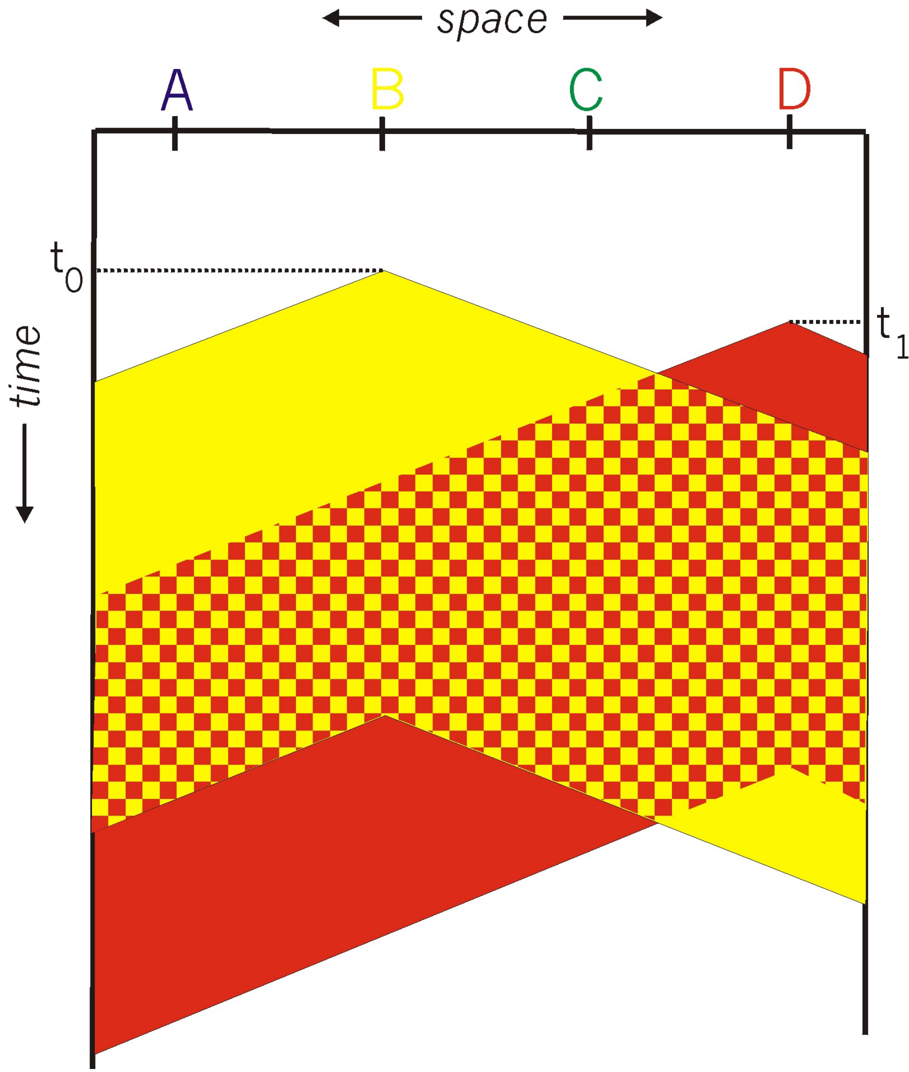
- Carrier sense
  - Listen before speaking
  - …and don’t interrupt!

- Collision detection
  - Detect simultaneous talking
  - … and shut up!

- Random access
  - Wait for a random period of time
  - … before trying to talk again!

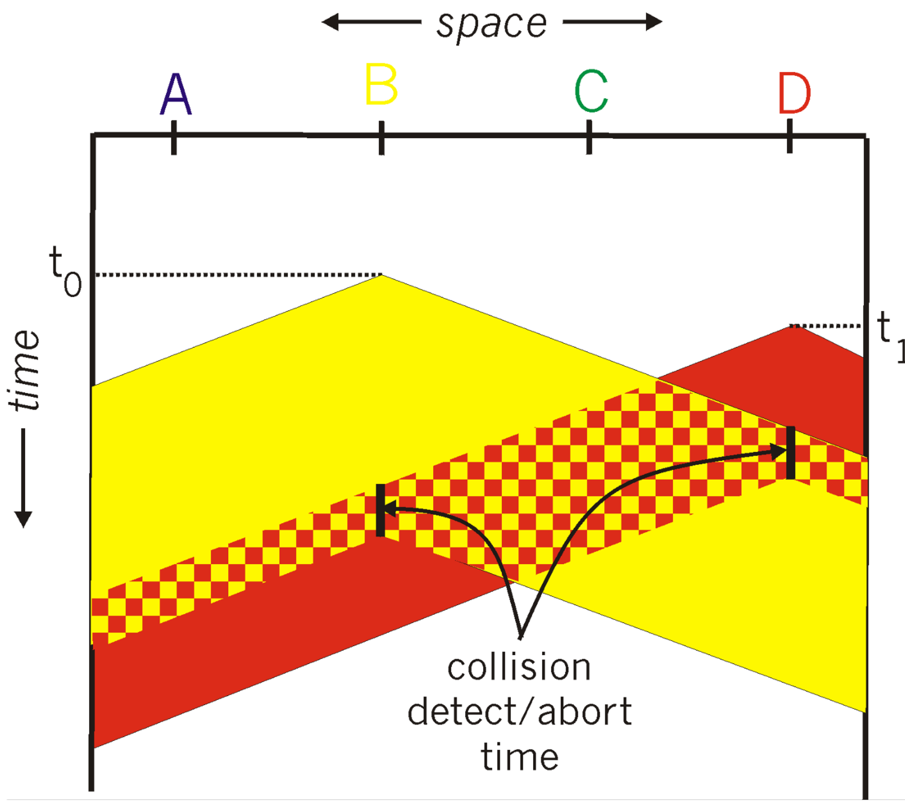
Carrier Sense Multiple Access

- Listen for other senders
  - Then transmit your data
- Collisions can still occur
  - Propagation delay
  - Wasted transmission



CSMA/CD Collision Detection

- Detect collision
  - Abort transmission
  - Jam the link
- Wait random time
  - Transmit again
- Hard in wireless
  - Must receive data while transmitting



Comparing the Three Approaches

- Channel partitioning is

  (a) Efficient/fair at high load, inefficient at low load

  (b) Inefficient at high load, efficient/fair at low load

- “Taking turns”

  (a) Inefficient at high load

  (b) Efficient at all loads

  (c) Robust to failures

- Random access

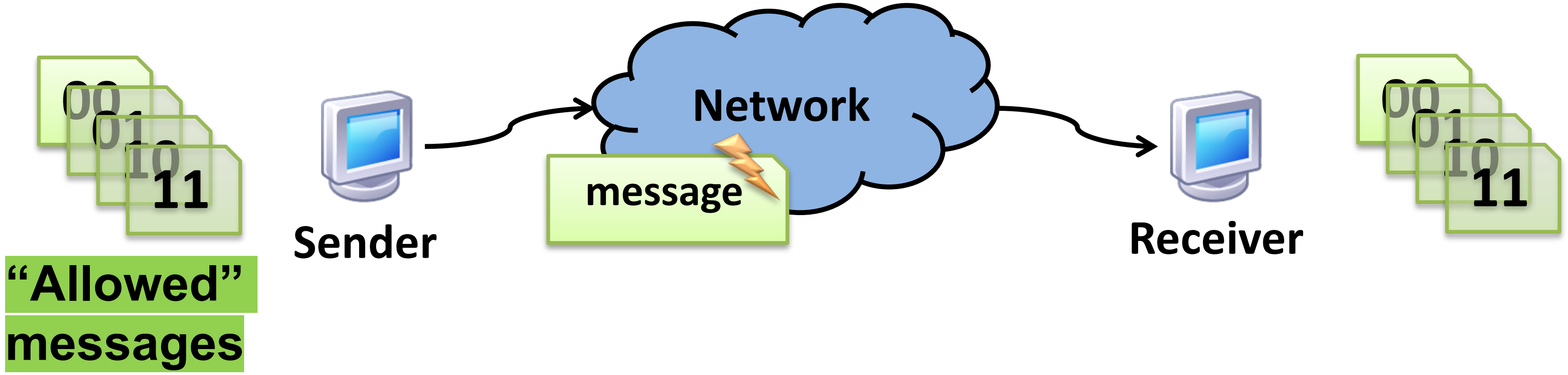
  (a) Inefficient at low load

  (b) Efficient at all load

  (c) Robust to failures

Error Control

Error control: Motivation

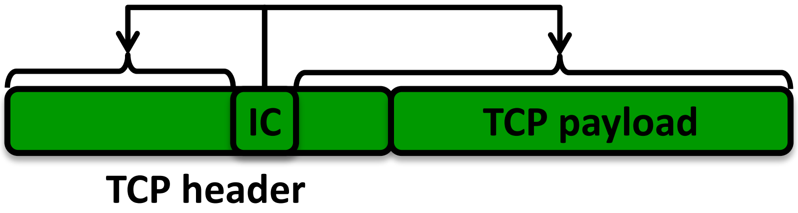


- *A priori,* any string of bits is an "allowed" **message**
  - Hence any **changes to the bits** (***bit errors***) the sender transmits produce "**allowed"** messages

- **Therefore without error control, receiver wouldn't know errors happened!**

Error control in the Internet stack

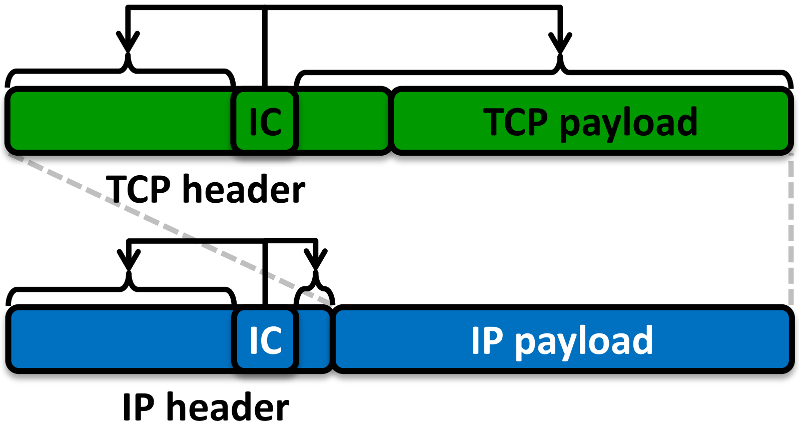
- Transport layer
  - **Internet Checksum (IC)** over TCP/UDP header, data



Error control in the Internet stack

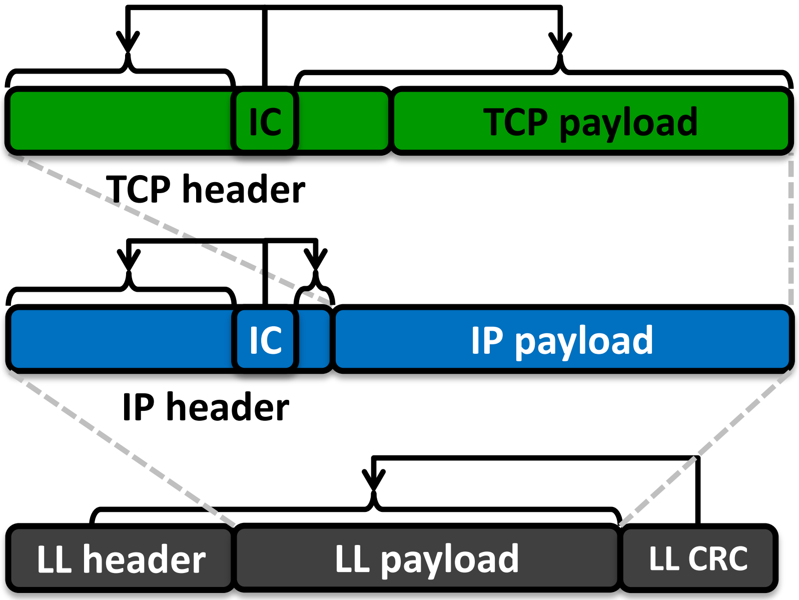
- **Transport layer**
  - **Internet Checksum (IC)** over TCP/UDP header, data

- **Network layer (L3)**
  - **IC** over IP header only



Error control in the Internet stack

- **Transport layer**
  - **Internet Checksum (IC)** over TCP/UDP header, data
- **Network layer (L3)**
  - **IC** over IP header only
- **Link layer (L2)**
  - **Cyclic Redundancy Check (CRC)**



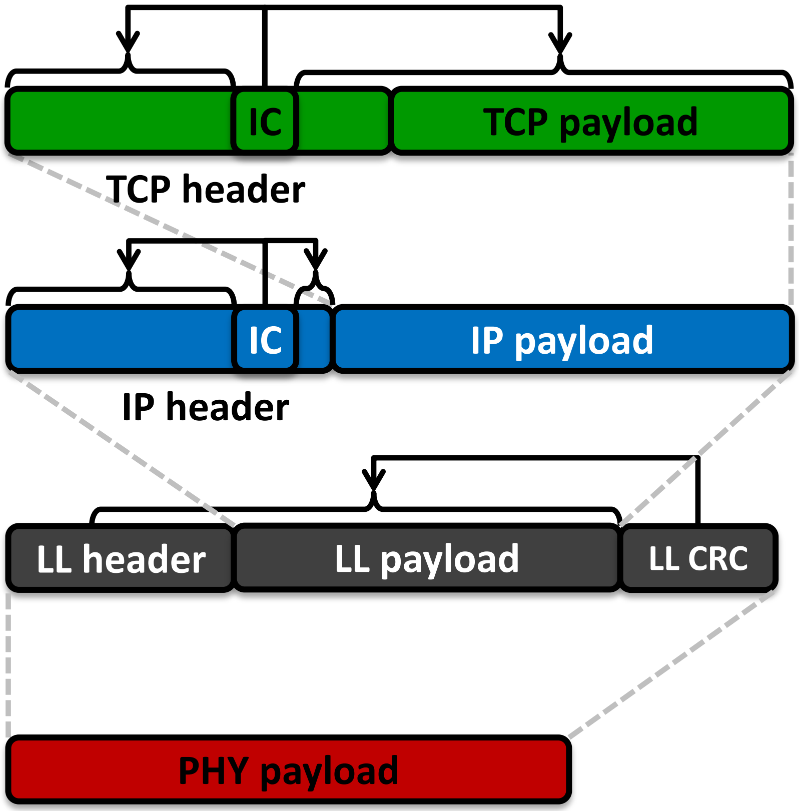
Error control in the Internet stack

- **Transport layer**
  - **Internet Checksum (IC)** over TCP/UDP header, data

- **Network layer (L3)**
  - **IC** over IP header only

- **Link layer (L2)**
  - **Cyclic Redundancy Check (CRC)**

- **Physical layer (PHY)**
  - **Error Control Coding (ECC), or**
  - **Forward Error Correction (FEC)**



Error control: Key Ideas

- **Reduce the set of “allowed” messages**
  - **Not every string of bits** is an “allowed” message
  - Receipt of a **disallowed** string of bits means that the **message was garbled** in transit over the network

- We call an allowable message (of *n* bits) a ***codeword***
  - **Not all** *n*-bit strings are codewords!
  - The remaining *n*-bit strings are **“space” between codewords**

- **Plan:** Receiver will **use that space** to both **detect** and **correct** errors in transmitted messages

Encoding and decoding

- **Problem: Not every string of bits is "allowed"**
  - But we want to be **able to send any** message!
  - *How can we send a "disallowed" message?*

- **Answer: Codes,** as a sender-receiver **protocol**
  - The sender must ***encode*** its messages ➜ codewords
  - The receiver then ***decodes*** received bits ➜ messages

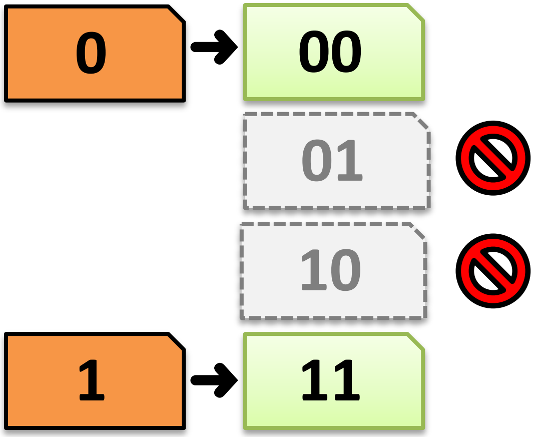
- The **relationship between messages and codewords** isn't always obvious!

A simple error-detecting code

- Let’s start simple: suppose messages are one bit long

- Take the message bit, and **repeat** it once
  - This is called a ***two-repetition code***

Sender:



0 → 00

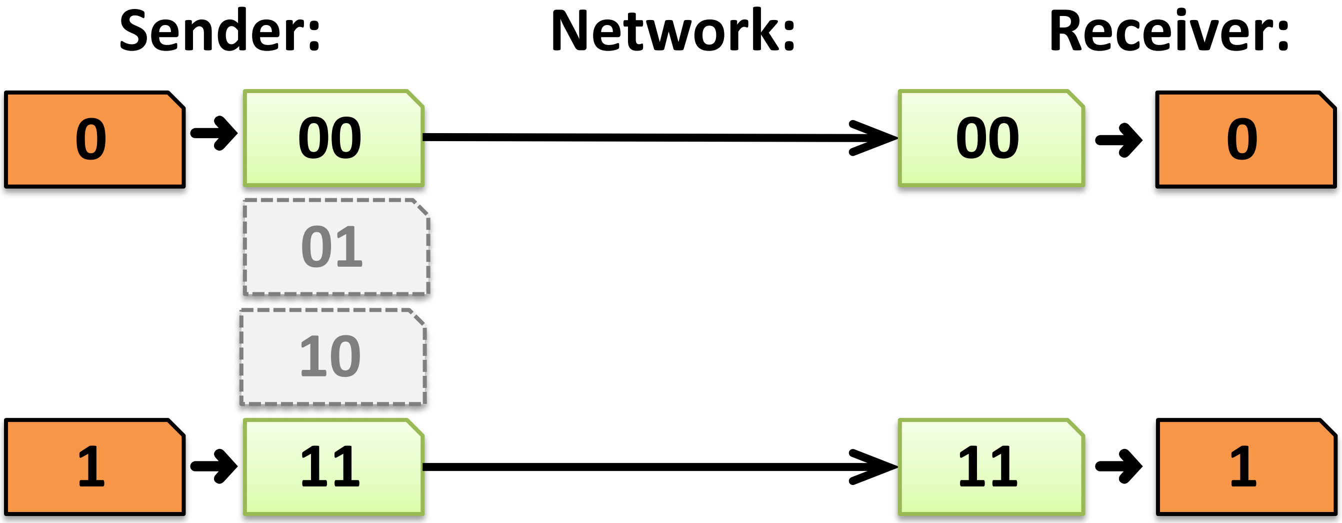
01 🚫

10 🚫

1 → 11

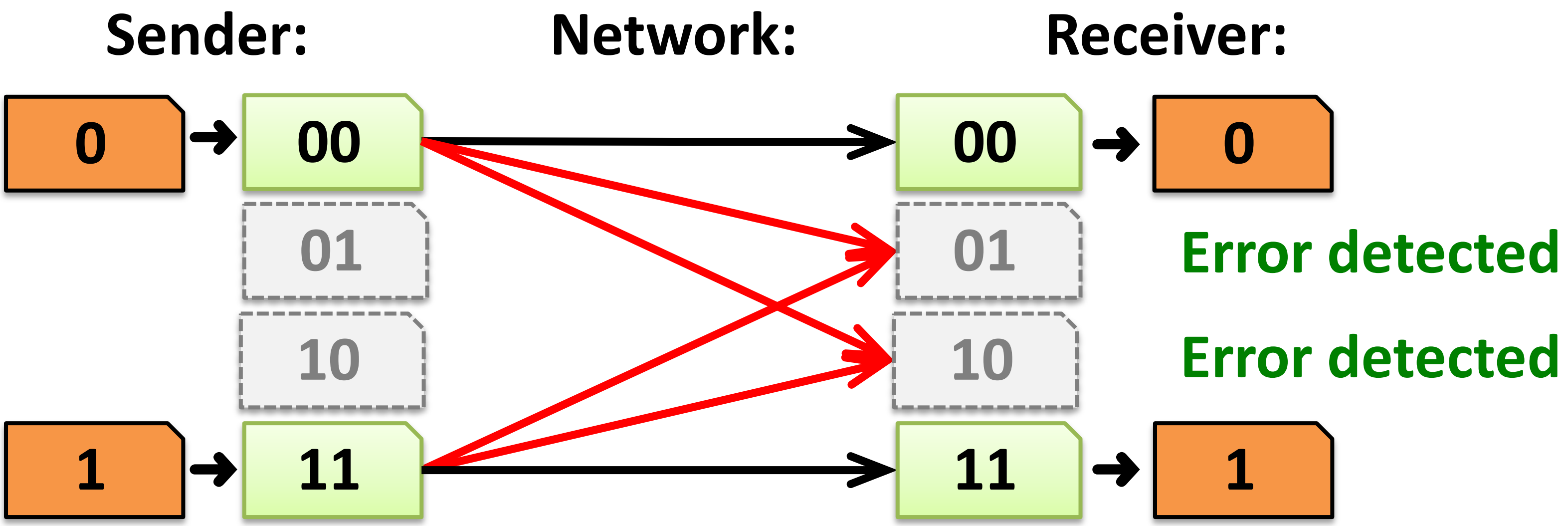
Receiving the two-repetition code

- Suppose the network causes **no bit error**
- Receiver **removes repetition** to **correctly *decode*** the message bits



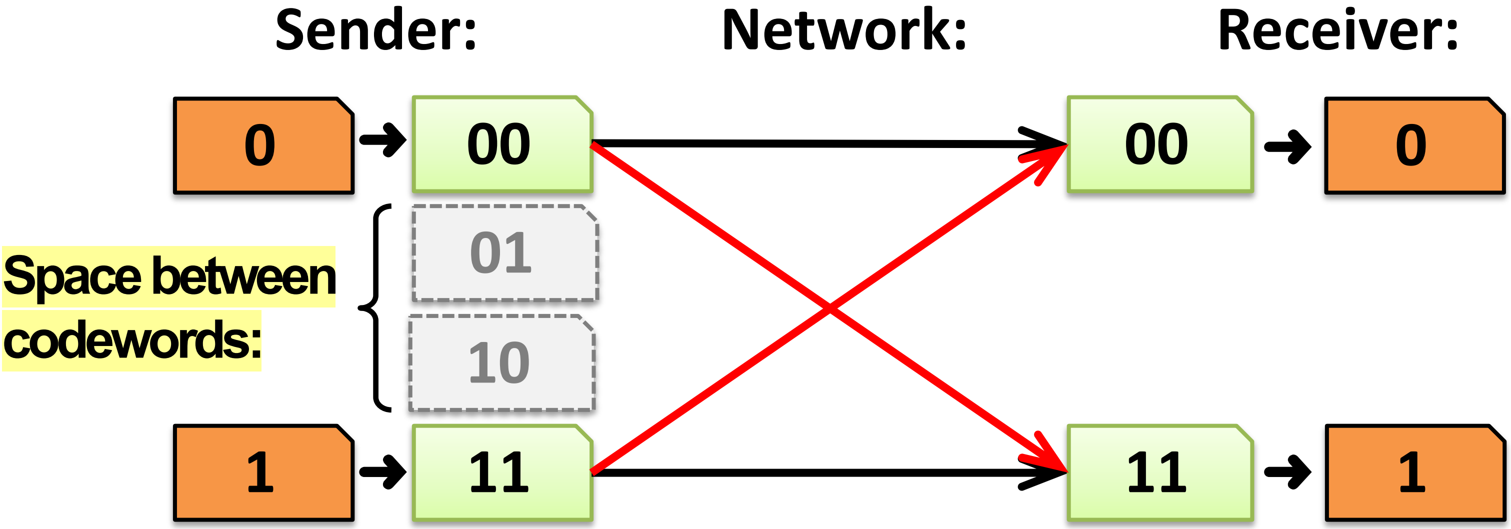
Detecting one bit error

- Suppose the network causes up to **one bit error**
- The receiver **can detect** the error:
  - It received a **non-codeword**
- Can the receiver **correct** the error?
  - **No!** The **other** codeword could have been sent as well



Reception with two bit errors

- Can receiver **detect** presence of **two bit errors?**
  - – **No:** It has no way of telling which codeword was sent!
    - Enough bit errors that the sent codeword **"jumped over" the space between** codewords

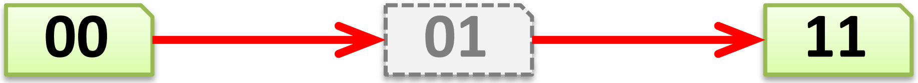


Hamming distance

- Measures the **number of bit flips** to change **one codeword into another**

- ***Hamming distance*** between two messages m_1, m_2: The number of bit flips needed to change m_1 into m_2

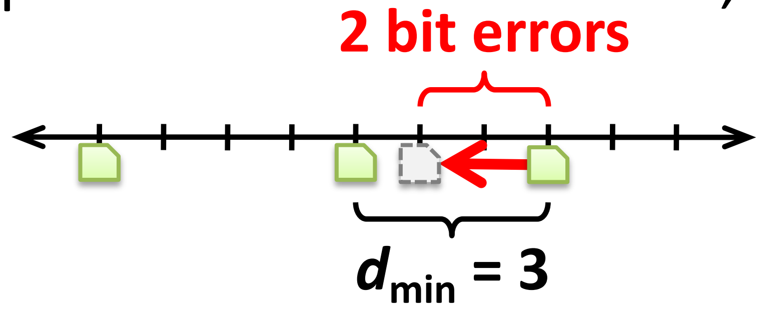
- **Example:** Two bit flips needed to change codeword 00 to codeword 11, so they are Hamming distance of **two** apart:



How many bit errors can we detect?

- Suppose the **minimum Hamming distance** between **any pair** of codewords is ***d*_min**

- Then, we **can detect at most *d*_min – 1 bit errors**
  - Will land in space between codewords, as we just saw



  - Receiver will flag message as **"Error detected"**

Decoding error **detecting** codes

- **The receiver decodes** in a **two-step** process:

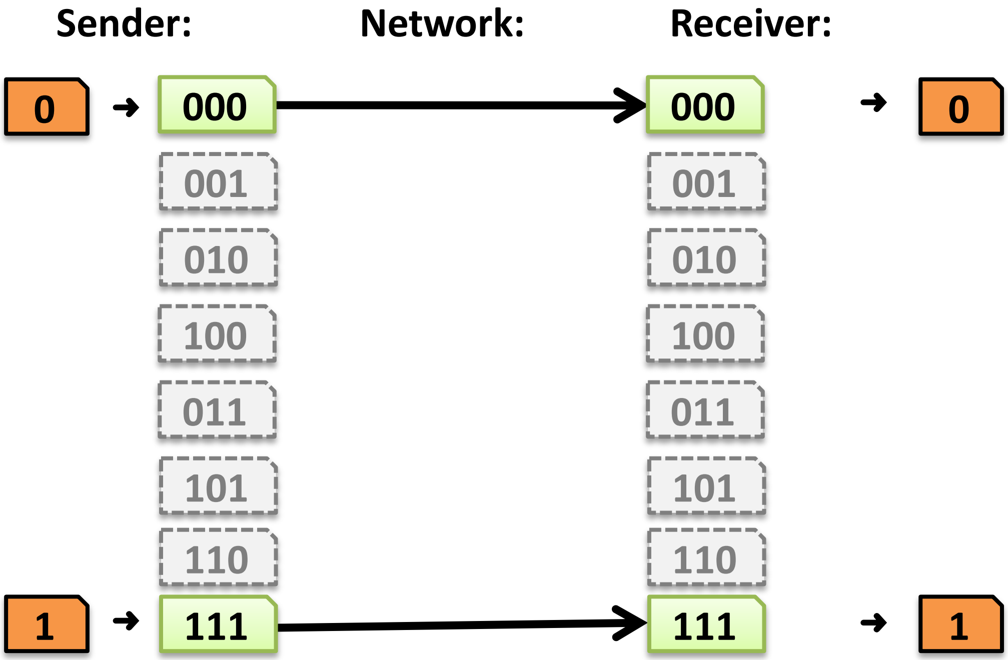
1. Map **received bits → codeword**
   - **Decoding rule:** Consider all codewords
     - **Choose** the one that **exactly matches** the received bits
     - **Return "error detected"** if none match

2. Map **codeword → source bits** and **"error detected"**
   - Use the **reverse map** of the sender

A simple error-correcting code

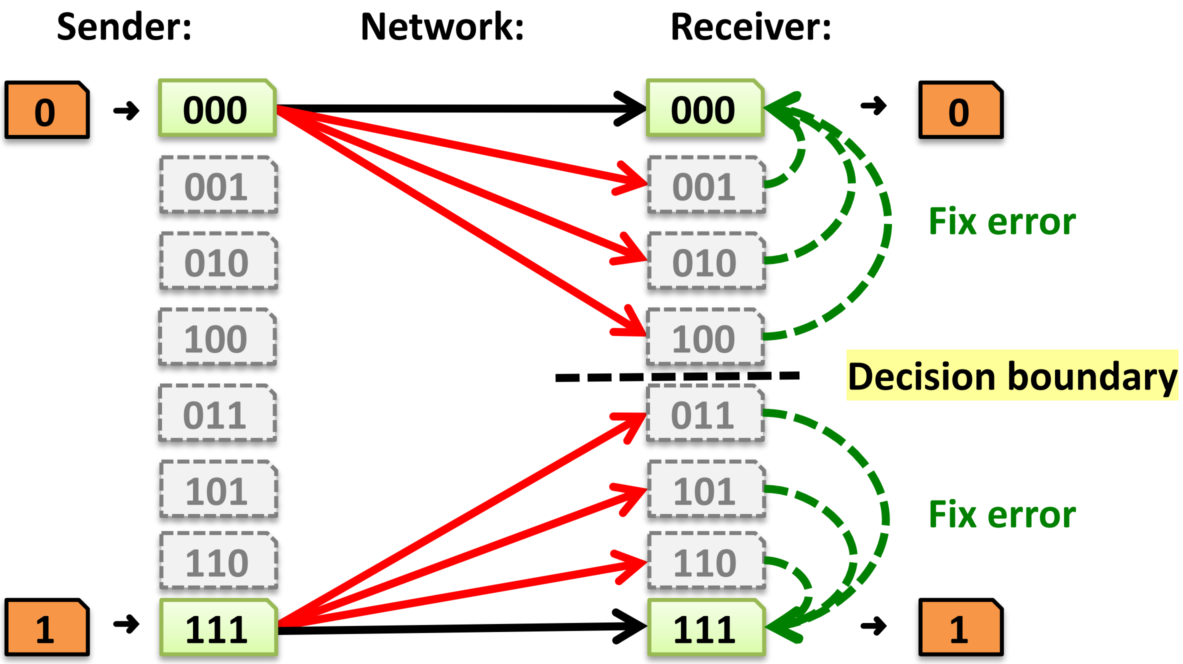
- Let's look at **a three-repetition code**

- If **no errors,** it works like the two-repetition code:



Correcting one bit error

- Receiver **chooses the closest codeword** (measured by Hamming distance) **to the received bits**
  - A ***decision boundary* exists** halfway between codewords



Decoding error correcting codes

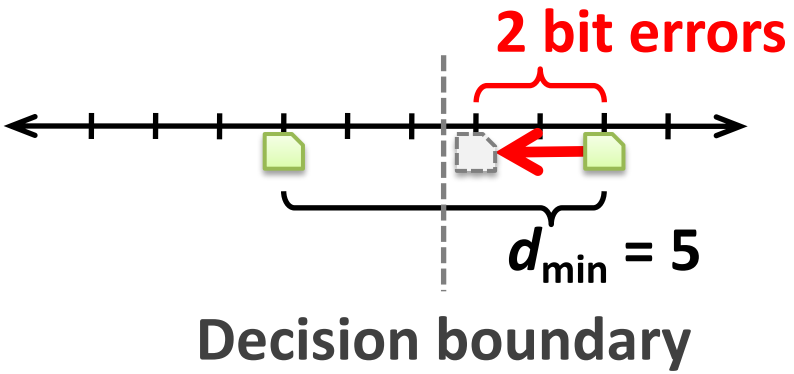
- **The receiver decodes** in a two-step process:

1. Map **received bits → codeword**
   - **Decoding rule:** Consider all codewords
     - **Choose one** with the **minimum Hamming distance** to the received bits

2. Map **codeword → source bits**
   - Use the **reverse map** of the sender

How many bit errors can we correct?

- There is **≥ d_{min}** **Hamming distance** between any two codewords
- So we can **correct ≤ $\left\lfloor {}^{d_{\min}-1}/_{2} \right\rfloor$ bit flips:**
  - This many bit flips can't move received bits closer to another codeword, **across the decision boundary:**

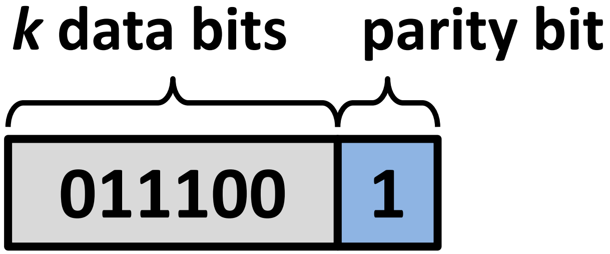


Code rate

- Suppose **codewords** of length ***n*****, messages** length ***k*** ($k < n$)
- The **code rate *R = k/n*** is a fraction between 0 and 1
- So, we have a **tradeoff:**
  - **High-rate codes** (*R* approaching one) generally **correct fewer errors,** but **add less overhead**
  - **Low-rate codes** (*R* close to zero) generally **correct more errors,** but **add more overhead**

Parity bit

- Given a message of k data bits $D_1, D_2, \ldots, D_k$, append a ***parity bit P*** to make a codeword of length $n = k + 1$
  - P is the exclusive-or of the data bits:
    - $P = D_1 \oplus D_2 \oplus \cdots \oplus D_k$
  - Pick the parity bit so that **total number of 1's is even**


***k* data bits**

parity bit

011100

1

Checking the parity bit

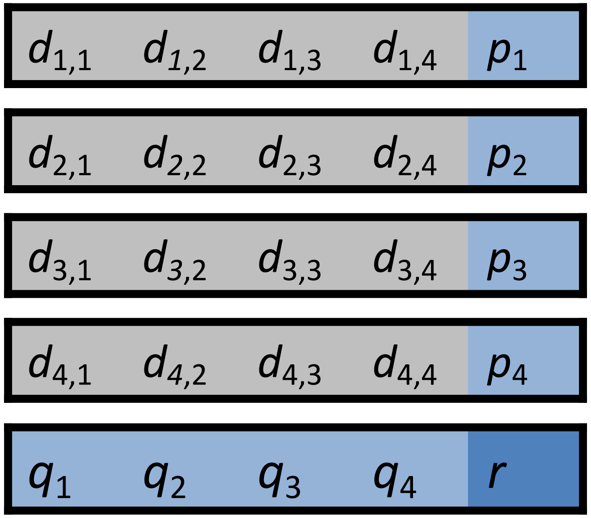
- **Receiver: counts number of 1s** in received message
  - **Even:** received message is a codeword
  - **Odd:** isn't a codeword, and **error detected**
    - But receiver doesn't know where, so **can't correct**
- What about d_{min}?
  - Change one data bit → change parity bit, so $d_{min} = 2$
    - So parity bit **detects 1 bit error, corrects 0**
- Can we **detect and correct more errors,** in general?

Two-dimensional parity

- Break up data into multiple rows
  - Parity bit **across** each row (***p**$_i$*)
  - Parity bit **down each column** (***q**$_i$*)
  - Add a parity bit ***r*** covering row parities

$$\begin{aligned}
\boldsymbol{p_j} &= \boldsymbol{d_{j,1} \oplus d_{j,2} \oplus d_{j,3} \oplus d_{j,4}} \\
\boldsymbol{q_j} &= \boldsymbol{d_{1,j} \oplus d_{2,j} \oplus d_{3,j} \oplus d_{4,j}} \\
\boldsymbol{r} &= \boldsymbol{p_1 \oplus p_2 \oplus p_3 \oplus p_4}
\end{aligned}$$

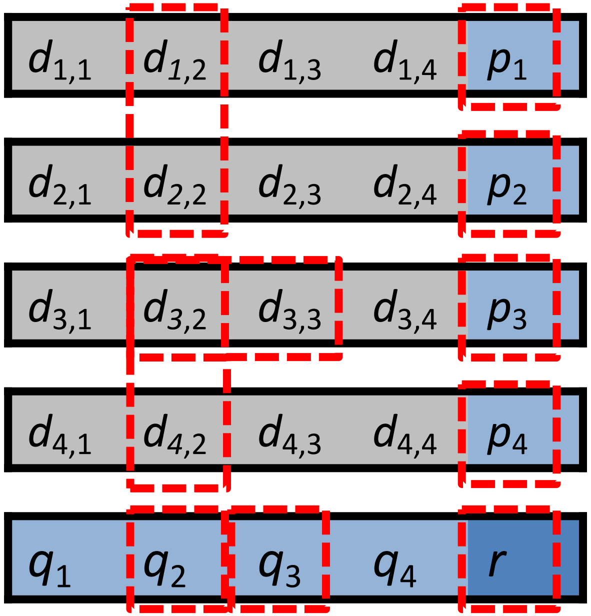
- This example has rate 16/25:



$d_{1,1}$	$d_{1,2}$	$d_{1,3}$	$d_{1,4}$	p_1
$d_{2,1}$	$d_{2,2}$	$d_{2,3}$	$d_{2,4}$	p_2
$d_{3,1}$	$d_{3,2}$	$d_{3,3}$	$d_{3,4}$	p_3
$d_{4,1}$	$d_{4,2}$	$d_{4,3}$	$d_{4,4}$	p_4
q_1	q_2	q_3	q_4	r

Two-dimensional parity: Properties

- Flip **1 data bit, 3 parity bits** flip
- Flip **2 data bits,** ≥ **2 parity bits** flip
- Flip **3 data bits, ≥ 3 parity bits** flip



$d_{1,1}$	$d_{1,2}$	$d_{1,3}$	$d_{1,4}$	p_1
$d_{2,1}$	$d_{2,2}$	$d_{2,3}$	$d_{2,4}$	p_2
$d_{3,1}$	$d_{3,2}$	$d_{3,3}$	$d_{3,4}$	p_3
$d_{4,1}$	$d_{4,2}$	$d_{4,3}$	$d_{4,4}$	p_4
q_1	q_2	q_3	q_4	r

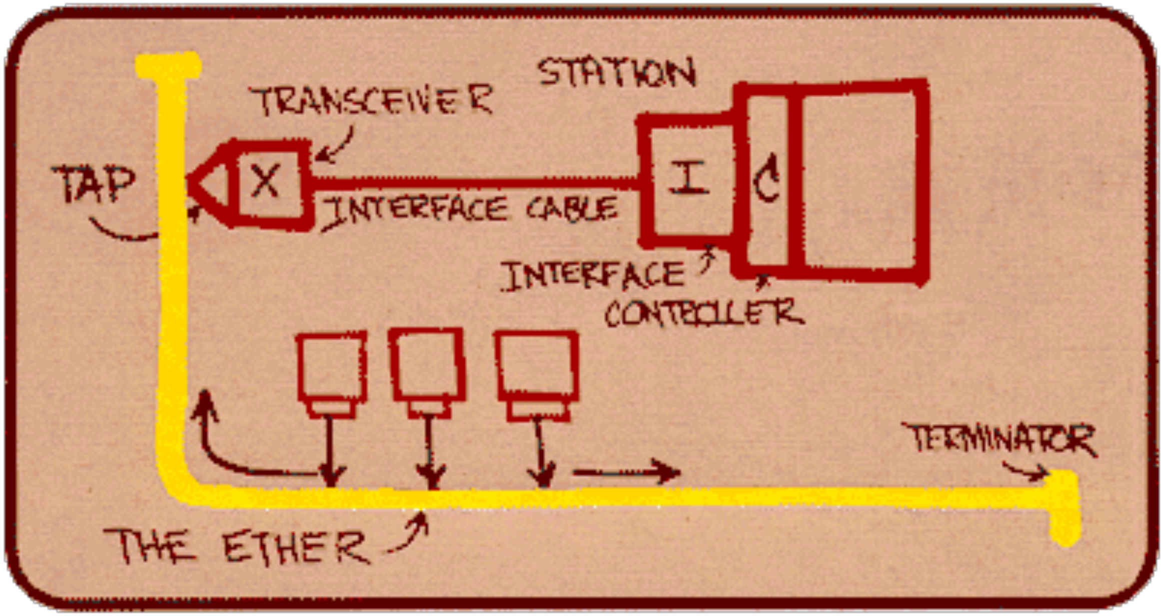
- Therefore, $\boldsymbol{d_{\min}}$ **= 4,** so
  - Can detect ≤ 3 bit errors
  - Can correct single-bit errors (*how?*)

- 2-D parity detects **most** four-bit errors

Ethernet

Ethernet

- Dominant wired LAN technology
- First widely used LAN technology
- Kept up with speed race: 10 Mbps – 40 Gbps

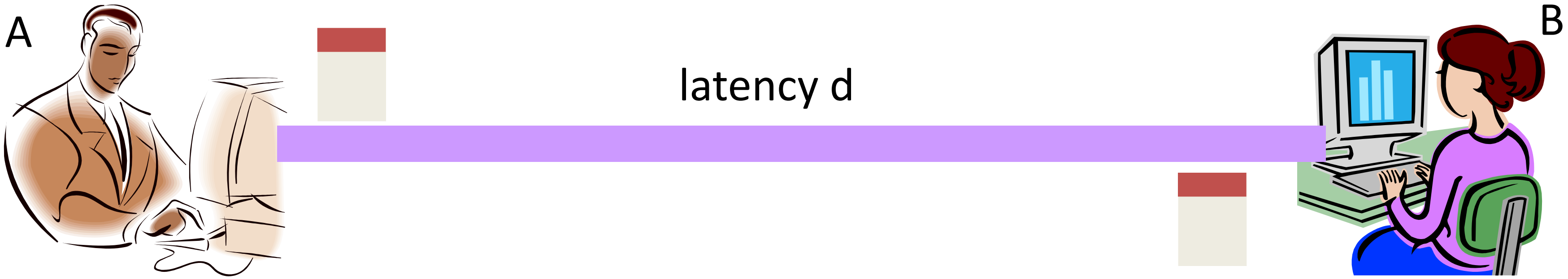


Metcalfe's Ethernet sketch

Ethernet Uses CSMA/CD

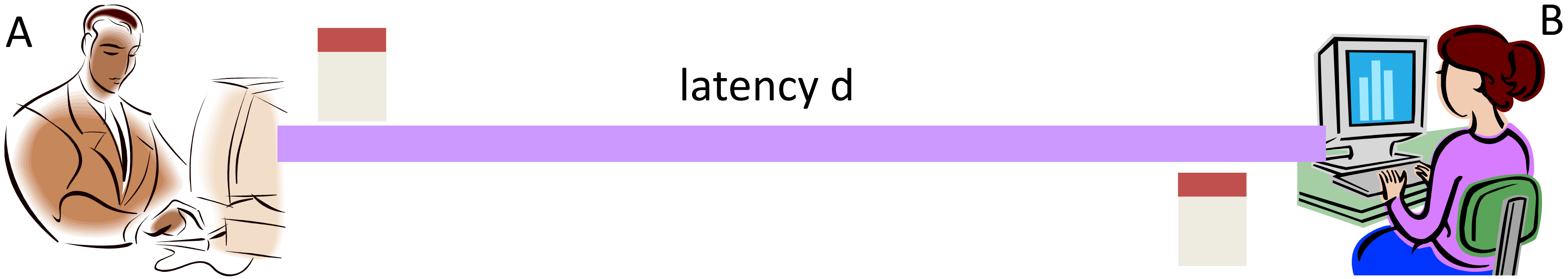
- Carrier Sense: wait for link to be idle
  - Channel idle: start transmitting
  - Channel busy: wait until idle
- Collision Detection: listen while transmitting
  - No collision: transmission is complete
  - Collision: abort transmission, and send jam signal
- Random Access: exponential back-off
  - After collision, wait random time before trying again
  - After mth collision, choose K randomly from {0, …, 2^m-1}
  - … and wait for K*512 bit times before trying again

Limitations on Ethernet Length



- Latency depends on physical length of link
  - Time to propagate a packet from one end to other
- Suppose A sends a packet at time t
  - And B sees an idle line at a time just before t+d
  - … so B happily starts transmitting a packet
- B detects a collision, and sends jamming signal
  - But A doesn’t see collision till t+2d

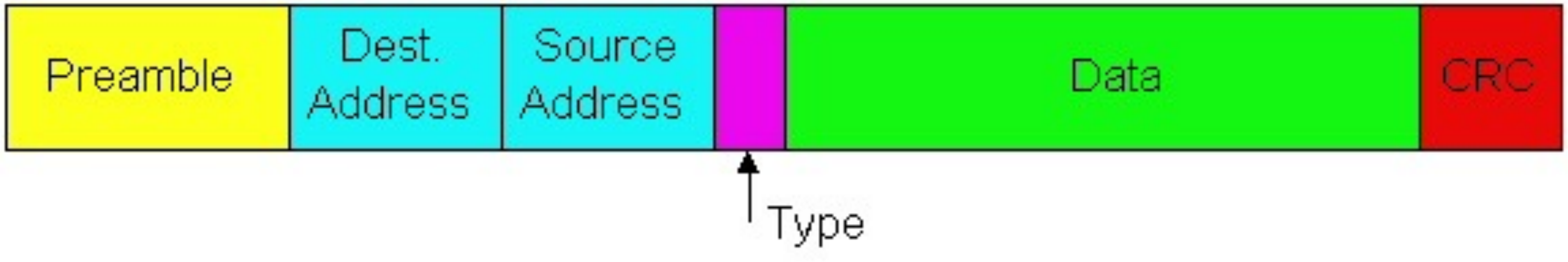
Limitations on Ethernet Length



- A needs to wait for time 2d to detect collision
  - So, A should keep transmitting during this period
  - … and keep an eye out for a possible collision
- Imposes restrictions on Ethernet
  - Maximum length of the wire: 2500 meters
  - Minimum length of the packet: 512 bits (64 bytes)

Ethernet Frame Structure

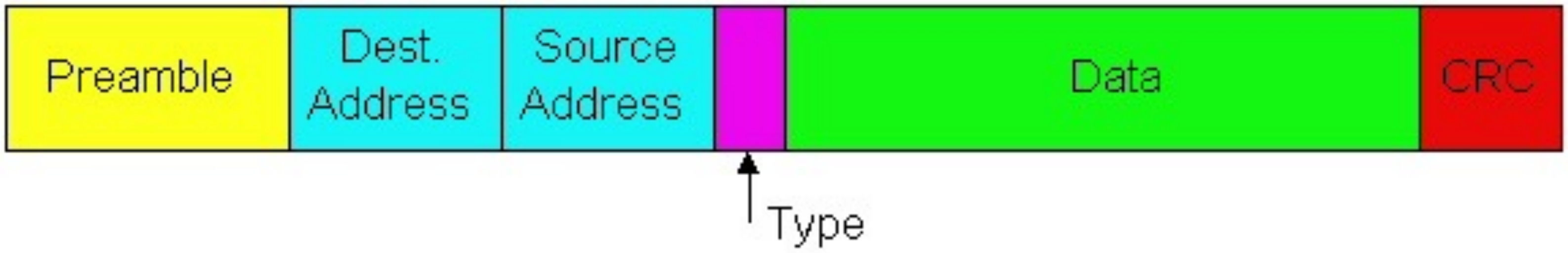
- Sending adapter encapsulates packet in frame



- Preamble: synchronization
  - Seven bytes with pattern 10101010, followed by one byte with pattern 10101011
  - Used to synchronize receiver, sender clock rates

Ethernet Frame Structure

- Addresses: source and destination MAC addresses
  - – Adaptor passes frame to network-level protocol
    - If destination is local MAC address or broadcast address
  - – Otherwise, adapter discards frame
- Type: indicates the higher layer protocol
  - – Usually IP
  - – But also Novell IPX, AppleTalk, …
- CRC: cyclic redundancy check

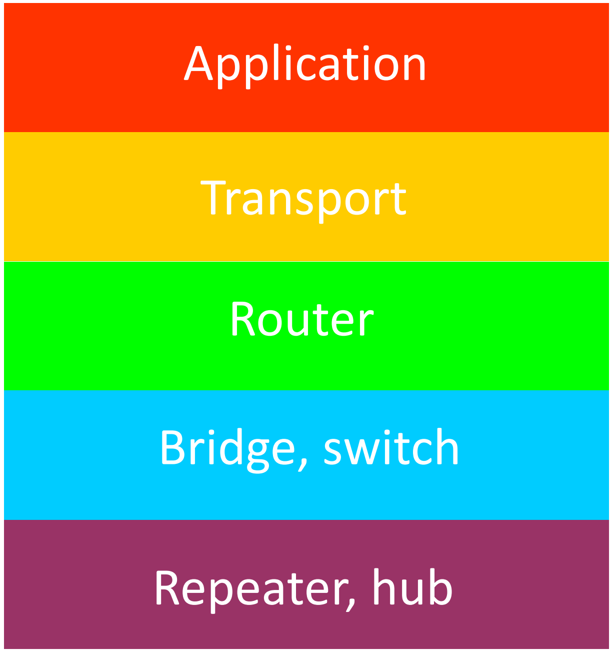


Unreliable, Connectionless Service

- Connectionless
  - No handshaking between send and receive adapter
- Unreliable
  - Receiving adapter doesn’t send ACKs or NACKs
  - Packets passed to network layer can have gaps
  - Gaps can be filled by transport protocol (e.g., TCP)
  - Otherwise, the application will see the gaps

Summary: Multiple Layers

- Different devices switch different things
  - Network layer: packets (routers)
  - Link layer: frames (bridges and switches)
  - Physical layer: electrical signals (repeaters and hubs)



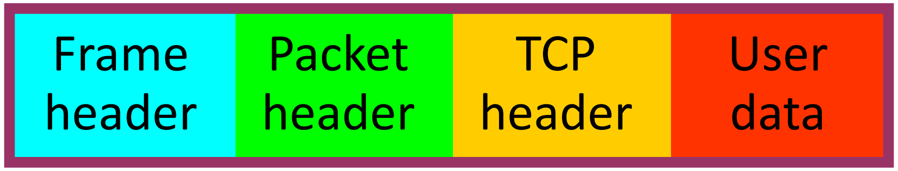
Application

Transport

Router

Bridge, switch

Repeater, hub



Frame header	Packet header	TCP header	User data

Conclusion

- Links
  - Connect two or more network adapters
  - … each with a unique address
  - … over a shared communication medium

- Coming next
  - Network layer (IP)