# Lecture 3
## Data Link Layer
(Computer Communication Networks)

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# §3.0.0 Contents



The contents of this lecture have been composed from various resources including those listed at the reference section.

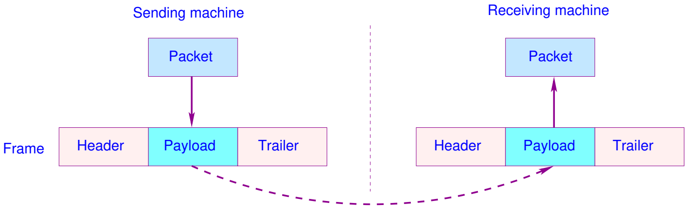
# §3.0.0 Glossaries

| | |
|---|---|
| ARQ | Automatic Repeat Request 41 |
| HDLC | High-Level Data Link Control 13 |
| IP | Internet Protocol 7 |
| LAP | Link Access Procedure 14 |
| LAPB | Link Access Procedure - Balanced 14 |
| LAPD | Link Access Procedure for the D channel 14 |
| LLC | Logical Link Control 14 |
| PPP | Point-to-Point Protocol 12 |
| TCP | Transport Control Protocol 7, 8 |
| TO | Time Out 54 |
| UDP | User Data Protocol 7 |

# §3.1.0 Data Link Layer Design Issues

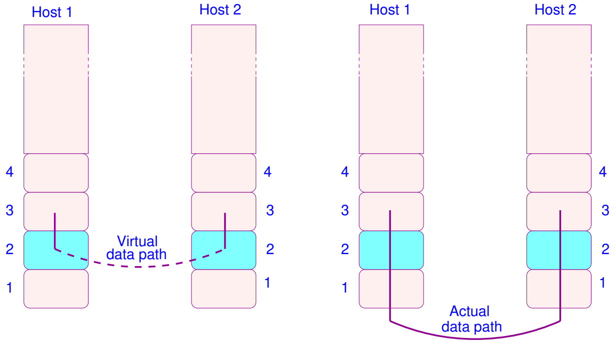
1. Network layer services
2. Framing
3. Error control
4. Flow control

# §3.1.1 Packets vs. Frames




- Packets
  - Layer 3 data units
  - Mostly variable size ⇒ $20 \leq \text{IP} \leq 65{,}535$ bytes = 64k bytes
  - Carry routing information
- Frames
  - Layer 2 data units
  - Fix size ⇒ Ethernet 1500 bytes, WiFi 2346 bytes
  - No or minimal routing information ⇒ forwarding

# §3.1.2 Virtual vs. Actual Connections




- Layer 3 doesn't know how layer 2 delivers its packet
- Layers 2 & 4 are designed to provide reliable connections *How?*
  - Connection-oriented
  - Acknowledgements
  - Request-Reply
- Layer 3 is designed to provide best effort delivery *How?*
  - Connection-less-oriented
  - Unreliable

# §3.1.3 Possible Services Offered

| | Services | | Examples |
|---|---|---|---|
| Connection–Oriented | Reliable | Message stream | Sequence of pages |
| | | Byte stream | Remote login |
| | Unreliable | Datagram /Pulse | Digitized voice |
| Connection–less–Oriented | Reliable | Acked datagram | Sequence of pages |
| | | Request–Reply | Registered mail |
| | Unreliable | Datagram | Database query |

1. Unacknowledged connectionless service
   - User Data Protocol (UDP)
2. Acknowledged connectionless service
   - Ethernet frames, Internet Protocol (IP)
3. Acknowledged connection-oriented service
   - Transport Control Protocol (TCP)

# §3.2.0 How can reliability be provided?

1. Acknowledgment,
2. Partial acknowledgment (cumulative acknowledgment) ⇒ TCP
3. Automatic-repeat and request (ARQ)
4. Byte-stream
5. Message sequencing

➥ *Reliability is a relative term*

## *What is the Problem?*

When two devices exchange data:

- Data is transmitted one bit at a time (typically)
- Transmitting and receiving data rates must be the same
- The transmitter/receiver must recognize the start/end of each bit
  - To make sure sampling can be done correctly
  - Also, a drift in time results errors

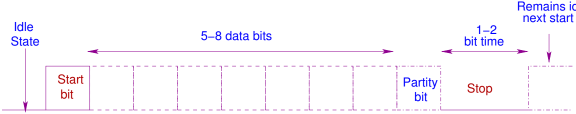
## *Two Approaches: Framing Methods*

1. Asynchronous data transmission
2. Synchronous data transmission

# §3.2.1 Transmission Methods

## 1 Asynchronous data transmission

- Timing problem is avoided by not sending long streams of bits
- Data is transmitted one character at a time
  - Byte (character-oriented) protocols
- Synchronization bits are required
  - Bits are synchronized, data is not
- Good for low-rate channels




## 2 Synchronous data transmission

- Bit-oriented protocols
- Transmitter and receiver clocks must be synchronized
  - Using separate timing circuit $\Rightarrow$ out-of-band signaling
  - Manchester coding
- There is a minimum frame length

# §3.3.0 Framing

## *What is a Frame?*

- A basic transmission unit
- Typically implemented by network adaptor
- Adaptor fetches/deposits frames out/in to memory
- The receiver must determine first and last bit of the frame

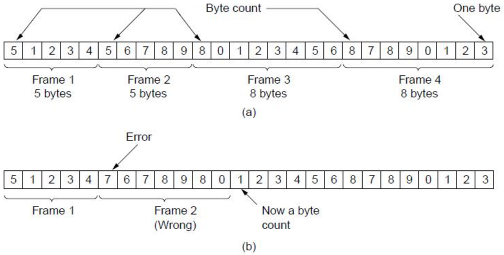
## *Basic Framing Techniques*

1. Byte count
2. Flag bytes with byte stuffing
3. Flag bits with bit stuffing
4. Physical layer coding violations
5. Clock-based Framing $\Rightarrow$ SONET

# §3.3.1 Framing Methods I

## 1 Byte Count Framing ⇒ Byte-Oriented Protocols

- Each frame starts with a **byte** that contains the frame size (in bytes)
- What would happen when an error occurs in a byte count?
  - Synchronization is lost
  - Correct start/end of the frames will be lost
  - Even if the **checksum** detects such an error, it cannot correct it
- A byte stream. (a) Without errors. (b) With one error



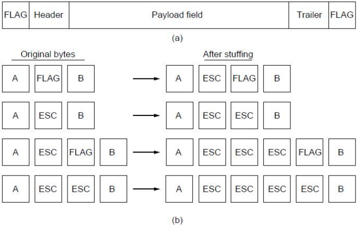

- Example: Digital Data Communication Message Protocol (DDCMP)

| 8 | 8 | 8 | 14 | | 16 |
|---|---|---|---|---|---|
| SYN | SYN | Class | Header | Body | CRC |

# §3.3.1 Framing Methods II

## 2 Framing With Flags

- A frame delimited by flag bytes
- What would happen if the `FLAG` appears in the text?
  - Use a escape character *How?*
  - Four examples of byte sequences before and after byte stuffing.




- Example: Point-to-Point Protocol (PPP)

| 8 | 8 | 8 | 16 | | 16 | 8 |
|---|---|---|---|---|---|---|
| Flag | Address | Control | Protocol | Payload | Checksum | Flag |

- Example: BISYNC(binary sync. comm.) (IBM)

| | | | | | |
|---|---|---|---|---|---|
| Preamble | Dest | Src | Type | Body | CRC |

# §3.3.1 Framing Methods III

3. Bit-oriented protocols
   - High-Level Data Link Control (HDLC) (OSI)
     - Synchronous Data Link Control (SDLC) - IBM

| 8 | 16 | | 16 | 8 |
|---|---|---|---|---|
| Beginning Sequence | Header | Body | CRC | Ending Sequence |

   - Delineate frame with a special bit-sequence: 01111110

## ***Bit Stuffing Protocol***

- Sender: any time five consecutive 1s have been transmitted from the body of the message, insert a 0.
- Receiver: should five consecutive 1s arrive, look at next bit(s):
  - if next bit is a 0: remove it $\Rightarrow$ un-stuff it
  - if next bits are 10: end-of-frame marker
  - if next bits are 11: error

# §3.3.1 Framing Methods IV

## Example 3.1 (Bit Stuffing)

(a) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

(b) 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0

Stuffed bits

(c) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

(a) The original data. (b) The data as they appear on the line
(c) The data stored in the receiver's memory after de-stuffing

### ***Other Bit-Oriented Protocols***

- Link Access Procedure (LAP) ⇒ CCITT
- Link Access Procedure - Balanced (LAPB) ⇒ ITU-T (for X.25)
- Link Access Procedure for the D channel (LAPD) ⇒ ITU-T (for ISDN)
- Hewlett Packard Data Link Control (HPDLC: HP)
- Advanced Data Communications Control Procedures (ADCCP) - ANSI
- Logical Link Control (LLC) ⇒ IEEE 802.2

# §3.4.0 Error Detection

- Reliability requires error detection and possibly correction
  - We cannot correct all the time
  - Two many bit errors may not be correctable
- Many techniques
  - From dictionary search to in-line (real-time) detection and possibly correction
  - Not all good equally for different noise (error) rate
- In general we extra bits to the data bits for the purpose of:
  - Detecting errors
  - Correcting errors if possible
- We start with simple techniques, and we cover more robust techniques
  - Used by NASA for various missions

## *Major Error Detection Techniques*

1. Parity
2. Checksum
3. Cyclic Redundancy Checks.

# §3.4.1 Parity Bit

- Detecting a single bit error ⇒ parity bit
  - Memory read/write (R/W) ⇒ 8 data bits + 1 parity bit

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | | |
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | odd parity, odd number of 1's |
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | even parity, even number of 1's |

  - Even number of bit errors goes undetected ⇓ *Why?*
    - Keeps the parity bit unchanged
- In general, we decode $m$ bits to $n = m + r$ bits ⇒ codewords
  - $r$ bits overhead ⇒ next
- Odd/even party is weak ⇒ 50% of errors cannot be detected

# §3.4.2 Two-Dimensional Parity Check

- Multiple bytes are sent in matrix form ⇒ blocks
- Each bit of data is checked by two parity bits
  - Row and column
- What happens if the parity itself received in error?
- 2D parity detects better but still misses a lot of errors undetected

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | Parity bit (even parity) |
| 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | Detects |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | Undetected |
| 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | Undetected |
| 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | |
| 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | Detects |
| 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | Parity byte |

Undetected

bit in error

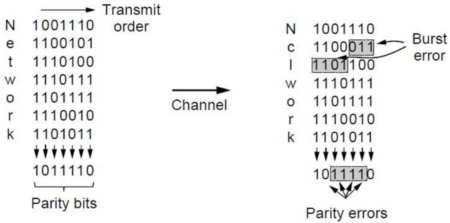
bits in error

## Homework 3.1

Show that (by example) 2D parity catches 1, 2, and 3-bit errors, and most 4-bit errors

# §3.4.3 Interleaving Parity Bits

- Errors often occur in bursts as a result of:
  - Transit-time noise ⇒ unpredictable
  - Random statistical fluctuations of the electric current ⇒ shot noise ⇒ unpredictable
  - ⋮
- Interleaving parity bit with data bits allows spread the bits
  - Better detection, and also help correction
- Data is horizontal, parity is vertical ⇒ scrambles the bits




- Used in fiber optics ⇒ minimal computations

# §3.4.4 Checksum

- Simple, but weak
- The sum of bytes computed as parity bits ⇒ 1's complement

| Data | Checksum | Data | Checksum |
|---|---|---|---|
| 0001 | 1 | 0011 | 3 |
| 0010 | 2 | 0000 | 0 |
| 0011 | 3 | 0001 | 1 |
| 0001 | 1 | 0011 | 3 |
| Total | 7 | Total | 7 |

- Does not detect all common errors
  ⇒ weak error detection (used in IP)
- Used in networks where speed is more important than errors
  - Other layers take care of error correction/detection

# §3.4.5 Cyclic Redundancy Check (CRC) I

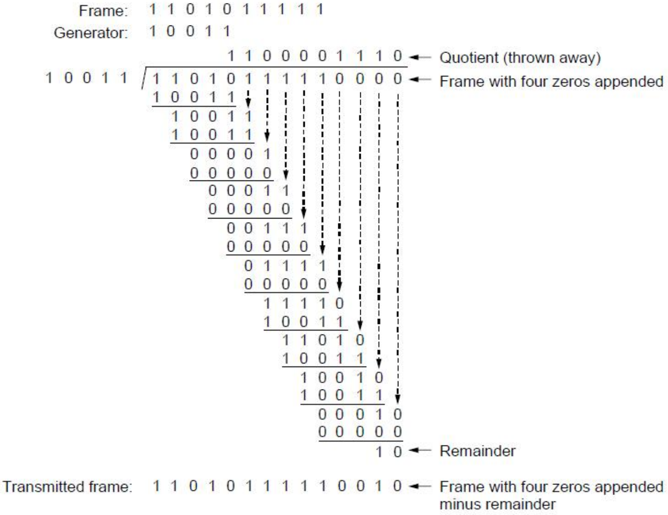
- Given a $m$-bit message, generate an $m+r$-bit frame such that $m+r$ bit frame evenly divisible by some predefined number

| Message Bits ($m$ bits) | Parity Bits ($r$ bits) |
|---|---|

- How does it work?
  1. Let $M(x)$ be the message 1101011111
     $M(x) = x^9 + x^8 + x^6 + x^4 + x^3 + x^2 + x + 1$
  2. Choose $G(x)$ with degree $r$ $\qquad G(x) = x^4 + x + 1 = 10011 = 19$
  3. Append $r$ zero bits to end of the frame $\Rightarrow\ x^r M(x)$
     $x^r M(x) = x^{13} + x^{12} + x^{10} + x^8 + x^7 + x^6 + x^5 + x^4 = 1101011111\ 0000$
  4. Let $E(x)$ be the reminder of $x^r M(x)/G(x)$ $\qquad E(x) = x = 10$
  5. Transmit $T(x) = x^r M(x) - E(x)$
     $T(x) = x^{13} + x^{12} + x^{10} + x^8 + x^7 + x^6 + x^5 + x^4 + x = 1101011111\ 0010$
  6. Recipient divides $T(x)$ by $G(x)$; with remainder $E(x)$
     if $E(x) = 0 \Rightarrow$ no error *Why?*
     if $E(x) \neq 0 \Rightarrow$ error *Why?*

➥ *Just detection, no correction*

# §3.4.5 Cyclic Redundancy Check (CRC) II




⇒ All done in Binary, Hardware, with Shift Registers + Adder

# §3.4.5 Cyclic Redundancy Check (CRC) III

- CRC codes can detect the following
  - All error bursts of length $m - r$ or less
  - All errors with an odd number of errors if generator $G(x)$ has an even number of nonzero coefficient
- Common CRC polynomials

| CRC | Generator $g(x)$ |
|---|---|
| CRC-8 | $x^8 + x^2 + x^1 + 1$ |
| CRC-10 | $x^{10} + x^9 + x^5 + x^4 + x^1 + 1$ |
| CRC-12 | $x^{12} + x^{11} + x^3 + x^2 + 1$ |
| CRC-16 | $x^{16} + x^{15} + x^2 + 1$ |
| CRC-CCITT | $x^{16} + x^{12} + x^5 + 1$ |
| CRC-32 | $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} +$ $x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$ |

# §3.5.0 Error Correction

## *Major Techniques*

1. Hamming codes
2. Binary convolutional codes
3. Reed-Solomon codes
4. Low-Density Parity Check codes

# §3.5.1 Hamming Code I

## Definition 3.1 (Hamming Distance)

Given two codewords $x$ and $y$,

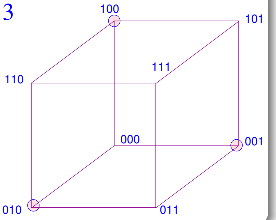
$$d(x, y) = \text{number of places that } x \text{ and } y \text{ differ} = \text{ \# of 1's in } x \oplus y$$

## Example 3.2

$d(100, 101) = 1 \quad d(100, 111) = 2 \quad d(100, 011) = 3$

$$d(101, 010) = 101 \oplus 010 = 111 \equiv 3$$

$d \Rightarrow$ distance in number of hops
$d \Rightarrow$ shows how far codewords are part




- We like codewords that are far apart $\Rightarrow$ how many can we have?
- The higher the distance, the better we can detect errors *Why?*

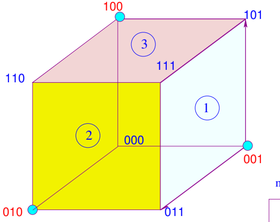
# §3.5.1 Hamming Code II

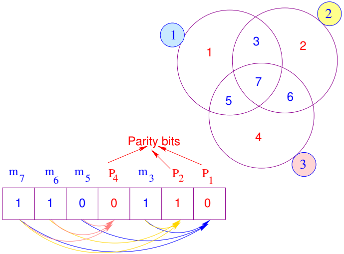
## Theorem 3.1 (Minimum Distance)

*To detect $\ell$-bit errors, $d_{min} \geq \ell + 1$.*

## Example 3.3 (Hamming Code, H(7,4) $n = 7$, $r = 3$, $m = 4$)

- 7-bit codeword, 3-bit error control



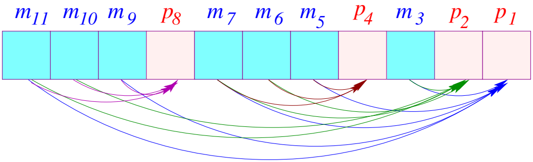




- Counting # of 1's in each circle (dimension)
  - $P_1 = m_3 \oplus m_5 \oplus m_7 = 2 \mod 2$ = 0 $\Rightarrow$ positions with 1st bit =1
  - $P_2 = m_3 \oplus m_6 \oplus m_7 = 3 \mod 2$ = 1 $\Rightarrow$ positions with 2nd bit =1
  - $P_4 = m_5 \oplus m_6 \oplus m_7 = 2 \mod 2$ = 0 $\Rightarrow$ positions with 3rd bit =1

# §3.5.1 Hamming Code III

## ***General Algorithm of Hamming Code***

1. Write the bit positions in binary; 001, 010, 011, etc.
2. Parity bits are power of 2 positions; 1, 2, 4, 8, etc.
3. All other bits are data bits
4. Each data bit is included in a unique set of parity bits
   1. Parity bit 1 covers bits positions with 1st bit = 1, ( 1, 3, 5, 7, 9, ... )
   2. Parity bit 2 covers bits positions with 2nd bit = 1, ( 2, 3, 6, 7, 10 ... )
   3. Parity bit 4 covers bits positions with 3rd bit = 1, ( 4-7, 12-15, 20-23, ... )
   4. Parity bit 8 covers bits positions with 4th bit = 1, ( 8-15, 24-31, 40-47, ... )
   5. In general each parity bit covers all bits where the bitwise AND of the parity position and the bit position is non-zero
5. Set a parity bit to 0 if the total number of 1's in the positions it checks is even
   - otherwise, 0



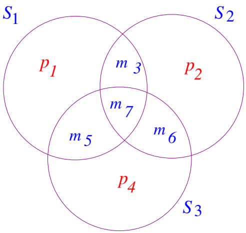
# §3.5.1 Hamming Code IV

## Example 3.4 (Hamming Code, H(7,4) $n = 7$, $r = 3$, $m = 4$)

- Let the codeword be $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1$

- Parity check equations:

$$
\begin{aligned}
S_1 = p_1 \oplus m_3 \oplus m_5 \oplus m_7 &= 0 \\
S_2 = m_3 \oplus p_2 \oplus m_6 \oplus m_7 &= 0 \\
S_3 = p_4 \oplus m_5 \oplus m_6 \oplus m_7 &= 0
\end{aligned}
$$




➥ *even parity in each circle*

➥ $S_1, S_2, S_3$ *is called the syndrome*

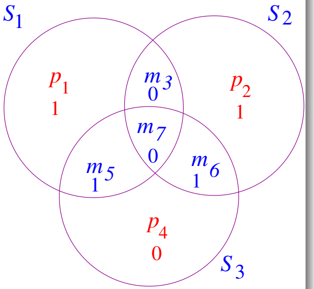
- There is an even number of 1's in each circle $\Rightarrow$ even parity
- Note:
  - If $A \oplus B = C$, then $A = B \oplus C$

# §3.5.1 Hamming Code V

## Example 3.5 (Hamming Code: Encoding)

- Let the message digits be $m_7\ m_6\ m_5\ m_3 = 0\ 1\ 1\ 0$

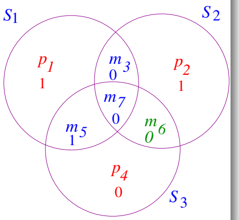
$$
\begin{aligned}
p_1 &= m_3 \oplus m_5 \oplus m_7 = 1 \\
p_2 &= m_3 \oplus m_6 \oplus m_7 = 1 \\
p_4 &= m_5 \oplus m_6 \oplus m_7 = 0
\end{aligned}
$$




- The codeword = $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1 = 0\ 1\ 1\ 0\ 0\ 1\ 1$

# §3.5.1 Hamming Code VI

## Example 3.6 (Hamming Code: Decoding)




- Transmitted message:
  $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1 = 0\ 1\ 1\ 0\ 0\ 1\ 1$
- Received message with one bit error:
  $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1 = 0\ \hat{0}\ 1\ 0\ 0\ 1\ 1$

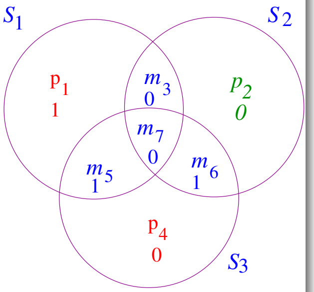
- By counting # of 1's in each circle, we find
  - There is no error in circle 1 $\Rightarrow$ $S_1 = p_1 \oplus m_3 \oplus m_5 \oplus m_7 = 0$
  - There is an error in circle 2 $\Rightarrow$ $S_2 = m_3 \oplus p_2 \oplus m_6 \oplus m_7 = 1$
  - There is an error in circle 3 $\Rightarrow$ $S_3 = p_4 \oplus m_5 \oplus m_6 \oplus m_7 = 1$
  - Therefor, the error is in the intersection of circle $S_2$ and $S_3$
    - $S_3 S_2 S_1 = 110 \Rightarrow m_6 = 1$ must be reverted to 1

- Note: If the bit error affects
  - two circles $\Rightarrow$ data bit
  - one circles $\Rightarrow$ parity bit

# §3.5.1 Hamming Code VII

## Example 3.7 (Hamming Code: Decoding)

- This time a parity bit is in error
- Transmitted message:
  $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1 = 0\ 1\ 1\ 0\ 0\ 1\ 1$
- Received message with one bit error:
  $m_7\ m_6\ m_5\ p_4\ m_3\ p_2\ p_1 = 0\ 1\ 1\ 0\ 0\ \hat{0}\ 1$




- By counting 1's in each circle we find
  - There is no error in circle 1 $\Rightarrow$ $S_1 = p_1 \oplus m_3 \oplus m_5 \oplus m_7 = 0$
  - There is an error in circle 2 $\Rightarrow$ $S_2 = m_3 \oplus \hat{p_2} \oplus m_6 \oplus m_7 = 1$
  - There is no error in circle 3 $\Rightarrow$ $S_3 = p_1 \oplus m_3 \oplus m_5 \oplus m_7 = 0$
  - Therefore, the error is $S_2$
    - $S_3S_2S_1 = 010 \Rightarrow$ second bit $\hat{p_2}$ must be reverted

# §3.5.1 Hamming Code VIII

- Similarly, H(11, 7), $n = 11$, $r = 4$, $m = 7$
  - $p_1 = m_3 \oplus m_5 \oplus m_7 \oplus m_9 \oplus m_{11}$ $\Rightarrow$ 1st bit =1
  - $p_2 = m_3 \oplus m_6 \oplus m_7 \oplus m_{10} \oplus m_{11}$ $\Rightarrow$ 2nd bit =1
  - $p_4 = m_5 \oplus m_6 \oplus m_7$ $\Rightarrow$ 3rd bit =1
  - $p_8 = m_9 \oplus m_{10} \oplus m_{11}$ $\Rightarrow$ 4th bit =1
- In general
  - Block length: $2^r - 1$
  - Message length : $2^r - r - 1$
  - Distance: 3
  - Notation: $H(m, m - r)$
  - Rate (efficiency): $1 - \frac{1}{2^r - 1}$

## ***The Magic***

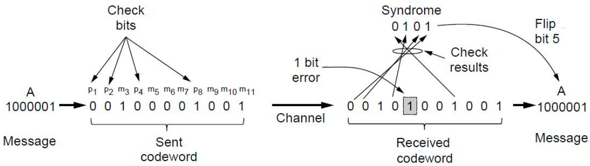
Any two different code words differ in at least 3 places in H(11,7)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1100011 | 1101000 | 1110100 | 1111111 | 1000101 | 1001110 | 1010010 | 1011001 |
| 0100110 | 0101101 | 0110001 | 0111010 | 0000000 | 0001011 | 0010111 | 0011100 |

- Why these specific bits? $\Rightarrow$ maximize code distance
- The knowledge of Hamming distance is used to:
  - Determine the capacity of a code $\Rightarrow$ how many bits for data and parity
  - Detect and correct errors

# §3.5.1 Hamming Code IX

## Example 3.8 (Hamming Code, H(11,7) $n = 11$, $r = 4$, $m = 7$)




- $m_5$ is the only bit that can cause the error *Why?*
  - $S_1 = p_1 \oplus m_3 \oplus m_5 \oplus m_7 \oplus m_9 \oplus m_{11} = 1$
  - $S_2 = p_2 \oplus m_3 \oplus m_6 \oplus m_7 \oplus m_{10} \oplus m_{11} = 0$
  - $S_3 = p_4 \oplus m_5 \oplus m_6 \oplus m_7 = 1$
  - $S_4 = p_8 \oplus m_9 \oplus m_{10} \oplus m_{11} = 0$
- $S_8S_4S_2S_1 = 0101 \Rightarrow$ 5th bit, $m_5$ must be reverted

# §3.5.1 Hamming Code X

## Theorem 3.2

*The number of errors that can be corrected is*

$$\frac{d_{\min} - 1}{2}$$

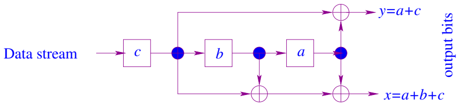
- (4,7) Hamming Code **detects** all 1-bit and 2-bit errors *Why?*
- (4,7) Hamming Code **corrects** all 1-bit errors *Why?*

# §3.5.2 Convolutional Coding I

- Generates redundant bits continuously
- More powerful than block codes
  - NASA Voyager 1977 and 802.11
  - Provides good performance at low cost

$k$ bits $\longrightarrow$ $\boxed{(n, k, L)}$ $\longrightarrow$ $n$ bits, $L$ lines

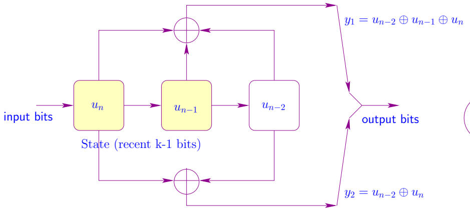
- (2,1,3) convolutional code

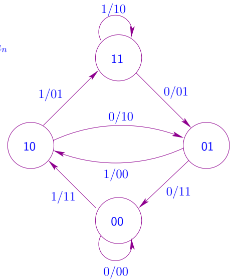



- Encodes information stream rather than information blocks
- Certain information bits affect the encoding on next information bits
- Easily implemented using shift register
  - Input processes $k$ bits at a time
  - Output produces $n$ bits for every $k$ input bits
  - $k$ and $n$ are very small
  - $L$ ( constraint) factor is the number of shifts over which an input bit can influence the encoder output
  - In general, the code rate $r = k/n$, 1/2 in this example

# §3.5.2 Convolutional Coding II

- Encoding



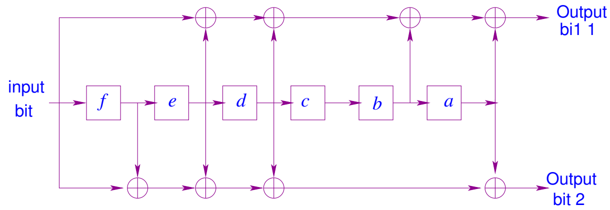




| Input | Initial Stata | Final State | Output Codeword |
|---|---|---|---|
| 0 | 00 | 00 | 00 |
| 1 | 00 | 10 | 11 |
| 0 | 01 | 00 | 11 |
| 1 | 01 | 10 | 00 |
| 0 | 10 | 01 | 10 |
| 1 | 10 | 11 | 01 |
| 0 | 11 | 01 | 01 |
| 1 | 11 | 11 | 10 |

- Decoding
  - Uses maximum likelihood for decoding (Tree of Trellis)
  - Viterbi algorithm is the most common

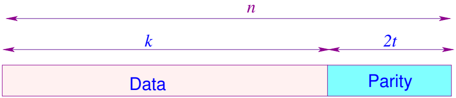
# §3.5.2 Convolutional Coding III

- (2,1,7) convolutional code



# §3.5.3 Reed Solomon (RS) Codes I

- Block-based error correcting codes with a wide range of applications
  - Storage devices (including tape, Compact Disk, DVD, blur-ray, DSL, WiMax, RAID, bar-codes, etc)
  - Wireless or mobile communications
    - Cellular telephones, microwave links, etc.
  - Satellite communications
  - Digital television, CD, DVD, RF, barcodes
  - High-speed modems such as ADSL, xDSL, etc.




- A popular Reed-Solomon code is RS(255,223) with 255 code word bytes, of which 223 bytes are data and 32 bytes are parity
  - $n = 2^s - 1 = 255 \Rightarrow s = 8$
  - $k = 223$
  - $2t = 32, t = 16$
- The decoder can correct any 16 symbol errors in the code word

# §3.5.3 Reed Solomon (RS) Codes II

- Errors in up to 16 bytes anywhere in the codeword can be automatically corrected $\Rightarrow$ very strong

## ***How Does it Work? (Details optional)***

- RS codeword is generated using a special polynomial (generator)

$$g(x) = (x - a^{i})(x - a^{i+1})(x - a^{i+2}) \cdots (x - a^{i+2t}) \quad (1)$$

- The codeword $c(x)$ is constructed using $g(x)$ and the information block $i(x) \Rightarrow$ shift the bits to the left

$$c(x) = g(x) \cdot i(x) \quad (2)$$

- The $2t$ parity symbols in a systematic Reed-Solomon codeword are given by

$$p(x) = i(x) \cdot x^{n-k} \mod g(x) \quad (3)$$

# §3.5.3 Reed Solomon (RS) Codes III

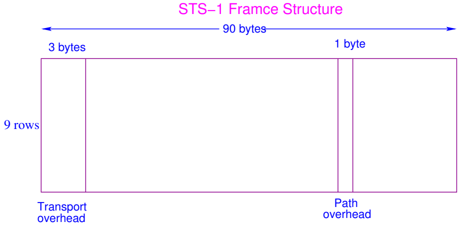
- The received codeword $r(x)$ is the original (transmitted) codeword $c(x)$ plus errors

$$r(x) = q(x) \cdot g(x) + e(x) \qquad q(x)g(x) = c(x) \tag{4}$$

- Finding the position of involves solving simultaneous equations with $t$ unknowns
  - Several fast algorithms are available

# §3.6.0 Clock-Based Framing: SONET I

- SONET: Synchronous Optical Network
- ITU standard for transmission over fiber
- STS-1 (51.84 Mbps)
- Byte-interleaved multiplexing
- Each frame is 125$\mu$s long.




- Each frame is 125 $\mu$s long $\Rightarrow$ 8000/s
- Frame length= $90 \times 9 \times 8 = 6,400$ bits long

# §3.7.0 Reliable Transmission

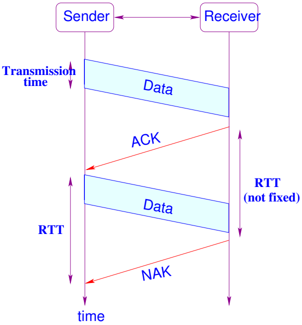
- Delivers frames
  - Without errors and
  - In proper order to the network layer *How?*
- How to recover from ‘from corrupt frames (errors)?
  1. Error Correction ⇒ also called Forward Error Correction (FEC)
  2. Acknowledgments and Timeouts ⇒ also called Automatic Repeat Request (ARQ)
- How to keep the proper order of delivery?
  - The sender should not flood the receiver,
  - But maximizes the throughput *How?*
- The sender is throttled until the receiver grants permission

➥ *Flow Control ⇒ ARQ*

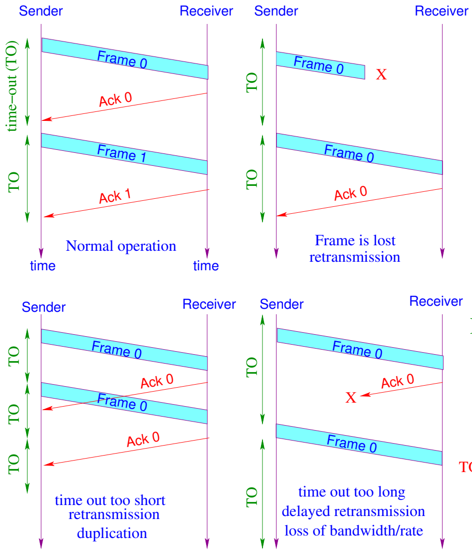
***Note:*** Refer to the book for the codes

# §3.8.0 Automatic Repeat Request (ARQ)

- Performed with the combination of:
  1. Error detection
  2. Acknowledgment
  3. Retransmission after timeout
  4. Negative acknowledgment



# §3.9.0 What Could Go Wrong




Flow is controlled partly by the length of time out

How to accurately set the time out?

TO > Access delay + Transmission delay + Propagation delay + queueing delay (non–determininstic)

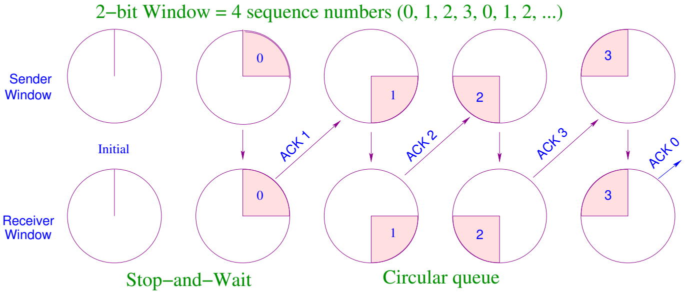
TO is vulnerable, How?

# §3.9.1 Frames in Error

- Possible errors
  - Damaged frames
    - Frames received with error
    - Frames lost
    - Last frame lost
  - Damaged ACK
    - One ACK lost, next one makes it
    - All ACKs lost
  - Damaged NACK
- How to handle frames in errors?
  1. Stop-and-Wait Protocol
  2. Go-Back-N Protocol
  3. Selective Reject Protocol

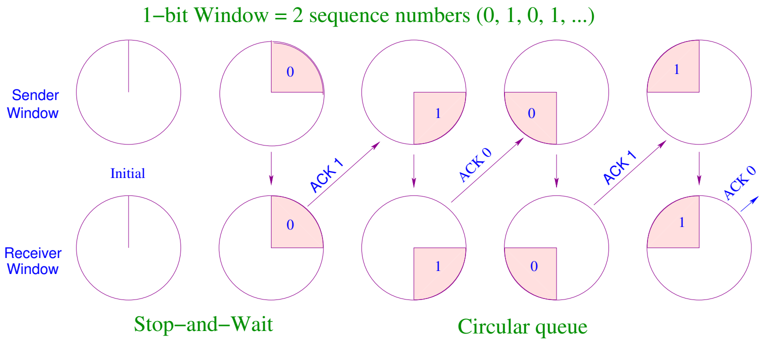
# §3.9.2 Stop-and-Wait Protocol I

- The sender/receiver each has two windows:
  - Sending window
  - Receiving window




- It is a duplex mechanism
  - One can send/receive at the same time *How?*
    - Piggybacking
- Save sequence numbers ⇒ reuse once it is released

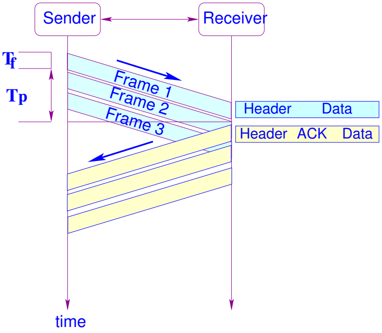
# §3.9.2 Stop-and-Wait Protocol II




- We always ACK the frame to be received *Why?*
  - Receiver knows which frame has been received
  - Receiver knows which frame the source is waiting for

# §3.9.2 Stop-and-Wait Protocol III

## ***Piggybacking***



# §3.9.3 How Good Stop-and-Wait Is?

## Example 3.9 (Utilization (or Efficiency) Problem)

- Assume 1.5 Mbps link and 45 ms RTT $\Rightarrow$ Pipe = 67.5 Kb (8KB)
- Frame size: 1 KB
- SW uses about 1/8 of the bandwidth
- How do we fix this
  - Send up to 8 frames before having to wait for an ACK

## Homework 3.2 (Efficiency vs. Utilization)

Describe efficiency and utilization in a communication channel. Under what condition they are equal?

# §3.9.4 Performance of SW Protocol I

- $T_f$: frame time and $T_p$: propagation delay

$$\alpha = \frac{T_p}{T_f} = \frac{\frac{\text{Distance}}{\text{Speed of signal}}}{\frac{\text{Frame size}}{\text{Bit rate}}} = \frac{\text{Distance} \times \text{Bit rate}}{\text{Frame size} \times \text{Speed of signal}} \tag{5}$$

$$\text{SW Utilization} = E = \frac{1}{1 + 2\alpha} \tag{6}$$

**Homework 3.3 (SW Efficiency)**

Prove that the efficiency of Stop-and-Wait protocol in Equation (6).

# §3.9.4 Performance of SW Protocol II

## Example 3.10

Long propagation delay

- Satellite link $\Rightarrow$ $T_p = 278$ ms
- Suppose the frame size is 4k bits = 4096 bits
- Suppose data rate is DS0, 56 kbps $\Rightarrow$ $T_f = 4096/56000 = 0.073$ sec.

$$\alpha = \frac{T_p}{T_f} = \frac{0.278}{0.073} = 3.8$$

3.8 frames fits into the pipe on one direction.

$$U = \frac{1}{1+2\alpha} = \frac{1}{1+7.6} = 0.12 \qquad U = 12\%$$

# §3.9.4 Performance of SW Protocol III

## Example 3.11

Short propagation delay $\Rightarrow$ Ethernet

- $T_p = 10\ \mu$s = $10^{-5}$ sec
- Frame = 4Kb = 4096 bits
- Data rate = 10 Mbps $\Rightarrow$ $T_f = 4096/10^7 = .0004096$ sec

$$\alpha = \frac{T_p}{T_f} = \frac{10^{-5}}{.0004096} = 0.0244$$

$$U = \frac{1}{1+2\alpha} = \frac{1}{1+0.0488} = 0.95 \qquad U = 95\%$$

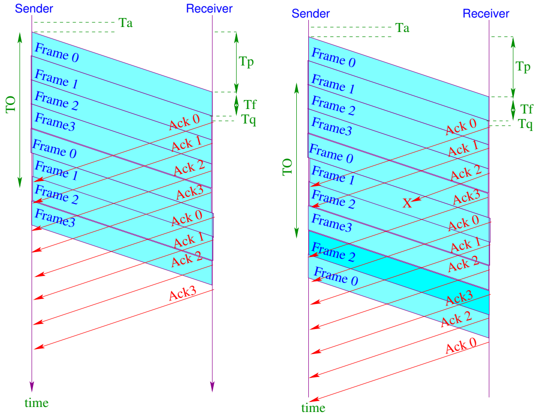
## *How to Solve the Efficiency Problem*

➥ *Keep the pipe/channel full to get better efficiency*

➥ *send more than one frame at a time*

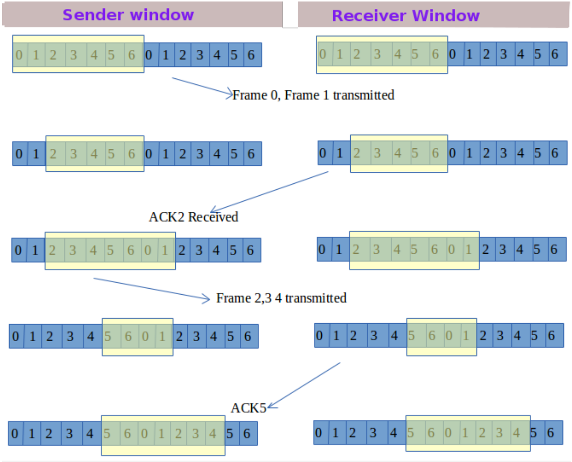
# §3.9.5 Sliding Window I

- Allow sender to transmit multiple frames before receiving an
  - keeping the pipe full




  - The receiver has two copies of frame 2
  - The 2nd incarnation discarded if both both have the same sequence numbers

# §3.9.5 Sliding Window II



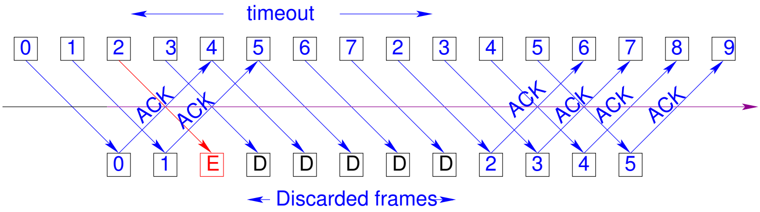

wikistack.com

- Window size = 7
  - Potentially can send 7 frames if it does not overwhelm the receive

# §3.9.5 Sliding Window III

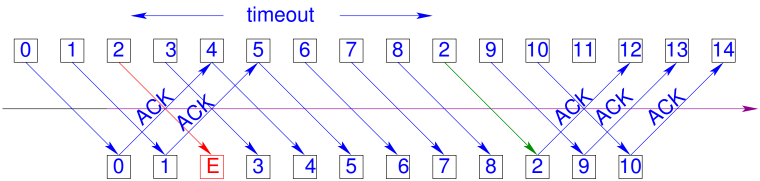
- Note that speed of light in:
  - vacuum is $300 \times 10^6$ m/s
  - fiber is $200 \times 10^6$ m/s
- The sender should not send frames at a higher rate than what the receiver can receive
  - Transmission rate = $\min\{$ sender rate, receiver rate $\}$
  - This is called Flow Control
- How?
  - Send only when an ACK arrives
  - Accurately calculate Time Out (TO)
- What could go wrong with sliding window?
  - Multiple frames can be lost
- How to handle that?
  - Use Go-Back-N Protocol or Selective-Reject Protocol
  - Selective-Reject Protocol performs well with devices with large buffers

# §3.9.6 Go-Back-N Protocol




See the video Go back N sliding window Protocol

# §3.9.7 Selective-Reject Protocol




See the video Selective Repeat sliding Window Protocol

# §3.9.8 Sequence Number Space

- `SeqNum` field is finite ⇒ wraps around *How?*
- `SeqNum` space > # of outstanding frames *Why?*
- `SWS` ≤ `MaxSeqNum-1` is not sufficient *Why?*

## Example 3.12 ( suppose 3-bit `SeqNum` field (`0..7`))

- `SWS=RWS=7`
- Sender transmit frames `0..6`
- Arrive successfully, but ACKs lost
- Sender retransmits `0..6`
- Receiver expecting `7,0..5`, but receives second incarnation of `0..5`
- `SWS < (MaxSeqNum+1)/2` is correct rule
  - Intuitively, `SeqNum` "frames" between two halves of sequence number space
- What does it mean? ⇒ Don't send more than half of your sequence number

# §3.10.0 References



[Tanenbaum and Wetherall, 2011] Tanenbaum, A. S. and Wetherall, D. J. (2011).
*Computer Networks: 5th Edition*.
Prentice Hall PTR.

# §3.11.0 Suggested Exercises From the Text I



2 The following character encoding is used in a data link protocol:
A: 01000111 B: 11100011 FLAG: 01111110 ESC: 11100000
Show the bit sequence transmitted (in binary) for the four-character frame A B ESC FLAG when each of the following framing methods is used: (a) Byte count.
(b) Flag bytes with byte stuffing.
(c) Starting and ending flag bytes with bit stuffing.

2 The following data fragment occurs in the middle of a data stream for which the bytestuffing algorithm described in the text is used: A B ESC C ESC FLAG FLAG D. What is the output after stuffing?

4 What is the maximum overhead in byte-stuffing algorithm?

6 A bit string, 0111101111101111110, needs to be transmitted at the data link layer. What is the string actually transmitted after bit stuffing?

8 To provide more reliability than a single parity bit can give, an error-detecting coding scheme uses one parity bit for checking all the odd-numbered bits and a second parity bit for all the even-numbered bits. What is the Hamming distance of this code?

9 Sixteen-bit messages are transmitted using a Hamming code. How many check bits are needed to ensure that the receiver can detect and correct single-bit errors? Show the bit pattern transmitted for the message 1101001100110101. Assume that even parity is used in the Hamming code.

14 Using the convolutional coder of Fig. 3-7, what is the output sequence when the input sequence is 10101010 (left to right) and the internal state is initially all zero?

15 Suppose that a message 1001 1100 1010 0011 is transmitted using Internet Checksum (4-bit word). What is the value of the checksum?

16 What is the remainder obtained by dividing $x^7 + x^5 + 1$ by the generator polynomial $x^3 + 1$?

# §3.11.0 Suggested Exercises From the Text II



18 A 1024-bit message is sent that contains 992 data bits and 32 CRC bits. CRC is computed using the IEEE 802 standardized, 32-degree CRC polynomial. For each of the following, explain whether the errors during message transmission will be detected by the receiver: (a) There was a single-bit error.
(b) There were two isolated bit errors.
(c) There were 18 isolated bit errors.
(d) There were 47 isolated bit errors.
(e) There was a 24-bit long burst error.
(f) There was a 35-bit long burst error.

19 In the discussion of ARQ protocol in Section 3.3.3, a scenario was outlined that resulted in the receiver accepting two copies of the same frame due to a loss of acknowledgement frame. Is it possible that a receiver may accept multiple copies of the same frame when none of the frames (message or acknowledgement) are lost?

20 A channel has a bit rate of 4 Kbps and a propagation delay of 20 msec. For what range of frame sizes does stop-and-wait give an efficiency of at least 50%?

27 The distance from earth to a distant planet is approximately $9 \times 10^{10}$ m. What is the channel utilization if a stop-and-wait protocol is used for frame transmission on a 64 Mbps point-to-point link? Assume that the frame size is 32 KB and the speed of light is $3 \times 10^{8}$ m/s.

28 In the previous problem, suppose a sliding window protocol is used instead. For what send window size will the link utilization be 100%? You may ignore the protocol processing times at the sender and the receiver.

32 Frames of 1000 bits are sent over a 1-Mbps channel using a geostationary satellite whose propagation time from the earth is 270 msec. Acknowledgements are always piggybacked onto data frames. The headers are very short. Three-bit sequence numbers are used. What is the maximum achievable channel utilization for (a) Stop-and-wait?
(b) Protocol 5?
(c) Protocol 6?

35 A 100-km-long cable runs at the T1 data rate. The propagation speed in the cable is 2/3 the speed of light in vacuum. How many bits fit in the cable?