Chapter 3
The Data Link Layer

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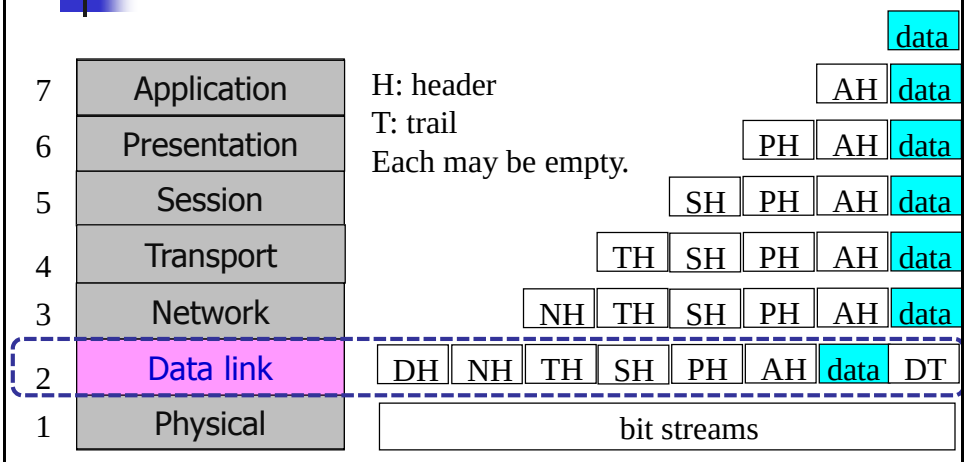
Adapted from Computer Networks,
Andrew S. Tanenbaum, Vrije University, Netherlands
& Computer Networking: A Top Down Approach,
Jim Kurose, Keith Ross

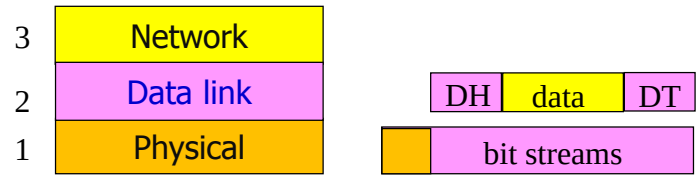
The Data Link Layer



OSI Reference Model

Data Link Layer Design Issues

- Network layer services



- Framing
- Error Control
- Flow Control

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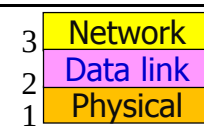
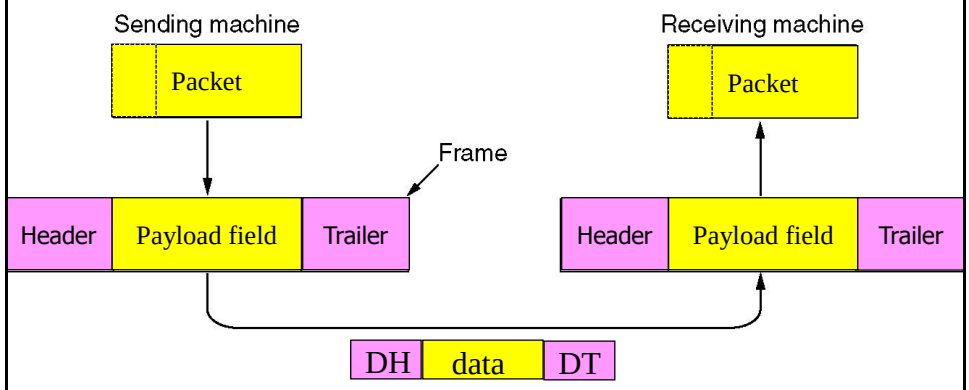
Packets and Frames



Relationship between packets and frames.



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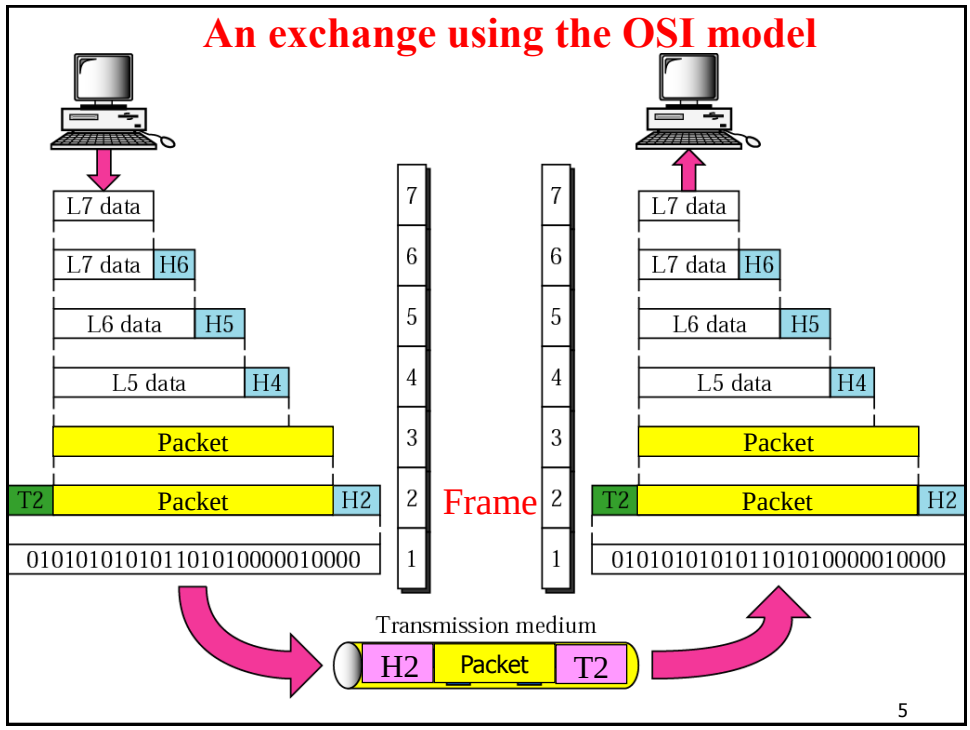
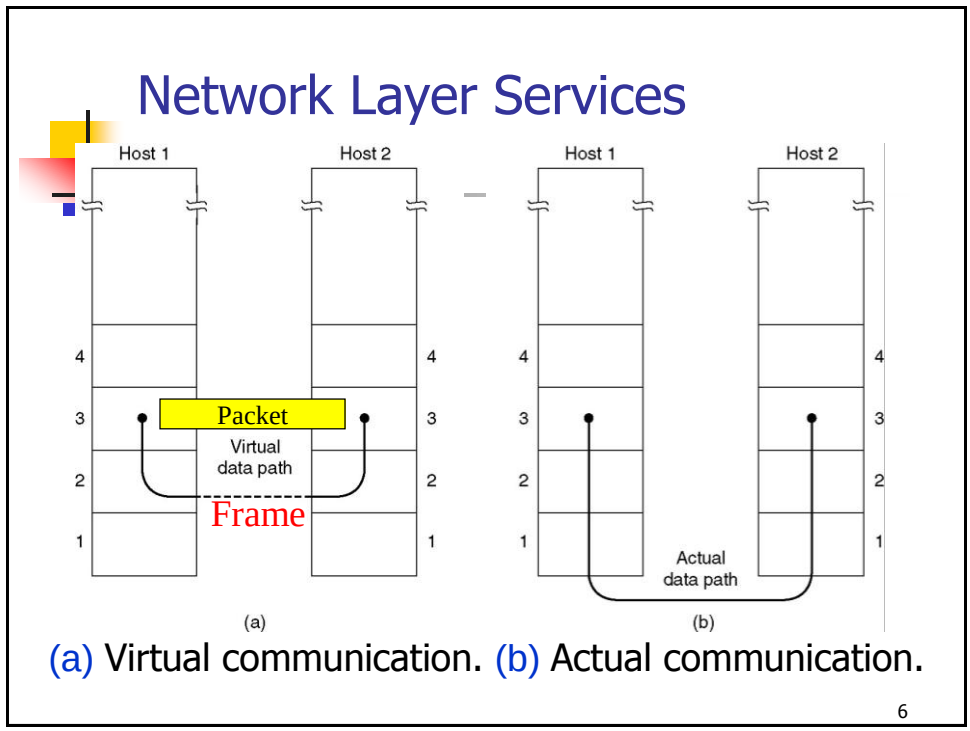

An exchange using the OSI model
L7 data
L7 data H6
L6 data H5
L5 data H4
Packet
T2 Packet H2
0101010101011010100000010000
7
6
5
4
3
2
1
Frame
Transmission medium
H2 Packet T2
5


Network Layer Services
Host 1
Host 2
Packet
Virtual data path
Frame
Actual data path
(a)
(b)
(a) Virtual communication. (b) Actual communication.
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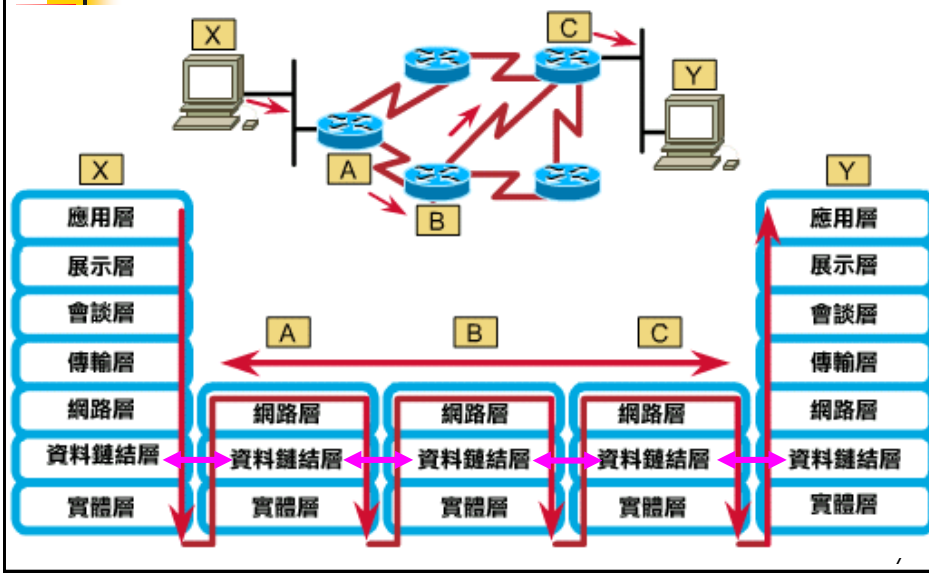
Services Provided to Network Layer



Possible Services Offered

(like Packet Switching)

1. Unacknowledged connectionless service: Ethernet

2. Acknowledged connectionless service: WLAN, WiFi

3. Acknowledged connection-oriented service: ATM, Frame Relay

(like Circuit Switching)

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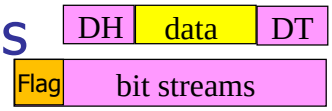
Framing methods



- Too risky to count on timing to mark the start and end of each frame
- Other methods:
  1. Byte Count (rarely used anymore)
  2. Flag bytes with byte stuffing (PPP)
  3. Flag bits with bit stuffing
  4. Physical layer coding violations

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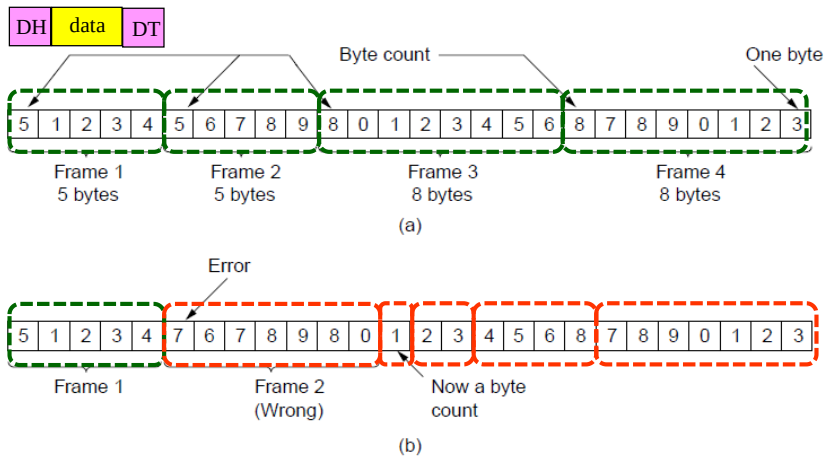
Framing (1): Byte Count

A byte stream. (a) Without errors. (b) With one error.



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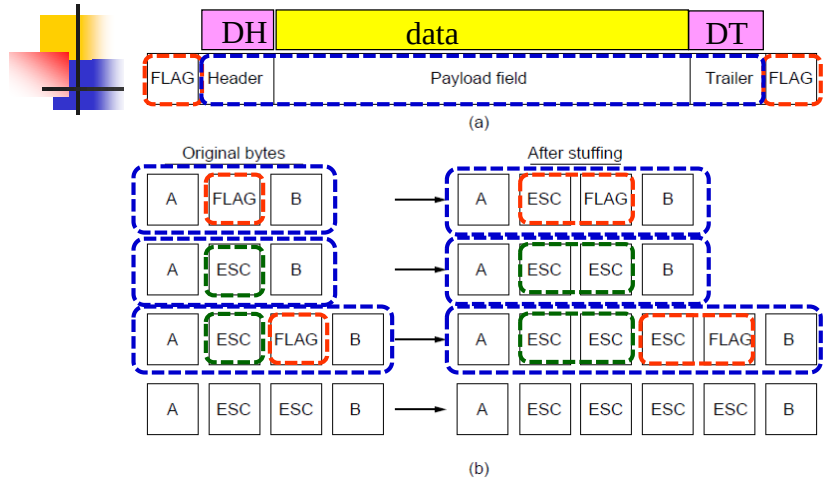
Framing (2):Flag bytes with byte stuffing



a) A frame delimited by flag bytes.

b) Four examples of byte sequences before and after byte stuffing.

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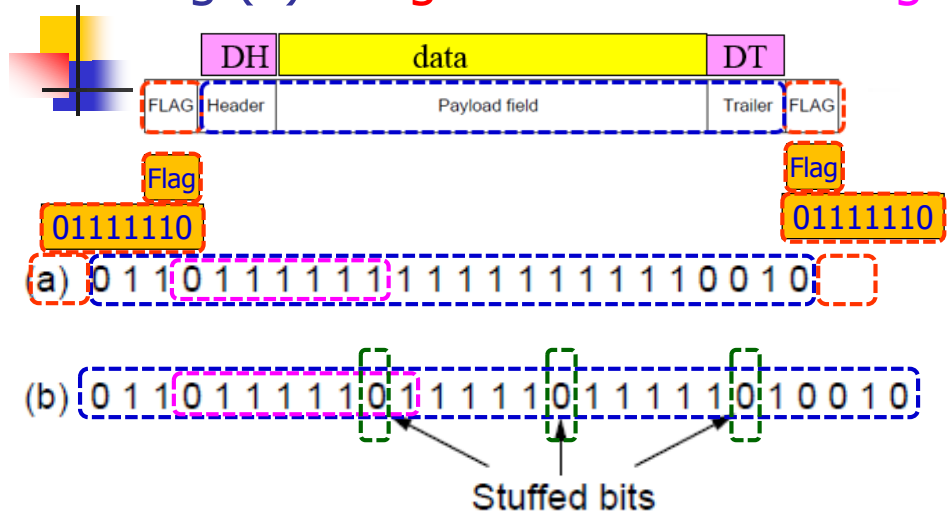
Framing (3): Flag bits with bit stuffing



Bit stuffing. (a) The original data. (b) The data as they appear on the line.

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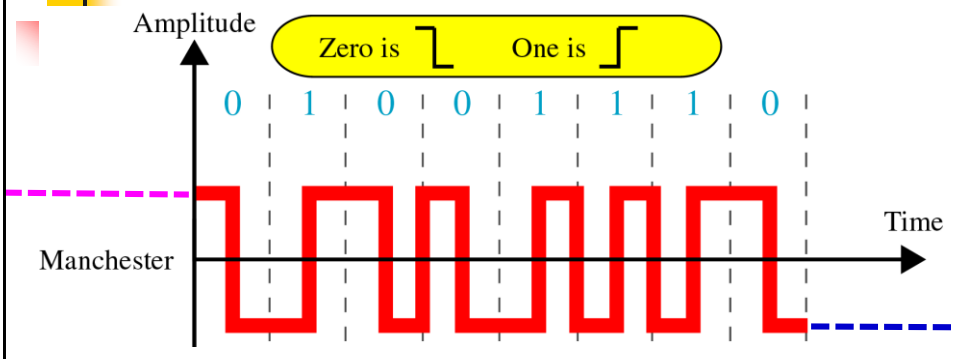
Framing (4): Physical layer coding violations



The combinations of low-low and high-high which are not used for data may be used for marking frame boundaries.

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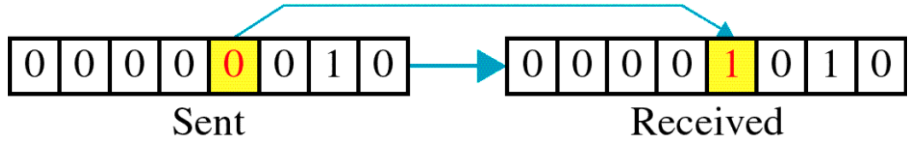
Error Control Process (1)

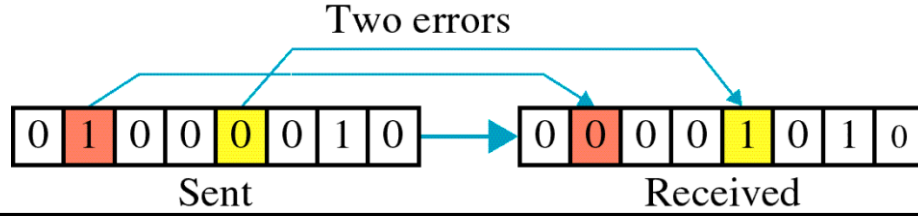
Single-bit error

0 changed to 1



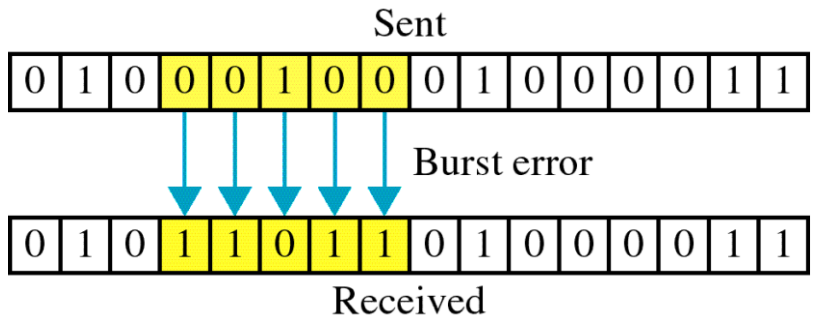
Multiple-bit error

Two errors



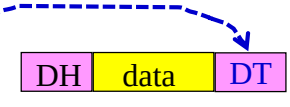
Error Control Process (2)

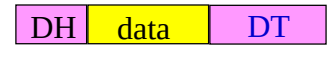
Burst error



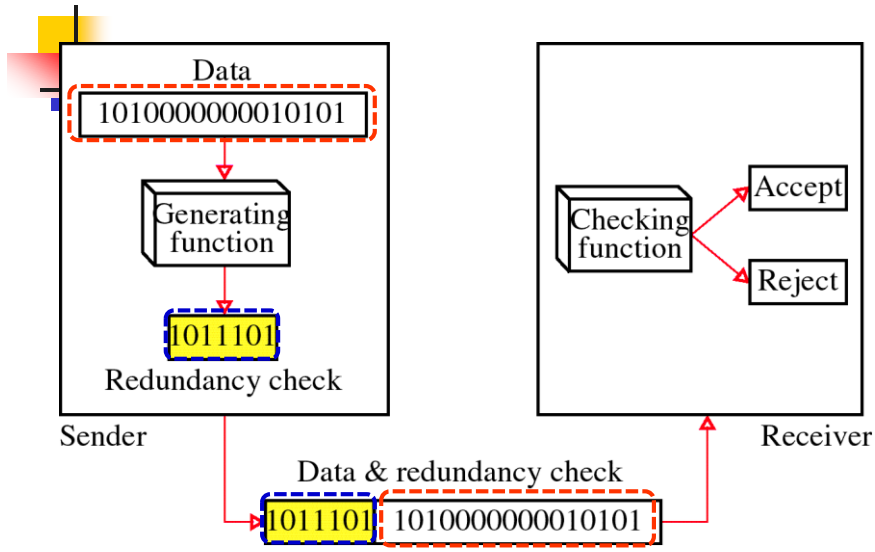
Error Control Process (3)

- All transmission media have potential for introduction of errors
- Error control process has two components
- Error detection
  - redundancy in data so that error can be detected
- Error correction
  - once error detected, frames corrected or retransmitted





Redundancy



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Error Detection Codes

Linear, systematic block codes

1. Parity.
2. Checksums.
3. Cyclic Redundancy Checks (CRCs).
4. Hamming codes.
5. Binary convolutional codes.
6. Reed-Solomon codes.
7. Low-Density Parity Check codes.

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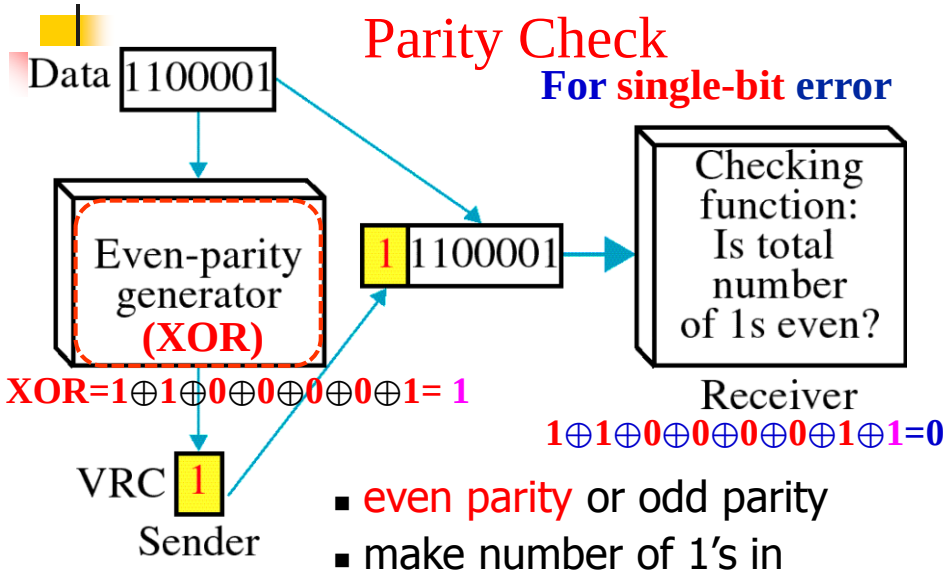
Error Detection Codes (1)

Parity Check

For single-bit error



- even parity or odd parity
- make number of 1's in character even or odd

WCB/McGraw-Hill

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XOR GATE

(Exclusive-OR gate)

BOOLEAN EXPRESSION

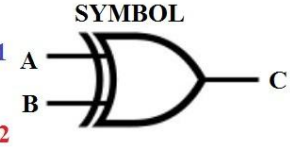
$$A \cdot \overline{B} + \overline{A} \cdot B$$

$$(A + B) \cdot (\overline{A} + \overline{B})$$

C = A⊕B

Input1 Input2 Output

SYMBOL



INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Sender:

Even parity bit of 1100001 = 1

(C= 1⊕1⊕0⊕0⊕0⊕0⊕1 = 1)

Receiver:

C'= 1⊕1⊕0⊕0⊕0⊕0⊕1⊕1=0

Note: Even parity = XOR = Modulo 2 sum

https://projectiot123.com/2019/05/26/introduction-to-xor-gate/

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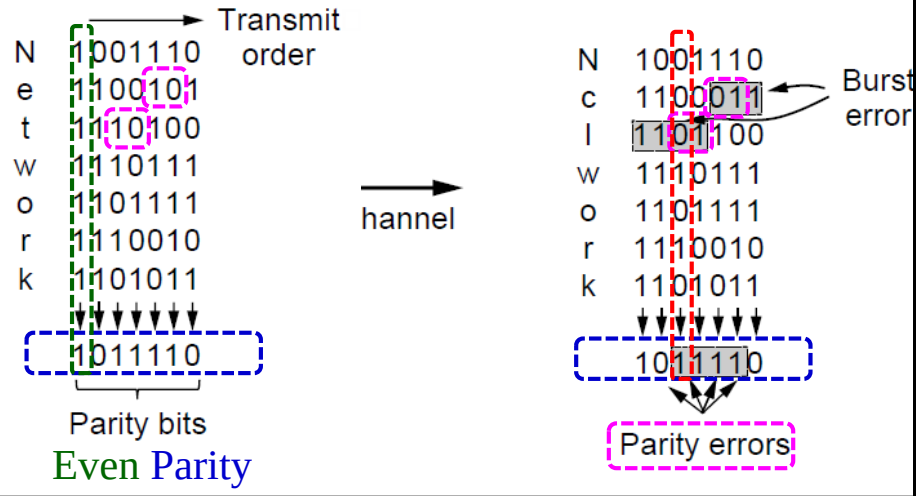
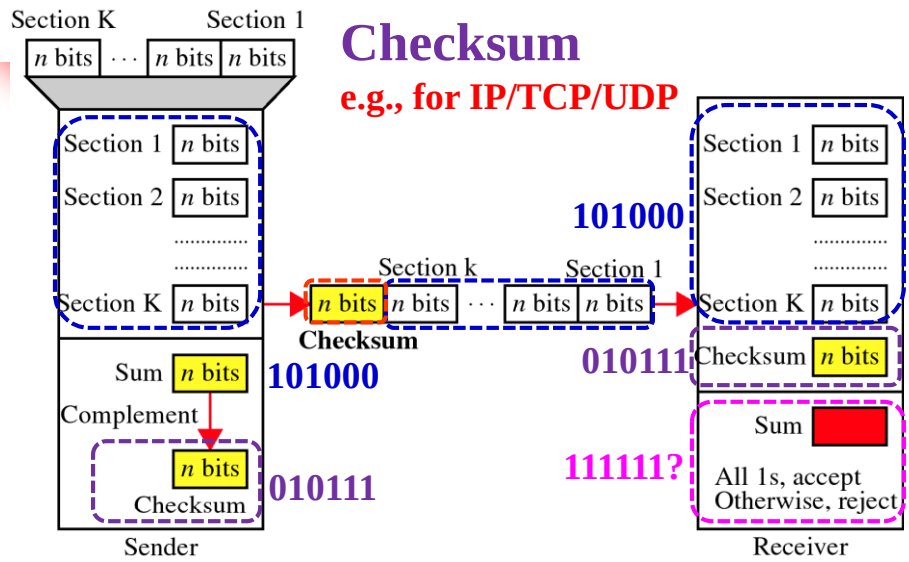
Error-Detecting Codes (1)

Interleaving of parity bits to detect a **burst error**.



Error-Detecting Codes (2)



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The checksum is the 16 bit one's complement of the one's complement sum of all 16 bit words.

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- Suppose that a message 1001 1100 1010 0011 is transmitted using Internet Checksum(4-bit word).

The 1's complement sum of words:

Receiver checking:

```
  1001
  1100
  1010
  0011
+ 1011 (checksum)
------
  1111 = 0100 + 1011
```

Sender

```
  1001
  1100
  1010
+ 0011
------
  0010
     1
     1
------
  0100
```

Then 1's complement of 0100 is 1011.

Thus the Internet checksum is 1011.

```
  1001
+ 1100
------
  0101
     1
------
  0110
+ 1010
------
  0000
     1
------
  0001
+ 0011
------
  0100
     0
------
  0100
```

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Error Detection Codes (3)

- Cyclic Redundancy Check (CRC)
  - treat frame as one long binary number
  - attach remainder to frame
  - 16-bit (32-bit) CRC

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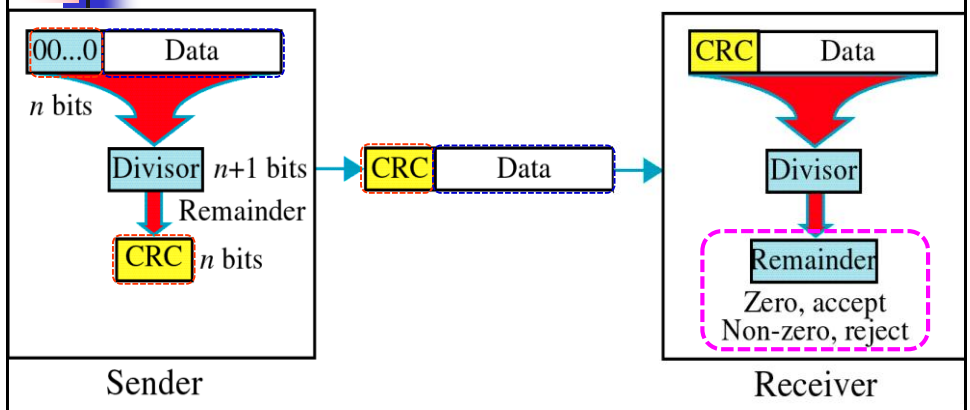
Error-Detecting Codes (3)

Error-Detecting Codes -- **CRC**

CRC (Cyclic Redundancy Check)



E.g., FCS(Frame Check Sequence)
in Ethernet/ WiFi frame format

Error-Detecting Codes (3)

Frame: 1 1 0 1 0 1 1 1 1 1 = $x^9 + x^8 + x^6 + x^4 + x^3 + x^2 + x^1 + 1$ (Dividend)
Generator: 1 0 0 1 1 = $1x^4 + 0x^3 + 0x^2 + 1x^1 + 1x^0 = x^4 + x + 1$ (Divisor)

```
                1 1 0 0 0 0 1 1 1 0   ← Quotient (thrown away)
          ┌─────────────────────────
1 0 0 1 1 │ 1 1 0 1 0 1 1 1 1 1 0 0 0 0   ← Frame with four zeros appended
          │ 1 0 0 1 1
          ├─────────
            1 0 0 1 1
          XOR 1 0 0 1 1
          ─────────
              0 0 0 0 1
              0 0 0 0 0
              ─────────
                0 0 0 1 1
                0 0 0 0 0
                ─────────
                  0 0 1 1 1
                  0 0 0 0 0
                  ─────────
                    0 1 1 1 1
                    0 0 0 0 0
                    ─────────
                      1 1 1 1 0
                    XOR 1 0 0 1 1
                    ─────────
                        1 1 0 1 0
                        1 0 0 1 1
                        ─────────
                          1 0 0 1 0
                          1 0 0 1 1
                          ─────────
                            0 0 0 1 0
                            0 0 0 0 0
                            ─────────
                              0 0 1 0   ← Remainder (n = 4 for n-bit CRC)
```

Divisor needs $n + 1 = 5$ bits

CRC uses Modulo 2 division
Subtraction rules:
1-1=0，0-0=0，1-0=1，0-1=1
(subtraction with no borrow)
➔ XOR operation

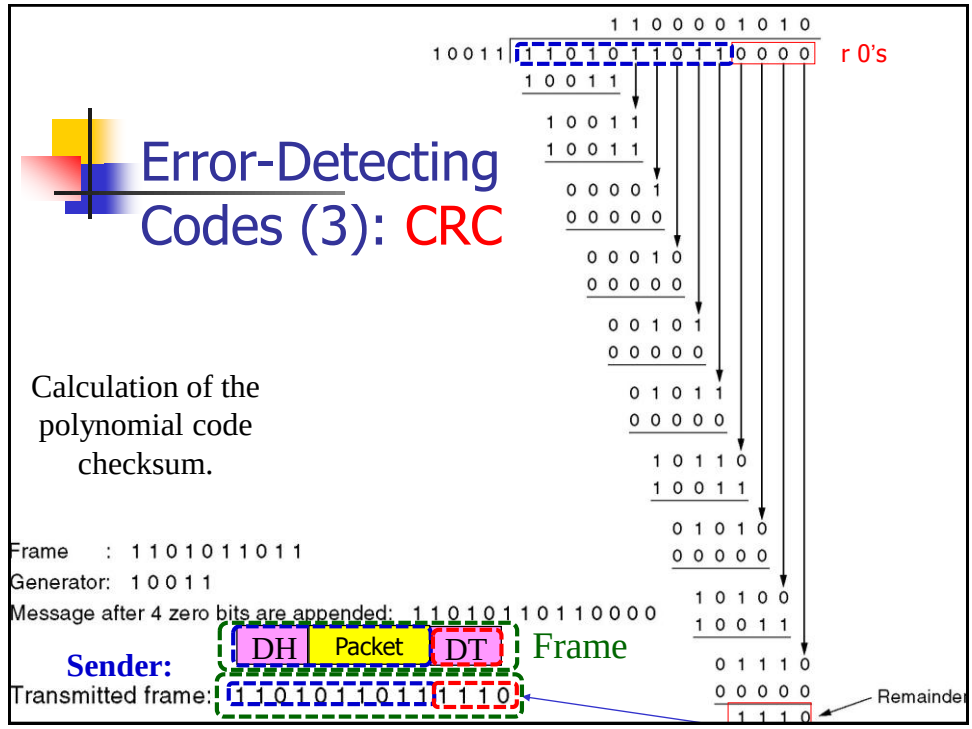
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Sender:
Transmitted frame: 1 1 0 1 0 1 1 1 1 1 0 0 1 0 ← Frame with four zeros appended minus remainder

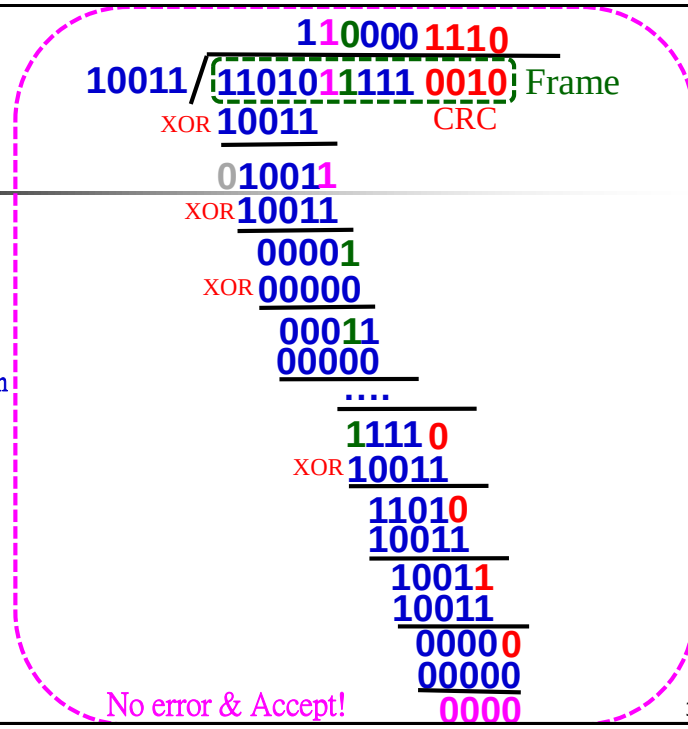
Example calculation of the CRC (CRC-4)

Error-Detecting Codes (3): CRC

Calculation of the polynomial code checksum.



Receiver CRC checking:



Modulo 2 Division (subtraction with no borrow) by XOR

A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

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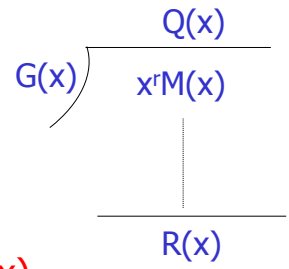
Error-Detecting Codes (3)

CRC (Cyclic Redundancy Check)

CRC Code = Polynomial Code
110001 = $x^5 + x^4 + x^0$
Original Message (dividend): M(x)
Generator (divisor): G(x)
Degree of G(x): r
Quotient: Q(x)
Remainder (CRC): R(x)
Transmitted Message: T(x)

Modulo 2 division
(add/sub = XOR)



$T(x) = x^r M(x) - R(x) = M(x)\&R(x)$

$T(x)/G(x) = 0$

If $T'(x)/G(x) = 0$ then Correct, otherwise Error

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Standard Polynomials

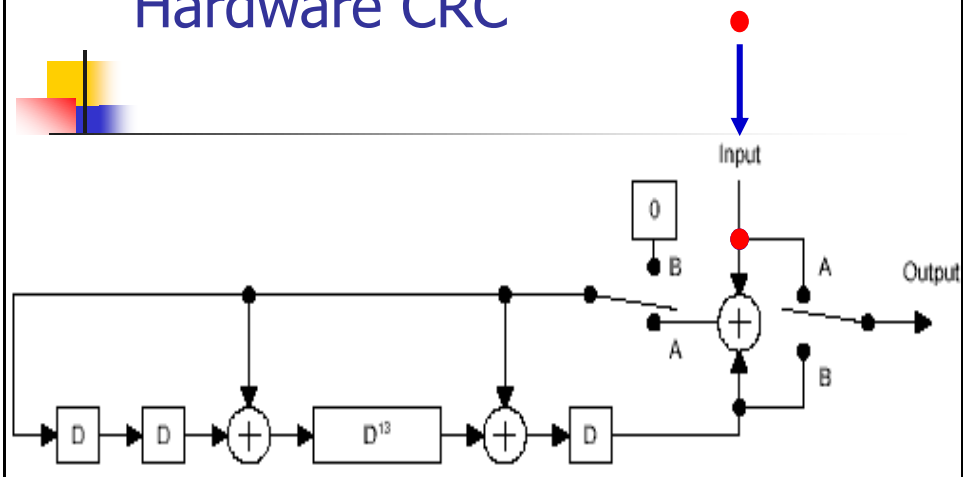
CRC-12	CRC-16	CRC-ITU
$x^{12}+x^{11}+x^3+x+1$	$x^{16}+x^{15}+x^2+1$	$x^{16}+x^{12}+x^5+1$
	(used in HDLC)	

CRC-32

$$x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+x^{11}+x^{10}+x^8+x^7+x^5+x^4+x^2+x+1$$

(used in Ethernet)

Hardware CRC



Source: http://www.erg.abdn.ac.uk/users/gorry/course/dl-pages/crc.html

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Error Correction (1)

- Two types of errors
  - Lost frame - never arrives
  - Damaged frame - error in bits
- Automatic Repeat reQuest (ARQ)
  - Error detection
  - Positive acknowledgment (ACK) if received
  - Retransmission after time-out if not ACK
  - Negative ACK (NACK)and retransmission if error
- Error-Correcting Codes

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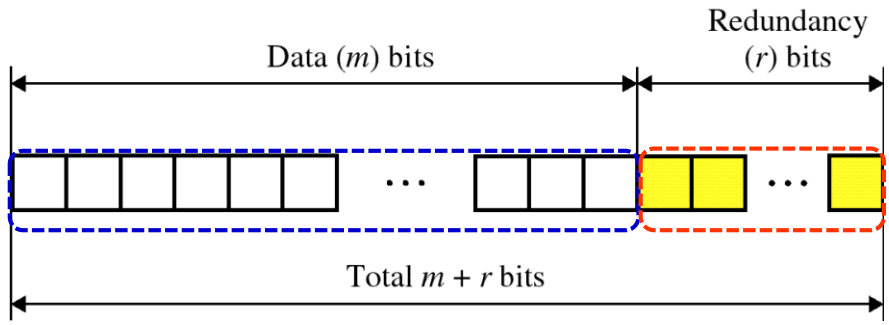
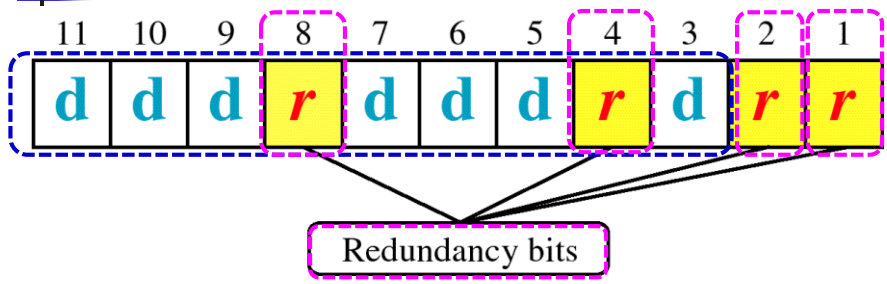
Error Correction (2)



Error Correction (3): **Hamming Code**

Hamming code with 7 data bits and 4 check bits

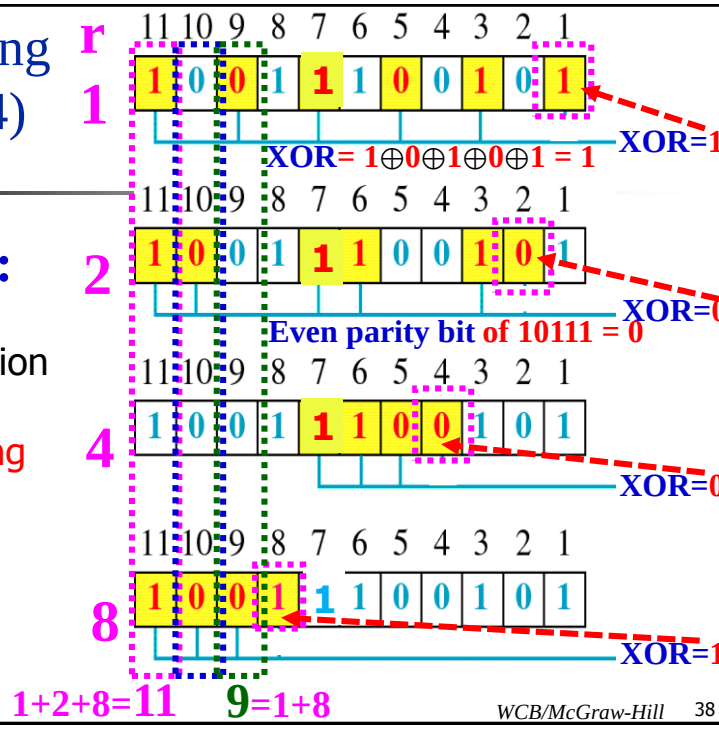


The bits that are powers of 2 (1, 2, 4, 8, 16, etc.) are check bits.
The rest (3, 5, 6, 7, 9, 11, etc.) are filled up with the *m* data bits.

Hamming Code (4)

Sender:

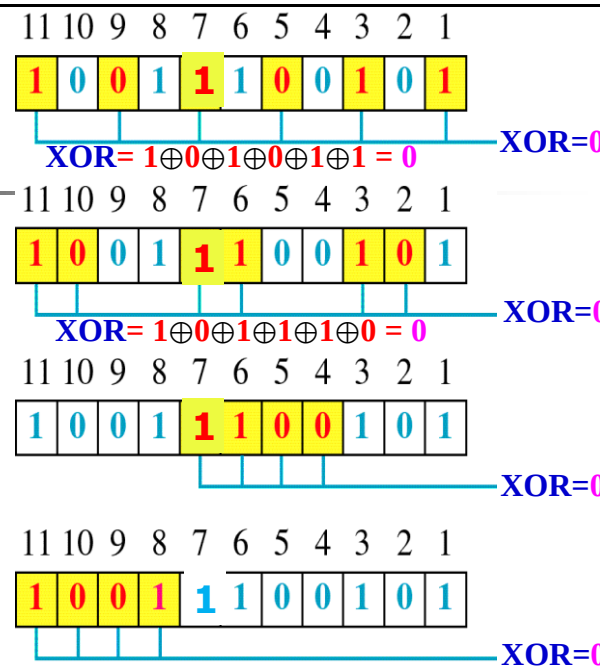
Generation of Hamming Code (**Even Parity** Check)



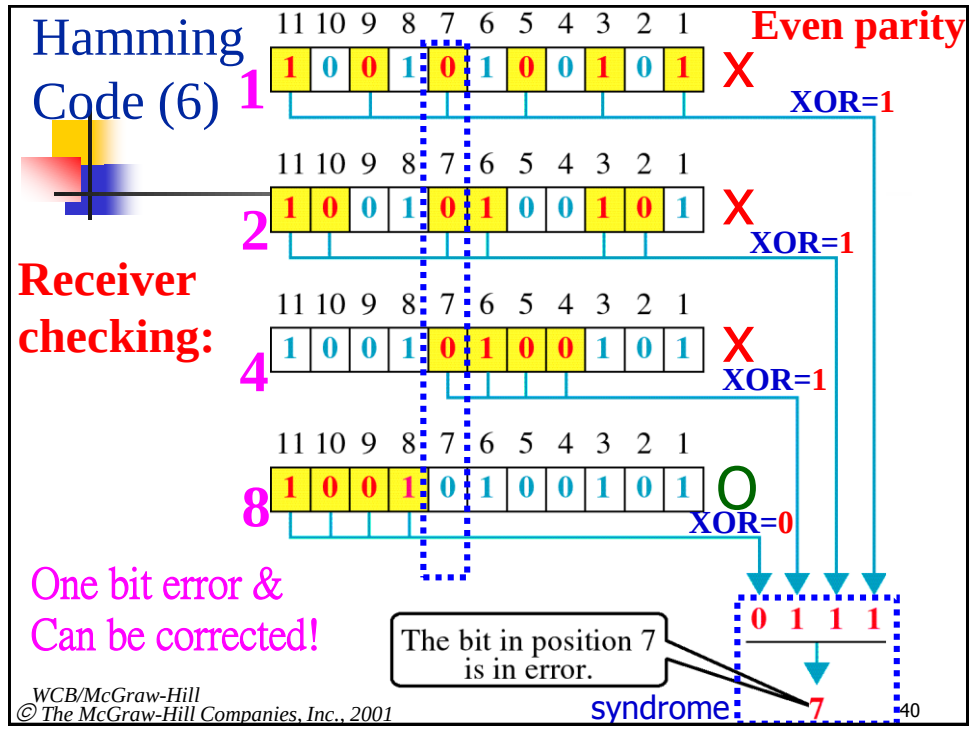
Hamming Code (5)

Receiver checking:

(**Even Parity** Check)



No error & Accept!



Error-Correcting Codes (7)

Use of a Hamming code to correct 1-bit errors.

Starting with bit 1 at the left end, bit 2 to its immediate right, and so on.

Char.	ASCII	Check bits (1,2,4,8)
H	1001000	00110010000
a	1100001	10111001001
m	1101101	11101010101
m	1101101	11101010101
i	1101001	01101011001
n	1101110	01101010110
g	1100111	01111001111
	0100000	10011000000
c	1100011	11111000011
o	1101111	10101011111
d	1100100	11111001100
e	1100101	00111000101

Order of bit transmission

Check bits may start with bit 1 at the left end

與上頁左右顛倒(也是可以)

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Example of an (11, 7) Hamming code correcting a single-bit error

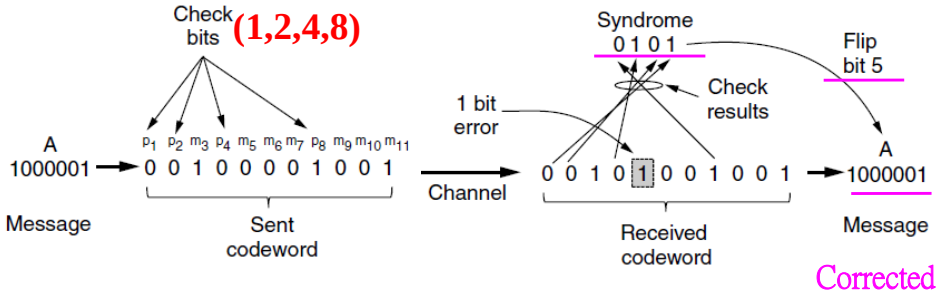

Figure 3-6. Example of an (11, 7) Hamming code correcting a single-bit error.

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Hamming code for 8-bit data

Codeword:	1	2	3	4	5	6	7	8	9	10	11	12
			D0		D1	D2	D3		D4	D5	D6	D7
	H0	H1		H2				H3				

Hamming code:

$H0 = D0 \oplus D1 \oplus D3 \oplus D4 \oplus D6$

$H1 = D0 \oplus D2 \oplus D3 \oplus D5 \oplus D6$

$H2 = D1 \oplus D2 \oplus D3 \oplus D7$

$H3 = D4 \oplus D5 \oplus D6 \oplus D7$

Note: $\oplus$ = XOR

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Hamming code (example)

An 8-bit byte with binary value 10101111

			D0		D1	D2	D3		D4	D5	D6	D7
	1	2	3	4	5	6	7	8	9	10	11	12
Codeword:			1		0	1	0		1	1	1	1
	H0 1	H1 0		H2 0				H3 0				

H0 = 1 ⊕ 0 ⊕ 0 ⊕ 1 ⊕ 1 = 1
H1 = 1 ⊕ 1 ⊕ 0 ⊕ 1 ⊕ 1 = 0
H2 = 0 ⊕ 1 ⊕ 0 ⊕ 1 = 0
H3 = 1 ⊕ 1 ⊕ 1 ⊕ 1 = 0

The encoded value (codeword) is 101001001111.

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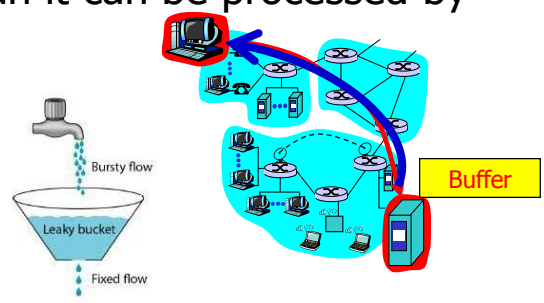
Flow Control

- Necessary when data is being sent faster than it can be processed by receiver



- Usually a buffer is filled, and transfer is stopped until buffer is emptied

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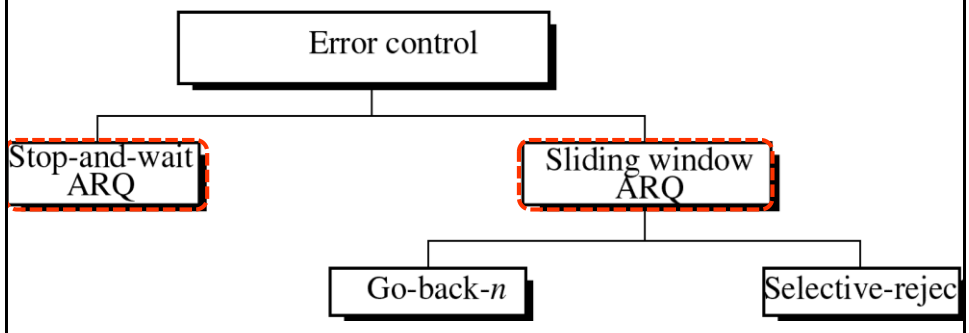
Flow Control with Error Control



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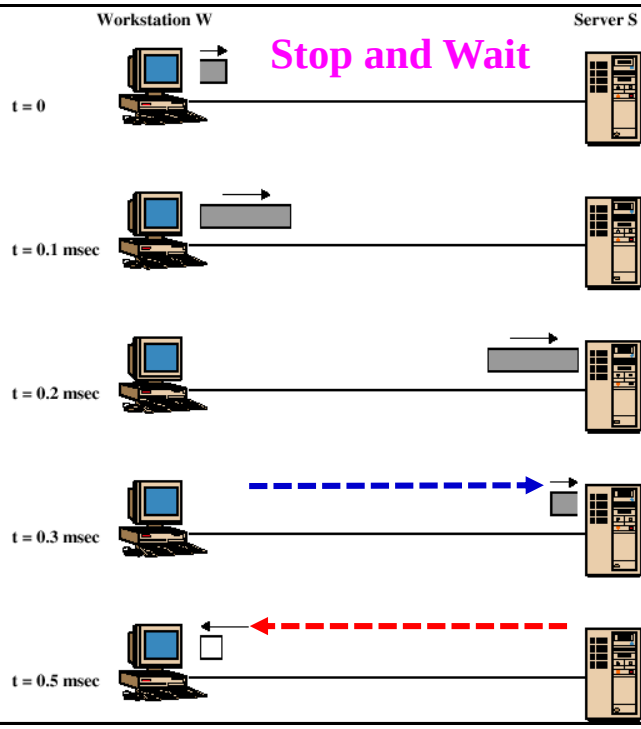
Stop and Wait



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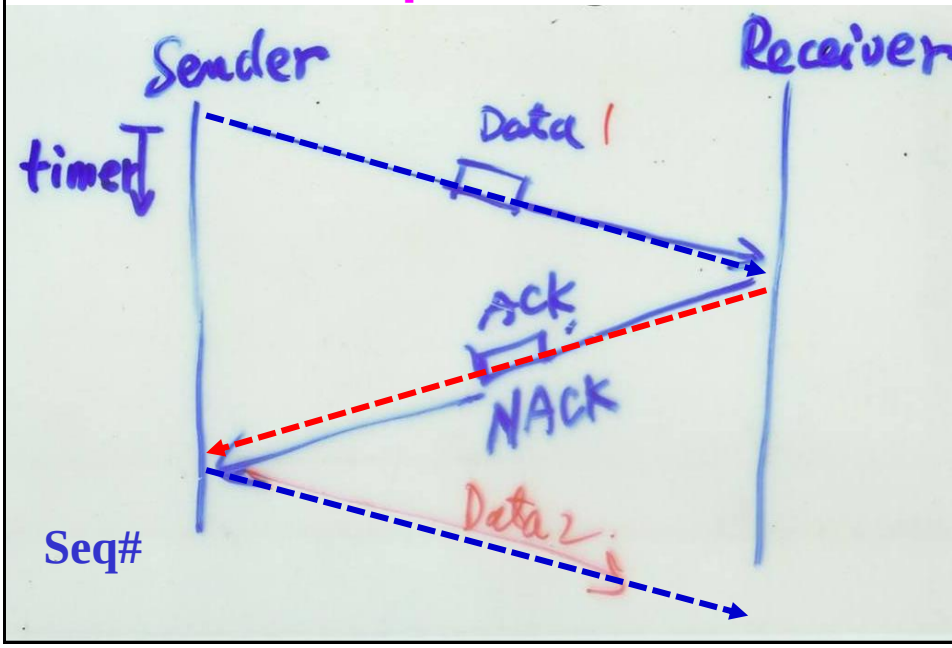
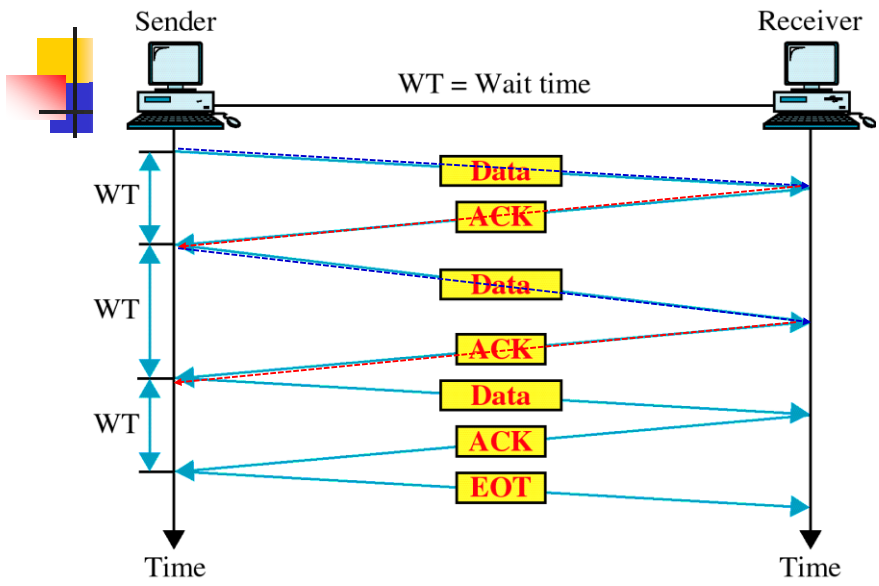
Stop-And-Wait



Stop and Wait ARQ



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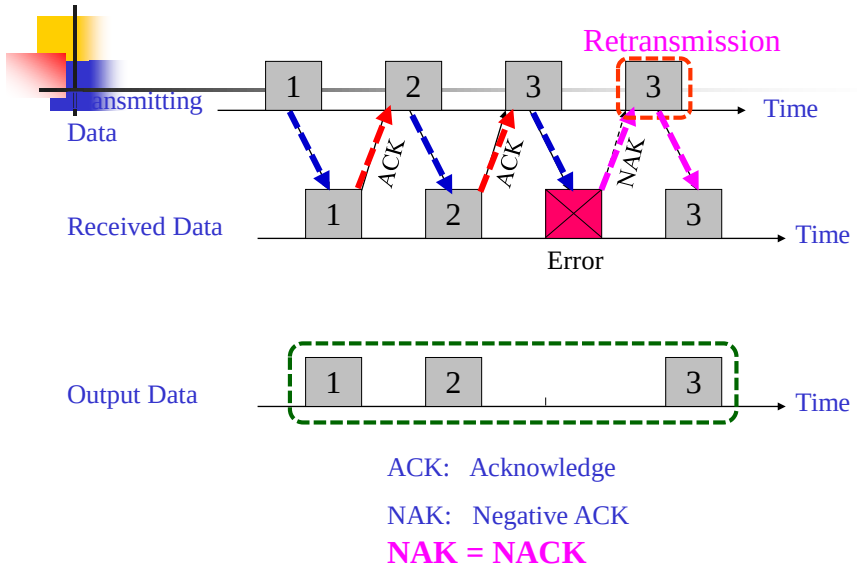
Stop-And-Wait ARQ



ACK: Acknowledge

NAK: Negative ACK

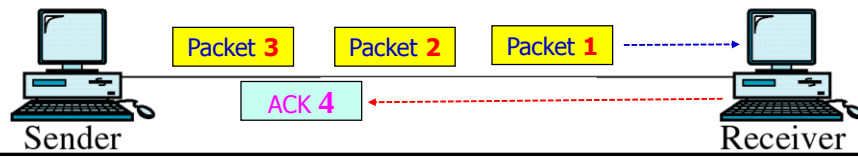
NAK = NACK

Stop-and-Wait Flow Control

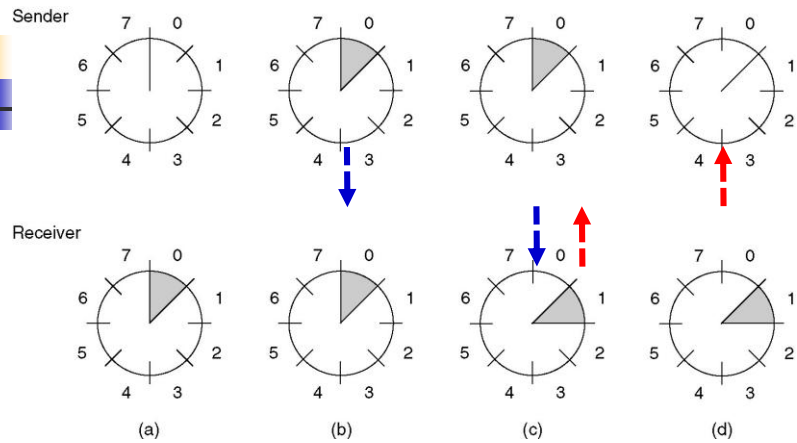
- Simplest form of Frame-Oriented Control
- Source may not send new frame until receiver acknowledges previous one
- Very inefficient, especially when a single message is broken into many small frames
  - buffer size of receiver is limited
  - if error, detected sooner and less data need be retransmitted

Sliding-Window Flow Control

- Allows multiple frames to be in transit
- Receiver sends acknowledgement with sequence number of next frame
- Sender maintains list of sequence numbers it can send, receiver maintains list of sequence numbers it can receive



Sliding Window Protocols (2)



A sliding window of size 1, with a **3-bit sequence number**.

(a) Initially. **(size = 1 相當於Stop-And-Wait ARQ)**

(b) After the first frame has been sent.

(c) After the first frame has been received.

(d) After the first acknowledgement has been received.

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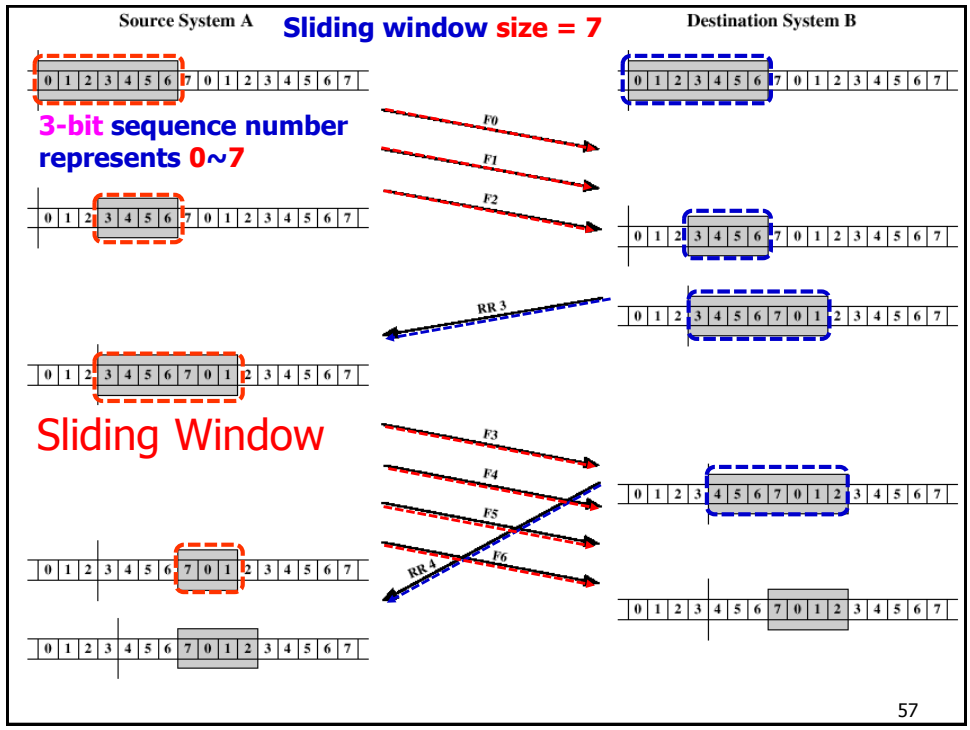
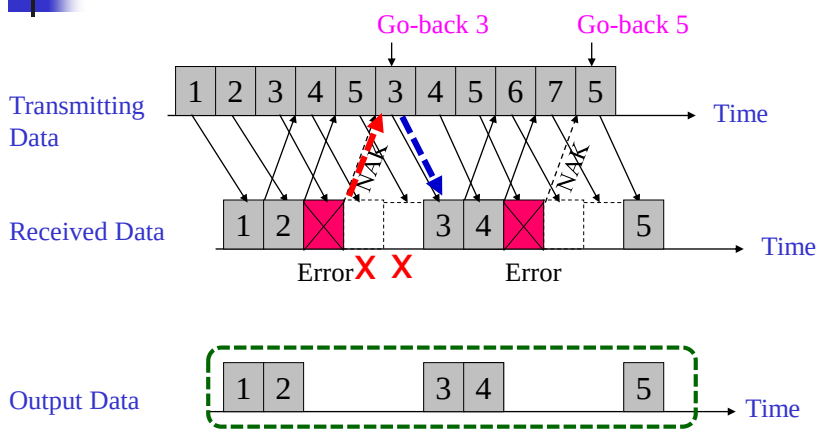
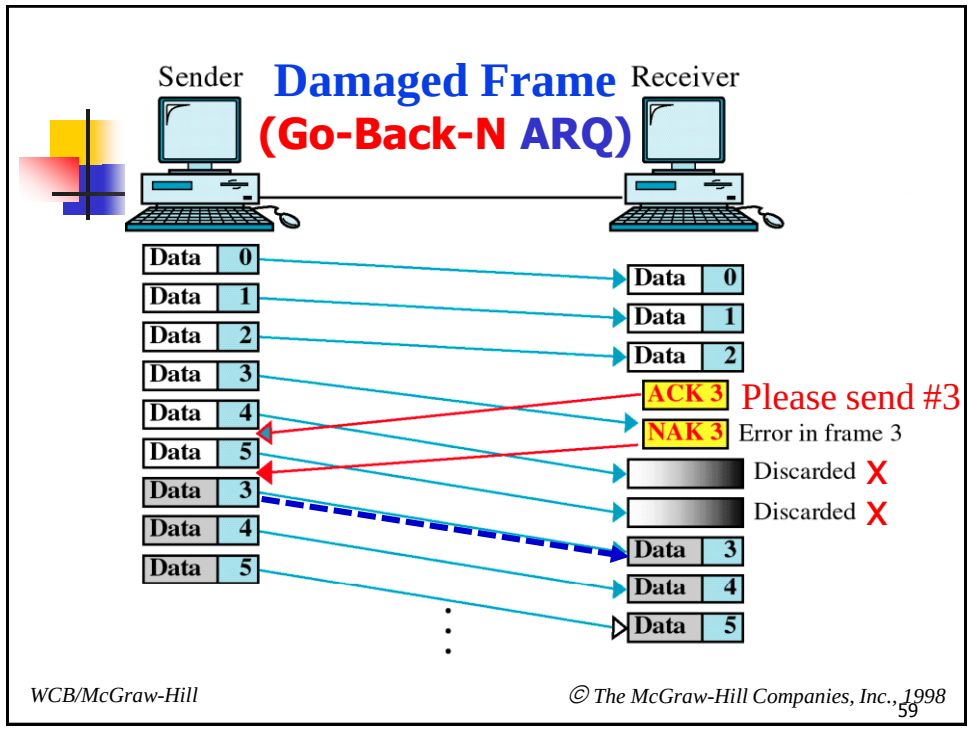


Sliding-Window Flow Control (1)

Go-Back-N ARQ (GBN ARQ)





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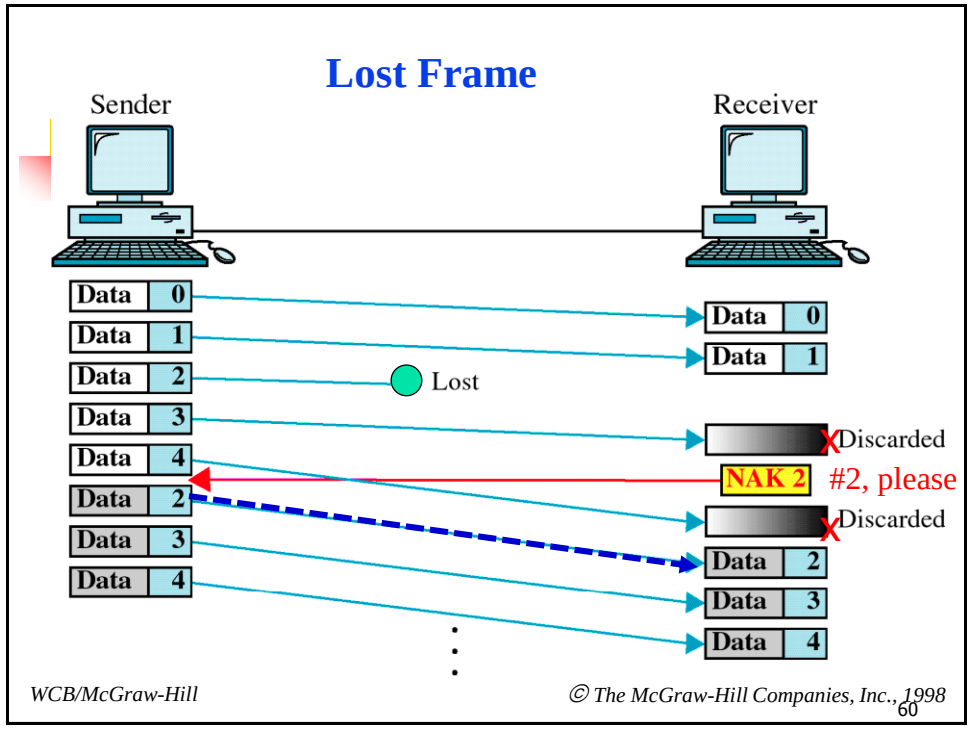

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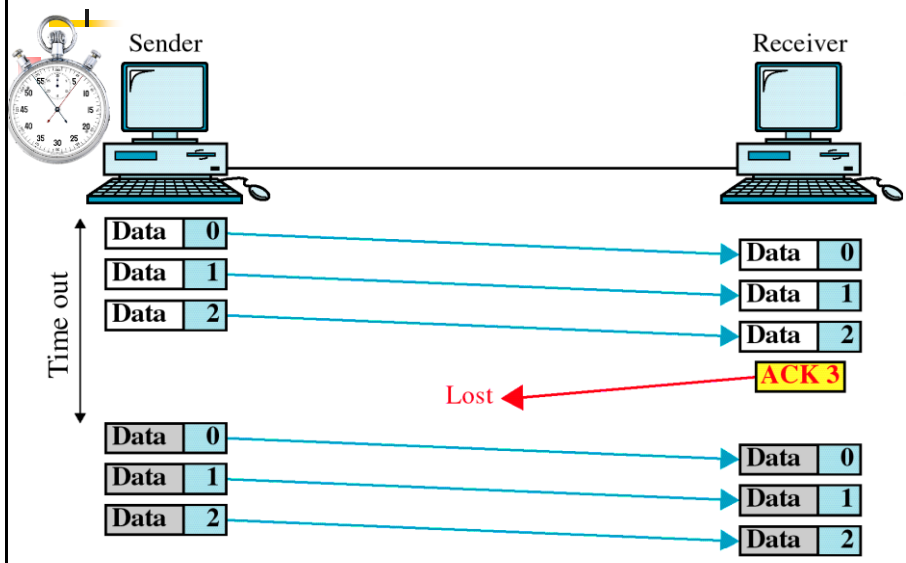
Lost ACK



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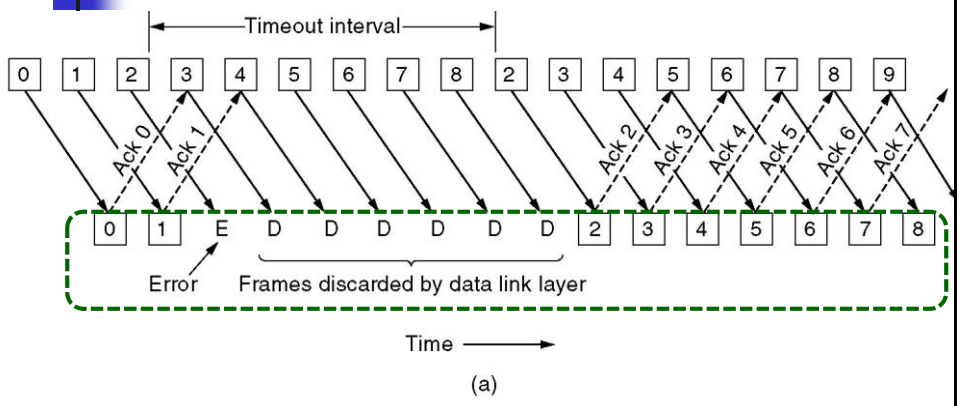
A Protocol Using Go Back N



Pipelining and error recovery.

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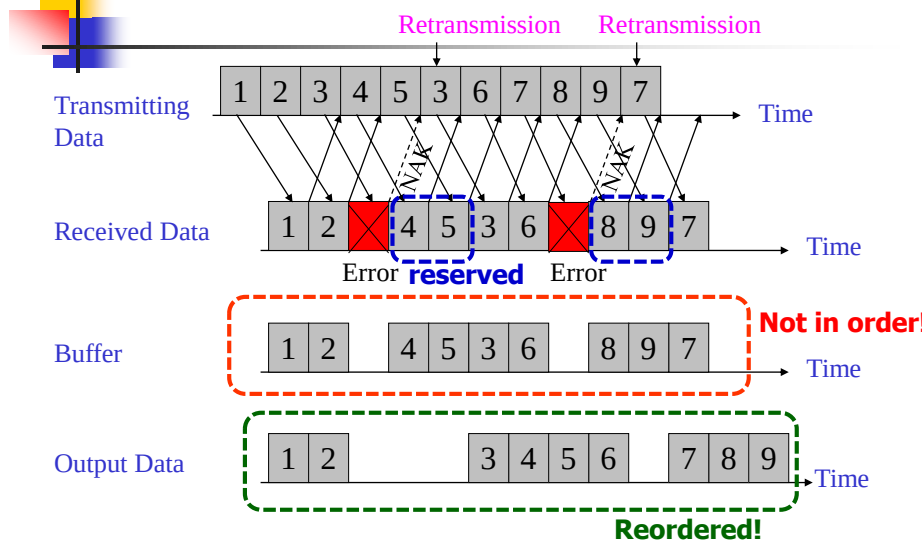
Sliding-Window Flow Control (2)

Selective-Repeat ARQ (SR ARQ)



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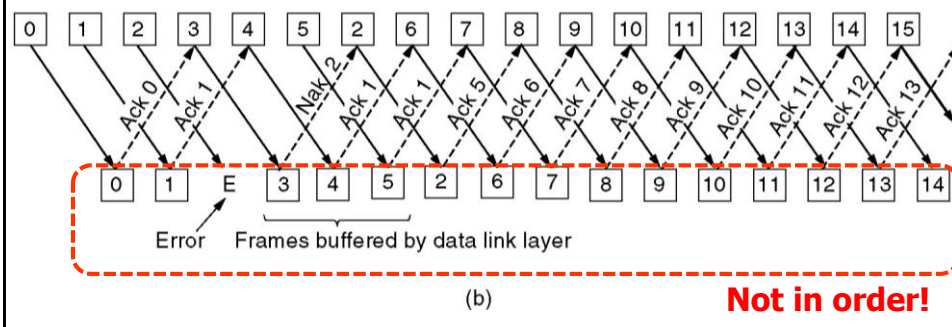
A Protocol Using Selective Repeat



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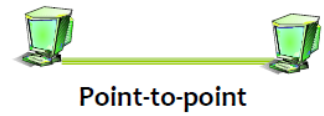
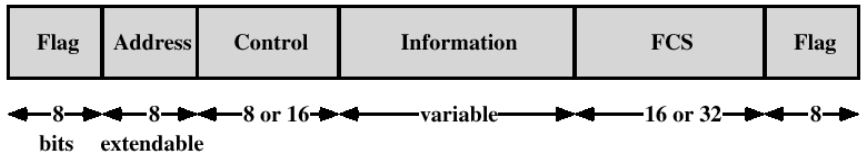
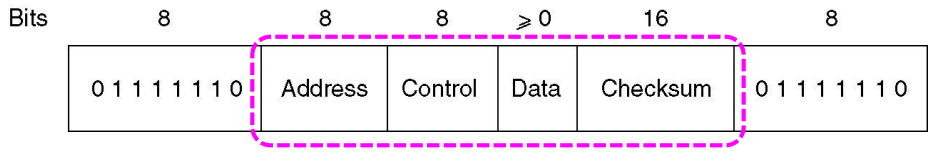
High-Level Data Link Control (HDLC)



Frame format for bit-oriented protocols.

(Bit stuffing in hardware)





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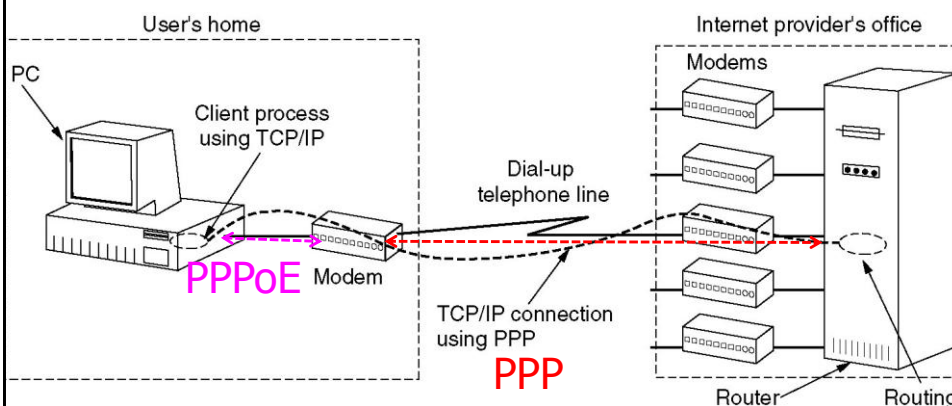
The Data Link Layer in the Internet: PPP

A home personal computer acting as an internet host.



Byte stuffing in software/ for modem

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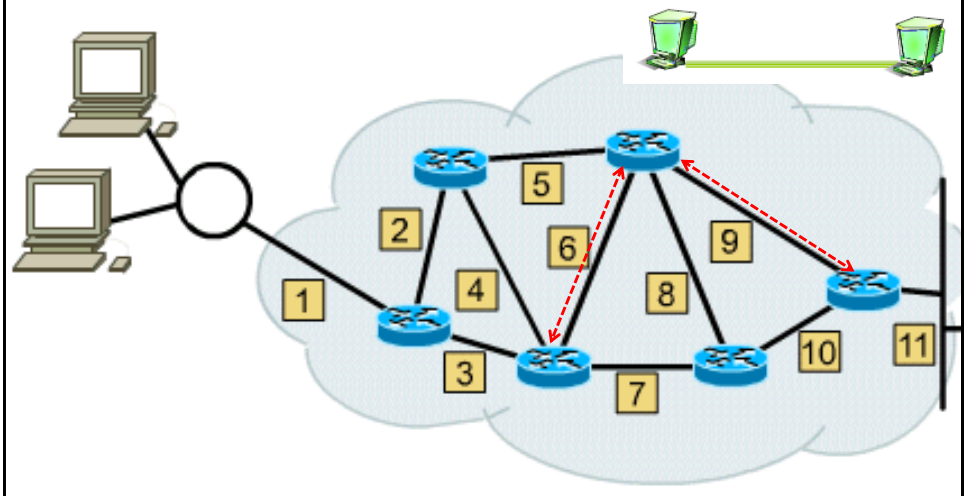
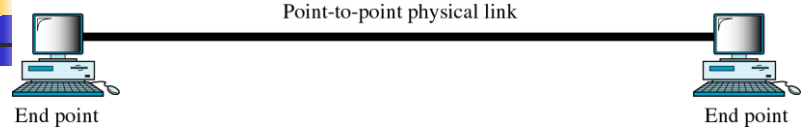
PPP (Point to Point Protocol)

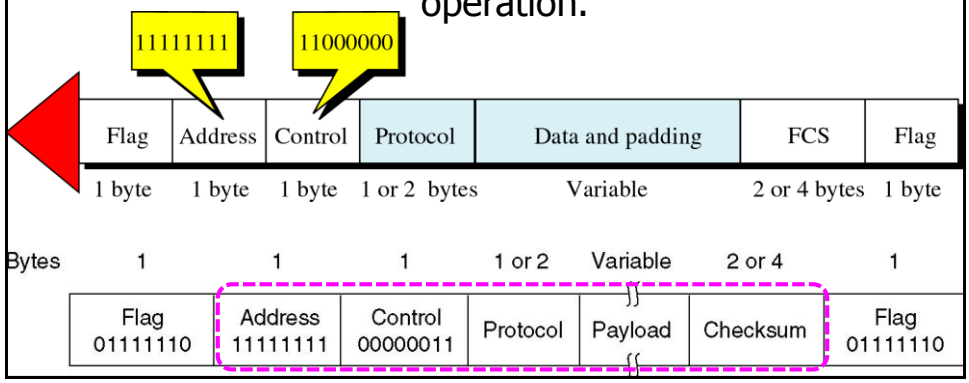


PPP – Point to Point Protocol

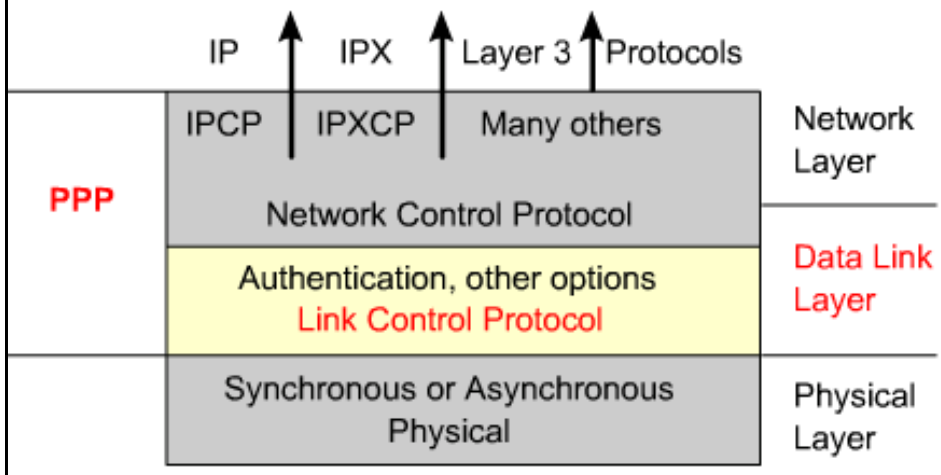
(Byte stuffing in software)



The PPP full frame format for unnumbered mode operation.



PPP – Point to Point Protocol (2)



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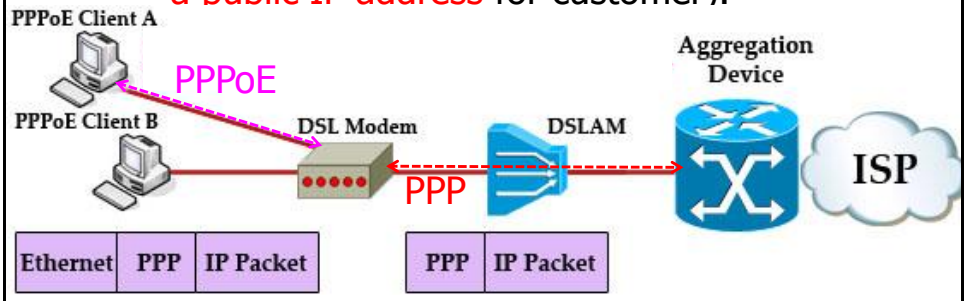
PPP over Ethernet (PPPoE)

- Internet Service Provider (ISP) still like PPP because of authentication (PPP supports CHAP), accounting (checking customer's bill), link management (ISP can use PPP to assign a public IP address for customer).



DSLAM: Digital Subscriber Line Access Multiplexer

Source: http://www.digitaltut.com/ppp-over-ethernet-pppoe-tutorial

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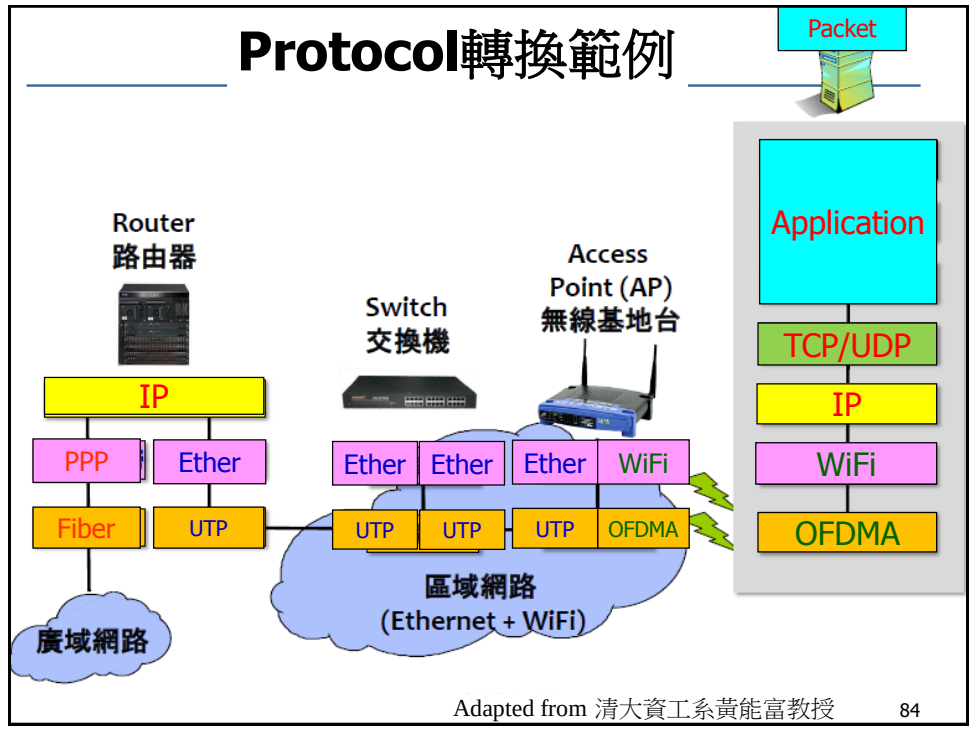
Protocol轉換範例
Packet
Application
TCP/UDP
IP
WiFi
OFDMA
Router
路由器
Switch
交換機
Access
Point (AP)
無線基地台
IP
PPP
Ether
Fiber
UTP
Ether
Ether
Ether
WiFi
UTP
UTP
UTP
OFDMA
區域網路
(Ethernet + WiFi)
廣域網路
Adapted from 清大資工系黃能富教授
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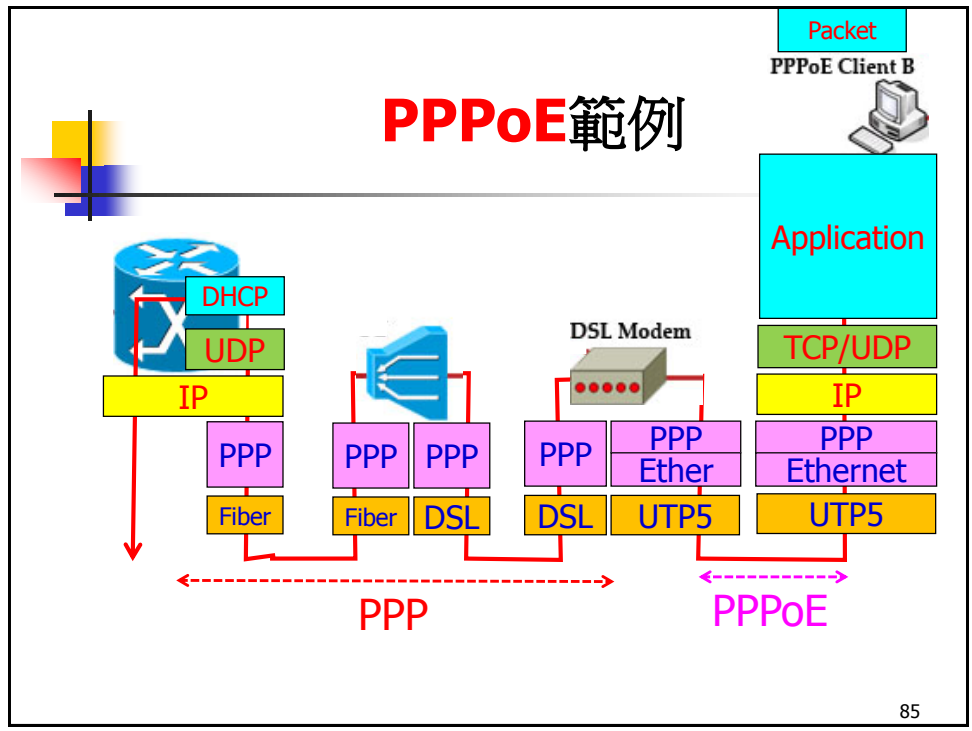
PPPoE範例
Packet
PPPoE Client B
Application
TCP/UDP
IP
PPP
Ethernet
UTP5
DHCP
UDP
IP
PPP
Fiber
DSL Modem
PPP
Fiber
PPP
DSL
PPP
DSL
PPP
Ether
UTP5
PPP
PPPoE
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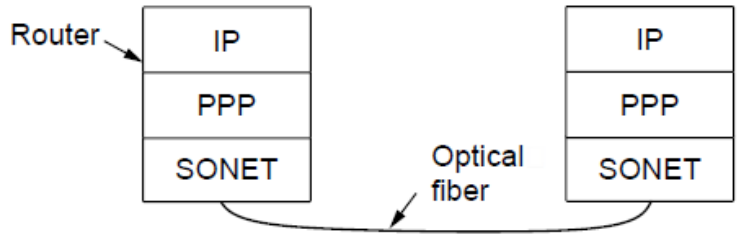
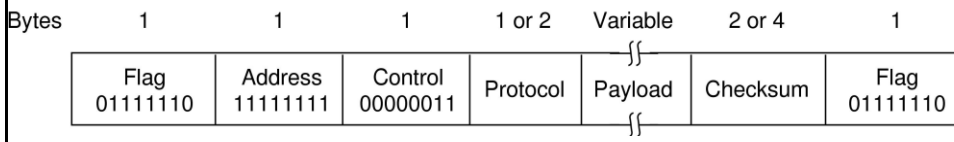
Packet over SONET

(a) A protocol stack. (b) Frame relationships





The PPP full frame format for unnumbered mode operation

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各個電腦自行利用PPPoE撥接ADSL上網

PPP over WLAN
PPP over WiFi

Source: http://www.im.isu.edu.tw/faculty/jbsuen/www/net/wireless.ppt

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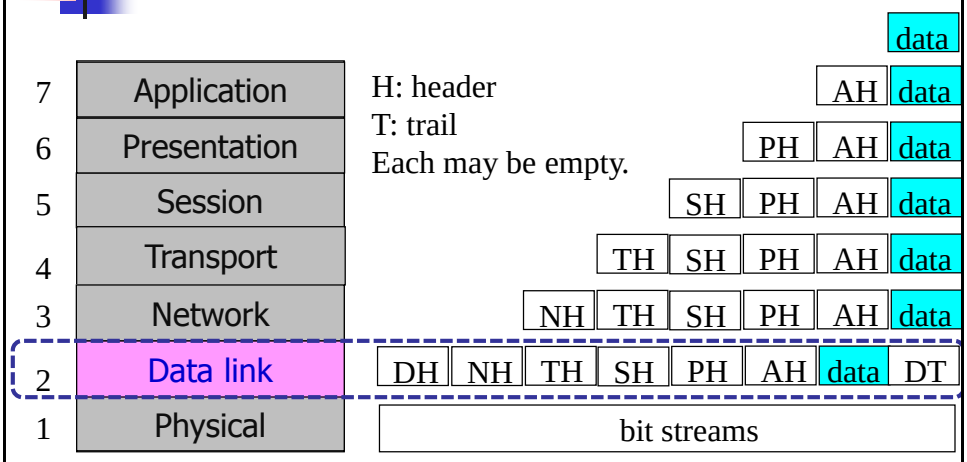
The Data Link Layer



OSI Reference Model

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End of Chapter 3

Questions?

Thank you!