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CHAPTER 6

CODING THEORY



Coding Theory

- In digital communications, when information is transmitted in the form of strings of 0's and 1's, certain problems arise.
- As a result of “**noise**” in the channel, when a certain signal is transmitted a different signal may be received, thus causing the receiver to make a wrong decision.



example

Word transmitted

0010111



Word received

0110110

Transmission
channel

errors



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Coding of Binary Information

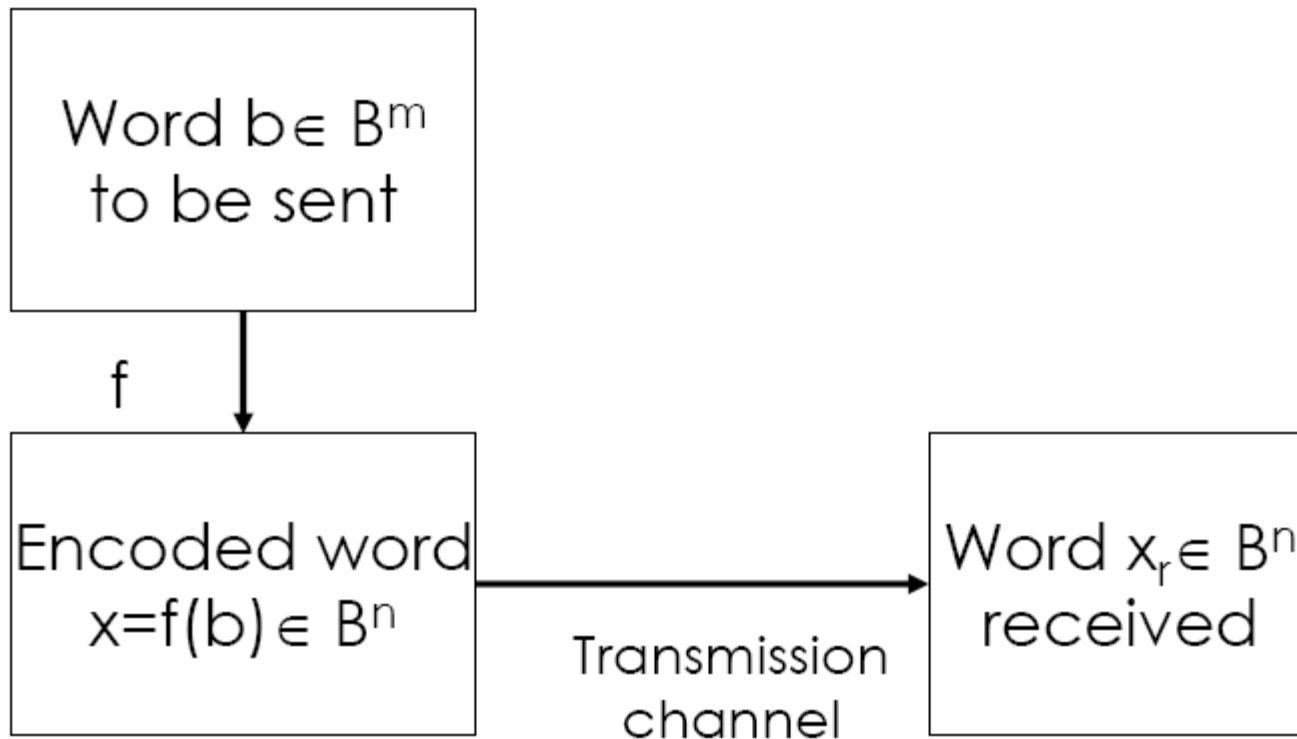
- The basic task in the transmission is to reduce the likelihood of receiving a word that differs from the word was sent.
- This is done as follows.



Coding of Binary Information

- Choose an integer $n > m$ and one-to-one function $f: B^m \rightarrow B^n$.
- The function f is called an (m,n) encoding function.
(representing every word in B^m as a word in B^n)

Coding of Binary Information





example

- Consider the following $(m, 3m)$ encoding function $f: B^m \rightarrow B^{3m}$ if

$$b = b_1 b_2 \dots b_m \in B^m$$

- Define

$$\begin{aligned} f(b) &= f(b_1 b_2 \dots b_m) \\ &= b_1 b_2 \dots b_m b_1 b_2 \dots b_m b_1 b_2 \dots b_m \end{aligned}$$



example

- Let $m=3$,
- Thus,
$$f(100)=100100100$$
$$f(011)=011011011$$
$$f(001)=001001001$$



Weight

- If $x \in B^n$, then the number of 1's in x is called the weight of x and is denoted by $|x|$.



example

- Find the weight each of the following words in B^5
 - i) 11000 = 2
 - ii) 11111 = 5
 - iii) 10101 = 3
 - iv) 01010 = 2



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exercise

- Find the weight each of the following words :
 - i) 1000110
 - ii) 0111001
 - iii) 11110001
 - iv) 10101010



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Exercise - Solution

- $1000110 = 3$
- $0111001 = 4$
- $11110001 = 5$
- $10101010 = 4$

Parity Check Code

- The encoding function $f: B^m \rightarrow B^{m+1}$ is called the parity $(m, m+1)$ check code:
if $b = b_1 b_2 \dots b_m \in B^m$, define

$$f(b) = b_1 b_2 \dots b_m b_{m+1}$$

where

$$b_{m+1} = \begin{cases} 0 & \text{if } |b| \text{ is even} \\ 1 & \text{if } |b| \text{ is odd} \end{cases}$$

Parity Check Code

- b_{m+1} is zero if and only if the number of 1's in b is an even number.
- Every code word $f(b)$ has even weight.
- A single error in the transmission of a code word will change the received word to a word of odd weight, and therefore can be detected.



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example

• Let $m=3$.

- $f(001) = 0011$
- $f(110) = 1100$
- $f(111) = 1111$
- $f(101) = 1010$



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exercise

- Consider the (3,4) parity check code. For each of received words, determine whether an error will be detected.
 - 0100
 - 1100
 - 0010
 - 1001



Exercise - Solution

- 0100 – error
 - 1 is odd
 - Should be 0101
- 1100 – no error
- 0010 – error
 - 1 is odd
 - Should be 0011
- 1001 – no error



Hamming Distance

- Let x and y be words in B^m .
- The Hamming distance, $H(x,y)$ between x and y is the weight $|x \oplus y|$ of $x \oplus y$.



Hamming Distance

• $x \oplus y$

$x \oplus y$	$x=0$	$x=1$
$y=0$	0	1
$y=1$	1	0



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example

- Find the distance between x and y:

$x=110110, y=000101$

$x=011101, y=100101$

$x=01011, y=11001$



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example

$x=110110,$ $y=000101$

$$110110 \oplus 000101 = 110011$$

110110
000101
110011

$$|110011| = 4$$



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example

$x = 011101,$ $y = 100101$

$$011101 \oplus 100101 = 111000$$

011101
100101
111000

$$|111000| = 3$$



example

$x=01011,$

$y=11001$

$$01011 \oplus 11001 = 10010$$

$$|10010| = 2$$

01011
11001
10010



Properties of the distance function

- Let x, y and z be elements of B^m . Then
 - $H(x, y) \geq 0$
 - $H(x, y) = 0$ if and only if $x=y$
 - $H(x, y) = H(y, x)$
 - $H(x, y) + H(y, z) \geq H(x, z)$



Minimum Distance

- The minimum distance of an encoding function $f: B^m \rightarrow B^n$ is the minimum of the distances between all distinct pairs of code words.

$$\min \{ H(f(x), f(y)) \mid x, y \in B^m \}$$



example

- Find the minimum distance of the (2,5) encoding function f:

$$f(00) = 00000$$

$$f(10) = 00111$$

$$f(01) = 01110$$

$$f(11) = 11111$$



example

- 6 distinct pairs of code words:

$f(00), f(10)$	$f(00), f(01)$	$f(00), f(11)$
$f(10), f(01)$	$f(10), f(11)$	$f(01), f(11)$

- Compute the distance for each pair.



example

$$\begin{aligned} |f(00) \oplus f(10)| &= |00000 \oplus 00111| \\ &= |00111| = 3 \end{aligned}$$

$$\begin{aligned} |f(00) \oplus f(01)| &= |00000 \oplus 01110| \\ &= |01110| = 3 \end{aligned}$$

$$\begin{aligned} |f(00) \oplus f(11)| &= |00000 \oplus 11111| \\ &= |11111| = 5 \end{aligned}$$



example

$$\begin{aligned} |f(10) \oplus f(01)| &= |00111 \oplus 01110| \\ &= |01001| = 2 \end{aligned}$$

$$\begin{aligned} |f(10) \oplus f(11)| &= |00111 \oplus 11111| \\ &= |11000| = 2 \end{aligned}$$

$$\begin{aligned} |f(01) \oplus f(11)| &= |01110 \oplus 11111| \\ &= |10001| = 2 \end{aligned}$$



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example

- Hamming distance,
3, 3, 5, 2, 2, 2

Minimum 2

- The minimum distance is 2.



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Theorem

- An (m,n) encoding function $f: B^m \rightarrow B^n$ can detect k or fewer errors if and only if its minimum distance is at least $k+1$.



example

- The minimum distance of f is 2.
- The code k or fewer errors if and only if its minimum distance is at least $k+1$.
- $2 \geq k+1$ or $k \leq 1$
- The code can detect 1 error.



exercise

- Consider the (2,5) encoding function

$$f: B^2 \rightarrow B^5$$

$$f(00) = 00000$$

$$f(01) = 01110$$

$$f(10) = 10101$$

$$f(11) = 11011$$

- How many errors will f detect?



Exercise - Solution

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- $|f(00) \oplus f(01)| = |00000 \oplus 01110| = |01110| = 3$
 - $|f(00) \oplus f(10)| = |00000 \oplus 10101| = |10101| = 3$
 - $|f(00) \oplus f(11)| = |00000 \oplus 11011| = |11011| = 4$
 - $|f(01) \oplus f(10)| = |01110 \oplus 10101| = |11011| = 4$
 - $|f(01) \oplus f(11)| = |01110 \oplus 11011| = |10101| = 3$
 - $|f(10) \oplus f(11)| = |10101 \oplus 11011| = |01110| = 3$
-
- Hamming distance: 3,3,4,4,3,3
 - Minimum distance = 3
 - $3 \geq k + 1$ so $k \leq 2$
 - The code can detect 2 errors



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Exercise Past Year 2015/2016

- a) Let C be the set of code words $\{00000000, 11111000, 01010111, 10101111\}$. How many errors can C detect? (6 marks)



Group Codes

- An encoding function $f : B^m \rightarrow B^n$ is called a group code if

$$f(B^m) = \{ f(b) \mid b \in B^m \}$$

is a subgroup of B^n .



Group Codes

- **N** is a subgroup of B^n if:
 - The identity i of B^n is in N .
 $\mathbf{x} \oplus \mathbf{i} = \mathbf{x}, \quad \mathbf{i} \oplus \mathbf{x} = \mathbf{x}, \quad \mathbf{x} \in B^n, \mathbf{x} \in N$



Group Codes

- if x and $y \in N$, then $x \oplus y \in N$.
- if $x \in N$, then $x^{-1} \in N$.
 $\mathbf{x \oplus x^{-1} = i, \quad x^{-1} \oplus x = i}$
(need not be checked, since every element in B^n is its own inverse)



example

- Show that the encoding function $f : B^2 \rightarrow B^5$ is a group code.

$$f(00) = 00000$$

$$f(01) = 01110$$

$$f(10) = 10101$$

$$f(11) = 11011$$



example

- We must show that the set of all code words

$$N = \{00000, 01110, 10101, 11011\}$$

is a subgroup of B^5 .



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example

Let

$a = 00000$

$b = 01110$

$c = 10101$

$d = 11011$

$a=00000$, $b=01110$, $c=10101$, $d=11011$

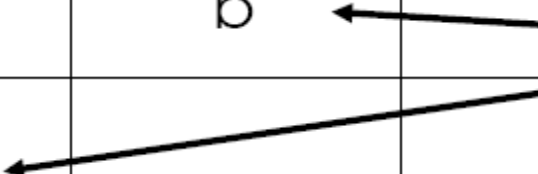
$x \oplus y$	a	b	c	d
a	a			
b				
c				
d				

$$\begin{array}{r}
 00000 \\
 \oplus 00000 \\
 \hline
 00000
 \end{array}$$

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b		
b	b			
c				
d				

$$\begin{array}{r}
 00000 \\
 \oplus 01110 \\
 \hline
 01110
 \end{array}$$



$a=00000$, $b=01110$, $c=10101$, $d=11011$

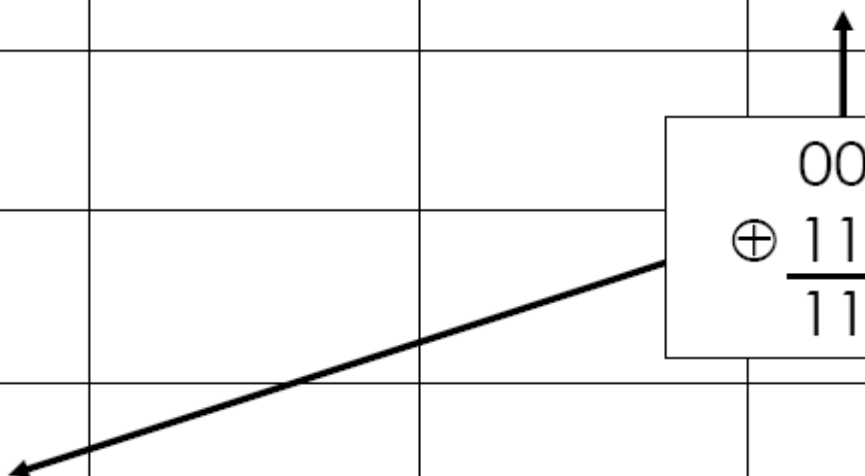
$x \oplus y$	a	b	c	d
a	a	b	c	
b	b			
c	c			
d				

$$\begin{array}{r}
 00000 \\
 \oplus 10101 \\
 \hline
 10101
 \end{array}$$

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b	c	d
b	b			
c	c			
d	d			

$$\begin{array}{r}
 00000 \\
 \oplus 11011 \\
 \hline
 11011
 \end{array}$$



$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b	c	d
b	b	a		
c	c			
d	d			

$$\begin{array}{r}
 01110 \\
 \oplus 01110 \\
 \hline
 00000
 \end{array}$$

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b	c	d
b	b	a	d	
c	c	d		
d	d			

$$\begin{array}{r}
 01110 \\
 \oplus 10101 \\
 \hline
 11011
 \end{array}$$

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	$\begin{array}{r} 10101 \\ \oplus 10101 \\ \hline 00000 \end{array}$	c	d
b	b	a	d	
c	c	d	a	
d	d			

$a=00000$, $b=01110$, $c=10101$, $d=11011$

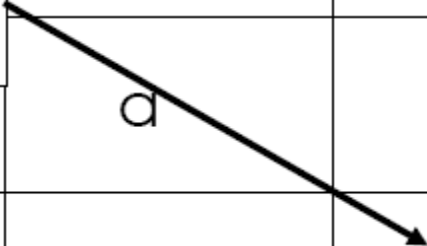
$x \oplus y$	a	b	c	d
a	a	$\begin{array}{r} 01110 \\ \oplus 11011 \\ \hline 10101 \end{array}$	c	d
b	b		d	c
c	c	d	a	
d	d	c		

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	$\begin{array}{r} 10101 \\ \oplus 11011 \\ \hline 01110 \end{array}$	c	d
b	b		d	c
c	c	d	a	b
d	d	c	b	

$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b	c	d
b	b	$\begin{array}{r} 11011 \\ \oplus 11011 \\ \hline 00000 \end{array}$	d	c
c	c	d	a	b
d	d	c	b	a



$a=00000$, $b=01110$, $c=10101$, $d=11011$

$x \oplus y$	a	b	c	d
a	a	b	c	d
b	b	a	d	c
c	c	d	a	b
d	d	c	b	a



example

- The identity of B^n belongs to N
 $i = 00000 = a$
- $x, y \in N, x \oplus y \in N$
- The encoding function f is a group code.



exercise

- Show that the encoding function $f : B^3 \rightarrow B^7$ is a group code.

$$f(000) = 0000000$$

$$f(001) = 0010110$$

$$f(010) = 0101000$$

$$f(011) = 0111110$$

$$f(100) = 1000101$$

$$f(101) = 1010011$$

$$f(110) = 1101101$$

$$f(111) = 1111011$$



- We must show that the set of all code words
 $N = \{0000000, 0101000, 1000101, 1101101, 0010110, 0111110, 1010011, 1111011\}$

is a subgroup of B^7

- Let

- $a = 0000000$
- $b = 0101000$
- $c = 1000101$
- $d = 1101101$
- $e = 0010110$
- $f = 0111110$
- $g = 1010011$
- $h = 1111011$



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Exercise - Solution

	a	b	c	d	e	f	g	h
a								
b								
c								
d								
e								
f								
g								
h								



Group Codes

- Let $D = [d_{ij}]$ and $E = [e_{ij}]$ be $m \times n$ Boolean matrices.
- We define the **mod 2 sum** $D \oplus E$ as the $m \times n$ Boolean matrix $F = [f_{ij}]$ where

$$\square f_{ij} = d_{ij} + e_{ij}$$



example

$$\text{Let } D = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \quad E = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 \end{bmatrix}$$

example

- $D \oplus E$

$$\begin{bmatrix} \boxed{1} & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \oplus \begin{bmatrix} \boxed{1} & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \boxed{1+1} & 0+1 & 1+0 & 1+1 \\ 0+1 & 1+1 & 1+0 & 0+1 \\ 1+0 & 0+1 & 0+1 & 1+1 \end{bmatrix} = \begin{bmatrix} \boxed{0} & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

Group Codes

- Let $D = [d_{ij}]$ be an $m \times p$ Boolean matrix and let $E = [e_{ij}]$ be a $p \times n$ Boolean matrix.
- We define the **mod 2 Boolean product** $D * E$ as the $m \times n$ matrix $F = [f_{ij}]$ where

$$\square f_{ij} = d_{i1}.e_{1j} + d_{i2}.e_{2j} + \dots + d_{ip}.e_{pj}$$



example

$$\text{Let } D = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \quad E = \begin{bmatrix} 1 & 0 \\ 1 & 1 \\ 0 & 1 \end{bmatrix}$$

example

• D^*E

$$\begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 \\ 1 & 1 \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1.1 + 1.1 + 0.0 & 1.0 + 1.1 + 0.1 \\ 0.1 + 1.1 + 1.0 & 0.0 + 1.1 + 1.1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Group Codes

- Let $m < n$ and $r = n - m$. An $n \times r$ Boolean matrix, **H**

whose last r rows form the identity matrix, is called a **parity check matrix**.

$$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1r} \\ h_{21} & h_{22} & \dots & h_{2r} \\ \vdots & \vdots & & \vdots \\ h_{m1} & h_{m2} & \dots & h_{mr} \\ 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} \left. \vphantom{\begin{bmatrix} h_{11} & h_{12} & \dots & h_{1r} \\ h_{21} & h_{22} & \dots & h_{2r} \\ \vdots & \vdots & & \vdots \\ h_{m1} & h_{m2} & \dots & h_{mr} \\ 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}} \right\} r = n - m$$



Group Codes

- We use H to define an encoding function $f_H: B^m \rightarrow B^n$
- If $b = b_1 b_2 \dots b_m$,
- Let $x = f_H(b)$

Group Codes

$$f_H(b) = b_1 b_2 \dots b_m x_1 x_2 \dots x_r$$

where,

$$[b_1 \quad b_2 \quad \dots \quad b_m] * \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1r} \\ h_{21} & h_{22} & \dots & h_{2r} \\ \vdots & \vdots & & \vdots \\ h_{m1} & h_{m2} & \dots & h_{mr} \end{bmatrix} \\ = [x_1 \quad x_2 \quad \dots \quad x_r]$$

example

- Let $m=2$, $n=5$ and

$$H = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Determine the group code $f_H: B^2 \rightarrow B^5$

example

- We have $B^2 = \{ 00, 01, 10, 11 \}$

- $b = b_1 b_2$ and $x = f_H(b) = b_1 b_2 x_1 x_2 x_3$

$$H = \begin{bmatrix} \boxed{\begin{matrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{matrix}} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} b_1 & b_2 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}$$



example

- $f_H(00) = 00 x_1 x_2 x_3$

- $b = 00$

$$\begin{aligned} & [0 \quad 0] * \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \\ &= [0.1 + 0.1 \quad 0.0 + 0.1 \quad 0.1 + 0.1] \\ &= [0 \quad 0 \quad 0] \end{aligned}$$

- $f_H(00) = 000000$

example

- $f_H(01) = 01 x_1 x_2 x_3$

- $b = 01$

$$\begin{aligned} & [0 \quad 1] * \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \\ &= [0.1 + 1.1 \quad 0.0 + 1.1 \quad 0.1 + 1.1] \\ &= [1 \quad 1 \quad 1] \end{aligned}$$

- $f_H(01) = 01111$



example

- $f_H(10) = 10 x_1 x_2 x_3$

- $b = 10$

$$\begin{bmatrix} 1 & 0 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1.1 + 0.1 & 1.0 + 0.1 & 1.1 + 0.1 \end{bmatrix}$$

$$f_H(10) = 10101$$

$$= \begin{bmatrix} 1 & 0 & 1 \end{bmatrix}$$

- $f_H(01) = 10101$



example

- $f_H(11) = 11 x_1 x_2 x_3$

- $b = 11$

$$\begin{aligned} & [1 \quad 1] * \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \\ &= [1.1 + 1.1 \quad 1.0 + 1.1 \quad 1.1 + 1.1] \\ &= [0 \quad 1 \quad 0] \end{aligned}$$

- $f_H(11) = 11010$



exercise

- Let,

$$H = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Determine the group code $f_H: B^2 \rightarrow B^5$



Exercise Past Year 2015/2016

- b) Suppose the encoding function be $f_H : B^4 \rightarrow B^7$ and the parity check matrix, H is given by

$$H = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Determine the code words representing word **1110** and **1011**.

(4 marks)

Decoding and Error Correction

- Consider an (m,n) encoding function $f: B^m \rightarrow B^n$.
- The encoded word, $x=f(b) \in B^n$, for $b \in B^m$, is received as the word x_r
- we are faced with the problem of identifying the word b that was the original message.

Decoding and Error Correction

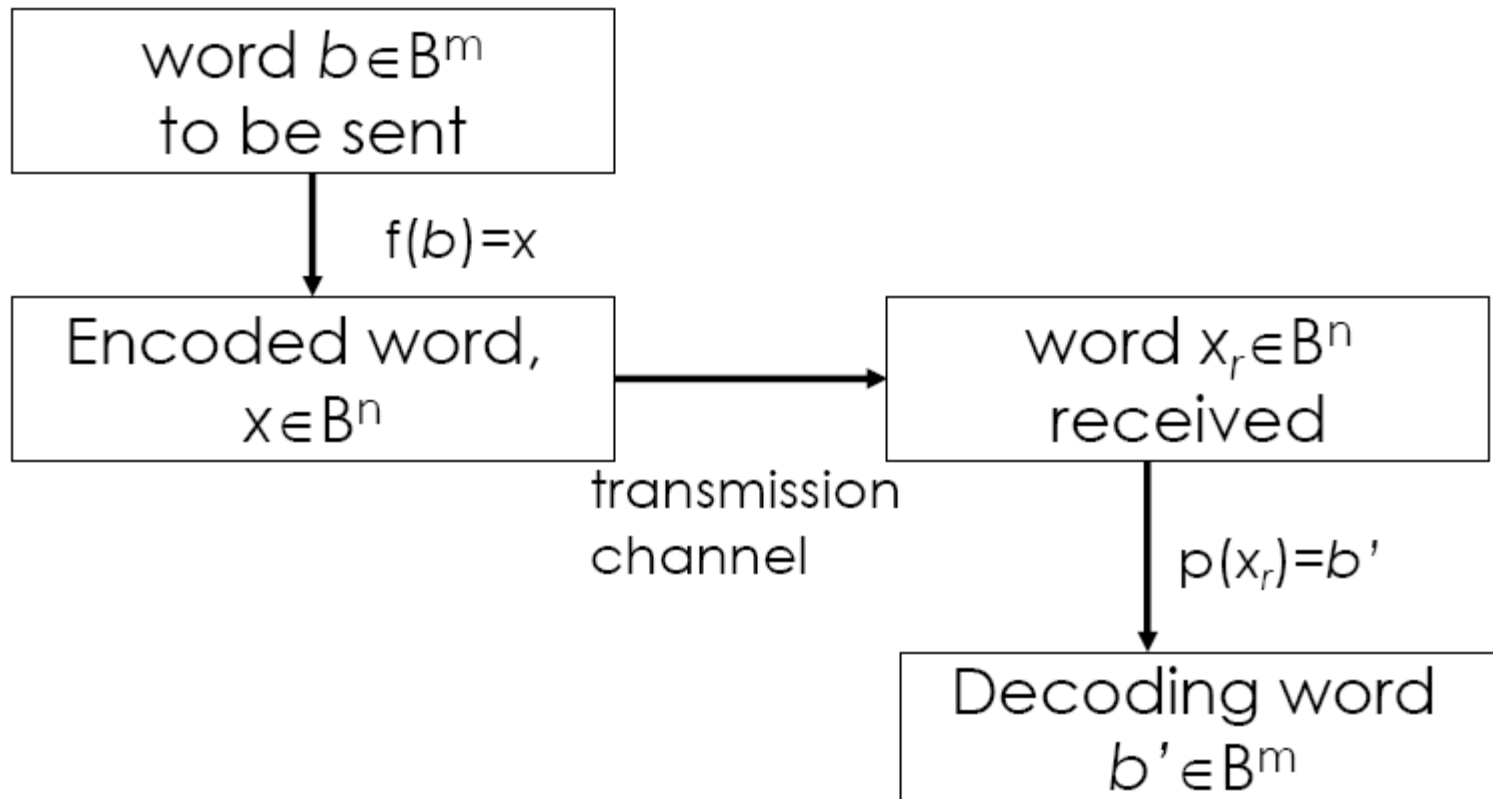
- An onto function $\mathbf{p}: \mathbf{B}^n \rightarrow \mathbf{B}^m$ is called an (n,m) decoding function associated with f , if

$$p(x_r) = b'$$

such that when the transmission channel has no noise then

$$b' = b$$

Decoding and Error Correction





Decoding and Error Correction

- The decoding function **p** is required to be **onto** so that every received word can be decoded to give a word in B^m .
- It decodes properly received words correctly, but decoding of improperly received words may or may not be correct.

example

- The parity check code, $f: B^m \rightarrow B^{m+1}$.
- The decoding function, $p: B^{m+1} \rightarrow B^m$
If $y = y_1 y_2 \dots y_m y_{m+1} \in B^{m+1}$,
then $p(y) = y_1 y_2 \dots y_m \in B^m$
- Let $m=4$,
 $p(10010)=1001$ $p(10001)=1000$



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Decoding and Error Correction

- Let f be an (m,n) encoding function
- Let p be an (n,m) decoding function associated with f .



Decoding and Error Correction

- The pair (f, p) correct k or fewer errors if whenever $x=f(b)$ is transmitted correctly or with k or fewer errors and x_r is received, then $p(x_r)=b$
- Thus x_r is decoded as the correct message b .



Decoding and Error Correction

- Given an (m,n) encoding function,
 $f: B^m \rightarrow B^n$
- We often need to determine an (m,n) decoding function,
 $p: B^n \rightarrow B^m$
associated with f .



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Decoding and Error Correction

- We now discuss a method, called the **maximum likelihood technique**, for determining a decoding function p for a given f .



Decoding and Error Correction

- Since B^m has m elements, there are 2^m code words in B^n .
- List the code words in a fixed order:

$$x^{(1)}, x^{(2)}, \dots, x^{(2^m)}$$



Decoding and Error Correction

- If the received word is x_r , we compute,
 $H(x^{(i)}, x_r)$ for $1 \leq i \leq 2^m$

and choose the first code word, say it is $x^{(s)}$, such that

$$\min_{1 \leq i \leq 2^m} \{H(x^{(i)}, x_r)\} = x^{(s)}$$



Decoding and Error Correction

- $x^{(s)}$ is a code word that is closest to x_r , and the first in the list.
- If $x^{(s)} = f(b)$, we define the maximum likelihood decoding function p associated with f by

$$p(x_r) = b$$



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Decoding and Error Correction

- p depends on the particular order in which code words in $f(B^m)$ are listed.
- If the code words are listed in a different order, we may obtain a different maximum likelihood decoding function p associated with f .

Decoding Procedure

- If $f: B^m \rightarrow B^n$ is a group code, the procedure for obtaining a maximum likelihood decoding function associated with f :
 1. Determine all the left cosets of $N=f(B^m)$ in B^n .
 2. For each coset, find a coset leader (a word of least weight)

Decoding Procedure

3. If the word x_r is received, determine the coset of N to which x_r belongs. There are $2^n/2^m$ distinct cosets of N in B^n .

4. Let e be a coset leader for the coset determined in (3).

Compute, $x = x_r \oplus e$

if $x=f(b)$, we let $p(x_r)=b$.

That is, we decode x_r as b .



Decoding Procedure

- Keep a complete list of all cosets of N in tabular form.
- Each row of the table containing one coset.
- Identify a coset leader in each row.



Decoding Procedure

- When a word x_r is received, we locate the row which contains it, find the coset leader for that row, and add it to x_r .
- This gives us the code word closest to x_r .

Decoding Procedure

- Let $N = \{x^{(1)}, x^{(2)}, \dots, x^{(2^m)}\}$

where $x^{(1)}$ is $\bar{0}$ the identity of B^n .

- List all the elements of N in a row, starting with identity at the left

$\nearrow \bar{0} \quad x^{(2)} \quad x^{(2)} \quad \dots \quad x^{(2^m)}$
 coset leader, e_1

Decoding Procedure

- Choose any word (least weight) e_2 in B^n which has not been listed in the first row.
- List the elements of the coset $e_2 \oplus N$ as the second row.

$$\begin{array}{ccccccc} e_2 & e_2 \oplus x^{(2)} & e_2 \oplus x^{(2)} & \dots & e_2 \oplus x^{(2^m)} \\ \nearrow & & & & \\ \text{coset leader} & & & & \end{array}$$

Decoding Procedure

- Choose another element (least weight) e_3 in B^n which has not been listed in either of the first two rows and form the third row.

$$\begin{matrix} \nearrow \\ e_3 \end{matrix} \quad e_3 \oplus x^{(2)} \quad e_3 \oplus x^{(2)} \quad \dots \quad e_3 \oplus x^{(2^m)}$$

coset leader

- Continue this process until all elements of B^n have been listed.



example

- Consider the (3,5) encoding function defined by

$f(000)=00000$	$f(100)=10011$
$f(001)=00110$	$f(101)=10101$
$f(010)=01001$	$f(110)=11010$
$f(011)=01111$	$f(111)=11100$



example

- Decode the following words relative to a maximum likelihood decoding function:
 - 11001
 - 01010
 - 00111



example

- $N = \{ 00000, 00110, 01001, 01111, 10011, 10101, 11010, 11100 \}$

$$= \{x^{(1)}, x^{(2)}, \dots, x^{(2^m)}\}$$

- $2^5/2^3 = 2^2 = 4$ cosets (4 rows)



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example

- Coset leader, e_1 the identity of B^n ($e_1 \in N$)
- $e_1 = 00000$

example

- Row 1,

$$e_1 = 00000$$

$$e_1 \oplus 00110 = 00110$$

$$e_1 \oplus 01001 = 01001$$

$$e_1 \oplus 01111 = 01111$$

$$e_1 \oplus 10011 = 10011$$

$$e_1 \oplus 10101 = 10101$$

$$e_1 \oplus 11010 = 11010$$

$$e_1 \oplus 11100 = 11100$$

example

- Row 2, coset leader $e_2=00001$

$$e_2 = 00001$$

$$e_2 \oplus 00110 = 00111$$

$$e_2 \oplus 01001 = 01000$$

$$e_2 \oplus 01111 = 01110$$

$$e_2 \oplus 10011 = 10010$$

$$e_2 \oplus 10101 = 10100$$

$$e_2 \oplus 11010 = 11011$$

$$e_2 \oplus 11100 = 11101$$

example

- Row 3, coset leader $e_3 = 00010$

$$e_3 = 00010$$

$$e_3 \oplus 00110 = 00100$$

$$e_3 \oplus 01001 = 01011$$

$$e_3 \oplus 01111 = 01101$$

$$e_3 \oplus 10011 = 10001$$

$$e_3 \oplus 10101 = 10111$$

$$e_3 \oplus 11010 = 11000$$

$$e_3 \oplus 11100 = 11110$$

example

- Row 4, coset leader $e_4 = 10000$

$$e_4 = 10000$$

$$e_4 \oplus 00110 = 10110$$

$$e_4 \oplus 01001 = 11001$$

$$e_4 \oplus 01111 = 11111$$

$$e_4 \oplus 10011 = 00011$$

$$e_4 \oplus 10101 = 00101$$

$$e_4 \oplus 11010 = 01010$$

$$e_4 \oplus 11100 = 01100$$

example

00000	00110	01001	01111	10011	10101	11010	11100
00001	00111	01000	01110	10010	10100	11011	11101
00010	00100	01011	01101	10001	10111	11000	11110
10000	10110	11001	11111	00011	00101	01010	01100

Decode the following words relative to a maximum likelihood decoding function:

- 11001
- 01010
- 00111



example

00000	00110	01001	01111	10011	10101	11010	11100
00001	00111	01000	01110	10010	10100	11011	11101
00010	00100	01011	01101	10001	10111	11000	11110
10000	10110	11001	11111	00011	00101	01010	01100

- 11001 Column 3, $11001 \oplus 10000 = 01001$

$$f(010) = 01001, \quad \rightarrow p(11001) = \mathbf{010}$$



example

00000	00110	01001	01111	10011	10101	11010	11100
00001	00111	01000	01110	10010	10100	11011	11101
00010	00100	01011	01101	10001	10111	11000	11110
10000	10110	11001	11111	00011	00101	01010	01100

•01010

Column 7, $01010 \oplus 10000 = 11010$

$f(110)=11010$, $\rightarrow p(01010)=$ **110**



example

00000	00110	01001	01111	10011	10101	11010	11100
00001	00111	01000	01110	10010	10100	11011	11101
00010	00100	01011	01101	10001	10111	11000	11110
10000	10110	11001	11111	00011	00101	01010	01100

- 00111 Column 2, $00111 \oplus 00001 = 00110$

$$f(001) = 00110, \rightarrow p(00111) = \mathbf{001}$$



exercise

Consider the (3,6) encoding function defined by

$f(000) = 000000$	$f(001) = 000110$
$f(010) = 010010$	$f(011) = 010100$
$f(100) = 100101$	$f(101) = 100011$
$f(110) = 110111$	$f(111) = 110001$

Decode the following words:

(a) 011110 (b) 101011 (c) 110010



Theorem

- Suppose that f is an (m,n) encoding function and p is a maximum likelihood decoding function associated with f .
- Then (f,p) **can correct k or fewer errors** if and only if the minimum distance of f is at least **$2k+1$** .

example

- Let f be the $(3,8)$ encoding function defined by

$f(000)=00000000$	$f(100)=10100100$
$f(001)=10111000$	$f(101)=10001001$
$f(010)=00101101$	$f(110)=00011100$
$f(011)=10010101$	$f(111)=00110001$
- Let p be an $(8,3)$ maximum likelihood decoding function associated with f .
- How many errors can (f,p) correct?

example

- The minimum distance of f is 3, as can be checked by computing the minimum of the distances between all 28 distinct pairs of code words.

- Since the minimum distance of f is 3, we have

$$3 \geq 2k+1, \quad k \leq 1$$

- Thus (f,p) can correct 1 error.

exercise

- Given the following encoding function, $f : B^2 \rightarrow B^5$
$$\begin{aligned} f(00) &= 00000 \\ f(01) &= 01010 \\ f(10) &= 10111 \\ f(11) &= 11110 \end{aligned}$$
- Let p be an $(5,2)$ maximum likelihood decoding function associated with f .
- How many errors can (f,p) correct?



Exercise Past Year 2015/2016

c) Let an encoding function, $f: B^2 \rightarrow B^5$, with f given by,

$$f(00) = 00000$$

$$f(01) = 01011$$

$$f(10) = 10110$$

$$f(11) = 11101$$

Decode the word **11110** and **10101** using the maximum likelihood method. (Note: Copy Table 6 in your answer booklet and complete the '?' cells). (10 marks)

Table 6

	$e_i \oplus 00000$	$e_i \oplus 01011$	$e_i \oplus 10101$	$e_i \oplus 11101$
$e_1 = 00000$	00000	01011	10101	11101
$e_2 = 10000$	10000	11011	00110	01100
$e_3 = ?$	?	?	?	?
$e_4 = 00100$	00100	01111	10010	11001
$e_5 = ?$	?	?	?	?
$e_6 = 00001$	00001	01010	10111	11100
$e_7 = ?$	?	?	?	?
$e_8 = 10100$	10100	10111	00010	01001