



Digital circuit design notes

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¹The notes are from the following books [1, 2]. Not intended for distribution outside the class.

Contents

1	Boolean Algebra	3
1.1	Learning objectives	3
1.2	Motivating Problem	3
1.3	Digital circuits or networks	5
1.4	Two input networks	5
1.5	Multi-input networks	6
1.6	Minterms and Maxterms	7
1.6.1	Minterms	7
1.6.2	Maxterms	9
1.7	Karnaugh maps	11
1.8	More Gates and notations summary	12
1.9	Boolean Algebra	13
1.9.1	Axioms of Boolean algebra	13
1.9.2	Single variable theorems (Prove by drawing K-maps)	14
1.9.3	Two and three variable properties (Prove by K-maps)	15

Chapter 1

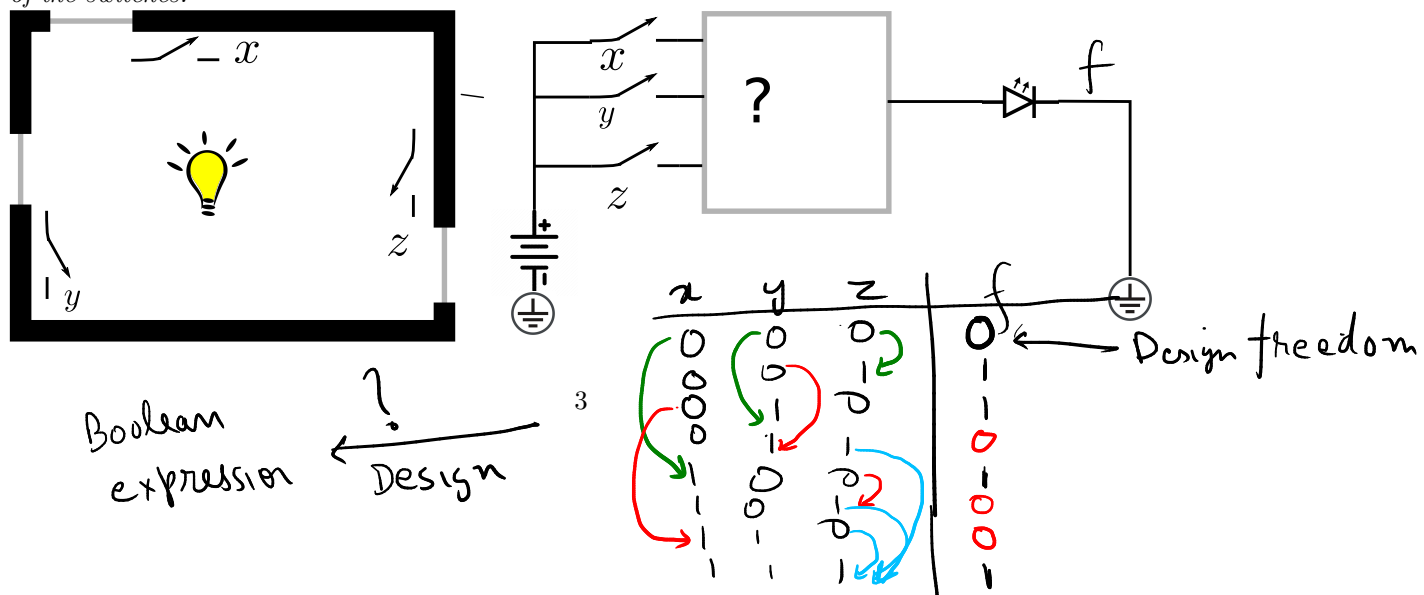
Boolean Algebra

1.1 Learning objectives

1. Representing digital circuits
2. Converting between different notations: Boolean expression, logic networks and switching circuits
3. Converting between different logic network specifications: truth table, minterm, maxterms, product of sums canonical form and sum of product canonical form.
4. Introduce truth tables as Behavioral Verilog
5. This handout has 11 homework problems totaling to **140 marks**

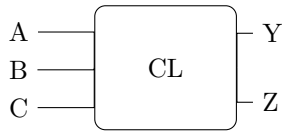
1.2 Motivating Problem

Example 1. Assume that a large room has three doors and that a switch near each door controls a light in the room. It has to be possible to turn the light on or off by changing the state of any one of the switches.



Name	C/Verilog	Boolean expr.	Truth Table	Switching circuit	(ANSI) symbol	Venn diagram															
AND Gate	L = x1 & x2	$L = x_1 \cdot x_2$	<table><tr><th>x_1</th><th>x_2</th><th>$x_1 \cdot x_2$</th></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>0</td></tr><tr><td>1</td><td>0</td><td>0</td></tr><tr><td>1</td><td>1</td><td>1</td></tr></table>	x_1	x_2	$x_1 \cdot x_2$	0	0	0	0	1	0	1	0	0	1	1	1			
x_1	x_2	$x_1 \cdot x_2$																			
0	0	0																			
0	1	0																			
1	0	0																			
1	1	1																			
OR Gate	L = x1 x2	$L = x_1 + x_2$	<table><tr><th>x_1</th><th>x_2</th><th>$x_1 + x_2$</th></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>1</td></tr><tr><td>1</td><td>0</td><td>1</td></tr><tr><td>1</td><td>1</td><td>1</td></tr></table>	x_1	x_2	$x_1 + x_2$	0	0	0	0	1	1	1	0	1	1	1	1			
x_1	x_2	$x_1 + x_2$																			
0	0	0																			
0	1	1																			
1	0	1																			
1	1	1																			
NOT Gate	L = ~ x1	$L = \bar{x}_1 = x'_1$	<table><tr><th>x_1</th><th>\bar{x}_1</th></tr><tr><td>0</td><td>1</td></tr><tr><td>1</td><td>0</td></tr></table>	x_1	\bar{x}_1	0	1	1	0												
x_1	\bar{x}_1																				
0	1																				
1	0																				

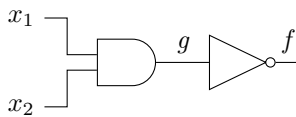
1.3 Digital circuits or networks



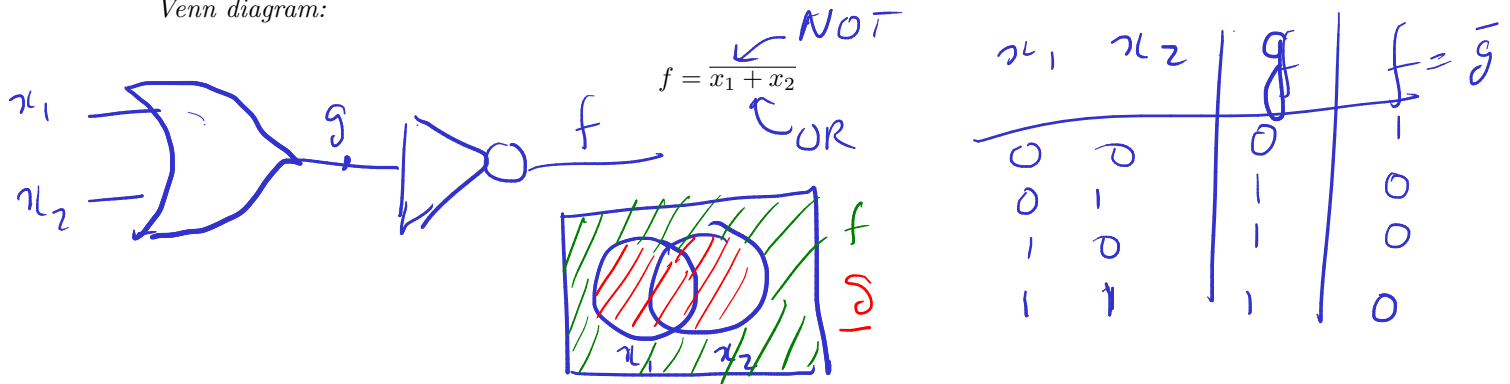
$$Y = F(A, B, C) \quad Z = G(A, B, C)$$

1.4 Two input networks

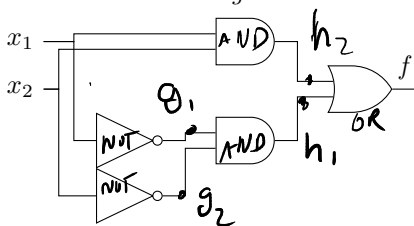
Example 2. Convert the following (ANSI) network into a Boolean expression, a truth table and a Venn diagram.



Example 3. Convert the following Boolean expression into a (ANSI) network, a truth table and a Venn diagram:



Problem 1 (10 marks). Convert the following (ANSI) network into a Boolean expression, a truth table and a Venn diagram.



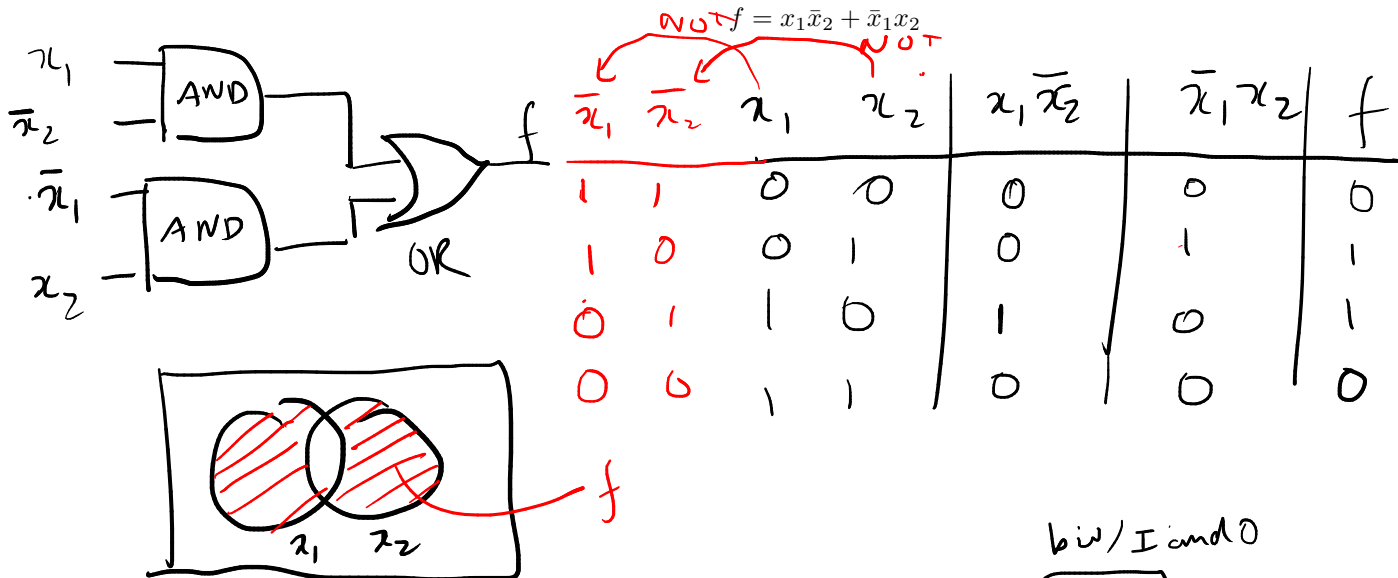
$$\begin{aligned} g_1 &= \bar{x}_1 \\ g_2 &= \bar{x}_2 \\ h_2 &= x_1 \cdot x_2 \\ h_1 &= g_1 \cdot g_2 \end{aligned}$$

$$f = x_1 x_2 + \bar{x}_1 \bar{x}_2$$

$$h_1 = g_1 g_2$$

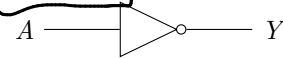
$$f = h_1 + h_2 = g_1 g_2 + x_1 x_2 = \bar{x}_1 \bar{x}_2 + x_1 x_2$$

Example 4. Convert the following Boolean expression into a network, a truth table and a Venn diagram:



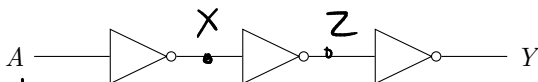
b/w
I and 0

Problem 2 (5 marks). Can two different circuits have the same truth table? Can two different truth tables have the same circuit? Consider the following two circuits for example



A	Y
0	1
1	0

A	X	Z	Y
0	1	0	1
1	0	1	0



Network / Circuit

Input / Output

ANSI / Boolean expression
networks

Analysis \rightarrow TT / Venn Diagram

Design \leftarrow

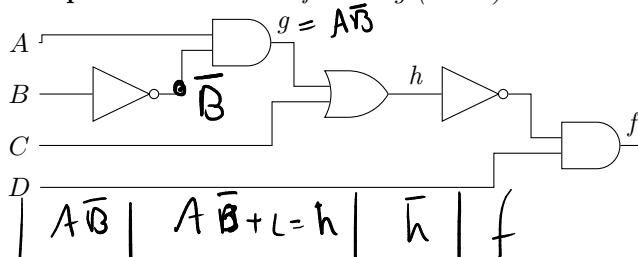
How (2)

What (1)

Remark 1. Truth tables and Venn diagrams define what the combinational circuit should do. Truth tables define output for every input. Boolean expression and networks define how to achieve the desired input output relationship.

1.5 Multi-input networks

Example 5. Convert the following (ANSI) network into a Boolean expression and a truth table.



$$h = A\bar{B} + C$$

$$f = D \cdot (\bar{h})$$

$$= D \cdot (\overline{A\bar{B} + C})$$

AB	C	D	\bar{B}	$A\bar{B}$	$A\bar{B} + C = h$	\bar{h}	f
00	0	0	1	0	0	1	0
00	0	1	1	0	0	1	0
00	1	0	1	0	1	0	0
00	1	1	1	0	1	0	0
01	0	0	0	0	0	1	0
01	0	1	0	0	0	1	0
01	1	0	0	0	1	0	0
01	1	1	0	0	1	0	0
10	0	0	1	1	1	0	0
10	0	1	1	1	1	0	0
10	1	0	1	1	1	0	0
10	1	1	1	1	1	0	0
11	0	0	0	0	0	1	0
11	0	1	0	0	0	1	0
11	1	0	0	0	1	0	0
11	1	1	0	0	1	0	0

A	B	C	D	\bar{B}	$A \bar{B}$	$A \bar{B} + C = h$	\bar{h}	$f = \bar{h}.D$
0	0	0	0	1	0	0	1	0
0	0	0	1	1	0	0	1	1
0	0	1	0	1	0	1	0	0
0	0	1	1	1	0	1	0	0
0	1	0	0	0	0	0	1	0
0	1	0	1	0	0	0	1	1
0	1	1	0	0	0	1	0	0
0	1	1	1	0	0	1	0	0
1	0	0	0	1	1	1	0	0
1	0	0	1	1	1	1	0	0
1	0	1	0	1	1	1	0	0
1	0	1	1	1	1	1	0	0
1	1	0	0	0	0	0	1	0
1	1	0	1	0	0	0	1	1
1	1	1	0	0	0	1	0	0
1	1	1	1	0	0	1	0	0

Decimal to Binary

Repeated division by 2 and noting all the remainders

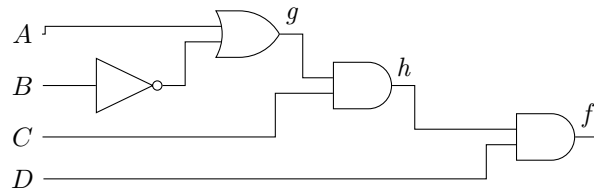
$$29_{10} = 11101_2$$

2	29	
2	14	1
2	7	0
2	3	1
2	1	1
	0	1

0	0
1	1
0	2
1	3
0	4
0	5
1	6
1	7
0	8
0	9
1	10
0	11
1	12
1	13
1	14
1	15

$$\frac{+1}{10}$$

Problem 3 (20 marks). Convert the following (ANSI) network into a Boolean expression and a



truth table.

1.6 Minterms and Maxterms

1.6.1 Minterms

Minterm is a product involving all inputs (or complements) to a function. Every row of a truth table has a corresponding minterm. Minterm is true if and only if the corresponding row in the table is active.

Minterms defined as follows for each row of a two input truth table:

A	B	minterm	minterm name
0	0	$\bar{A}\bar{B}$	m_0
0	1	$\bar{A}B$	m_1
1	0	$A\bar{B}$	m_2
1	1	AB	m_3

	A	B	$\bar{A}\bar{B}$	$\bar{A}B$
m_0	0	0	1	0
1	0	1	0	1
2	1	0	0	0
3	1	1	0	1

Consider a two input circuit whose output Y is given by the truth table:

A	B	Y	minterm	minterm name
0	0	0	$\bar{A}\bar{B}$	m_0
0	1	1	$\bar{A}B$	m_1
1	0	0	$A\bar{B}$	m_2
1	1	1	AB	m_3

then $Y = \bar{A}B + AB = m_1 + m_3 = \sum(1, 3)$.

Minterms and Maxterms

① Are product terms

② Contain all inputs inverted or not
NOT gate

③ In the truth table of a minterm one and only one row is 1, all other rows are zero

④ They are denoted by small m with an index of the row number that is 1 in the truth table

Two inputs

	A	B	$m_3 = \bar{A}B$	$m_0 = A\bar{B}$	$m_1 = \bar{A}\bar{B}$	$m_2 = AB$
0	0	0	0	1	1	0
1	0	1	1	0	0	0
2	1	0	0	0	1	0
3	1	1	0	0	0	1

A, B

$m_2 = ?$

Binary

10

$$m_2 = A\bar{B}$$

A, B

m_0

Binary

00

$$m_0 = \bar{A}\bar{B}$$

$m_3 = ?$

Binary

11

$$m_3 = AB$$

Most significant bit (MSB)

x_3, x_2, x_1, x_0

Least significant bit (LSB)

$$m_{11} = ?$$

for 4 inputs

x_3, x_2, x_1, x_0

Binary

1011

$$m_{11} = x_3 \bar{x}_2 x_1 x_0$$

$m_{13} = ?$

for 4 inputs

x_3, x_2, x_1, x_0

A, B, C, D

MSB

LSB

$13_{10} = 1101_2$

$$m_{13} = x_3 x_2 \bar{x}_1 x_0 \checkmark$$

$$m_{13} = ABC\bar{D} \checkmark$$

Why minterms?

	A	B	$m_3 = \overline{A}B$	$m_0 = \overline{A}\overline{B}$	$m_1 = \overline{A}B$	$m_2 = A\overline{B}$	Given
0	0	0	0	1	0	0	1
1	0	1	1	0	1	0	0
2	1	0	0	0	0	1	1
3	1	1	1	0	0	0	0

$f = m_0 + m_2 = \overline{A}\overline{B} + A\overline{B}$

x	y	z	f
0	0	0	0
1	0	0	0
2	0	1	1
3	0	1	0
4	1	0	0
5	1	0	1
6	1	1	0
7	1	1	1

Minterm notation
 $f = m_1 + m_2 + m_4 + m_7 = \sum m(1, 2, 4, 7)$
 $= \overline{x}\overline{y}z + \overline{x}y\overline{z} + x\overline{y}\overline{z} + xyz$
 Sum of products canonical form \neq sum of products form
 (Not discussed yet)

Maxterms (Dual of minterm)

	A	B	$M_0 = A+B$	$M_1 = A+\overline{B}$	$M_2 = \overline{A}+B$	$M_3 = \overline{A}+\overline{B}$
0	0	0	0	1	1	1
1	0	1	1	0	1	1
2	1	0	1	1	0	1
3	1	1	1	1	1	0

Maxterm

- Sum of all input inverted or not
- contains all inputs
- one and only one row of TT is 0 all others are 1
- Denote by capital M, subscripted by the row that is 0

Shortcut conversion of Maxterm into boolean expression

$M_2 = ?$
 Binary $10 \rightarrow \overline{A} + B$

M_{11} for 4 input A, B, C, D
 Binary $1011 \rightarrow \overline{A} + B + \overline{C} + D$

How to write Boolean expression from TT using Maxterms

A	B	f
0	0	1
1	0	0 ✓
2	1	1
3	1	0 ✓

Maxterm notation
 $f = M_1 \cdot M_3 = \prod M(1, 3)$
 $= (A + \overline{B}) \cdot (\overline{A} + \overline{B})$

Product of sums canonical form

This also gives the *sum of products canonical form*.

Example 6. What is the minterm m_{13} for a 4-input circuit with inputs x, y, z, w (ordered from MSB to LSB).

$$m_{13} = x\bar{y}zw \quad \text{because } 13_{10} = 1101_2$$

Problem 4 (5 marks). What is the minterm m_{23} for a 5-input circuit with inputs a, b, c, d, e (ordered from MSB to LSB).

Example 7. Convert the following 4-input truth table into sum of minterms and sum of products canonical form.

minterm name	A	B	C	D	f
m_0	0	0	0	0	0
m_1	0	0	0	1	1
m_2	0	0	1	0	0
m_3	0	0	1	1	0
m_4	0	1	0	0	0
m_5	0	1	0	1	1
m_6	0	1	1	0	0
m_7	0	1	1	1	0
m_8	1	0	0	0	0
m_9	1	0	0	1	0
m_{10}	1	0	1	0	0
m_{11}	1	0	1	1	0
m_{12}	1	1	0	0	0
m_{13}	1	1	0	1	1
m_{14}	1	1	1	0	0
m_{15}	1	1	1	1	0

$$f = m_1 + m_5 + m_{13} = \bar{A}\bar{B}CD + \bar{A}B\bar{C}D + A\bar{B}\bar{C}D$$

Sum of minterms Sum of products canonical form

Problem 5 (10 marks). Convert the following 4-input truth table into sum of minterms and sum of products canonical form.

<i>minterm name</i>	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>f</i>
m_0	0	0	0	0	0
m_1	0	0	0	1	0
m_2	0	0	1	0	0
m_3	0	0	1	1	1
m_4	0	1	0	0	0
m_5	0	1	0	1	0
m_6	0	1	1	0	0
m_7	0	1	1	1	1
m_8	1	0	0	0	0
m_9	1	0	0	1	0
m_{10}	1	0	1	0	0
m_{11}	1	0	1	1	1
m_{12}	1	1	0	0	0
m_{13}	1	1	0	1	1
m_{14}	1	1	1	0	1
m_{15}	1	1	1	1	0

1.6.2 Maxterms

Maxterm is a sum involving all inputs (or complements) to a function. Every row of a truth table has a corresponding maxterm. Minterm is false if and only if the corresponding row in the table is active.

Maxterms are defined as follows for each row of a two input truth table:

<i>A</i>	<i>B</i>	maxterm	maxterm name
0	0	$A + B$	M_0
0	1	$A + \bar{B}$	M_1
1	0	$\bar{A} + B$	M_2
1	1	$\bar{A} + \bar{B}$	M_3

Consider a two input circuit whose output Y is given by the truth table:

<i>A</i>	<i>B</i>	<i>Y</i>	maxterm	maxterm name
0	0	0	$A + B$	M_0
0	1	1	$A + \bar{B}$	M_1
1	0	0	$\bar{A} + B$	M_2
1	1	1	$\bar{A} + \bar{B}$	M_3

then $Y = (A + B)(\bar{A} + B) = M_0M_2$.

Writing a functional specification in terms of minterms is also called product of sums canonical form.

Example 8. Write the maxterm M_{11} for 4-input Boolean function with the ordered inputs A, B, C, D .

$$M_{11} = A + B + C + D$$

Example 9. Convert the following 4-input truth table into product of maxterms and product of sums canonical form.

maxterm name	A	B	C	D	f
M ₀	0	0	0	0	0
M ₁	0	0	0	1	0
M ₂	0	0	1	0	0
M ₃	0	0	1	1	1
M ₄	0	1	0	0	0
M ₅	0	1	0	1	0
M ₆	0	1	1	0	0
M ₇	0	1	1	1	1
M ₈	1	0	0	0	0
M ₉	1	0	0	1	0
M ₁₀	1	0	1	0	0
M ₁₁	1	0	1	1	1
M ₁₂	1	1	0	0	0
M ₁₃	1	1	0	1	1
M ₁₄	1	1	1	0	1
M ₁₅	1	1	1	1	0

$$f = M_0 M_1 M_2 M_4 M_5 M_6 M_8 M_9 M_{10} M_{12} M_{15}$$

Product of Maxterms

$$f = (A+B+C+D) \cdot (A+B+C+\bar{D}) \cdot (A+B+\bar{C}+D) \cdot (A+\bar{B}+C+D) \cdot (A+\bar{B}+C+\bar{D}) \cdot (A+\bar{B}+\bar{C}+D) \cdot (\bar{A}+B+C+D) \cdot (\bar{A}+B+C+\bar{D}) \cdot (\bar{A}+B+\bar{C}+D) \cdot (\bar{A}+\bar{B}+C+D) \cdot (\bar{A}+\bar{B}+\bar{C}+D)$$

$M_0 \quad M_1 \quad M_2 \quad M_4 \quad M_5 \quad M_6 \quad M_8 \quad M_9 \quad M_{10} \quad M_{12} \quad M_{15}$

Product of sums canonical form

Problem 6 (10 marks). Convert the following 4-input truth table into product of maxterms and products of sums canonical form.

maxterm name	A	B	C	D	f
M ₀	0	0	0	0	0
M ₁	0	0	0	1	1
M ₂	0	0	1	0	1
M ₃	0	0	1	1	1
M ₄	0	1	0	0	1
M ₅	0	1	0	1	0
M ₆	0	1	1	0	1
M ₇	0	1	1	1	1
M ₈	1	0	0	0	0
M ₉	1	0	0	1	1
M ₁₀	1	0	1	0	1
M ₁₁	1	0	1	1	1
M ₁₂	1	1	0	0	0
M ₁₃	1	1	0	1	1
M ₁₄	1	1	1	0	1
M ₁₅	1	1	1	1	0

Example 10. Write the 3-input truth table for the function $f = m_2 + m_3 + m_7$.

```

row num|ABC|f
0|000|0
1|001|0
2|010|1
3|011|1
4|100|0
5|101|0
6|110|0
7|111|1

```

Problem 7 (10 marks). Write the 3-input truth table for the function $f = M_4 M_5 M_7$.

Problem 8 (10 marks). *Write the truth table for the function $f = \bar{A}B\bar{C} + AB\bar{C}$.*

1.7 Karnaugh maps

Two input K-maps

Three input K-maps

Four input K-maps

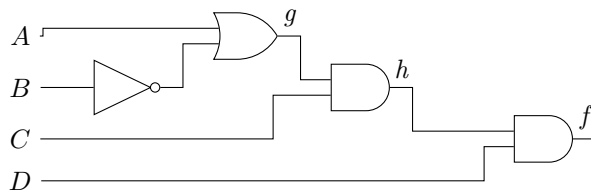
Five input K-maps

1.8 More Gates and notations summary

Name	C/Verilog	Boolean expr.	Truth Table	(ANSI) symbol	K-map															
NAND Gate	$Q = \sim(x1 \& x2)$	$Q = \overline{x_1 \cdot x_2} = \overline{x_1}x_2 + x_1\overline{x_2}$	<table><tr><th>x_1</th><th>x_2</th><th>$\overline{x_1 \cdot x_2}$</th></tr><tr><td>0</td><td>0</td><td>1</td></tr><tr><td>0</td><td>1</td><td>1</td></tr><tr><td>1</td><td>0</td><td>1</td></tr><tr><td>1</td><td>1</td><td>0</td></tr></table>	x_1	x_2	$\overline{x_1 \cdot x_2}$	0	0	1	0	1	1	1	0	1	1	1	0		
x_1	x_2	$\overline{x_1 \cdot x_2}$																		
0	0	1																		
0	1	1																		
1	0	1																		
1	1	0																		
NOR Gate	$Q = \sim(x1 \mid x2)$	$Q = \overline{x_1 + x_2}$	<table><tr><th>x_1</th><th>x_2</th><th>$\overline{x_1 + x_2}$</th></tr><tr><td>0</td><td>0</td><td>1</td></tr><tr><td>0</td><td>1</td><td>0</td></tr><tr><td>1</td><td>0</td><td>0</td></tr><tr><td>1</td><td>1</td><td>0</td></tr></table>	x_1	x_2	$\overline{x_1 + x_2}$	0	0	1	0	1	0	1	0	0	1	1	0		
x_1	x_2	$\overline{x_1 + x_2}$																		
0	0	1																		
0	1	0																		
1	0	0																		
1	1	0																		
XOR Gate	$Q = x1 \wedge x2$	$Q = x_1 \oplus x_2$	<table><tr><th>x_1</th><th>x_2</th><th>$x_1 \oplus x_2$</th></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>1</td></tr><tr><td>1</td><td>0</td><td>1</td></tr><tr><td>1</td><td>1</td><td>0</td></tr></table>	x_1	x_2	$x_1 \oplus x_2$	0	0	0	0	1	1	1	0	1	1	1	0		
x_1	x_2	$x_1 \oplus x_2$																		
0	0	0																		
0	1	1																		
1	0	1																		
1	1	0																		
XNOR Gate	$Q = \sim(x1 \wedge x2)$	$Q = \overline{x_1 \oplus x_2}$	<table><tr><th>x_1</th><th>x_2</th><th>$\overline{x_1 \oplus x_2}$</th></tr><tr><td>0</td><td>0</td><td>1</td></tr><tr><td>0</td><td>1</td><td>0</td></tr><tr><td>1</td><td>0</td><td>0</td></tr><tr><td>1</td><td>1</td><td>1</td></tr></table>	x_1	x_2	$\overline{x_1 \oplus x_2}$	0	0	1	0	1	0	1	0	0	1	1	1		
x_1	x_2	$\overline{x_1 \oplus x_2}$																		
0	0	1																		
0	1	0																		
1	0	0																		
1	1	1																		

Example 11. Convert the following Boolean expression into a K-map. $f = \overline{A\overline{B}} + CD$

Problem 9. Convert the following logic circuit into a K-map.



1.9 Boolean Algebra

1.9.1 Axioms of Boolean algebra

1. $0 \cdot 0 = 0$
2. $1 + 1 = 1$

3. $1 \cdot 1 = 1$

4. $0 + 0 = 0$

5. $0 \cdot 1 = 1 \cdot 0 = 0$

6. $\bar{0} = 1$

7. $\bar{1} = 0$

8. $x = 0$ if $x \neq 1$

9. $x = 1$ if $x \neq 0$

1.9.2 Single variable theorems (Prove by drawing K-maps)

1. $x \cdot 0 = 0$

2. $x + 1 = 1$

3. $x \cdot 1 = x$

4. $x + 0 = x$

5. $x \cdot x = x$

6. $x + x = x$

7. $x \cdot \bar{x} = 0$

8. $x + \bar{x} = 1$

9. $\bar{\bar{x}} = x$

Remark 2 (Duality). *Swap $+$ with \cdot and 0 with 1 to get another theorem*

1.9.3 Two and three variable properties (Prove by K-maps)

1. Commutative: $x \cdot y = y \cdot x$, $x + y = y + x$

2. Associative: $x \cdot (y \cdot z) = (x \cdot y) \cdot z$, $x + (y + z) = (x + y) + z$

3. Distributive: $x \cdot (y + z) = x \cdot y + x \cdot z$, $x + y \cdot z = (x + y) \cdot (y + z)$

4. Absorption: $x + x \cdot y = x$, $x \cdot (x + y) = x$

5. Combining: $x \cdot y + x \cdot \bar{y}, (x + y) \cdot (x + \bar{y}) = x$

6. DeMorgan's theorem: $\overline{x \cdot y} = \bar{x} + \bar{y}, \overline{x + y} = \bar{x} \cdot \bar{y}.$

7. Concensus:

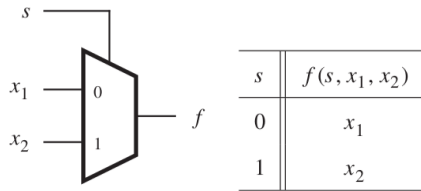
(a) $x + \bar{x} \cdot y = x + y$

(b) $x \cdot (\bar{x} + y) = x \cdot y$

(c) $x \cdot y + y \cdot z + \bar{x} \cdot z = x \cdot y + \bar{x} \cdot z$

(d) $(x + y) \cdot (y + z) \cdot (\bar{x} + z) = (x + y) \cdot (\bar{x} + z)$

Example 12 (Multiplexer). *Multiplexer is a circuit used to select one of the input lines x_1 and x_2 based only select input s . When $s = 0$, x_1 is selected, x_2 is selected otherwise. Find a boolean expression and a circuit for multiplexer*



Example 13. *Simplify $f = \bar{A}\bar{B}\bar{C} + \bar{A}\bar{B}C + A\bar{B}\bar{C}$ using boolean algebra.*

Problem 10 (30 marks, Exercise 2.14 [1]). *Simplify the following Boolean equations using Boolean theorems.*

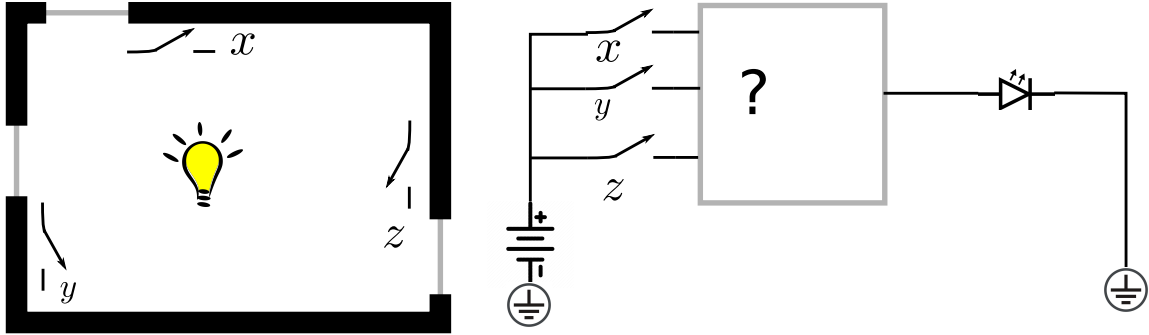
$$Y = \bar{A}BC + \bar{A}\bar{B}\bar{C} \quad (1.1)$$

$$Y = A\bar{B}C + A\bar{B} \quad (1.2)$$

$$Y = ABC\bar{D} + AB\bar{C}D + (A + B + C + D) \quad (1.3)$$

Example 14. *Simplify $f = \bar{A}\bar{A}\bar{C} + \bar{A}\bar{B}C$ using K-maps.*

Example 15. *Assume that a large room has three doors and that a switch near each door controls a light in the room. It has to be possible to turn the light on or off by changing the state of any one of the switches.*



Problem 11 (20 marks, Exercise 2.38 [1]). An M -bit thermometer code for the number k consists of k 1's in the least significant bit positions and $M - k$ 0's in all the more significant bit positions. A binary-to-thermometer code converter has N inputs and $2^N - 1$ outputs. It produces a $2^N - 1$ bit thermometer code for the number specified by the input. For example, if the input is 110, the output should be 0111111. Design a 3:7 binary-to-thermometer code converter. Give a simplified Boolean equation for each output.

Bibliography

- [1] Sarah L Harris and David Harris. *Digital design and computer architecture*. Morgan Kaufmann, 2022.
- [2] Brown Stephen and Vranesic Zvonko. *Fundamentals of digital Logic with Verilog design*. McGraw Hill, 2022.