

# 3 Combinatorial Logic

## Student Group

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## 3. Combinatorial Logic

### introductory example

Fig. 1: Simulation of a 7-segment encoder and display

The combinatorial logic shown in `<impref pic1>` enables to output distinct logic values for each logic input. When you change the input nibble you can see that the correct number appears on the 7-segment-display. By clicking onto the bits of the input nibble, you can change the number.

Tasks:

1. Which output  $Y_0$  ...  $Y_6$  is generated from the input nibble 1000? Which from 1001?
2. Is the output only depending on the input? Is there a dependence on the history?

### 3.1 Combinatorial Circuit

Up to now, we looked onto simple logic circuits. These are relatively easy to analyze and synthesize (=develop). The main question in this chapter is: how can we set up and optimize logic circuits?

In the following we have a look onto combinatorial circuits. These are generally logic circuits with

- $n$  inputs  $X_0, X_1, \dots, X_{n-1}$
- $m$  outputs  $Y_0, Y_1, \dots, Y_{m-1}$
- no "memory", that is: a given set of input bits results in a distinct output

They can be described by

- truth table
- boolean formula
- hardware description language

The latter one is not in the focus of this course.

The applications range:

- (simple) half/full adder
- [digital comparators](#) (logic circuit to compare 2 values)
- Multiplexer / demultiplexer
- Arithmetic logic units in microcontrollers and processors
- much more

#### 3.1.1 Example

In order to understand the synthesis of a combinatoric logic we will follow a step-by-step example for

this chapter.

Imagine you are working for a company called “mechatronics and robotics”. One customer wants to have an intelligent switch as input device connected to a microcontroller for controlling an oven. For this project “Therm-o-Safety” he needs a combinatoric logic:

- The intelligent switch has 4 user selectable positions: \$1\$, \$2\$, \$3\$, \$4\$
- Additionally there are 2 non-selectable positions for the case of failure.
- The output \$Y=1\$ will activate a temperature monitoring.
- The temperature monitoring has to be active for \$3\$ and \$4\$ and in case of a major failure. A major failure is for example, when the switch position is unclear. In this case the input of the combinatorial circuit is “ON”.
- There are no other cases of inputs.

This requirements are put into a truth table:

Therm-o-Safety				
Input	X2	X1	X0	Y
	0	0	0	-
1	0	0	1	0
2	0	1	0	0
3	0	1	1	1
4	1	0	0	1
	1	0	1	-
OFF	1	1	0	0
ON	1	1	1	1

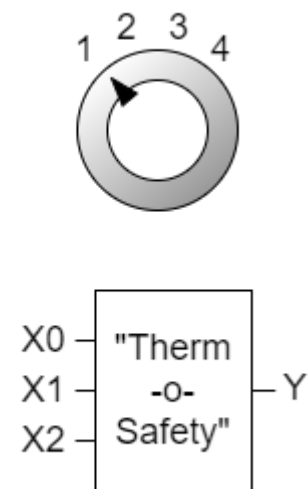


Fig. 2: Therm-o-Safety truth table

figure 2 shows one implementation of this requirements. The inputs 001 ... 011 represent the inputs \$1\$...\$4\$. The cases of failure are coded with 110 and 111. The output \$Y\$ is activated as requested. For the two combinations 000 and 101 there is no output value defined. Depending on the requirements for a project these shall either better be 0 or 1 or the output of these does not matter. We had this “does not matter” before: the technical term is “I don't care”, and it is written as a - or a x.

By this, we have done the first step in order to synthesize the requested logic.

### 3.1.2 Sum of Products

Now, we want to investigate some of the input combinations (= lines in the truth table). At first, we have a look onto the input combination 011, where the output has to be \$Y=1\$.

If this input combination would be the only one for the output of \$Y=1\$, the following could be stated: “\$Y=1\$ (only) when the \$X\_0\$ is \$1\$ AND \$X\_1\$ is \$1\$ AND \$X\_2\$ is \$0\$”. It can also be re-arranged to:

“ $Y=1$  (only) when the  $X_0$  is  $1$  AND  $X_1$  is  $1$  AND  $X_2$  is not  $1$  ”.

This statement is similar to  $X_0 \& X_1 \& \overline{X_2}$ . The used conjunction results only in  $1$ , when all inputs are  $1$ . The negation of  $X_2$  takes account of the fact, that  $X_2$  has to be  $0$ .

Fig. 3: Therm-o-Safety truth table - first analysis

Therm-o-Safety				
Input	X2	X1	X0	Y
	0	0	0	-
1	0	0	1	0
2	0	1	0	0
3	0	1	1	1
4	1	0	0	1
	1	0	1	-
OFF	1	1	0	0
ON	1	1	1	1

$$\overline{X_2} \& X_1 \& X_0$$

figure 3 shows the boolean expression for ths combination. In figure 4, this boolean expression is converted into a struction with logic gates.

Fig. 4: logic circuit for the combination '100'

With the same idea in mind, we can have a look for the other combinations resulting in  $Y=1$ . These are the combinations 100 and 111:

- For 100 The statement would be: “ $Y=1$  (only) when the  $X_0$  is  $0$  AND  $X_1$  is  $0$  AND  $X_2$  is  $1$ ”. Similary to the combination above this leads to:  $\overline{X_0} \& \overline{X_1} \& X_2$ .
- For 111, the boolean expression is  $X_0 \& X_1 \& X_2$ .

**Note!**

- Each row in a truth table (=one distinct combination) can be represented by a **minterm** or **maxterm**
- A **minterm** is the conjunction (AND'ing) of all inputs, where unter ceratin instances an negation have to be used
- In a minterm an input variable with 0 has to be negated, in order to use it as an input for the AND.  
e.g.  $X_0 = 0$  AND  $X_1 = 1 \quad \rightarrow \quad \overline{X_0} \& X_1$

Fig. 5: Therm-o-Safety truth table - sum of products

Therm-o-Safety					
Input	X2	X1	X0	Y	minterm
	0	0	0	-	
1	0	0	1	0	
2	0	1	0	0	
3	0	1	1	1	$\overline{X_2} \cdot X_1 \cdot X_0$
4	1	0	0	1	$X_2 \cdot \overline{X_1} \cdot \overline{X_0}$
	1	0	1	-	
OFF	1	1	0	0	
ON	1	1	1	1	$X_2 \cdot X_1 \cdot X_0$

In [figure 5](#) all minterms for  $Y=1$  are shown. The [figure 6](#) depicts all the logic circuits for the three minterms. These lead to the outputs  $Y'$ ,  $Y''$ , and  $Y'''$ .

Fig. 6: logic circuit for the combinations '100', '110', '111'

For the final step we have to combine the single results for the minterms. The output has to be  $1$  when at least one of the minterms is  $1$ . Therefore, the minterms have to be connected disjunctive:

$$Y = Y' + Y'' + Y''' \quad Y = (X_0 \wedge X_1 \wedge \overline{X_2}) + (\overline{X_0} \wedge \overline{X_1} \wedge X_2) + (X_0 \wedge X_1 \wedge X_2)$$

This leads to the logic circuit shown in [figure 7](#). Here, you can input the different combinations by clicking onto the bits of the input nibble.

Fig. 7: logic circuit for therm-o-safety

### Note!

- The disjunction of the minterms is called **sum of products, SoP, disjunctive normal form** or **DNF**.
- When all inputs are used in each of the minterms the normal form is called **full disjunctive normal form**
- When synthesizing a logic circuit by sum of products, all 'don't care' terms outputting  $0$ .

We have seen, that the sum of products is one tool to derive a logic circuit based on a truth table. Alternatively it is also possible to insert an intermediate step, where the logic formula is simplified.

In the following one possible optimization is shown:

```

\begin{align*} Y &= & (X_0 \& X_1 \& \overline{X_2}) & \quad + & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & (\overline{X_0} \& X_1 \& \overline{X_2}) & \quad + & (X_0 \& X_1 \& \overline{X_2}) & \quad + & (X_0 \& \overline{X_1} \& X_2) & \quad + & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & (\overline{X_0} \& X_1 \& X_2) & \quad + & (X_0 \& X_1 \& X_2) & \quad | & \text{\textit{associative law}} \\ Y &= & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & (X_0 \& X_1 \& \overline{X_2}) & \quad + & (X_0 \& \overline{X_1} \& X_2) & \quad + & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & ((X_0 \& X_1) \& \overline{X_2}) & \quad + & ((X_0 \& \overline{X_1}) \& X_2) & \quad + & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & ((X_0 \& X_1) \& (\overline{X_2} + X_2)) & \quad | & \text{\textit{distributive law}} \\ Y &= & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & ((X_0 \& X_1) \& \overline{X_2}) & \quad + & ((X_0 \& \overline{X_1}) \& X_2) & \quad + & ((X_0 \& X_1) \& (\overline{X_2} + X_2)) & \quad | & \text{\textit{complementary element}} \\ Y &= & (\overline{X_0} \& \overline{X_1} \& X_2) & \quad + & (X_0 \& X_1) & \quad | & \text{\textit{complementary element}} \end{align*}
    
```

### 3.1.3 Product of Sums

In the sub-chapter before we had a look onto the combinations which generates an output of  $Y=1$  by means of the AND operator. Now we are investigating the combinations with  $Y=0$ . Therefore, we need an operator, which results in  $0$  for only on distinct combination.

The first combination to look for is  $001$ . If this input combination would be the only one for the output of  $Y=0$ , the following could be stated:

" $Y=0$  (only) when the  $X_0$  is  $1$  AND  $X_1$  is  $0$  AND  $X_2$  is  $0$ ". With having the duality in mind (see cpt. [the\\_set\\_of\\_rules](#)):

" $Y=1$  when  $X_0$  is  $0$  OR  $X_1$  is  $1$  OR  $X_2$  is  $1$ "

This requirements are put into a truth table:

Therm-o-Safety				
Input	X2	X1	X0	Y
	0	0	0	-
1	0	0	1	0
2	0	1	0	0
3	0	1	1	1
4	1	0	0	1
	1	0	1	-
OFF	1	1	0	0
ON	1	1	1	1

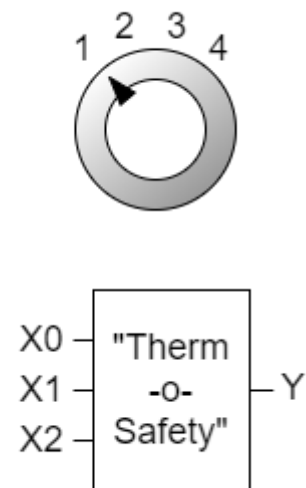


Fig. 8: Therm-o-Safety truth table

**Note!**

- The disjunction of the minterms is called **products of sum, PoS, conjunctive normal form** or **CNF**.
- The products of sum is the DeMorgan dual of the sum of products.

## 3.2

### 3.2.1 The Karnaugh Map

[interactive example](#)

#### Exercise 3.1.x Further Questions

1. compare the results with the output given [here](#) (the output \$\$ can be changed by clicking onto it)

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