Improved colored cubes teaching kit in representing and simplifying Boolean logic functions

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ABSTRACT

This work presents, explains, and discusses a colored variables cubes teaching kit. The cubes teaching kit is designed based on the cubes method that was developed to graphically simplify the Boolean logic functions with three, four, five, and six variables. This renewed method is developed to overcome the limitation of the conventional Karnaugh maps method in terms of simplifying Boolean functions with a maximum of four variables only. Students can use the teaching kit to place each cube in its right position. Based on the label of each cube, students will be able to figure out the function minterm number. After that, the students will sort the cubes to represent the function. Eventually, the students will develop the competency to check the cubes adjacency, and this will lead them to formulate simplified Boolean expressions. Students' engagement is expected to improve when theoretical knowledge is implemented using a three-dimensional physical cube teaching kit. The aim of this work is that both the educators and students, in engineering and engineering technology programs, can benefit from the adaptation and even more from the modification of the proposed approach to facilitate the achievement of their learning objectives.

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1. INTRODUCTION

A number of methods have been proposed to simplify any given Boolean function in order to achieve gate-level reduction. In 1953, Karnaugh [1] was the first to introduce a new two-dimensional graphical method which became known later as Karnaugh maps (K-map). The method is an improved version of the chart method that has been introduced by Veitch in 1952 [2]. The K-maps method has been improved, and many refined versions have been proposed as in [3]. The goal of simplifying Boolean expression is to implement the digital circuit using the least number of gates which results in reducing circuit size. K-map is not the only way to simplify Boolean expressions. Quine [4] introduced an algorithm, which was improved by McCluskey to minimize Boolean algebra. This algorithm is called Quine-McCluskey algorithm (QMC) [4], [5]. QMC tends to be a computational method due to its complexity [6]–[9].

The concept of applying practical hands-on teaching activities to simplify engineering topics for students is gaining more attention. Hussain *et al.* [10] suggested that using activities in embedded system and interfacing course for under-graduate students helped them to improve their engineering skills throughout mini projects development during the course. Another tool used has been proposed by Beloiu [11] to teach the basics of control systems. The designed tool can implement basic mathematical operations commonly used in control systems. The board can obtain differentiation, integration, derivation, and inverting. By implementing such a tool, undergraduate students can make the necessary connections between systems representations and real systems [12].

This work is an improved version of the Wooden teaching kit that has been presented in [13]. The cubes method has been published in [14] to simplify Boolean expressions up to 6 variables. This method uses 3-dimentional cubes and can be used by computer engineering, electrical engineering and engineering technology faculty. The suggested method is argued to improve students' engagement skills. The cubes kit is designed to help students in representing and simplifying Boolean expressions graphically. Representing any systematic method graphically helps students to better understand the theory as discussed in many literatures like [7], [15]–[20].

In this work, a colored variables cubes teaching kit will be presented and explained to help engineering educators and students. The cubes teaching kit is designed based on the cubes method that was developed to graphically simplify the Boolean logic functions with three, four, five, and six variables. The proposed teaching kit can help in conducting different in-class activities. Eventually, the students will develop the competency to check the cubes adjacency, and this will lead them to formulate simplified Boolean expressions. By giving each variable a different color, the students will easily visualize the Boolean logic function representation. The aim of this work is that both educators and students in engineering and engineering technology programs can benefit from the adaptation and even more from the modification of the proposed approach to facilitate the achievement of their learning objectives.

The paper is organized as follows. Section 2 discusses the colored cubes teaching kit and explains the content of each cube. In section 3, three different classroom exercises are introduced to help educators in using the colored teaching kit. Section 4 discusses the reason behind choosing the colors of each letter in each cube of the sixty-four cubes. The conclusion is provided in section 5.

2. COLORED CUBES TEACHING KIT

The colored cube model, as illustrated in Figure 1, is developed to represent any given six variable Boolean expression $G(A, B, C, D, E, F)$ in a 3 dimensional (3D) model, with A and F being the most and least significant bits respectively. From Figure 1, it is observed that the cube's three internal sites represent all the possible combinations for the variables. Three out of the six internal sides of our colored cube are used for this purpose. For instance, as shown in Figure 1, bit C is represented on the left side of the left wall's two bottom rows and bit E is represented on the same wall's two right columns. In the space created 64 smaller sized colored cubes are placed with 4 of their sides. For the implementation of the proposed model, it is recommended to use any solid material that can be easily manufactured, such as plastic, wood, or metal.

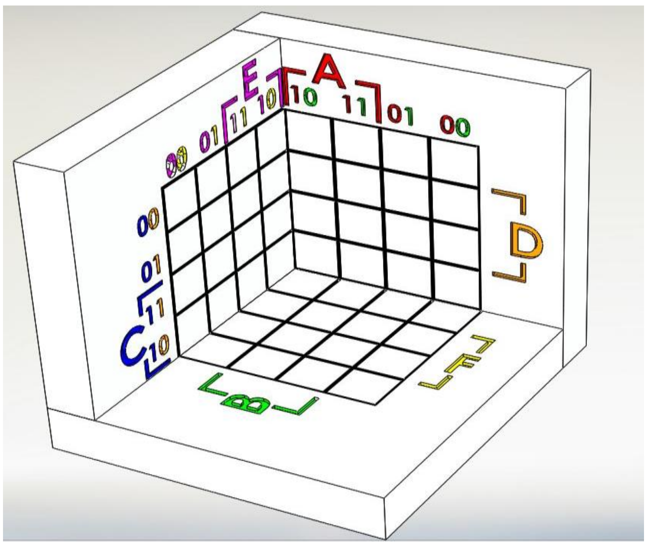
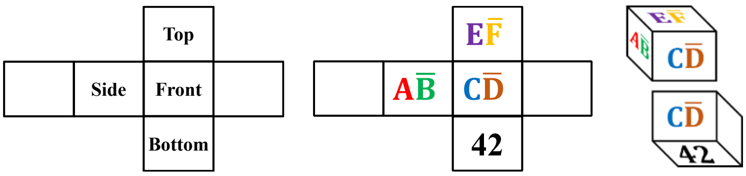


Figure 1. The structure of the 3D-colored cubes teaching kit

Each of the 64 colored cubes represents a decimal number from 0 to 63. Four out of the 6 sides of the cube are used as follows. The left side, front side and top side are used to complete the binary representation of the number in discussion, and the bottom side has the decimal number represented. Thus, as it is observed from Figures 2(a) and 2(b), the 3 sides (side left, front, top) are used to represent any possible minterm, and the fourth side (bottom) gives the respective decimal number. Specifically, for Figure 2(b) starting from the left side of the cube the minterm expression can be extracted ($A\overline{B}\;C\overline{D}\;E\overline{F}$), and at the bottom, the corresponding decimal number 42 can be found in the case discussed. The three sides are colored using a different color for each of our bits, and marked with one of the combinations of AB, CD, and EF or their adjacent to show the appropriate minterm expression. As a result, the left side will be labeled with one of the four combinations $\overline{A}\;\overline{B}, \overline{A}B, AB,$ or $A\overline{B}$, the front side will be labeled with one of the four combinations $\overline{C}\;\overline{D}, \overline{C}D, CD$ or $C\overline{D}$ and top side of the cube will be labeled with one of the four combinations $\overline{E}\;\overline{F}, \overline{E}F, EF$ or $E\overline{F}$. As shown in Figure 2(c), the right and bottom sides of the cube are not used for our model.

Table 1 demonstrates all 64 minterms numbered from 0 to 63 showing each side of the cube with what letter combinations it will be labeled with. Each minterm corresponds to a unique combination of variable values, which are reflected in the cube's labeling. This systematic representation ensures clarity and consistency when visualizing Boolean logic functions.



(a) (b) (c)

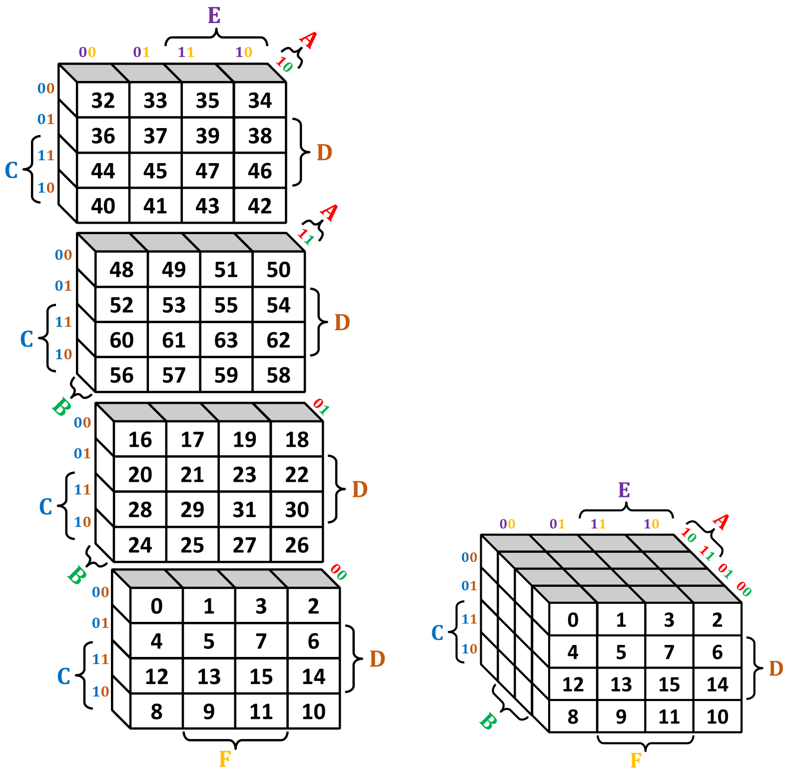
Figure 2. The labeling scheme of each cube from different views: (a) flat cube view with side names, (b) flat cube view with labeled sides, and (c) 3D cube view with labeled sides

Table 1. Cubes' labels list

A	B	C	D	E	F	Side	Front	Top	Bottom	A	B	C	D	E	F	Side	Front	Top	Bottom
0	0	0	0	0	0	$\bar{A}\,\bar{B}$	$\bar{C}\bar{D}$	$\bar{E}\bar{F}$	0	1	0	0	0	0	0	$A\,\bar{B}$	$\bar{C}\bar{D}$	$\bar{E}\bar{F}$	32
0	0	0	0	0	1	$\bar{A}\,\bar{B}$	$\bar{C}\bar{D}$	$\bar{E}F$	1	1	0	0	0	0	1	$A\,\bar{B}$	$\bar{C}\bar{D}$	$\bar{E}F$	33
0	0	0	0	1	0	$\bar{A}\,\bar{B}$	$\bar{C}\bar{D}$	$E\bar{F}$	2	1	0	0	0	1	0	$A\,\bar{B}$	$\bar{C}\bar{D}$	$E\bar{F}$	34
0	0	0	0	1	1	$\bar{A}\,\bar{B}$	$\bar{C}\bar{D}$	EF	3	1	0	0	0	1	1	$A\,\bar{B}$	$\bar{C}\bar{D}$	EF	35
0	0	0	1	0	0	$\bar{A}\,\bar{B}$	$\bar{C}D$	$\bar{E}\bar{F}$	4	1	0	0	1	0	0	$A\,\bar{B}$	$\bar{C}D$	$\bar{E}\bar{F}$	36
0	0	0	1	0	1	$\bar{A}\,\bar{B}$	$\bar{C}D$	$\bar{E}F$	5	1	0	0	1	0	1	$A\,\bar{B}$	$\bar{C}D$	$\bar{E}F$	37
0	0	0	1	1	0	$\bar{A}\,\bar{B}$	$\bar{C}D$	$E\bar{F}$	6	1	0	0	1	1	0	$A\,\bar{B}$	$\bar{C}D$	$E\bar{F}$	38
0	0	0	1	1	1	$\bar{A}\,\bar{B}$	$\bar{C}D$	EF	7	1	0	0	1	1	1	$A\,\bar{B}$	$\bar{C}D$	EF	39
0	0	1	0	0	0	$\bar{A}\,\bar{B}$	$C\bar{D}$	$\bar{E}\bar{F}$	8	1	0	1	0	0	0	$A\,\bar{B}$	$C\bar{D}$	$\bar{E}\bar{F}$	40
0	0	1	0	0	1	$\bar{A}\,\bar{B}$	$C\bar{D}$	$\bar{E}F$	9	1	0	1	0	0	1	$A\,\bar{B}$	$C\bar{D}$	$\bar{E}F$	41
0	0	1	0	1	0	$\bar{A}\,\bar{B}$	$C\bar{D}$	$E\bar{F}$	10	1	0	1	0	1	0	$A\,\bar{B}$	$C\bar{D}$	$E\bar{F}$	42
0	0	1	0	1	1	$\bar{A}\,\bar{B}$	$C\bar{D}$	EF	11	1	0	1	0	1	1	$A\,\bar{B}$	$C\bar{D}$	EF	43
0	0	1	1	0	0	$\bar{A}\,\bar{B}$	CD	$\bar{E}\bar{F}$	12	1	0	1	1	0	0	$A\,\bar{B}$	CD	$\bar{E}\bar{F}$	44
0	0	1	1	0	1	$\bar{A}\,\bar{B}$	CD	$\bar{E}F$	13	1	0	1	1	0	1	$A\,\bar{B}$	CD	$\bar{E}F$	45
0	0	1	1	1	0	$\bar{A}\,\bar{B}$	CD	$E\bar{F}$	14	1	0	1	1	1	0	$A\,\bar{B}$	CD	$E\bar{F}$	46
0	0	1	1	1	1	$\bar{A}\,\bar{B}$	CD	EF	15	1	0	1	1	1	1	$A\,\bar{B}$	CD	EF	47
0	1	0	0	0	0	$\bar{A}\,B$	$\bar{C}\bar{D}$	$\bar{E}\bar{F}$	16	1	1	0	0	0	0	A B	$\bar{C}\bar{D}$	$\bar{E}\bar{F}$	48
0	1	0	0	0	1	$\bar{A}\,B$	$\bar{C}\bar{D}$	$\bar{E}F$	17	1	1	0	0	0	1	A B	$\bar{C}\bar{D}$	$\bar{E}F$	49
0	1	0	0	1	0	$\bar{A}\,B$	$\bar{C}\bar{D}$	$E\bar{F}$	18	1	1	0	0	1	0	A B	$\bar{C}\bar{D}$	$E\bar{F}$	50
0	1	0	0	1	1	$\bar{A}\,B$	$\bar{C}\bar{D}$	EF	19	1	1	0	0	1	1	A B	$\bar{C}\bar{D}$	EF	51
0	1	0	1	0	0	$\bar{A}\,B$	$\bar{C}D$	$\bar{E}\bar{F}$	20	1	1	0	1	0	0	A B	$\bar{C}D$	$\bar{E}\bar{F}$	52
0	1	0	1	0	1	$\bar{A}\,B$	$\bar{C}D$	$\bar{E}F$	21	1	1	0	1	0	1	A B	$\bar{C}D$	$\bar{E}F$	53
0	1	0	1	1	0	$\bar{A}\,B$	$\bar{C}D$	$E\bar{F}$	22	1	1	0	1	1	0	A B	$\bar{C}D$	$E\bar{F}$	54
0	1	0	1	1	1	$\bar{A}\,B$	$\bar{C}D$	EF	23	1	1	0	1	1	1	A B	$\bar{C}D$	EF	55
0	1	1	0	0	0	$\bar{A}\,B$	$C\bar{D}$	$\bar{E}\bar{F}$	24	1	1	1	0	0	0	A B	$C\bar{D}$	$\bar{E}\bar{F}$	56
0	1	1	0	0	1	$\bar{A}\,B$	$C\bar{D}$	$\bar{E}F$	25	1	1	1	0	0	1	A B	$C\bar{D}$	$\bar{E}F$	57
0	1	1	0	1	0	$\bar{A}\,B$	$C\bar{D}$	$E\bar{F}$	26	1	1	1	0	1	0	A B	$C\bar{D}$	$E\bar{F}$	58
0	1	1	0	1	1	$\bar{A}\,B$	$C\bar{D}$	EF	27	1	1	1	0	1	1	A B	$C\bar{D}$	EF	59
0	1	1	1	0	0	$\bar{A}\,B$	CD	$\bar{E}\bar{F}$	28	1	1	1	1	0	0	A B	CD	$\bar{E}\bar{F}$	60
0	1	1	1	0	1	$\bar{A}\,B$	CD	$\bar{E}F$	29	1	1	1	1	0	1	A B	CD	$\bar{E}F$	61
0	1	1	1	1	0	$\bar{A}\,B$	CD	$E\bar{F}$	30	1	1	1	1	1	0	A B	CD	$E\bar{F}$	62
0	1	1	1	1	1	$\bar{A}\,B$	CD	EF	31	1	1	1	1	1	1	A B	CD	EF	63

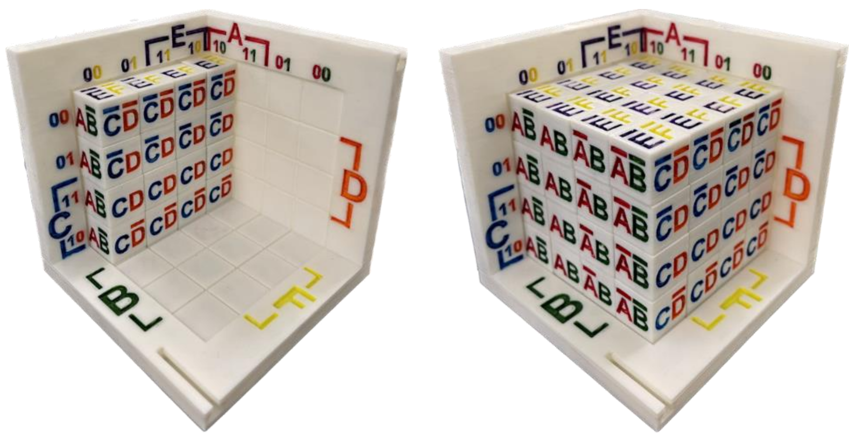
The 64 cubes will be arranged utilizing the grey code sequence, such that adjacent cubes will differ by only one bit when moving from one cube to another. The same rule is applied also when moving from one outer cube to another. For example, when moving from cube 8 to cube 10, cube 2 to cube 0 or cube 34 to cube 32. Figures 3(a) and 3(b) represent how cubes will be arranged.

Figure 4(a) shows the actual-colored cubes teaching kit model with the last 16 cubes arranged in sequence. This arrangement highlights the progressive organization of the cubes, aiding in the visualization of their logical sequence. Figure 4(b) demonstrates the complete kit view with all cubes sorted correctly, providing a comprehensive view of the cubes teaching kit in its final arrangement.



(a) (b)

Figure 3. Colored cubes arrangement (a) expanded cube arrangement and (b) complete cube arrangement without showing minterm numbers for the back cubes



(a) (b)

Figure 4. Actual colored cubes teaching kit model (a) cubes teaching kit with the last 16 cubes arranged, and (b) fully sorted cubes teaching kit in correct order

3. CLASSROOM EXERCISES

This teaching kit is proposed to students as a teaching tool to aid them in representing Boolean Logic Functions with 6 variables. To achieve this objective, several exercises should be presented to the students during the lecture. Those exercises are listed below.

3.1. Exercise 1 - finding the cube's number

The objective of this exercise is to show students how to evaluate the minterm decimal equivalent value that has been written in the bottom side of each cube. In the beginning, the bottom side of the cube will be assumed to be unknown. Then, students will try to find the minterm of each colored cube using the other sides. Students should follow the sequence: side, front, and top. Students then should write the binary equivalent. The bar over the variable ($\overline{X}$) represents 0 in binary, while variable without a bar represents 1 in binary. Variables can be any letter from A to F. The last step of this exercise is to find the number of this cube by converting the binary number from the previous step to a decimal number. This is the number of the colored cube that the students have.

For example, given the cube in Figure 5, assuming that the number of the cube on the bottom side is hidden, then by looking to the side of the cube, then to the front, and finally to the top of the cube, students will discover that this cube has the following minterm: $AB\bar{C}D\bar{E}\overline{F}$. Now, students will get the binary number of this minterm by replacing each bar variable with the number 0, and each variable without a bar with the number 1, which leads to the following binary number: 110100. The next step is to convert this number into a binary number, which is equivalent to 52 on decimal number. This is the number placed in the bottom side of the colored cube.

52	**0**		
26	**0**		
13	**1**	→	**$(110100)_2$**
6	**0**		
3	**1**		
1	**1**		

Figure 5. Decimal to binary conversion

3.2. Exercise 2 - finding the cube's position

In this exercise, students will have to find the position of the cube based on cube's-colored variables on each side of the cube. First, students will have to read the variables of the cube with following order: side-front-top. The represented variables in complement form ($\overline{X}$), which represents 0 in binary, otherwise the variables representing 1 in binary. Next, students will get minterm of this cube by combining the variables of the sides of the cube with the same sequence. Finally, using this minterm, students can find the position of the cube inside the box.

For example, consider cube in Figure 5. The sequence of reading the variables from the cube will be as follow: side-front-top. This means: side represents AB, and front represents $\bar{C}D$, while top represents $\bar{E}\overline{F}$. Next students will get the minterm of this cube by combining all variables with the same sequence which result to minterm of $AB\bar{C}D\bar{E}\overline{F}$. Finally, students will have to match each variable to its place in the box.

3.3. Exercise 3 - labeling cubes' sides

In this practice, students will be able to differentiate and label the side, front, and top of the cube using only the number on the bottom of the cube. This is a decimal number, which needs to be converted first to a binary number. The driven binary number is representing the minterm of this cube. Binary 0 means that the variable is expressed by its complement ($\overline{X}$), while binary 1 expresses the variable X, where X can be any variable from A to F. This minterm will express the sides of the cube in the same sequence used with Exercises 1 and 2.

For instance, by looking at the conversion in Figure 5. Students will be given a cube with the number 52 on the bottom side of the cube, while the side, front, and top of the cube can be considered as unknown. As discussed, students will have to convert this number to a binary number as shown in Figure 5. The driven binary number will be 110100. This means that this cube is representing the minterm: $AB\bar{C}D\bar{E}\overline{F}$. Following side's sequence, AB is the colored variables on the side of the cube, $\bar{C}D$ is the colored variables on the front of the cube, and $\bar{E}\overline{F}$ is the colored variables on the top of the cube.

4. REASONS FOR THE SPECIFIC COLOR CHOICE

In color theory, each combination of colors creates a visual impact on the eye. These are specific methods and guidelines used by designers to interact with the users. Using a vast knowledge collection of human optical abilities and psychology, designers and artists rely on the color wheel to accomplish their visual creations. The color wheel and color theory studies date back to scientific discoveries [21]. Isaac Newton, in his 1,704 book "Opticks" made a breakthrough in proving that light was made of different colors [22]. Controversial at the time; considering light was thought of as colorless at that time; his experiments became important stepping stones for color theory. He even organized an early color wheel based on the color combinations he saw when refracting light waves through a prism. Later publications, as explained by French chemist Michel Eugene Chevreul in [23], [24], were considered the founding documents of color theory in their combination of art and science. All of these studies led to applications in modern times by use of the color schemes in advertising, marketing, cinema, and brain functions related to memorizing and strengthening mental connections made by visual associations. The abilities of human interpretation of colors and biological perception did not only benefit visual artists and designers, it also elevated technologies such as cameras and printers to fashion and architecture, all the way to education itself. Currently in modern society, color theory is being used to enhance education and mental aspects of the brain [25]–[29]. In a study conducted for classroom management for students who have autism, color theory schemes seemed to be the most frequently used methods to help mental processes and connections. It resulted in a faster trail of learning and a lighter overall classroom environment, as well as increased focus and understanding [30].

The rules of the color theory are followed in this color-coded cube with the intention of adjusting primary colors with their complementary partners [31], [32]. High contrast colors have been proven to create a stronger visual connection in the brains of individuals. Each color has its contrasting or complementary color, which is why their use in a practical visual object will make visual connections clearer and more obvious especially to students learning new methods. Color coding is an essential feature in any visual-logic item. The colors chosen and integrated in this project are primary alongside their contrasting partners; the combination goes one warm color one cool color, in order to bring the most out of both colors used.

In this way, training the mind of any student by using visual connections will help the brain make faster, more deeply embedded, images related to the logic that is functioning. All receptors memorize visual areas much more easily, and the brain is very susceptible to visual effects. It is why marketing and advertising are a successful element in society and just as colors are used there for a purpose, they are used in this cube for attending to students' needs and ease their mental processes into focusing smoothly on the task at hand. By using this approach, students will have an advantage to learning faster and memorizing the paths and methods they applied.

5. CONCLUSION

This work explained a physical three-dimensional teaching kit for the simplification of Boolean functions of up to six variables. The colored variables teaching kit presented is used for the representation of Boolean logic variables as colored sides of the described cubes model. With the help of this model, the learners will have the ability to visually associate these variables as different colors of different sides of the cube model. The color selection is made by following the well-established color theory and its founding rules to associate variables to corresponding colors.

The teaching kit aims to provide a hands-on learning experience for students engaging with Boolean logic. The three suggested exercises are designed in order to develop the learners' understanding and visual awareness of firstly the teaching kit's configuration. Afterwards, the learners can practice their skills in color association of the cubes' minterms and position on the structure, binary to decimal, and decimal to binary conversions.

The educational oriented approach during the design, development, and manufacture of the kit encourages further exploration of its uses in several educational disciplines. Towards science, technology, engineering and mathematics (STEM) education besides the obvious use of understanding Boolean functions expressions and their simplifications by electrical engineering, computer and communications engineering programs educators in design optimization and manufacturing engineering can use this kit. Furthermore, collaborations amongst learners from different programs can be achieved by developing the kit into an innovative solution, throughout a project-based approach. The kit's design and portability can be addressed along with ideas of making it compatible for different education levels.

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