Research for a Teaching Approach: An Example of Addressing the High School Students' Conceptual and Reasoning Difficulties in the Study of Direct Current Simple Electric Circuits

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Abstract—With this work we aim at presenting a research on high school students' (ages 16–17, Greece 2015–2017) understanding into the study of basic direct current (DC) circuits. Studies on this subject in over the world have contributed to a rich research base. Students' conceptual and reasoning difficulties are presented and analyzed, aiming at the development of methodologies and teaching approaches, accompanied by instructional material to resolve them. The difficulties experienced by these students indicate a significant discrepancy between their conceptions and the scientific view. To address these difficulties, the design and the development of two types of programs were chosen. The first is based on educational models in the laboratory and the second consists of auxiliary courses and educational material for its simultaneous use in classroom teachings. The conclusion is that the existing literature is confirmed and enriched with new findings, while a different teaching approach accompanied by appropriate educational material seems to help the address of the conceptual and reasoning difficulties.

Keywords—DC electric circuits, students' difficulties, Ohm's law, Kirchhoff's laws, addressing difficulties

1 Introduction

Students' understanding of the concepts and phenomena of electricity has been the focus of many studies in education which have contributed to a large research base. Surveys have demonstrated that conceptions, such as current [1], potential difference [2], [3], terminal voltage and resistance [4] create many difficulties to the students' understanding. In addition it has been repeatedly proven that students have a series of misunderstandings and alternative ideas about these concepts [2], [5], [6], [7], [8], with a consequence the creation of many problems in understanding and applying complex concepts and laws, such as Ohm's and Kirchhoff's laws [9], [10], [11]. Even after a systematic and fairly advanced study of the topic in high school or college, in which students become quite efficient in carrying out complicated algorithms (e.g., using Ohm's and Kirchhoff's laws), they are still incapable of qualitatively analyzing simple circuits [2], [3], [12].

Studies conducted in many countries with different educational system indicate that the students' problems and difficulties in the study of DC electric circuits are common and insist strongly. For example see [13]. This article describe how the data of these researches can be used to guide the development of a teaching approach aiming the addressing the students' difficulties in the study of DC simple electric circuits.

The objectives of the survey are:

1) To point out the difficulties, misconceptions and alternatives ideas in simple problems on circuit operation encountered in two samples of high school students in Greece.
2) To perform an error analysis of the students' conceptual and reasoning difficulties.
3) To develop teaching materials and educational strategies that will try to address the difficulties of the students.

2 Research sample

The sample of the research consisted of 221 high school students (ages 16–17) in Greece who had attended middle school courses to the basic concepts of electricity and electric DC circuit and continue the courses in the high school studying of simple electrical circuits by applying complex concepts and the laws of Kirchhoff and Ohm. In Greece, high school students choose groups of courses depending on the University faculty they want to attend. So, in the class of 16 and 17-year-old students, two groups of courses are created: Sciences Pathway (ScPw) with additional courses in Physics and Mathematics and Humanities Pathway (HuPw) with additional human studies courses, while there are also some common courses such as lessons of electrical phenomena.

Two groups of students constituted the total sample. (a) Sample 1 (171 students) who attended courses with the typical teaching process. From them, 110 students had chosen ScPw's courses and 61 students had chosen HuPw's courses. (b) Sample 2 (50 students) who attended courses with a different teaching approach to overcome the learning difficulties and misconceptions. From them, 32 students had chosen ScPw's courses and 18 students had chosen HuPw's courses. The division of the students into two groups (Sample 1 and Sample 2) became in such a way that the two groups to be as homogeneous as possible.

3 Methodology

In the first part of the research are presented the frequent errors and misunderstandings created by the students in the study of DC simple electrical circuits, as resulted by the above mentioned surveys and mainly are probed: the relationship (Ohm's law $V = IR$) between potential difference (p.d.) current and resistance, the power dissipated on passive elements and its formulas expression ($P = VI$, $P = I^2R$, $P = V^2/R$), the role of the battery and its internal resistance and the Kirchhoff's laws. At the same time, an attempt is being made to identify the causes that lead to these specific errors with examples containing questions, simple electrical circuits and student answers.

In the second part to address the identified difficulties, was chosen the design and development of two types of programs. The first one is based on educational models in the laboratory and the second type of program consists of auxiliary courses and educational material for its simultaneous use in classroom teachings. The educational approach is to encourage students and force them to drive through the whole process, to construct a conceptual model for the behavior of an electrical circuit, based on laboratory experience with electrical sources and lamps. At the same time, auxiliary courses focus on important elements of the curriculum and with carefully structured exercises lead the students through defined subjects that require justification of their reasoning. Students predict the outcome of specific changes in a system, observe, analyze and solve problems that focus on the qualitative understanding. Worksheets and appropriate questions lead students to make important observations and thoughts necessary for configuring the model. In the auxiliary lesson, small groups of students work together to analyze circuits of a different form and as they attempt to apply the model, students have to face and solve some common conceptual and reasoning difficulties.

The questions and circuits used included electrical sources (ideal and real), lamps (resistors), ammeters, voltmeters and relations of voltage, current, resistance and power.

4 Students' errors and misconceptions

From the existing literature we can highlight some very often students' errors and misconceptions into the study of the DC electric circuits.

4.1 The electrical source supplies in the circuit constant current

Many students seem to consider the battery as a source of constant current, namely they consider that the current provided by the battery is independent of any modifications to the circuit [2], [14], [15], [16], [17], [18], [19].

This misconception is resulting from the students' answers in relative problems like the follow one.

Question 1: The voltage source $\mathcal{E}$ in the Figure 1 has no internal resistance, and both lamps L1 and L2 are lit. L2 is removed from its socket. Consequently the suggestion: "The bulb L1 lights more strongly" is: (i) True or (ii) False

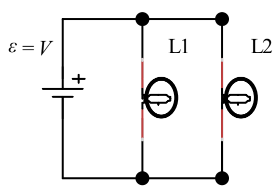

Fig. 1. Two lamps connected in parallel with an ideal battery

Many students chose the option "True". Why? Because they consider that the battery produces a constant current; this fact implies that, when the lamp L2 is taken away, the same current, which was split in two branches before, will now all go through L1, causing a greater brightness.

Another problem follows, in which the present answer choice correspond, on the basis of the reasoning given, to this misconception.

Question 2: In the circuit given in the Figure 2, the reading of the ammeter is *I* when the switch (S) remains open. If the switch is closed the reading *I* does not change. Explain if this suggestion is: (i) True or (ii) False

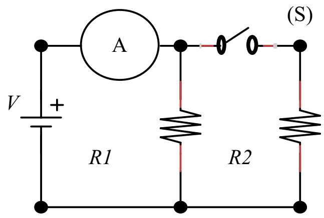

Fig. 2. The function of the switch and the variation of the current

For a significant fraction of students the suggestion is true. Under their opinion the battery produces a constant current which, when encountering the two parallel resistors, is divided into two currents and at the exit we will find a current equal to that entering, therefore the ammeter reading will not change. This means that the current provided by the battery is independent of any modifications to the circuit.

It is obvious that the role of the battery in the circuit creates difficulties for students that prevent them from properly processing data and information when studying a simple DC circuit.

4.2 The connection of the resistors

Resistance is an impediment to the current flow, considering that any addition of another resistance in the circuit leads to an increase in total resistance regardless of how the resistors are connected [2], [20], [17], [19], [18], [8].

For example question 3 asked about the effect of the resistor's R removal upon the brightness of the lamps L1 and L2 in the circuit of Figure 3.

A rigorous solution to the problem requires consideration of the whole circuit and the role of the resistor *R*, but few students did this; their most common solution used the following argument. If *R* is taken away, then the total resistance will decrease and more current will flow through the lamps. Consequently L1 and L2 become brighter.

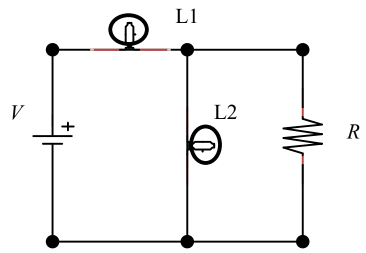

Fig. 3. The variation of the circuit's total resistance and the brightness of a lamp

4.3 The case of the Ohm's law

The Ohm's law is a special case of current and potential difference (p.d) relationship of great practical importance, which also introduces the important concept of resistance [21], [22], [23]. The students very often resort to its use trying to study simple DC electric circuits, but also very often make errors because there is in their mind a wrong interpretation of Ohm's law and its functional meaning [24], [9].

For example given the question 4: The potential difference (p.d.) between the ends of a resistor in which current flows is determined by:

(a) The current which flows through it.
(b) The heat dissipated in it.
(c) The difference in energy between the charges moving at its two ends.

A very often choice, made by the students, is the (a) and a typical reasoning given for the wrong answer is "The p.d. at the ends of a resistor, in which a current is flowing, is consequent to the circulating current, as by Ohm's law stated".

Another question follows, in which the students' answers showcase this misconception.

Question 5: In the circuit given in the Figure 4, the reading of the ammeter is *I*. An additional resistor *R2* is connected, in parallel with the lamp L, between B and C. Explain if the suggestion: "The reading *I* increases and the p.d. between B and C increases" is (a) True or (b) False

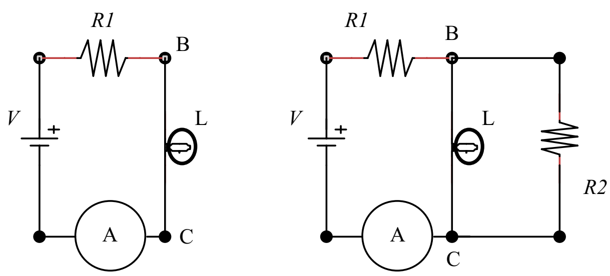

Fig. 4. The relationship (Ohm's law) between potential difference, current and resistance

For many students the suggestion is true because under their opinion when a resistor is added in parallel to the lamp, the total resistance will decrease. This fact implies an increase in current I with consequent increase in V_{BC} between B and C.

It is obvious that in the mind of many students the functional relationship (Ohm's law $V = IR$) between potential difference (p.d.), current and resistance is unclear.

4.4 The Power's calculation

In many problems of studying simple DC electrical circuits, students are asked to calculate the power and its variation (like the brightness of a lamp). From the students' answers in these problems result the difficulty of the power calculation dissipated on passive circuit elements [24], [17], [8].

The questions 6 and 7 are concerned with probing this students' misunderstanding.

Question 6: The electricity supply at our homes is a voltage source of 220V. Two lamps in a room are connected to this source in series. Both are designed for use with the domestic voltage, the one for 30W and the other for 120W. Explain if the two lamps will light almost normally or not.

Most students giving answers consider that in the circuit there is a certain power at disposal which breaks up in parts proportional to the power of the lamps. A typical answer is "The 30watt lamp will be 4 times less bright, since the 120watt lamp has a dissipated power 4 times higher". Any analysis on the circuit and therefore on the p.d. present at the ends of each lamp or on the current flowing through them is missing.

Question 7: The electricity supply at our homes is a voltage source of 220V. One lamp and the electric oven are connected to this source in parallel. Both elements are designed for use with the domestic voltage, the one for 50W and the other for 2500W. Explain which element has the greater resistance.

Choosing most students the electric oven as the element with the greater resistance, becomes cleared that the central problem in student understanding is the manipulation of the power formula ($P = VI$, $P = I^2R$, $P = V^2/R$) which hides the real issue of lack of conceptual understanding.

4.5 The real electric source

In electric circuits studying by the students, where the electrical source is real, the degree of difficulty of reasoning is greater, since students should use and combine complex concepts and laws [10], such as the concept of the electromotive force (emf) [25] and the laws of the Kirchhoff.

A characteristic example is the question below.

Question 8: In the circuit given in the Figure 5a, the battery is real (emf $\mathcal{E}$, internal resistance r). If an additional identical lamp L2 be connected in parallel with the lamp L1 (see Figure 5b) will the brightness of the lamp L1: (a) increase (b) decrease (c) stay the same.

Explain your choice.

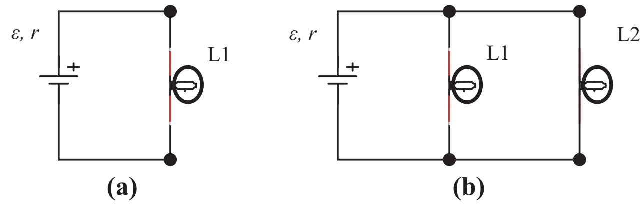

Fig. 5. The variation of the lamp brightness in an electric circuit with a real battery

From the students' answers result that the main conceptual misunderstanding arises from the concept of the emf, which creates additional difficulties in the understanding and using of the Kirchhoff's laws or their different expressions. Garzón [26] concludes that many students try to explain their choices and ideas based on the formula, which attributes the same physical meaning to two different concepts (emf and terminal voltage) that may have the same numerical value within a given situation. The students appear to put more trust in the quantitative correctness of the equation than in logical conceptual arguments. They also consider that many teachers have difficulties in using the concept of potential difference in explaining electrical circuits and therefor students have problems using the concepts of the potential difference (p.d.), terminal voltage (V_{term}) and the emf $\mathcal{E}$ in their explanations, due to an incomplete conceptual understanding.

In addition, in the Greek school bibliography, there is a lack of describing energy transformations in a circuit within a coherent framework and thus, a diminishing importance of the distinction between the concepts of the p.d. or terminal voltage and emf. For example, students' answers like "The emf depends on the current that passes through the battery ($V_{term} = \mathcal{E} - IR$)" or "The emf $\mathcal{E}$ only differs from V_{term} by the internal resistance" show that the tendency of the majority of students is to attribute the same characteristics to emf and terminal voltage and finally to confuse the electromotive force with terminal voltage.

4.6 Summary

The difficulties faced by students with the electrical circuits are both conceptual and reasoning. The changing of the electrical elements and operating conditions in a simple circuit (like adding—removing a light bulb or opening—closing a switch) or/and the existence in the circuit of a real electrical source, creates many problems for students, especially in qualitative problems, and prevents them from using properly complex concepts and the laws of Kirchhoff and Ohm. Even undergraduate students in introductory Physics courses face similar difficulties, according to a large research at the University of Washington [11].

The students very often prefer to use mathematical formulas (even with fantastic algebraic values), or even respond intuitively when they face mostly qualitative problems. The mathematical processes and their difficulties however, in which focused by the students might mask the conceptual misunderstanding.

According to the above, it seems that there is no conceptual framework for thinking and processing data and information that will help the students to answer correctly and construct appropriately new knowledge.

5 Addressing conceptual and reasoning difficulties

The design and development of two types of programs were chosen to address the identified difficulties. Many researches [27] maintain that the education of the Physics requires experimental practice in order to enhance the understanding phenomena and processes on the concepts it is based on. So, the first program is based on educational models in the laboratory performing experimental exercises to analyze and understand basic knowledge of theory and the second type of program consists of auxiliary courses and educational material for the simultaneous use in classroom teachings.

5.1 Development of educational laboratory model

The students perform experiments and write their conclusions from their observations in order to construct the basic concepts for studying simple DC circuits such as current, resistance etc. They use both inductive and guided thoughts to synthesize these concepts in a quality model for the electrical circuit. This mental picture with the set of rules supplies students with a conceptual framework that allows them to predict and explain the behavior of simple circuits. As students apply the model to increasingly complex circuits, there is a need to introduce and use additional concepts, such as the potential difference. The process of building the model continues with the use of quantitative data, drawings, illustrations that extend the applicability of the model. Pure algebraic formalism is introduced only after the completion and stabilization of a remarkable qualitative foundation.

With the help of ammeter and voltmeter students develop operational definitions for the concepts of current, resistance and voltage. Having defined functional definitions of basic electrical concepts, they extend the model by including algebraic relations. They design circuits in the lab, make measurements that lead them to the Kirchhoff rules and determine the relationship between current and the potential difference (voltage) for ohmic materials. Alternatively they can use the website with interactive simulations of the University of Colorado (Phet Colorado). For example, in https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_el.html the students design the circuit of the Figure 6a and they can confirm Kirchhoff's 1st law ($\sum I = 0$) by giving various values of the voltage V of the electric source and of the resistances of the circuit and corresponding the values of the ammeters for the values of the current passing through the resistances in the three branches of the circuit.

In a similar way, students can, in https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_el.html design the circuit of the Figure 6b and confirm the 2nd Kirchhoff's law ($\sum V = 0$). By varying the voltage's value V of the source and for different values of the resistances, they take measurements for the voltages of the resistances and are guided each time in Kirchhoff's 2nd law.

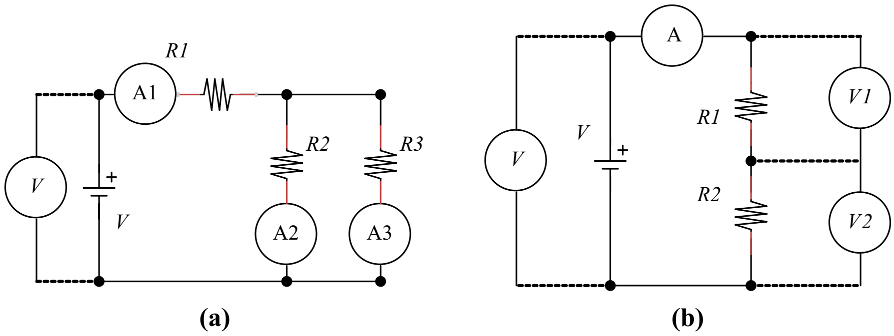

Fig. 6. The Kirchhoff's first (a) and second (b) law

The students can also take measurements with an ammeter and a voltmeter and observe how the circuit's current and the battery's terminal voltage change by adding parallel branches with lamps (see Figure 7). They observe some minor variations in the expected results of these laboratory experiments. For example, they observe that the brightness of the lamp does not remain constant as they add lamps in parallel to the battery and at the same time the value of the terminal voltage decreases while the value of the total current increases. Finally, they recognize the extension of the model by including the internal resistance of the electrical source and the concept of its emf. They distinguish the ideal and real electrical source, also confirming it in laboratory, as in the example of the circuit of Figure 7 with the interactive simulations of the University of Colorado https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_el.html.

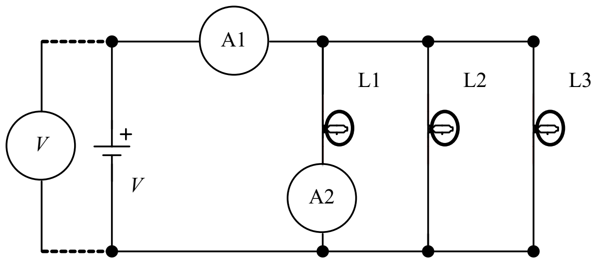

Fig. 7. The real electrical source

Of course, for this process to be successful, it is necessary for students to persist in developing their way of reasoning, not only for structuring model, but also applying it. It has been shown that this practice helps the simultaneous development of reasoning ability and conceptual clarity. Creating a model requires both inductive and guided thinking. Concepts and physical quantities are initially introduced in their simple form and later a combination of them, where necessary, interprets and calculates more complex phenomena. Repeated practice by applying the model and making predictions helps reinforce the correct interpretation of the concepts. One such example of the application of the Ohm's and Kirchhoff's laws is the question 9, which was given to students.

Question 9: In the circuit given in the Figure 8 (real battery with emf $\mathcal{E}$, and internal resistance r) one resistance R is connected with a lamp L (resistance R_L) in parallel 8a and in series 8b respectively. If the value of the resistance R increases, will the brightness of the lamp L:

(a) Increase (b) Decrease (c) Stay the same. Explain your choice.

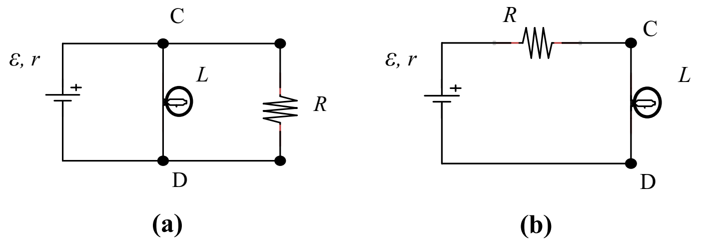

Fig. 8. Application of the Ohm's and Kirchhoff's laws

The students' ideas. An important difficulty is for students to recognize the more and different information given by existence of the real electrical source, in relation to the ideal source. Thinking inductively and guided by the need for power's calculation ($P = I^2R$, $P = V^2/R$), the students find that the lamp's voltage V_{CD} in this situation is not equal to the emf $\mathcal{E}$ of the battery but equal to the battery's potential difference, namely equal to its terminal voltage ($V_{term} = \mathcal{E}-Ir$). They perceive that both the current intensity I and the terminal voltage V_{term} of the source, and thus the lamp's voltage V_{CD}, depend on the value of resistance R.

Particularly for the circuit of Figure 8a students follow the following reasoning: the value of the resistance R increases, increasing the equivalent resistance R_{eq} of the circuit. Therefore the circuit's current I decreases and the value of the lamp's voltage ($V_{CD} = V_{term} = \mathcal{E}-I\cdot r$) increases. Eventually, the power and brightness of the lamp will increase ($P = V_{CD}^2/R_L$).

In a similar way for the circuit of Figure 8b students are led to the next reasoning: the circuit's elements are connected in series. If the resistance R will increase the circuit's equivalent resistance R_{eq} will increase too and according the Ohm's law [$\mathcal{E} = I(R_{eq}+r)$] the value of the current I will decrease. Eventually, the power and brightness of the lamp will decrease ($P = I^2-R_L$).

It is worth to highlight a very often repeated reasoning obstacle presented to students, which comes from their question about the choice of power relationship: "*Why in the first circuit the relationship* $P = V_{CD}^2/R_L$ *is used, while in the second one is used the relationship* $P = I^2R_L$*?*"

Obviously there is no restriction or prohibition for any of the two relations. Students usually choose the formula with the current ($P = I^2\cdot R_L$) because they have the belief that they understand better the concept of the current and can use it more correctly. However, the wrong reasoning that appears very often is that in similar cases of the first circuit (see Figure 8a) they compare the total current of the circuit, and not the current passing through the lamp L.

The difficulties presented by the need for such reasoning is not easy to address. During this research it was found that similar qualitative problems create the greatest reasoning difficulties for students. It has also been found that the reverse reasoning helps sometimes to address these obstacles: the students namely to try to explain a known result of the problem given.

For this purpose, students were asked to design the two circuits of the Figure 8 in the virtual lab of the University of Colorado [https://phet.colorado.edu/sims/html/circuit-construction-kit-dc/latest/circuit-construction-kit-dc_el.html (see Figure 9)] using voltmeter and ammeter. While they increase the value of the resistance were asked to observe the changes of the values in the terminal voltage V_{term} and in the circuit's current I. Observing these changes, they were also asked to explain why these are happening.

In the first circuit (see Figure 9a), the students observe the increasing of the terminal voltage V_{term} (equal to the p.d. of the lamp) and conclude that the brightness of the lamp also increases. Given that the terminal voltage of the source is calculated by the relation $V_{term} = \mathcal{E} - I \cdot r$, they recognize that this increase is due to the decrease of the total current's value ($\mathcal{E}$ and r remain constant), which means that the circuit's equivalent resistance is increasing. By similar reasoning into the second circuit (see Figure 9b) they read the reduction of the circuit's current I and therefore they are led to the conclusion of the lamp's brightness reduction.

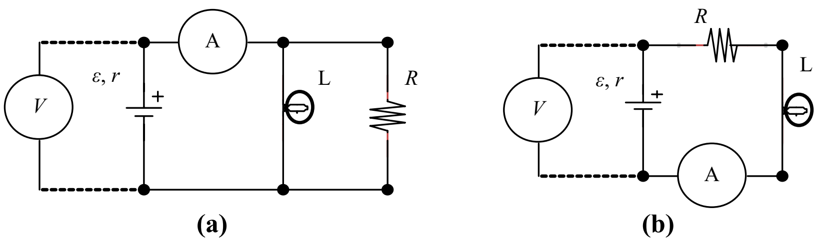

Fig. 9. Interactive simulations for the application of the Ohm's and Kirchhoff's laws

However, the change in the circuit's current is due to the reverse variation in the equivalent resistance of the circuit, according the law of Ohm. The sequence of these considerations seems to allow several students to address some of the difficulties that arise, such as the distinction between emf and p.d. or terminal voltage, the using of the Ohm's and Kirchhoff's laws as well as their different expressions, to a study of similar circuits.

No claim was made that the students' ideas were suddenly and permanently altered by the evidence, but most students were able to see that the scientific model was confirmed by the experimental results.

5.2 Application of the model

To help students address the obstacles and the misconceptions created, it is not enough hearing what mistakes they should avoid. They often ignore the dissonance between the teacher's words and their own thoughts. In order to achieve a specific conceptual change, students must be actively involved in the learning process, such as to be produced a conceptual conflict and the students be asked to face it. An educational strategy proposed is that the teacher presents a typical error revealing itself slowly with the active participation of students; the fundamental difficulty then finally be addressed.

The process that can generally be applied should be a series of sequential steps that will retrieve information, face and resolve difficulties. These steps do not define a single strategy but a continuing one. The students should be given multiple opportunities to apply the same concepts in different cases, to process information from these experiences and to learn to generalize.

An example of this is the next question given to the students.

Question 10: In the circuit given in the Figure 10a applies:

i) $V_{AB} = 0$ *and* $V_{CD} = \mathcal{E}$
ii) $V_{AB} = \mathcal{E}$ *and* $V_{CD} = 0$
iii) $V_{AB} = 0$ *and* $V_{CD} = 0$

Answer suggested: Correct choice is (iii).

The circuit is open at points *C* and *D*. So there is no current across the circuit ($I = 0$). According the Ohm's law the potential difference is proportional to the current. Therefore the potential difference between the points *A*, *B* and *C*, *D* should be zero.

Results: Many students made similar thoughts and they considered the choice correct and the reasoning acceptable. Before beginning any discussion with the students, they were asked to make the corresponding circuit (either in the real lab or in the virtual lab) and taking measurements to verify the proposed option. For example, several students used the interactive simulations of the University of Colorado in https://phet.colorado.edu/sims/html/circuit-construction-kit-dc/latest/circuit-construction-kit-dc_el.html and designed the circuit of the Figure 10b; by selecting values for emf $\mathcal{E}$ and the internal resistance *r* of the battery they measured the current's values of the circuit and the voltages required.

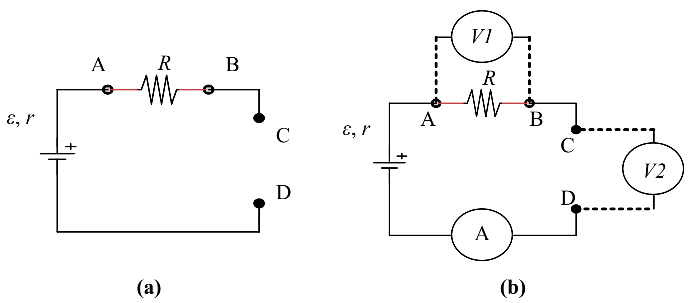

Fig. 10. The potential difference and the electromotive force

Experimental measurements have shown that the proposed choice is not correct and a conceptual conflict was produced so the students were asked to face it.

The combination of theory's elements and experimental measurement data, as well as the discussion that followed, seemed to help some students overcome the difficulty caused by some concepts like of the potential difference, the emf and the wrong interpretation the Ohm's law.

With this process, to some students, concepts that create obstacles in their thinking and in their understanding of more complex concepts and laws seemed to be addressed. A process like this seems to help students, but it should be noted that it requires a lot of time and continuous contact with students.

Adaptation of the teaching from the lab to classroom. It is obvious that a curriculum and a teaching method can't be based on teaching in the laboratory. A more pragmatic approach is necessary. Auxiliary courses and educational material at the same time as traditional teachings would help in this direction. The objective is to counter the passive learning environment of a typical teaching and to develop a mental involvement and participation of students in it. The purpose is not to deliver additional information, but to help students deepen their conceptual understanding and develop scientific thinking skills.

Dialogues with questions and answers that help students individually to reach to their own conclusions are replaced by group discussions. Inevitably attention is shifted from the development of concepts to their application.

The auxiliary courses. Auxiliary courses with their corresponding material consist of units of related activities that focus on important elements of the standard curriculum. Carefully structured exercises guide students through defined topics that require justification of their reasoning. Students predict the effect of specific changes in a system, observe, analyze, and solve problems that focus on the qualitative understanding.

The proposed environment for such intellectual activity is characterized by small groups of students. For example and for classes of 22 to 25 students, they can work together in groups of 3–4. In a modified form of teaching approach, the auxiliary courses can also be used as the basis of an interactive teaching. In any case, the teacher works more like a person responsible for conducting and facilitating the discussion than providing the knowledge.

During the auxiliary courses tests and course examinations are served. The tests inform the teacher about the level of students' perception and understanding and help him recognize what the students expect to learn from these lessons. Worksheets and questions from the instructor lead students to make important observations and reasoning necessary for configuring the model. Small groups of students work together to study circuits of a different form. As they try to apply the model, students have to face and solve some common conceptual and reasoning difficulties.

The process of adapting a series of laboratory activities to a standard course contributed significantly to the knowledge of how students read and learn Physics. Data collected from class attendance and tests provided detailed information about the students' difficulties, like their nature, their frequency and their persistence. The enrichment of the research base has led to the continuous modification of both auxiliary courses and traditional teachings.

Below is an example of questions, exercises, and activities as a worksheet been given to students to study, discuss, and express their thoughts and reasoning.

Worksheet. During the auxiliary courses the students were given worksheets with questions and problems to answer, so that, through their study and analysis they would be helped in their understanding and reasoning. It is worth highlighting that these worksheets were not intended to be a test but to give students the chance to discuss with each other through appropriate questions and exercises with their supervisor, their thoughts, their concerns, the alternative ideas that are created, and in general to analyze and investigate their reasoning to overcome the difficulties they face.

The worksheets have had a form like the one shown in Appendix.

5.3 Effectiveness of instructional approach

Assessment of laboratory lessons. During laboratory lessons, the teacher does not "lecture" but manages and controls the students' process of learning through experiments and exercises. He encourages the students to engage in dialogues that allow and lead to deep exploration. In addition, students transfer their laboratory experiences to homework and to tests. The quality of oral and written answers provides evidence of significant conceptual perception and understanding of the subject matter of the electrical circuits developed by the students in contrary to this in standard courses. For example, the experiment team students were asked to answer the next question.

Question 11: Try to make the circuit shown in Figure 11, where there are: a battery (emf $\mathcal{E}$, internal resistance $r = 0$) and three identical lamps L1, L2, L3.

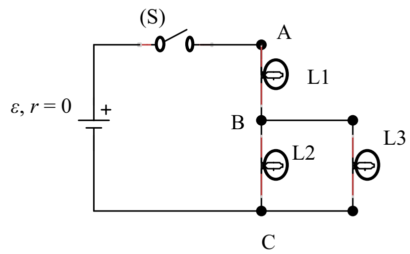

Fig. 11. The brightness of the lamp

If the switch S will close,

(1) Will the brightness in L1 be more as that in L2 and L3
(2) The lamps L2 and L3 will have the same brightness and greater than that of the lamp L1
(3) Will the brightness in L1, L2, L3 be the same

Select the correct answer and justify your choice.

Investigating students' ideas and reasoning. Before starting the experimental process, the students of each group, expressed their ideas and their concerns, they discussed with each other and eventually chose an answer. A large fraction of students considering it easier to use the power's expression with the current ($P = I^2R$) and applying the 1st law of the Kirchhoff $\left(\sum_{junction} I = 0\right)$, they been led easily in option 1. After the experiment, the correctness of their choice was established. Students then were asked to repeat the experimental process at home using the interactive simulations of the University of Colorado (Phet Colorado) in https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_el.html and eventually they were asked to confirm the correct answer and write their reasoning. From the previous discussion, the main points of the difficulties were identified in:

1) Selection power's formula ($P = I^2R$, $P = V^2/R$, $P = \mathcal{E}I$).

   Some students have doubt about the power's formula which they may use. This difficulty results from the incompletely understanding of the concepts of the current, the potential difference, the emf, where it appears and their relations among them.
2) The use of the Ohm's law for a circuit and for an individual element.

   Students appear to use Ohm's law merely as a calculational convenience without analyzing when or whether it applies. Some students consider that they can use the Ohm's law to an individual element with resistance with the same way that it can be used in the entire circuit; many times the students consider the circuit's total current equals, in any case, to the current flowing through a branch of the circuit.
3) If the electrical source was real would change something about the circuit study and the correct selection?

   As be already highlighted, the students attribute the same properties to the emf and the potential difference or its expression known as terminal voltage. This fact creates huge problems in the study of the simple DC electrical circuits, which become more complicate due the difficulty of the concepts' relation manipulation.

   The students' ideas were analyzed, investigated and discussed, in order to remove some of the conceptual difficulties and obstacles that they encountered.

Assessment of auxiliary courses and educational material. An index of the evaluation of the effectiveness of the auxiliary courses was considered the comparison the students' performance participated in these courses with that of students who confined themselves to the traditional teaching approach. For this purpose exercises and questions were used in a test form, like the example below.

Question 12: The circuit shown in Figure 12 is containing a real battery (emf $\mathcal{E}$, internal resistance r) and three identical lamps L1, L2, L3. The switch S is closed and the lamps are lit. If the switch S will open, will the brightness of the lamps L2 and L3:

(1) Increase (2) Decrease (3) Remain the same

Select the correct answer

Justify your answer.

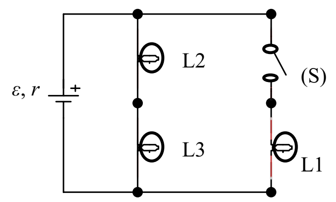

Fig. 12. The variation of the lamps brightness

Results: 221 students participated and answered. From them 171 students were in control group (110 of the ScPw and 61 of the HuPw) who attended courses with the standard teaching approach. The rest 50 students were in the experimental group (32 of the ScPw and 18 of the HuPw) who had attended courses with the different teaching approach (laboratory and auxiliary courses as already described) and they had consisted the experimental group.

This exercise was perhaps the most difficult of those given to the students to do during the research because the circuit included three lamps (ohmic resistances) and a real electrical source, with the consequence that students would have to follow a series of considerations to achieve a correct conclusion. In each exercise with lamp's brightness it is assumed that the mathematical relationship of power must be used. First of all, students should recognize which expression of the power's relationship is convenient to be used for their reasoning. A second element that the students should consider is the circuit's equivalent resistance when the switch is closed and opened, and how this resistance's value affects the current of the circuit. The third point is the existence of the internal resistance of the source which means that the terminal voltage is not constant but depends on the circuit's current. Finally the lamps L2 and L3 are identical (equal resistances) and are connected in series so their voltage is equal to the half of the terminal voltage according the 2nd Kirchhoff's law $\left(\sum_{closed\,loop} V = 0\right)$; all of this has created many difficulties in the thinking of students, both those in the control group and those of the experimentation team.

In summary, the results are shown in the Table 1.

Table 1. Students' performance

Percentage (%) of Students Answers Overall and by Studies				
		Correct Reasoning	**Incorrect Reasoning**	**Without Reasoning**
Control group	Total (n = 171)	16%	66.5%	17.5%
	ScPw (n_1 = 110)	20%	67.5%	12.5%
	HuPw (n_2 = 61)	8%	66%	26%
Experimentation team	Total (n = 50)	22%	74%	4%
	ScPw (n_1 = 32)	28%	72%	0%
	HuPw (n_2 = 18)	11%	78%	11%

Note: Overview of students (n: number of students) performance on the question 12 (Assessment of auxiliary courses and educational material).

The processing and analysis of the results has shown the following data:

1) In several students' responses were identified mistakes due to more than one cause.
2) 27 students from the control group had answers with correct reasoning (22 of the ScPw and 5 of the HuPw), while in the experimental group the answers with correct reasoning were 11 (9 students of the ScPw and 2 of the HuPw).
3) Answers without reasoning mean wrong answers and were fewer in the experimental group, namely 30(17.5%) and 2(4%) respectively.
4) Many students, especially of the HuPw tried to justify their choice using the power's expression with the current ($P = I^2R$); they could not recognize the need of the use of the terminal voltage's conception and the 2nd Kirchhoff's law ($V_{term} = \mathcal{E} - Ir$). The students' mistakes were due either to the not appropriate use of Ohm's law, or to the calculation of equivalent resistance, or to the comparison of currents with opened

and closed switch as they consider that the current passing through the L2 and L3 lamps is in any case the total circuit's current, calculated by the Ohm's law for a closed loop. This mistake is one of the most repeated mistakes in similar questions.

5.4 Summary

Obviously, it is difficult to determine the effectiveness of a teaching approach through only laboratory courses [28]; a more realistic approach is necessary and for this purpose the auxiliary courses with the educational material have been used. Classroom observations, tests and interviews have been used to monitor student progress and according to the analysis of the experimentation team students' ideas and their reasoning, there is a strong indication resulting that this educational approach to studying electrical circuits is more effective than the traditional approach.

In addition, the responses of the two groups of students (sample 1 and sample 2), which required conceptual perception and understanding, showed a remarkable difference. Not only as a final result but also as a way of thinking in the students' effort to answer and justify their choice. Students who participated in the auxiliary courses generally had a better performance on all the qualitative problems of written tests and the discussions that took place throughout the laboratory and auxiliary courses. Moreover, the auxiliary courses seem to have more success than the standard courses to address some of the students' serious misconceptions.

As part of the continuous improvement of the educational approach to similar issues, a modified form of this research could be applied to other similar surveys with a larger sample.

6 Conclusions

On the basis of the results obtained, it is possible to state the following. There are common misunderstandings, shared by large groups of students, confirmed by findings also from previous studies on students' understanding of electrical phenomena. We have found common types of misunderstanding in the students of both the two groups of courses (ScPw and HuPw) and similar reasoning patterns by them when answering questions and qualitative problems related to study of the simple DC circuits. In general, when the students have confronted qualitative questions, they encountered conceptual and reasoning difficulties and in the same time they have shown a reluctance to explain their ideas. Many students took an almost entirely mathematical approach because they consider these concepts more like variables in algebraic relationships. For very simple and typical problems this can be satisfactory. However, for the students to be able to face more complex situations, they need to integrate these concepts into a coherent framework. We strongly believe that this reluctance and this approach are due to a lack of understanding of the concepts and laws; so the poor performance of the students in the questions and tests was not surprising. In addition, in Greek school bibliography and in the traditional teaching approaches, is presented the theory as facts with the rapid introduction of the related concepts. Many lessons delivered in the class still use lecture methods. This situation makes students bored and tired in learning even basic concepts of Physics [29]. Therefore is exacerbated the difficulty of these concepts and laws understanding. The results of this work, but also of others, indicate that the traditional approach to circuit study leads to major conceptual and reasoning obstacles and does not help the students to overcome their difficulties. Senior cognitive skills, such as problem solving can be improved through students' active learning methods, which aim at participants' exploring and applying knowledge, themselves [30].

Proposed modifications to teaching strategies as regard circuit study, may contribute to alleviating the problems faced by the students. The results were used to design educational material that helps to address the difficulties identified. This material, in the form of auxiliary courses, was tested in the classroom and further research was used to evaluate its effectiveness.

It was described how a construction model, as a general educational strategy, can help students develop a functional perception and understanding of the electrical circuits' study in order to address the particular difficulties presented.

It is worth noting that there is a need for continuing systematic investigation of the nature of the difficulties faced by students in standard teaching. However, the enrichment of the research base should not be limited to identifying and analyzing the difficulties, but also include a description of educational strategies that appear to be effective. In addition, methods that seem not to work should be reported. Building and enriching a research base and using it as a guide to an educational curriculum development, could result in helping students understand Physics.

7 Acknowledgment

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9 Appendix: the worksheets' form

(I) complete the phrase by selecting the correct sentence

The 1st law of Kirchhoff follows from

a: the law of conservation of energy
b: the principle of the momentum preservation
c: the conservation of electric charge
d: the principle of the mass preservation

The 2nd law of Kirchhoff follows from

a: the law of conservation of energy
b: the principle of the momentum preservation
c: the conservation of electric charge
d: the principle of the mass preservation

Intensity's current $I = 1$A passes through two resistors (equal resistances) connected in series with an ideal battery (voltage V). When the same resistors are connected in parallel with the same battery the current will be

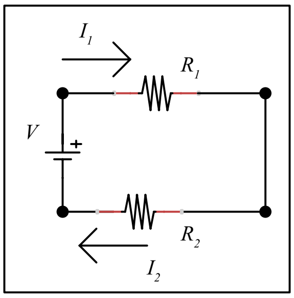

Fig. A1. The current and the voltage in a simple electric dc circuit

a: $I_1 = I_2 = 0.5A$ *b:* $I_1 = I_2 = 2A$

c: $I_1 = I_2 = 1A$ *d: none of these answers*

Two metallic conductors with resistances R_1 and R_2 ($R_1 > R_2$) are connected as shown in the circuit of the Figure A1. If I_1, I_2 their currents and V_1, V_2 their voltages respectively then

a: $I_1 = V/R_1$ *and* $I_2 = V/R_2$ *b:* $V_1 = V_2 = V/2$

c: $V = V_1 + V_2$ *d:* $I_1 + I_2 = V/(R_1+R_2)$

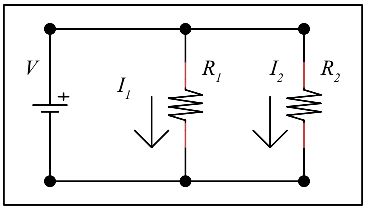

Fig. A2. The current and the voltage in a simple electric dc circuit

Two metallic conductors with resistances R_1 and R_2 ($R_1 > R_2$) are connected as shown in the circuit of the Figure A2. If I_1, I_2 their currents and V_1, V_2 their voltages respectively; then

a: $I_1 = V/R_1$ *and* $I_2 = V/R_2$ *b:* $V_1 = V_2 = V/2$

c: $V = V_1 + V_2$ *d:* $I_1 + I_2 = V/(R_1+R_2)$

(II) Mark the following suggestions as True (T) or False (F).

A lamp (L), considered as an ohmic resistance and a resistor (resistance *R*) are connected as shown in the circuit of the Figure A3. Then

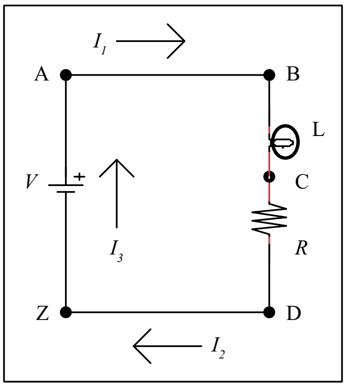

Fig. A3. The current and the voltage in a simple electric dc circuit

1) $I_1 > I_2$
2) $V_A = V_B$
3) $V_{AZ} = V_{BC} + V_{CD}$
4) $V_{AB} + V_{BC} + V_{CD} + V_{DZ} + V_{ZA} = 0$
5) $V_C > V_D$
6) $I_3 = I_1 + I_2$

(III) Question. Two metallic conductors with resistances R_1 and R_2 are connected in series with an ideal battery (emf $\mathcal{E} = V$, $r = 0$) as shown in the circuit of the Figure A4.

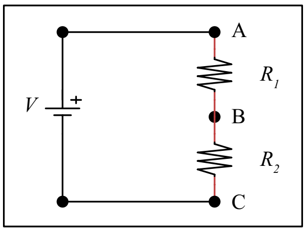

Fig. A4. The Potential difference (voltage)

(1) If $V_{AB} = V_1$ and $V_{BC} = V_2$ the voltages of the resistances R_1, R_2 respectively, then

i) $V_1/V_2 = R_1/R_2$
ii) $V_1/V_2 = R_2/R_1$
iii) $V_1/V_2 = R_1/(R_1+R_2)$

Select the correct answer
Justify your answer

(2) If $V_{AB} = V_1$ the voltage of the resistance R_1 and $V = \mathcal{E}$ the voltage of the battery, then

i) $V_1 / V = R_1 / R_2$

ii) $V_1 / V = (R_1 + R_2) / R_1$

iii) $V_1 / V = R_1 / (R_1 + R_2)$

Select the correct answer
Justify your answer

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