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The Persistence of Prior Concepts about Electric Potential, Current Intensity and Ohm's Law in Students of Engineering

Persistencia de las ideas previas sobre potencial eléctrico, intensidad de corriente y Ley de Ohm en los estudiantes de segundo curso de Ingeniería

María Cristina Periago (*)
cristina.periago@upc.edu

Xavier Bohigas (*)
xavier.bohigas@upc.edu

* Departament de Física i Enginyeria Nuclear
Universitat Politècnica de Catalunya

Av. Diagonal 647, 08028
Barcelona, España

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Abstract

The aim of this research was to evaluate and analyze second-year industrial-engineering and chemical-engineering students' prior knowledge of conceptual aspects of circuit theory. Specifically, we have focused on the basic concepts of electric potential and current intensity and on the fundamental relationship between these as expressed by Ohm's Law. In order to find out what the students' prior

concepts were, we applied a survey containing nine questions dealing with the most basic concepts of circuit theory. Let us emphasize that there was little information available about the prior concepts of the population type (university students) investigated in this research.

Key words: Prior concepts, circuit theory, engineering students.

Resumen

El objetivo del trabajo que se presenta es la evaluación y el análisis de los conocimientos previos sobre los contenidos conceptuales de Teoría de circuitos que tienen los alumnos de segundo curso de Ingeniería Industrial e Ingeniería Química, con la finalidad de detectar la persistencia de estos conocimientos desde niveles educativos anteriores. Concretamente, nos hemos centrado en los conceptos básicos de potencial eléctrico e intensidad de la corriente, así como la relación fundamental entre ellos, expresada a través de la Ley de Ohm. Para detectar las ideas previas de los estudiantes se les ha propuesto un formulario que consta de nueve cuestiones todas ellas relacionadas con los conceptos más básicos de la Teoría de circuitos. Los resultados obtenidos nos confirman la hipótesis principal de la investigación: las ideas previas de los alumnos en el campo de la Teoría de circuitos persisten desde los niveles educativos anteriores hasta el universitario. Hay que destacar que el estudio se ha llevado a cabo en un tipo de población (los estudiantes universitarios), de los cuales no se tiene mucha información en lo que se refiere a sus ideas previas.

Palabras clave: Ideas previas, teoría de circuitos, estudiantes de Ingeniería.

Introduction

In the teaching of experimental science, one of the most dynamic areas of research in recent years is that which explores the ideas held by students for the interpretation of various phenomena before and after receiving formal teaching about the theme in question (Brown, 1992; Campanario and Otero, 2000, Clement, Brown and Zietsman, 1989; Cohen, Eylon and Ganiel, 1983; Furio and Guisasola, 1999). This line of research has evolved over the years, as evidenced by the various bibliographic compilations on the subject (Carrascosa, 1983; Carrascosa, 1985, Gil and Carrascosa, 1992).

Since students always have wrong answers to the questions raised in the classroom, the traditional response of the teacher has been to penalize them for this. However, in recent years these errors are being considered from another perspective. As a result of numerous didactic studies, there has been detected empirical evidence that, before they receive formal instruction, students already have their own ideas about natural phenomena and what they want to be taught

(Brown, 1992; Clement *et al.*, 1989; Driver, 1983; Suárez, 2001; Wandersee, Mintzes and Novak, 1994). This may involve a deficiency in learning the major concepts, principles and scientific models used to interpret natural phenomena, especially if the teacher does not pay attention to the students' preconceptions, and does not take these into account when scheduling learning activities and classroom presentations.

Several research papers have constituted an attempt to identify the source of previous ideas. On the one hand, it seems that certain conceptual schemes are widespread in all cultures, and sometimes collide with the relevant scientific theories. Moreover, some of the students' previous ideas are rooted in everyday experience. The common language, with its usual lack of precision, and the use of faulty analogies in the school environment itself may be the source of some spontaneous ideas reinforced by inadequate learning in the social setting or communications media (Bell and Otero, 2000; Viennot, 1996).

Perhaps the most worrying aspect of the previous ideas is not their existence but their persistence. All the results obtained so far show the greatest resistance to change presented by the mental structures students have. It has been proved that only rarely does exposure to "correct" scientific ideas make students abandon their previous ideas, which tend to remain unchanged after long periods of teaching, and coexist with the scientific ideas. This is true even after learners receive training based on programs specifically designed to modify these preconceptions (Furió and Guisasola, 2001).

The result is that students maintain two parallel schemes of knowledge. On one side is their academic knowledge about phenomena, theories, laws, formulas and methods, which they use at school to solve exercises and exams. On the other, in addition, students maintain their arsenal of previous ideas, useful to them for understanding reality and interacting with their environment. It is even common to find university students and graduates who have completed their studies, and yet maintain misconceptions about some scientific phenomena (Furió and Guisasola, 1999).

It is important to note that a student does not assimilate a new conceptual framework if she* is not aware of the possible limitations of the one she already has, and does not understand the need to change. Therefore, the meaningful learning of science will take place, not through the accumulation of information transmitted, but through conceptual change; this is a process similar to the way in which scientific progress is made.

* Translator's note: Before the feminist movement arose, in situations including both genders it was customary to use the masculine pronoun. Today, however, pronouns of both genders are used to avoid what is now seen as sexist language. To avoid the awkwardness of a continual repetition of such forms as "s/he", "his/her", in this paper we shall sometimes use the feminine pronoun, and sometimes the masculine.

The student must therefore be aware of the need for change, if we want to involve her actively in the assimilation of new concepts and laws. For all this, it is essential for students to know what their conceptual scheme is, and what their own ways of explaining phenomena are. Conceptual change cannot be, therefore, the simple substitution of a correct concept in place of a misconception; the process of change must involve relations between preconceptions, so not just one isolated concept is entering in crisis, but all. This process of teaching and learning is what is known as the *constructivist* focus: the conceptual schemes are actively constructed by the learner (Bell and Moya, 1999; Driver, 1986; Driver and Oldham, 1986). From this perspective, the process of learning implies that the learner, when faced with a situation he is trying to understand, must contribute *his own patterns* or existing ways of thinking. We must understand that this necessary restructuring of ideas and patterns will not occur over a short time, but may take years, rather than just one or two lessons. The teacher's role is to place his students face-to-face with problems for which the learner must imagine solutions, design experiments of contrast to the hypothesis, and so on. Thus students can follow a methodology similar to that of the scientific work and, consequently, construct knowledge (Driver, 1983). In this way, the teacher as a provocateur of his students' conceptual change, should be aware of their previous ideas so as to schedule appropriate activities that will facilitate these conceptual changes.

Objectives of the study

In the field of physics, the greater number of studies on misconceptions has to do with mechanics, especially concerning the relationship between force and motion (Carrascosa, 1985). Another field of physics historically less explored, but subject to frequent educational research, is the *Circuit Theory*, understood as the basic concepts of intensity of electric current, potential difference and resistance, as well as the fundamental relationship between them expressed through Ohm's Law. Students' personal views on this subject have been investigated for some time, and all studies have concurred on the same result: the existence of numerous conceptual errors at almost all educational levels (Cohen *et al.*, 1983; Furió and Guisasola, 1999). The vast majority of studies to date have explored high school students' prior ideas, but few have focused on analyzing the presence of these in college students (Pontes, 1999). For this reason, although most of the misconceptions in the field of circuit theory have already been identified in junior high school and high school students, we thought it interesting to investigate whether these misconceptions persist at higher levels such as the university, particularly in Engineering students.

This led us to formulate the main research hypothesis: University students' prior concepts in the field of Circuit Theory persist from previous educational levels.

The operation of this hypothesis in the first stage involves identifying the college students' previous ideas of circuit theory, for a subsequent evaluation of these ideas' carry-over from the previous educational levels.

The information obtained may also be extremely useful in the future, to design activities in which students especially learn the conceptual schemes for circuit theory. This would be a second stage of work, which could be addressed in future studies based on the results obtained here.

This article presents the results of a survey conducted with second-year Engineering students; through this it intends to find out students' preconceptions about the fundamental principles of circuit theory, such as electric potential, current intensity and Ohm's Law.

Description of the study

The present study was carried out at the beginning of the year with four groups of students taking a class on Electromagnetism (184 students in total). Three groups are from Industrial Engineering and one from Chemical Engineering, both degrees offered at the Polytechnic University of Catalonia (Spain). This is a compulsory core subject in the fourth quarter of the degree program in both majors. Especially emphasized should be the fact that students who enter the second year have passed the first, which is selective. No student can be in the third quarter if he has not passed the first two in a maximum period of two years. In these two first-year quarters, students have taken, among other classes, two courses in Physics (Mechanics and Thermodynamics) and four in Mathematics, which include Differential and Integral Calculus as well as Algebra and Geometry. Moreover, let us point out that these students have already received prior instruction in the Unified Multipurpose Baccalaureate (BUP)** and the University Orientation Course (COU) about the theoretical contents regarding circuits to be analyzed (these are students who completed high school prior to the implementation of the Fundamental Law of Education (LOGSE).

Thus, the learners studied here can be classified as falling into a medium-high academic level. On the one hand, they have passed the selection phase (only 60% of freshmen pass it) and on the other, they are students who have passed the admissions exam for entering engineering studies (the test grade required has been 65 (C+) or above in recent years.)

To identify students' previous ideas, they were given a survey with nine questions, all related to the most basic concepts of circuit theory, electric current, electric potential, current intensity, resistance, resistance assembly and Ohm's Law.

** Acronyms are based on the Spanish-language names of the bodies and organizations

The questions were chosen so that they could not be answered by the mere application of various laws and standard procedures, but would reveal ideas which students had formed about some concepts and the relations between them. Most of these questions had been previously used by other authors (Furió and Guisasola, 1999; Hierrezuelo and Montero, 1991; Pontes, 1999; Shipstone, 1984). This decision had been made so as to compare, where possible, the results of these university students with those obtained from other studies analyzing previous or equal (high school or university) educational levels. In both cases the comparison would be useful for investigating the persistence of ideas or their universality.

The 9-question form presented to students is included in Annex I.

Results

The answers obtained for each of the questions are presented in detail in Annex II.

To perform an objective analysis we have classified these answers into three categories following the criteria previously proposed by others (Pontes, 1999):

- Category I is that which includes the correct answer, as accepted by the scientific community, and which we can find explained in specific books. These answers include an explanation or justification where requested in the wording of the question. These are answers that can be considered correct and complete.
- Category II is for those answers which are correct, but are not justified, or are not justified very clearly; where they belong to closed questions, they include some mistake. These are incomplete answers.
- Category III includes incorrect answers as well as those that are difficult to classify because they show confusion; also in this category are questions not answered.

Based on this classification, we have collected data on student responses in Table I.

Table I. Percentage of answers classified in each of the three categories defined

Question	Category I (%)	Category II (%)	Category III (%)
Q1	59.2	30.4	10.4
Q2	22.3	41.8	35.9
Q3	15.8	20.1	64.2
Q4	48.9	47.8	3.2
Q5	65.2	29.3	5.4
Q6	57.6	32.0	10.3
Q7	4.3	83.7	12.0
Q8	0.5	79.3	20.1
Q9	1.6	19.0	79.4

4.1. Analysis of responses

For each question we have specifically explained the conceptual content or the schematic the student had to use in order to answer correctly the question being asked. Also, there is given the percentage of answers included in each category, and the possible correlations with other answers on the questionnaire. If this question had been used previously by other authors in other works we have tried, wherever possible, to compare the results.

The questions are presented in Annex I.

Q1: The purpose of this question is to find out whether the student associates the fact that a light bulb emits light with the passage of current; moreover, that the current flow takes place in a closed circuit. (We are always considering stationary regimes, not transitory ones). Thus, there are presented three drawings (realistic) with a light bulb connected in three different ways to a battery. In only one case is the flow of electrical current possible.

The answers indicate that most students (59.2% of Category I, plus 30.4% of Category II) consider a closed circuit necessary for the current to circulate and light up the bulb. At any rate, it is striking that there should be a percentage of the students (almost 10%, Class III) who think that a light bulb can emit light when connected to a single pole of a battery. This coincides with the idea that a battery is like a water fountain, and therefore needs only one pole to produce current. This belief has been found in students from other educational levels (Cohen *et al.*, 1983), although the fact that college sophomores still accept this interpretation indicates the persistence of preconceptions about electric current (García and Rodríguez, 1988).

Q2: There is presented a simple circuit consisting of two batteries (mounted in opposition and with different emf) and a light bulb in series. This question is an attempt to detect whether students relate the existence of a potential difference

between two points of a closed circuit with the passage of current; i.e. it is a conceptual application of Ohm's Law, which is familiar to them. Analysis of the answers indicates, first, that most students interpreted correctly that two cells of different emf connected in opposition produce a potential difference between the ends of the assembly (64.1% in Categories I and II); but conspicuous, on the other hand, is the fact that 35.9% did not (Category III). Perhaps some students did not notice that the two batteries have different emf, although this was clearly indicated in the drawing; the battery graphics were even of different sizes to prevent this possible confusion. This result is similar to that presented by Furió and Guisasola (1999), who indicated that of responses to the question we asked, 47% said there was no potential difference between terminals A and B. Those filling out the questionnaire based their answer on the grounds that since the positive poles of the batteries are connected together, there is no potential difference; they did not consider the influence of the batteries at all. Regarding the correlation between the answers that indicate whether or not potential difference exists between points A and B, and whether or not there is current flowing through the bulb, it is clear that students did not relate potential difference between the battery terminals with electric current flow. In short, they have different concepts engraved in the memory. It is also important to note that a high percentage (7.6%) of surveyees did not know what to answer, surely because they did not know how to solve the problem of having two cells connected in opposition.

A majority of the students (71.2%) are not clear on whether there is a potential difference in a circuit where current flow is produced. As to the 21.2% who answered that there was no potential difference between points A and B, they may not have paid attention to the device, or simply thought the potential difference would be null because the batteries are mounted in opposition. At any rate, their other responses are consistent with these initial answers, because they say there is no current flow. What this 21.2% of the surveyees thought and understood should be clarified through personal interviews.

Regarding the passage of current, in all the responses included in Category II, students said that there is potential difference between points A and B; however, 35.3% of all those surveyed maintain that there is no current flow between these points. This clearly tells us that these students do not relate the existence of a potential difference between two points on a circuit, with current flow. This confusion is described well in the bibliography (Hierrezuelo and Montero, 1991), and we confirmed it even in university students, including after they had studied physics and had correctly solved (evidenced by the fact that they had gone on to more advanced studies) problems in which they had to handle these concepts. In spite of identifying the existence of potential difference between A and B, 38% believed that no current circulates through conductor C. This answer goes along with the idea that batteries are a source of current, from which it flows like water flows from a fountain, and that it is not necessary for a current to be closed in order for current to flow through it (Cohen *et al.*, 1983).

Finally, we must take note of the high number of surveyees who belong to Category III: 35.9%.

Q3: A preconception deeply rooted in the population is the belief that the current in a circuit becomes weaker as it circulates (Shipstone, 1984). In order to detect this interpretation, students were asked which of the two bulbs will shine more. Students were also asked to argue for their response (see Annex I). The number of responses with a convincing explanation is very small; only 15.8% of surveyees fall into Category I. If we include the answers in Category II, 35.9% respond almost correctly. We note that 58.2% of the students thought that two bulbs associated in series do not shine in the same way, although they knew the bulbs were identical. Since in our case there was a resistor located between the two bulbs, we can interpret these answers with the idea that the current “is used up” as it progresses or when it passes through a resistor. This interpretation is confirmed by the results of question Q4, in which 44% of the students affirmed that the current decreases along the circuit.

The idea that the current is “used up” through the circuit also appears in Q5, in which 26.6% indicate that the current flowing through elements connected in series in a circuit is not of the same intensity. This idea has been mentioned many times (Hierrezuelo and Montero, 1991), and persists even after people have received specific instructions in circuit theory. Certainly the persistence of this idea lies in the misunderstanding of the concepts of *intensity* and of *potential difference*, about which, normally, there is not too much emphasis in teaching, and the concepts are used merely as tools to solve numerical problems, rather than making qualitative analyses of different situations.

Q4: This question tries to find out whether students think it is necessary for the circuit to be closed in order for current to flow, and whether or not it is used up as it flows along the circuit. There is no response that says a bulb can shine when connected only to a single pole of a battery. This response is not surprising, since in question Q1 a similar situation was presented, and 6% thought that the light bulb could shine.

Only 48.9% of the answers are correct. There are 44% who insisted upon the idea that power is used up as it moves along the circuit, which is quite consistent with those obtained in question Q3. In the text of this question it was explicitly stated that the current comes out of one pole, and that less current reaches the other pole of the battery (see Annex I).

Q5: In this question we analyze a circuit belonging to a flashlight; the circuit consists of three batteries and a bulb, all associated in series. It tries to find out if students believe that current flows through the interior of the batteries, and if the intensity remains constant in an assembly in series. It was largely accepted (65.2%) that current flows inside the batteries. Only 4.9% of answers indicated that there would be no current through them. Although this result can be

considered as insignificant, we must emphasize the fact that 29.3% gave incomplete answers, thinking that the intensity varies along the circuit. This idea is repeated in other responses, as already discussed.

Q6: The purpose of this question and the ones following was to find out to what extent students relate the magnitudes of current intensity with the potential difference and resistance; that is, if they used Ohm's Law properly, from the conceptual point of view. More than half—57.6% of the responses—correctly associated the drop in potential in those resistive elements. But 32% of the responses, an important portion, were not completely correct; the answers were difficult to analyze because they did not seem to correspond to any criteria. It is surprising that some 10% of students think there is potential difference between two points without resistance between them, since in most of the circuits they have solved, it was assumed that the conductor wires had no resistance. This indicates that these students passed the subject without understanding exactly what they were doing, and were limited to using Ohm's Law in a mechanical way.

Finally, there was an outstandingly high percentage of responses that could not be classified (10.3%), which tells us that this question should be reformulated if we want to get information more valuable on the preconceptions of our students.

Q7: We believe that learning Ohm's Law using repetitive application and little thought is reflected in the results obtained in this question and those following. It has to do with comparing the brightness of bulbs connected to a battery, in three different situations. In the first, a single bulb is connected to the battery; in the second there are two bulbs connected to the battery in series; and in the third, the two bulbs are connected to the battery in parallel. Only 4.3% answered the questions correctly. The majority of answers (83.7%) can be associated with the assumption that the battery is a generator of constant current. For this reason, learners did not differentiate the brightness of the bulbs if one or two of these are placed in series, between the ends of the generator. Furthermore, they thought that in the assembly in parallel, the intensity circulating through each light bulb is less than in the other cases. Believing that the battery is a source of constant current, they assume that the intensity circulating through each bulb in the parallel assembly will be half of the assembly in series. The reasoning is correct, but based on a false hypothesis. This idea has been extensively studied and discussed in the bibliography (Cohen *et al.*, 1983).

Apart from of the conceptual error regarding the battery, we note that 25.5% of the surveyees indicated that one of the bulbs in the assembly in series was brighter than the other. Moreover, the bulb that shines brighter is the one that is closest to the positive terminal of the battery; this indicates to us the persistence of the idea that electrical current decreases as it moves along the circuit. It seems to us that students are very clear on the concept that current flows from positive to negative, since we have not found a single answer saying that the bulb located farthest from

the positive pole shines brighter—an aspect we have already mentioned in analyzing questions Q4, Q5 and Q6.

The majority of surveyees (58.2%) accept the constancy of current intensity along the circuit, although they were not able to relate the brightness of bulbs in different circuits. This we interpret as an inability to apply Ohm's Law properly in these three situations, so as to know the intensity circulating through each bulb. This inability may be surprising if one takes into account the fact that these are students who have passed physics courses in which they had to solve problems by using Ohm's Law. However, this case departs from the typical problem in which students are given known values and then asked to calculate some other value. In this case, by facilitating the value of one component of the problem's data, we were giving the student the information that this value is a constant. This allowed him to solve it satisfactorily, although he had not learned the meaning of the concepts and laws necessary for its resolution. This is a consequence of teaching based on the numerical resolution of problems without dealing too much, or dealing in a superficial manner, with the conceptual understanding of the problem to be solved.

We suggest that students did not properly use Ohm's Law for this question, and that they solved it by applying the analogy of the hydrodynamic model to the electrical current.

Q8: The results of this question confirm the above. Most students (79.9%) correctly answered the first part of the question. In fact, it is a simple exercise in the application of Ohm's Law, of the kind most commonly presented to high school students when they are studying the subject of power. This tells us that they remember how to solve problems associated with resistance by using Ohm's Law. We should not be surprised at this, considering that the survey was conducted with second-year engineering students at a school which requires a grade average of 65 (C) for enrollment; which is to say, they are students of medium to high academic level.

The results in the second part of the question are completely different. Only one student out of 184 (0.5%) answered correctly. It seems that the others tried to solve the problem in an intuitive way, using reasoning based on the current; i.e., still thinking that the battery is a power source. For this reason, 65.2% said that light bulb B1 will shine in the same way. If the reasoning had begun with the supposition that the potential difference between the battery ends is constant, they would have gotten different results. Another point to note is that they made an analysis of the circuit, so that they considered each element making it up as an independent element equipped with its own characteristics, and not dependent on changes in the other elements of the circuit. For this reason, 46.2% thought that after disconnecting bulb B3, the current flowing through bulb B1 would be the same, and therefore would shine in the same way as in the previous situation, and that all the power now reaching the bifurcation B2 to B3, since there was no bulb

B3, would pass through B2, and thus emit more light in this situation than in the previous one.

Q9: It is interesting to note that 27.2% replied that the potential difference between points D and E is zero. We can guess that the idea of students choosing this response was based on considering the fact that if between two points there is no electrical component, the potential difference between them is null. This comes from a topologically incorrect interpretation of the circuit under study. Problems of this type have been studied previously (Cohen *et al.*, 1983; Pontes, 1999). There were 22.3% who believed that the potential difference remains the same as it was before removing the bulb. Only 1.6% (3 students on 184) answered correctly. The percentage of correct answers obtained on this survey differs from previously-published studies (Cohen *et al.*, 1983), which indicate that 15% of high school students and only 4% of practicing teachers answered correctly. It also indicates that the option preferred by students was, with 45%, the one which says that the potential difference between points D and E is zero; while the teachers—48% of them—mostly chose the option stating that VDE would remain constant. In our study, the percentage of surveyees who said that $V_{DE} = 0$ or $V_{DE} = \text{constant}$ are very similar: 22.3% and 27.2% respectively. These results seem to be remote from those published in other works, but we must bear in mind that in our case 26.1% did not answer, and 22.8% gave answers difficult to analyze. These two percentages represent 48.9% of the population studied. Therefore, if we consider only the responses where we could get clear information, the percentage of responses in our study for the answers $V_{DE} = 0$ and $V_{DE} = \text{constant}$ are similar to those mentioned above.

We can conclude that the application of Ohm's Law has not been learned meaningfully; although students may know how to use it in certain situations, they do not seem to know how to apply it situations somewhat different from the more common ones they had to resolve during their learning period.

Conclusions and implications for teaching

Detailed analysis of the answers to the various questions on the survey confirm the presence of some misconceptions. The most outstanding are:

- *The battery is a power source that supplies the charges moving through the circuit.* This idea, common in elementary and high school, still persists at college level, although to a lesser degree. It is reflected in Q1, with 9.3%; and in Q2, with 38% of the answers based on this idea.
- *Battery power always provides the same current regardless of the circuit to which it is connected.* This idea is reflected in almost all the questions asked; in fact, it is a recurring theme appearing in almost all the students' reasoning. The questions in which this idea is most clearly presented are Q7, with 83.7%, and Q8, with 65.2%.

- *The power the battery supplies “is used up” as it circulates through the circuit.* This idea is confirmed by the answers students gave to the following questions: 58.2% for Q3, 44% for Q4 and 26.6% for Q5.
- *The potential difference is a consequence of current flow, not its cause.* This idea is reflected especially in Q6, where 32% confused the dependence between the intensity of current and the potential difference.
- *Incorrect application of Ohm’s Law*—reflected in most responses to this questionnaire, and in particular to questions Q3, Q6, Q7, Q8 and Q9.

These misconceptions, present in college students who begin the study of electromagnetism in Engineering, hinder meaningful learning of circuit theory. If we remember that these students had already received prior instruction in high school, we can confirm the principal hypothesis of the research: that the preconceived ideas strongly persist, since these previous ideas have been identified in students before they receive instruction in the area of physics (Shipstone, 1984).

Why are students’ previous ideas so resistant to change? The answer must be related to both the nature of the previous ideas, and also to the type of education received for the purpose of changing the concepts. Among the psychological factors, we can emphasize that students tended to consider only the evidence that supported their hypothesis, rather than seeking that which would help to prove it false. They have such confidence in their hypotheses that they do not worry about verifying them.

Other factors that support the persistence of the previous ideas are related to the way classes are developed, i.e. the system used in teaching. First, the vast majority of teachers do not know the students’ previous ideas, so they find it impossible to design the activities necessary to overcome these prior concepts. Similarly, evaluation methods do not analyze the existence of precepts or the degree to which they are overcome, as evidenced by the fact that students who pass with good grades retain the same ideas as their peers.

Often, students begin the study of electricity in a very theoretical manner, and have few opportunities to manipulate and operate electric circuits and assemblies. In many cases, the study of electricity is quick and superficial, based primarily on numerical calculations, missing the many opportunities offered by this subject for reasoning and free exploration (Furió and Guisasola, 1998).

Based on the results obtained in our study, we list some ideas that can improve meaningful learning of the basic concepts of circuit theory, on which we have focused in this work:

- *The need for the circuit to be closed in order to work.* Students’ use of the unipolar model is related to the role they assign to the battery: if what the battery does is provide electricity, it is logical that it needs only one pole for the

current to get to the item where it is consumed. To combat this error, students should see the circuit as a whole, as a system in which all the elements are interrelated. It would also be beneficial to insist that any element placed in a circuit should always have an input terminal for the current, and an output terminal.

- *The battery is not a current source.* The idea that the battery is a *source of constant current* appears, as shown, in university levels. It should be made very clear that potential difference is the independent variable of the problem, while the intensity depends on it. This dependence is obscured by the habitual use made of Ohm's Law, which is usually written as: $V_A - V_B = RI$. We believe it would be more appropriate to present it as: $I = \frac{(V_A - V_B)}{R}$
- Mathematically there is no difference, but physically there is one: in the second form it is clear that I depends on the value of V , and not vice versa. Some authors propose to introduce voltage as a primary concept in DC circuits, and describe in detail the sequence to follow (Psillos, Koumas and Tiberghien, 1988; Röneck, 1985).
- *Distinguish between of voltage source and power source.* For this, it would be useful to analyze different circuits fed by a power source and energized by a voltage source. Analyzing the similarities and differences would help students to understand that a battery is a voltage source, not a power source.
 - *Current is not synonymous with energy.* This would be the idea underlying the persistent error that says the current is used up as it flows through the circuit. It seems clear that this idea is caused by the misuse of everyday language, and if we consider that the student is not very clear on the nature of power, it would be easy for him to apply this idea to the analysis of the circuits proposed. At this point one should resort to a meticulous explanation of electric power, and insist on the principle of conservation of the charge. It might also be useful to carry out various measurements of current intensity at different points in the series circuit, to support the idea that intensity is the same at all points.
 - *Avoid sequential reasoning.* The concept of the electric circuit as a whole would help us combat another common misconception: any variation in an element of a circuit affects only the elements located behind it. It should be noted that the effect of locating a particular element at one point or another of the series circuit does not depend on the order in which it is placed within the circuit.
 - *Insist on the conceptual management of potential and intensity.* For those it would be interesting to analyze different circuits qualitatively, in order to prevent the students from applying Ohm's Law in a mechanical and unthinking manner.

It seems clear that one of the weaknesses of the teaching method commonly used is the negligible importance given to qualitative reasoning about the interdependence of the electric magnitudes present in the circuits.

There is much emphasis on the mathematical application of Ohm's Law, but no in-depth qualitative analysis from the physical point of view. As an attempt to remedy this lack, it would be interesting to take advantage of possibilities offered by new technologies in the form of autonomous and interactive programs, virtual physics experiments using applets, simulation exercises on the Internet, etc. (Bohigas, Jaén and Novell, 2003, Clinch and Richards, 2002; Hisano and Utges, 2000).

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Translator: Lessie Evona York-Weatherman

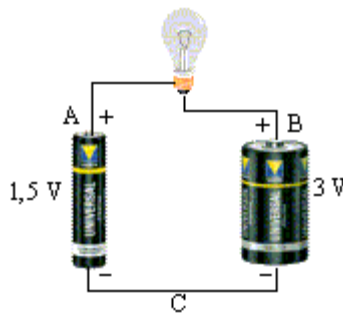
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Annex I

Q1. Tell whether the bulb will light up in the following situations. Indicate by an arrow where the electrical current flows.)

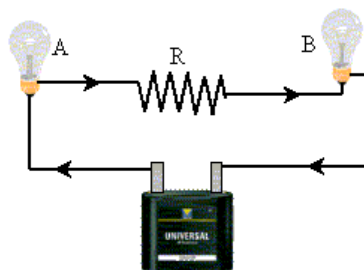


Q2. We have two batteries and one light bulb connected as indicated in the figure.



- | | Yes | No | Don't know |
|---|--------------------------|--------------------------|--------------------------|
| a) Is there a difference in potential between points A and B? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| b) Does current flow through the bulb? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| c) Does current flow through cable C? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Q3. In the circuit shown in the figure we have one battery, two equal light bulbs A and B, and a resistor R inserted between the two light bulbs.



Indicate which of the following situations will be produced, and give a short explanation.

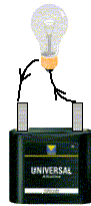
- a) Bulb B will give off more light than bulb A.
- b) The two bulbs will give off the same amount of light.
- c) Bulb A will give off more light than bulb B.

Q4. Of the following situations, tell which one correctly explains what happens with the electric current:

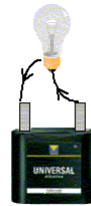
- a) The current comes from one pole of the battery and is used up in the light bulb.
- b) The current comes out of one pole of the battery, passes through the light bulb, and less current returns to the battery, entering through the other pole.
- c) The current comes out of one pole of the battery, passes through the light bulb, and the same current enters by the other pole.
- d) The current comes out of both poles of the battery and is used up in the light bulb.



a)



b)



c)



d)

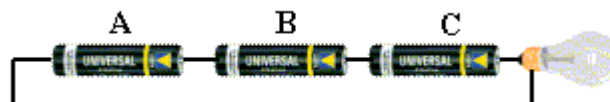
Q5. Inside a flashlight there are three batteries placed as indicated in the figure. When we turn the flashlight on and the bulb shines:

a) Is there current going through the batteries?

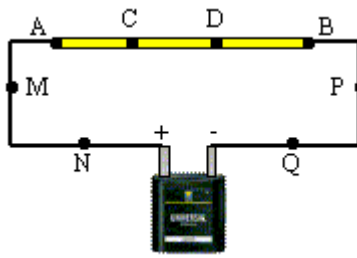
yes no

b) If yes, then through which battery does the most current flow?

A B C all the same current



Q6. We have a metal bar AB with resistance, connected to a battery by two conductor cables without resistance.

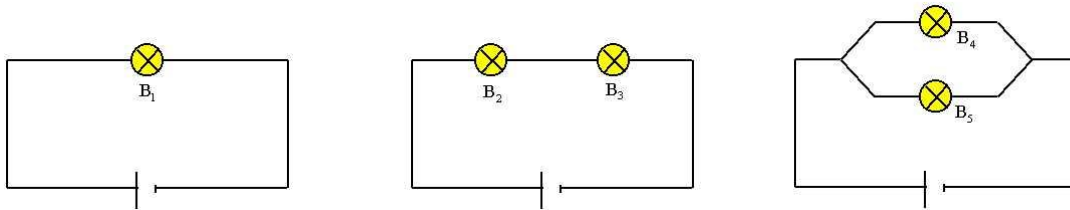


Is there a difference in potential between the pairs of points indicated below?

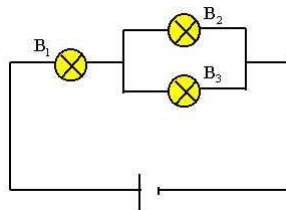
- a) between A and B yes no
- b) between C and D yes no
- c) between M and N yes no
- d) between P and Q yes no

Q7. In the following circuits all the light bulbs and batteries are the same.

Which light bulbs will give off more light? Which will give off less? Put them in order from more to less.



Q8. In the following circuit all the light bulbs are the same.



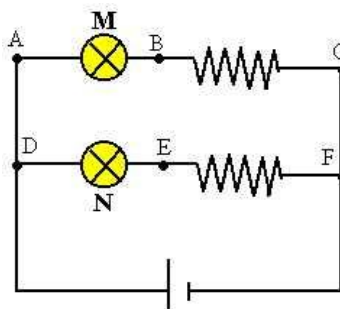
- a) Which bulbs will give off more light?
- b) Which bulbs will give off less light?

We disconnect light bulb B3 from the circuit and put nothing in its place.

c) Will bulb B2 shine more, less, or the same as before?

d) And light bulb B1?

Q9. We have a circuit made up of a battery, two light bulbs M and N, and two resistors. If we disconnect light bulb N and put nothing in its place, explain:



a) How will the potential difference vary between points D and E?

b) How will the brightness of bulb M change?

(Comment on the variations regarding the first situation, when bulb N was still connected).

Annex II. Answers obtained for each of the questions

Question 1

Answer	Freq.	
The second light bulb shines, and indicates arrows correctly.	109	59.2%
The second light bulb shines, but does not indicate arrows.	34	18.5%
The second light bulb shines, but only indicates outgoing current.	13	7.1%
The second light bulb shines, but the arrows are not clear.	9	4.9%
The second light bulb does not shine, and the others do.	11	6.0%
No answer	6	3.3%
Other answers not classifiable	2	1.1%

Question 2

Answer	Freq.	
There is potential difference between A and B, current in the light bulb and in cable C.	41	22.3%
There is potential difference between A and B, current in the light bulb, but not in cable C.	12	6.5%
There potential difference between A and B, but there is no current either in the light bulb or in cable C.	58	31.5%
There is potential difference between A and B, and no current in the light bulb, but there is current in the cable.	7	3.8%
There is no potential difference between A and B, no current in the light bulb, and no current in cable C.	39	21.2%
No answer	14	7.6%
Other answers not classifiable	13	7.1%

Question 3

Answer	Freq.	
The two light bulbs give off the same amount of light (with clear explanation).	29	15.8%
The two light bulbs give off the same amount of light (with partial or unclear explanation).	7	3.8%
The two light bulbs give off the same amount of light (no explanation).	30	16.3%
Light bulb A gives off more light than B.	107	58.2%
No answer	9	4.9%
Other answers not classifiable	2	1.1%

Question 4

Answer	Freq.	
The current remains constant when it passes through the light bulb.	90	48.9%
The current is used when it passes through the light bulb.	81	44.0%
The current comes out of both poles and dies in the light bulb	7	3.8%
The current comes out of one pole and dies in the light bulb	0	0.0%
No answer	3	1.6%
Other answers not classifiable	3	1.6%

Question 5

Answer	Freq.	
The current flowing through the batteries is the same for all three.	120	65.2%
The current decreases as it flows through the batteries.	49	26.6%
There is current flowing through the batteries, but they don't know how it is.	5	2.7%
There is no current flowing through the batteries.	9	4.9%
No answer	1	0.5%

Question 6

Answer	Freq.	
There is potential difference between points of the metal bar, but not in the exterior cables.	106	57.6%
There is potential difference only between A and B; between the rest of the points, no.	32	17.4%
There is potential difference between all the points of the bar and of the exterior cables	12	6.5%
There is no potential difference between the points of the bar; in the bar: no answer.	7	3.8%
There is no potential difference between any of the points of the circuit.	8	4.3%
No answer	12	6.5%
Other answers not classifiable	7	3.8%

Question 7

Answer	Freq.	
$B1 = B4 = B5 > B2 = B3$	8	4.3%
B1, B2 = B3, B4 = B5 (without specifying the relation between the three circuits)	107	58.2%
$B1, B2 > B3, B4 = B5$ (without specifying the relation between the three circuits)	47	25.5%
Other answers not cataloguable	18	9.8%
No answer	4	2.2%

Question 8

Answer	Freq.	
$B1 > B2 = B3$. When B3 is disconnected, B2 shines brighter and B1 is dimmer.	1	0.5%
$B1 > B2 = B3$. When B3 is disconnected, B2 shines brighter and B1 is the same.	85	46.2%
$B1 > B2 = B3$. When B3 is disconnected, B2 and B1 shine brighter.	10	5.4%
$B1 > B2 = B3$. When B3 is disconnected, B2 and B1 shine the same.	35	19.0%
$B1 > B2 = B3$. When B3 is disconnected, don't know what happens.	16	8.7%
Other answers not cataloguable	25	13.6%
No answer	12	6.5%

Question 9

Answer	Freq.	
Light bulb M shines the same, and the potential difference between D and E increases.	3	1.6%
Light bulb M shines the same, and the potential difference between D and E remains the same.	16	8.7%
Light bulb M shines the same, and the potential difference between D and E becomes zero.	19	10.3%
Light bulb M shines brighter, and the potential difference between D and E remains the same.	25	13.6%
Light bulb M becomes dimmer, and the potential difference between D and E becomes zero.	22	12.0%
Light bulb M becomes dimmer, and the potential difference becomes zero.	9	4.9%
Other answers not cataloguable	42	22.8%