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Analogy for Drude's free electron model to promote students' understanding of electric circuits in lower secondary school

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Aiming at a deep understanding of some basic concepts of electric circuits in lower secondary schools, this work introduces an analogy between the behavior of children playing in a school yard with a central lake, subject to different conditions, rules, and stimuli, and Drude's free electron model of metals. Using this analogy from the first school contacts with electric phenomena, one can promote students' understanding of concepts such as electric current, the role of generators, potential difference effects, energy transfer, open and closed circuits, resistances, and their combinations in series and parallel. One believes that through this analogy well-known previous misconceptions of young students about electric circuit behaviors can be overcome. Furthermore, students' understanding will enable them to predict, and justify with self-constructed arguments, the behavior of different elementary circuits. The students' predictions can be verified—as a challenge of self-produced understanding schemes—using laboratory experiments. At a preliminary stage, our previsions were confirmed through a pilot study with three classrooms of 9th level Portuguese students.

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I. INTRODUCTION

If one wants students to learn how to use physics models to understand nature's behavior, someone has to teach them those models [1]. This must be done in such a way that students can understand how the model works and have some idea about the meaning of the involved concepts [2]. This knowledge cannot be acquired through students' intuition, using unprepared daily observation. Even by collecting experimental results in a laboratory, it is highly improbable that students will discover [3] and understand even simple empirical laws that took ages for scientists to refine and allow the technical applications and the high standards of life we have nowadays. Teachers are expected to "inculture" students [4], teaching them how to use current society based knowledge in order to better understand it, aiming at the development of cognitive competencies for problem solving ("paper and pencil" and laboratory ones) later transferable to daily life and future progression of science and technology.

Most physics concepts are associated with very common words. However, in everyday language the same meaning can be attributed to several words which must never be scientifically confused such as, for instance, energy, capacity, force, intensity, potential [5,6]. When teachers and students, trying to communicate with each other, start discussing any physics subject without adequately defining the meaning of the used words, either written or spoken, they are using common semantic speech, but with different meanings for emitters and receivers: whatever the teacher says or writes can be differently perceived by each student and whatever the students say to express their own understanding cannot be interpreted in a clear way. Hence, the exchanged discourse and developed activities can have a misleading pedagogical effect.

In order to allow the students to start building a well-grounded future structure of physics knowledge, we maintain that physics teaching should always begin by the communication, discussion, and consequent students' understanding through application, of the meaning of the physics concepts (sometimes simplified, but nonetheless always fundamentally correct) of the scientific words they will be using [5]. This must be done by allowing the students to take part in the discussion of appropriate situations or examples, being adequately coached by the teacher whenever the scientific words are incorrectly used. Students can be trained with a sort of scientific "linguistic formula" which helps physics understanding [5,6], such as "work done by force F when applied to a body whose displacement is d" or "effect produced on B by the force applied by A on B," "heat transferred from A to its surroundings at a lower temperature," "intensity I of an electric current through the metallic wire," "potential difference between the resistance extreme points," or "between the generator's poles," etc.

To be able to learn adequately, students must feel motivated and willing to actively participate in the learning

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process. It is impossible to learn physics just by memorizing information transmitted by the teacher; the students have to build their own learning [7], which means to process the received information or the results of observed evidences within their own previous knowledge [1,8]; but the teachers' contribution to the learning process is of fundamental importance in order to promote students' cognitive development [9], introducing the scientific concepts and models, challenging and helping students to overcome eventual cognitive struggles when they try to construct and develop their own mental models [10,11].

Sometimes teachers use analogies or metaphors between behavior of easily understood systems and impenetrable invisible analogues characterized by physics abstract concepts. Reports on the most used analogies for students' learning vary from acknowledging that pupils do not use them frequently due to difficulties of transferring logical deductions between different physical systems [12], up to strongly advocating their use, classifying them as powerful science education tools which allow a first correct understanding of abstract concepts, through a scientific metaknowledge process [13]. Analogies are reported to improve scientific reasoning skills and to induce conceptual change, hence, their use should be strongly encouraged [14,15]; however, the effectiveness of analogies on students learning must always be carefully evaluated [16]. The use of analogies to induce meaningful knowledge can be time consuming [17], but the effectiveness of using analogue systems can be proved when educational experiences are designed to compare students' learning results through different teaching methods [18]. To facilitate transposition of understanding between source and target, the first system must be familiar and easily understood by the students [13,16]. Furthermore, the new abstract concepts to be learned must be repeatedly used by the students when dealing directly with the target system's behavior—for instance, solving both laboratory and paper-and-pencil problems focusing on the newly learned scientific concepts [2].

One of the issues causing the most discomfort in school teachers is the time available for teaching; but one cannot conclude that having done a few experiments and explained and solved two or three problems in class, the subject can be considered as understood by every student. The first contacts with physics in school (in Portugal on the 3rd cycle of basic school, ages 12 to 15) coincide with the first attempts of youths to build abstract models to understand the world [7]. Hence, the need of particular care towards students' construction of first physics understanding schemes must be emphasized.

Problematic situations must be created by teachers to deepen students' understanding. These must be especially designed to challenge possible developments of misconceptions, which, otherwise, most of the time remain undetected [19]. The first challenges can be fairly easy to solve—to engage students in their search for correct answers, but the level of difficulty must steadily grow and students must be encouraged to ask questions themselves. Problems should always imply students' presentation of reasons for their previous views and/or conclusions; teachers must be aware of and attentive to students' cognitive progressions, correcting and coaching them on their attempts to explain situations and leading every student to their highest possible level of learning [2,9].

Students' motivation is a vital contribution to learning self-engagement. Most of our youths feel rewarded to be able to play a game and to play it well at a continuously growing level of difficulty. To do it they accept that they have to know the game's rules and sometimes to practice some of its more difficult steps or passages. Being able to solve problems or to understand physics—present in most actions and problem solving situations in everyday life—can be presented as a rewarding activity. But in order to do so, students must correctly understand the concepts used and the physics laws that can be applied.

Schools must develop every contribution to the adequate behavior of future citizens. This includes much more than learning information about physics concepts and laws. The most important contribution anyone can give to future generations lies in how they can process the available information, eventually producing new important knowledge. Learning physics as a way to develop a lot of competencies—the most important one being the ability to face and solve problematic situations [4]—is certainly useful to society. In the physics classroom one can face challenges and analyze carefully, alone or within a group, the situation and its final purposes; foresee, based on previous knowledge, the possible ways to reach the desired aims and find the most promising ones to try; and look for the complementary information or tools needed to attain the final solution. Furthermore, one learns to explain one's own thoughts, to find and produce arguments based on previous knowledge and/or evidences, to listen to and respect colleagues' arguments, and to formulate appropriate questions in order to be able to understand and consequently make decisions.

Teachers can use different methodologies to teach physics [20]. But as a whole they should induce in students an open scientific inquiry mind, the ability to use their own knowledge and skills and a willingness to continuously enlarge them, attentiveness to the ideas of others and the ability to express one's own beliefs, readiness to develop new skills, and to face and contribute to the solution of new problems whenever they prove to be important to anyone.

This work focuses on the first contacts of lower secondary school students with the study of direct current circuits. Portuguese Curricular Guidelines propose a first contact with these circuits in the physics and chemistry course of the 9th level (students aged 14 to 15 years old). They mention [21] that *"…students can start by making simple circuits, identifying components, measuring current* *intensities and voltage differences between two points in the circuit, analysing energy transfers…"* They suggest that *"… students should calculate the electric resistance of several conductors (Ohm's law and its applicability limits)…"* mentioning the *"… importance of studying parallel and series resistance combinations…"*

One can interpret these recommendations as an influence for teachers to begin the study of electric circuits with a "hands on" methodology, based on empirical evidence and on learning information by discovery. They do not reveal any concern about promoting, least of all about verifying, students understanding about physics electric circuit phenomena, or even about the meaning of the concepts whose values they are supposed to measure. This option can be a consequence of the "invisibility" of electric circuits' behavior and abstractedness of the introduced concepts, apart from the lit or unlit lamps and the different indications on the measurement instruments.

Recent educational research results do not particularly favor this methodology [3], mainly at initial secondary school levels when students' understanding schemes for abstract concepts and systems' behaviors are starting to be built [7].

In this work we propose an alternative approach, bridged by the use of an analogy we believe will develop correct understanding of simple electric circuits by 9th level students. This approach allows students to attribute meaning to the scientific concepts used; to be able to reason based on the acquired perceptions; to develop adequate understanding enabling them to predict from fundamentals different circuits' behavior, which they can subsequently check experimentally, discussing the observed results. Through this alternative approach students can face learning of electric circuits through a simultaneous "hands on" and "minds on" strategy.

Our research questions are the following:

1. Is it possible to develop one analogy adequate to the development of students' understanding of the different abstract concepts used by scientists to describe the behavior of simple electric circuits?
2. Is the use of this analogy effective to correct well-known students' misconceptions about electric circuits' behavior?
3. Will the use of this analogy, together with the requirement for producing justifications for answers, enhance students' problem solving capacities applied to electric circuits?

At the end of this work we analyze the results of a pilot study on the pedagogical efficacy of the proposed analogy, using three classrooms of 9th level students, two experimental and a control one.

II. THEORETICAL FRAMEWORK

Analogies pedagogically used for physics teaching bridge the behavior of visible systems conditioned by familiar stimuli, which are well known or easily explainable by teachers to promote students' comprehension—the base or source system—and physics abstract systems, apparently hermetic, subject to unfamiliar influences whose characteristics or even actions are not completely detectable by vision, which show behaviors whose interpretation and understanding present serious difficulties, but must be dealt with by the students—the target system [13,15].

Analogies are frequently used by teachers as a pedagogical tool to develop students' understanding of physical models [22,23] and appear frequently in school manuals [24]. They can produce conceptual change on students [25], inducing new ways of thinking about physical systems behavior coherent with scientific models [14,15], hence, correcting well known scientific misconceptions [18]. Using analogies is especially useful for systems whose behavior is somehow "invisible" and only explained through abstract concepts [13,15]. Electric circuits fulfil these conditions, creating understanding difficulties both for students and for teachers [26]. Some authors indicate that personal analogies, where students can put themselves within the base system, can induce motivation and help deep understanding, although sometimes appealing to intuitive feelings can be misleading in physics learning [13].

Several analogies have already been described and used in the classroom for the study of electric circuits, using different base systems. Some of them were qualified as highly effective in promoting understanding of some specific concepts and behaviors, as, for example, the train analogy, using continuous movement produced by workers to illustrate the constant value of current in a series arrangement and the generator's role [15], or the moving crowd analogy to promote understanding of electric resistance [13]. The water analogy is also frequently used, but there are some problems associated with the complete understanding of the base system itself by a large number of students [13,17].

Analogies can be used to promote the correction of students' existing conceptual schemes [15,25] uncorrelated with the scientific ones and already heavily resistant to correction probably due to a succession of deficient scientific learning opportunities [19]; but they can also aim at conceptual growth and enlargement of deeper knowledge mainly when used during the first school contacts of students with some physics systems. This is the aim of the present work which introduces an analogy to be used when studying electric circuits for the first time in school. We believe it can develop a reasonable understanding of the basic physics concepts of the free electron model, to explain simple electric circuits' behavior, as proposed by Drude at the beginning of the twentieth century [27]. This analogy enables students to create a first understanding which acts as a solid ground to eliminate previous misconceptions and to reason about effects on currents and energy release due to different circuit configurations, which can be confirmed by experiment.

III. THE ANALOGY "CHILDREN IN A SCHOOL YARD FACING THE POSSIBILITY OF BEING GIVEN AN ICE CREAM"

Through this analogy students may understand the fundamental aspects of Drude's free electron model in metals, developing their comprehension of concepts of electric current, intensity of current, and the role of a generator and of its effect in a closed circuit (e.g., giving rise to a direct current, promoting the transfer of energy to the circuit elements, which in turn will give it away to the environment). It is expected that students will understand the meaning of the electromotive force of a generator, potential difference between two points of the circuit, and resistance of its different components which can have distinct values including the possibility of having connecting wires with negligible resistance. They will be able to learn the difference between a situation where the circuit is closed and one in which it is open, the effects of associating resistances both in series and in parallel, as well as the variation of resistance of metallic conductors with temperature. Having understood these concepts, the students will be able to foresee changes occurring in circuits when any of their components changes.

As a starting point, students must be acquainted with the fact that identical atoms in a metal "lose" their valence electrons into a "sea" of free electrons. The resulting positive ions occupy fixed mean positions in a stable periodic lattice in which the "free electrons", with high mobility, are evenly distributed. In Portugal, this topic is treated in the scope of the "chemistry component" of the 9th grade syllabus and should be familiar to the students before they start the study of electric circuits.

A. The source or base system

The base or source system consists of school children in a playground with a central lake with groups of trees distributed in some regions with an overall regular pattern. This is illustrated in Fig. 1, where children are not represented.

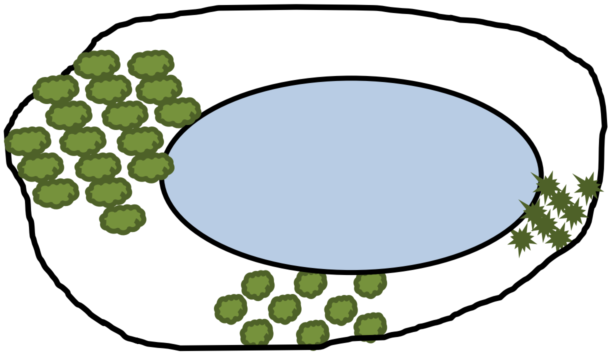

FIG. 1. School yard with a central lake and bunches of trees.

1. Closed circuit without a generator

If children have no special motivation to choose any particular point of the schoolyard, they will spread and move randomly in the available space. There will be no globally oriented movement of children: if, for example, a number of them move clockwise, the same number moves anticlockwise, in other words, the probability of both types of movement is the same. Therefore, the distribution of children remains uniform within the schoolyard: if this is photographed from above, the same number of children (but not the same children) will be observed within the same region, in pictures taken at different times.

2. Closed circuit with a generator

As is common, a man with an ice cream car (I.C.) enters the schoolyard offering ice cream and parks inside it, as depicted in Fig. 2. He comes in ringing a bell, so that all children notice simultaneously that he has arrived. They also know its parking place and how the car is positioned in the yard.

Now there is a tendency for the movement of the children to be oriented, since they try to get closer to the ice cream car. However, they must obey the following rules of the "game":

(i) Accumulation of children or empty spaces at any part in the schoolyard are forbidden; if children, trying to approach the ice cream car, start moving in both possible directions around the yard, they leave empty spaces behind them and accumulate close to the car, which is not allowed. The only way to obey the rules and come close to the ice cream car is for them to move as a whole in only one direction around the yard. If some children run a little, or move sideways, or even in the "wrong" direction, other children ought to move oppositely to fill the left empty spaces. Hence, their global movement is

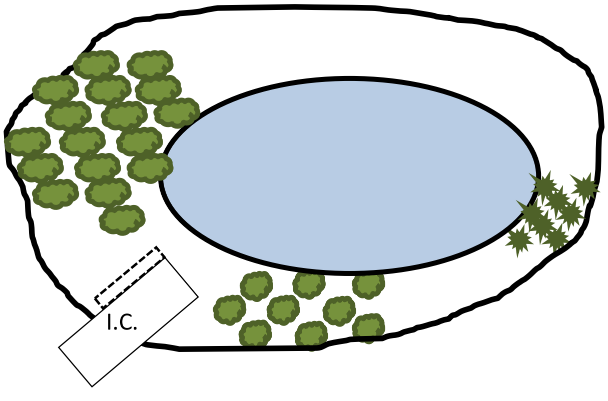

FIG. 2. School yard with an ice cream car, I.C.

oriented in one direction, leading them closer and closer to their objective—passing by the ice cream car. Moreover, it is a slow movement, due to possible collisions of children with the trees and to the fact that they cannot accumulate at any point.

(ii) Children must approach the ice cream car from only one side, the "service zone" (represented by a dashed line in the figure) and they know how the car generally stops; in the example of Fig. 2, the oriented movement of children around the schoolyard must be anticlockwise.

(iii) Each child only receives one ice cream every time they meet the ice cream car; having received one ice cream each child must go on moving around the schoolyard, and only after a full turn, can the same child get a second ice cream.

To conclude, the presence and the orientation of the ice cream car, simultaneously detected by all children, fixes the direction of their global movement; children are active and highly motivated and, thus, try to run around towards the ice cream; but, since there are trees in their way they must frequently deviate from their trajectory, or even turn back, though proceeding slowly towards their objective, following the global motion.

We may now identify the oriented movement of children with a "current of children." The number of children crossing per unit time a line drawn on the ground at any point in the schoolyard may be identified with the intensity of the current. Since there can be no accumulation of children, in the presence of the same stimulus (getting an ice cream) and of the same circuit (the playground with the trees) the intensity of the current does not vary with time and is the same at any point in the circuit.

It is easy to understand that this intensity depends on the attractiveness of the ice cream offered—a characteristic associated with the presence of the ice cream car—as well as on the difficulties offered to the movement of children by the configuration of the pathway itself—its dimensions and the arrangement of trees.

3. Resistance (to the oriented motion); regions in the schoolyard with different resistances

The concept of resistance is associated with the difficulty felt by the children in their oriented movement around the playground. This difficulty, or resistance, depends on the dimensions of the circuit and on the type and distribution of trees. As far as dimensions are concerned, the resistance will increase with the length of the pathway, and decrease with an increase of its width (measured, at each point, between the margin of the lake and the wall surrounding the yard); the wider the path, the easier for the children to move around it. Considering the type of trees and their distribution, it is easy to understand that the resistance will be higher wherever the distribution of trees is more compact; it also depends on the size (type) of the trees, namely, on the size of the branches and type of leaves—dense and low, or more sparse and high.

It should also be noted that the resistance offered by the trees on a calm day when the trees branches hardly move, is lower than their resistance on a windy day, when the branches oscillate with considerable amplitude.

Depending on the type and distribution of trees and on the length and width of the yard there will be portions of the circuit where the resistance to the children's movement is high and, consequently, their mobility is low and others with low resistance facilitating children's movement. However, as accumulation of children is forbidden, the intensity of the current of children will be mainly influenced by the high resistance of particular regions. In other words, if the current of children must be low in a zone of high resistance, it will be low in the whole circuit. The intensity of the current must be the same along the simple circuit.

4. Open circuit with a generator

If there is an impassable ditch across the schoolyard—a disruption that does not permit the passage of children as represented in Fig. 3 by the dotted square—although children remain within the yard and the ice cream car is there with ice cream to be distributed, no oriented movement is possible, since the rules are clear: no accumulation or deficiency is permitted at any point in the schoolyard. Hence, when it is not possible for the children to complete the whole circuit, any oriented movement cannot exist: the intensity of the current of children is zero.

5. Closed circuit with a region of high resistance

A narrow bridge placed above the previously described ditch represents a portion of the circuit with high resistance; this situation will enable oriented movement of children along the circuit, as the circuit is now closed and thus it is possible to complete one turn (see Fig. 4); but this movement is highly affected by the presence of the high resistance zone; children cannot move rapidly up to the entrance of the bridge and then slow down, waiting for

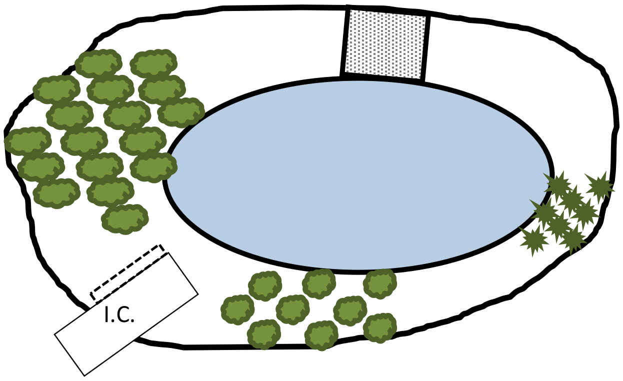

FIG. 3. School yard with an impassable ditch.

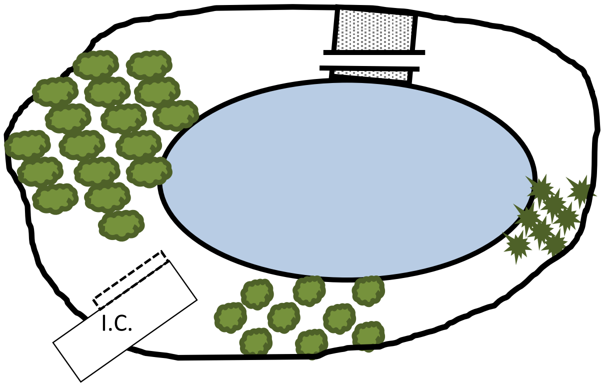

FIG. 4. School yard with a narrow bridge over the ditch.

those ahead who have not yet managed to cross the bridge—remember the rule: no accumulation is permitted. The intensity of the current of children will therefore decrease in the whole circuit.

6. Resistances associated in series

Imagine that the ditch is wider and, instead of one, there are now two narrow bridges with the same length and in sequence above it as in Fig. 5—i.e., two bridges in series; it is easy to understand that this association represents an increased difficulty for the children to move, because the narrow path is longer than in the previous case. Hence, although movement along the whole circuit is still possible, the intensity of the current decreases relatively to that in the previous situation (only one bridge) because the total resistance is now higher. Moreover, if, for example, an accident causes a large gap preventing passage through one of the bridges, oriented movement will be impossible, since there is no closed path around the circuit, thus the intensity of the current is zero at any point.

7. Resistances associated in parallel

If the two bridges over the ditch are constructed side by side we say that they are associated in parallel, as can be seen in Fig. 6. It is easy to understand that the resistance to the oriented movement is now smaller than in the case where there is only one bridge. If the associated bridges have equal lengths and widths, the intensity of the children's current in each one is half the intensity in the main circuit.

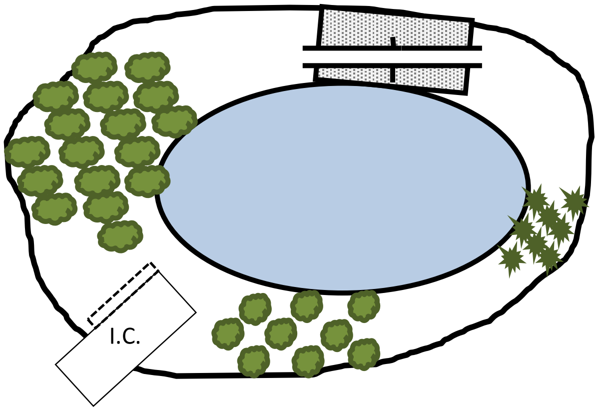

FIG. 5. School yard with two narrow bridges, in series, over a ditch.

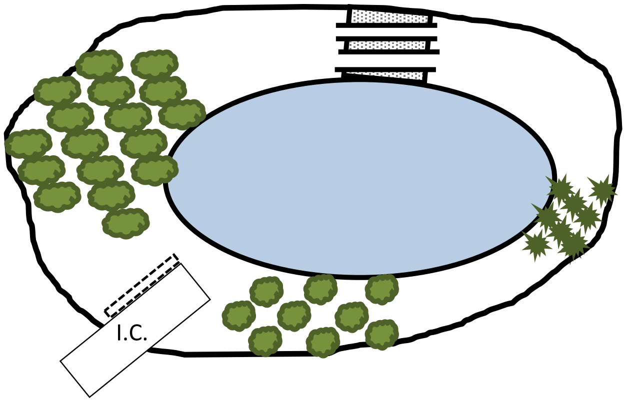

FIG. 6. School yard with two narrow bridges, in parallel, over the ditch.

When the two bridges are built in parallel, a large hole in one of them preventing passage through it does not inhibit oriented movement, since children can walk along the second bridge in a closed circuit; however, the intensity of the current is affected by the new situation.

B. The target system

The correspondence between the concepts and behavior presented above with the target system we want to introduce—real direct current circuits—is straightforward.

The schoolyard with its regions offering different resistance to the children's motion, represented by the presence of different types and arrangements of trees, ditches, or bridges, is equivalent to an *electric circuit* with *distinct resistive components*—metallic wires with different resistivity, length, and thickness.

The variable resistance offered by trees depending on whether they are still or agitated by the wind enables the introduction of the concept of *increased resistance of metallic wires due to the conduction of current*, which causes an increase in temperature and, consequently, in the amplitude of oscillation of ions in the periodic lattice. The ditch simulates a situation of infinite resistance which prevents current from flowing in the circuit—an *open circuit*.

Children quickly moving around in the playground in a random way are the analogues of *electric charges with high mobility, high random velocity, and uniform distribution*—the free electrons in metallic components of the circuit.

It should be emphasized that children are present in the playground, even if the ice cream car is absent; similarly, free electrons exist in the metal, they are not provided by the generator, which only drives the oriented movement originating an electric current. The man with the ice cream car, whose role is to promote the oriented movement of children (motivated by the ice cream he offers) is the equivalent of the *generator* which *transfers energy to the free electrons* and gives rise to their oriented movement in the closed circuit. The *electromotive force of the generator* (which, in the case of an ideal generator, is equal to the *potential difference between its terminals*) *is constant* as long as the generator is able to produce an electric current in the circuit. Analogously, the presence of the ice cream car promotes an oriented movement of children as long as there is ice cream to be offered. Each generator has a characteristic electromotive force: different ice cream cars can have different kinds of ice cream to offer, with different attractiveness.

Diagrams in which the ice cream car is depicted enable students to understand that *a generator has a characteristic internal resistance* (which may be negligible). In fact, the analogy clearly shows that the ice cream car offers some resistance to the movement of children; its magnitude is a characteristic of the car, which may leave a wider or a narrower path for the children to get through.

The association of generators in series may be represented by a sequence of gifts to the children: there may not only be ice cream, but also chocolate bars being offered.

Using this analogy it is easy to emphasize that the electromotive force of the generator as well as all the resistances included in the circuit determine the intensity of the electric current in the circuit—an introduction to *Ohm's law*.

In a simple circuit with only one generator and resistances in series, although a different resistance is associated with different parts of the circuit, *the intensity of the current has the same value at any point*, since accumulation or deficiency of electrons is not possible, i.e., their distribution is uniform. *The intensity of the current is determined by the generator and the total resistance of the circuit.*

Students can also be guided by this analogy to understand that it is possible to have *connecting wires* between different components of the circuit (thick, short, made out of metals with low resistivity such as copper) whose resistance is so small that their presence hardly changes the intensity of the current. They can be associated with spaces around the yard with almost no trees. Hence, their resistance may be neglected, for instance, when applying Ohm's law; their role is only to provide a closed circuit.

Children sense the presence of the ice cream car simultaneously, because they hear the bell is ringing—this information is carried by sound waves that propagate with the velocity of sound in the air. Similarly, in a real electric circuit, *electrons simultaneously "feel" the presence of a particular generator with specific characteristics as well as any change in the circuit*, such as opening or closing the circuit by means of a switch. In the electric circuit information is propagated by electromagnetic waves, *at the velocity of light*. It is this information that dictates the fact that deficiency or accumulation of electrons is impossible at any point in the circuit.

The ice cream offered to the children is equivalent to the *energy transferred by the generator to the components of the circuit* by electrons with an oriented movement. Potential electric energy is received by electrons as they pass through the generator. Collisions with the metallic ions constitute the mechanism for energy exchange with each circuit component (which in turn will give it away to the surrounding environment); thus, electrons move with a constant drift velocity (in time) and the intensity of the current remains constant (both in time and along the whole circuit). The potential energy lost by electrons at any circuit component depends on the intensity of the current and the resistance of the component—introduction to *Joule's law*. The interactions of electrons with ions in a metal, which in Drude's model are represented by collisions with hard spheres, enable energy transfer from electrons to (the lattice of) each component, which in turn will give it away to the environment, as heat, light, or induced motion, e.g., when motors are introduced in the circuit. Within the scope of this model it is easy to understand that *electrons do not lose energy along connecting wires with negligible resistance*, which is the equivalent of stating that there is *no potential drop along such wires*.

Students will easily understand that two *resistances associated in series* are equivalent to one resistance with a higher value (equivalent to a longer wire); and that two *resistances associated in parallel* are equivalent to one with a lower value (equivalent to a thicker wire) than that of any resistance in the association. Furthermore, they will understand what happens when the circuit is interrupted at different points.

A word should be said about the potential drop between the terminals of a generator which drives the oriented movement of the electrons, thus producing an electric current in the circuit. The expression used is self-explanatory: there is a difference between the electric potential at each terminal of the generator, one will be at a lower and the other at a higher potential. This *generator's polarity* is indicated by the different size of the segments used in its symbolic representation and determines the direction of the current in a simple electric circuit. This asymmetry of the generator is represented in the proposed analogy by an asymmetry of the ice cream car; in fact, the car is approached by the children moving in a given direction that depends on the orientation of the car in the playground. Although all children hear the bell simultaneously, they may not be able to detect its orientation; therefore, this information must be substituted by the rule of the game that fixes the direction of movement in accordance with the known orientation of the car. In a real circuit this information reaches all components "simultaneously" since it is transmitted by electromagnetic waves, at the velocity of light.

One particular point that should be raised is the source of some difficulty found by physics teachers in clarifying doubts in their students' minds. The approach based on the present analogy is appropriate to introduce the situation occurring in electric circuits formed by metallic conductors, where the moving particles are electrons. Hence, *the real direction of the electric current* is that of the motion of electrons, with a negative charge.

It is, however, universally accepted as a convention that the direction of the current is that of the movement of positive charges (note that in electrolytes there are as many positive as negative ions, which under the same stimulus will move in opposite directions). The direction of positive charge motion is called the *conventional direction of the current*. This convention (that is advantageous in analyzing certain electric circuits) is possible because it does not alter any of the above considerations concerning electric circuits.

In fact, in a circuit with a generator the electron movement outside the generator is from its negative to its positive pole, where they have a lower electric potential energy. Inside the generator they "receive" the energy lost in passing through the several components of the circuit. If we think in terms of positive charges, outside the generator these will move from its positive pole to its negative pole, where they have lower potential energy. They also "receive" energy when passing through the generator. Therefore, the real and the conventional directions of the current are opposite. But, as was shown, *the mobile charges always lose electric energy along the circuit, and always recover it when passing through the generator*, no matter their sign. Hence, either real or conventional direction for the current can be chosen.

In this perspective, when the generator has no more internal potential energy to transfer to the mobile charges, the electric current through the circuit ceases even if the circuit is closed. It is rather unfortunate that in such circumstances we commonly say that the generator is "discharged." This wording, often used by physics teachers, may be one of the reasons why students think that "the generator is a source of charges given to the circuit and these charges are subsequently lost in the circuit components."

C. Eventual negative effects of the proposed analogy—how to deal with them?

A possible undesired consequence of the use of this analogy is the incorrect association that students can make between the ice cream offered by the seller and the moving charges in the circuit. This represents a deficient understanding of the analogy that may be induced in the students by an erroneous use of language (see considerations above). In fact, when there is no more ice cream the current of children ceases, but this is not due to lack of children in the playground. It is just a consequence of the absence of the previously existing stimulus that promotes the oriented movement—the fact that they are sure to get an ice cream when they pass by the ice cream car; this is the cause of their oriented movement.

When using this analogy in a class, attention has to be given to the students' tendency to analyze any situation in a sequential mode. For example, students should be alerted to the fact that, when two identical bridges instead of only one are introduced in the circuit, the "local" resistance is halved but the intensity of current is not necessarily doubled when compared with the previous intensity (when only one bridge was present); it must be emphasized that the intensity of the current depends on the total resistance in the circuit.

Care should also be taken to avoid students' confusion between the drift velocity of the electrons (which can differ in different parts of the circuit) and the intensity of the current (which must maintain the same value everywhere in a series circuit). The former depends on the local dimensions of the circuit, whereas the latter is determined by the number of electrons through any cross section of the circuit per unit time. As the intensity must remain constant along the circuit due to the "nonaccumulation rule," electrons must move faster (higher drift velocity) in a zone of high resistance (for instance, a narrower section) and slower across a section with low resistance (for instance, a wider passage). An analogous situation occurs in fluid dynamics where, if the flow is to remain constant, the fluid must move faster across a section of smaller area.

In the in-class pilot study which will now be described, these effects were not detected but physics teachers should be aware of possible misunderstandings, which must be tested and timely corrected when necessary.

IV. PEDAGOGICAL EFFICACY OF THE PROPOSED ANALOGY

During school year 2011–2012, one of the authors, A. S., oriented by the other two, M. J. A. and M. M. C., developed a pilot study to verify in practice the efficacy of using the analogy "children in a school yard" to teach electric circuits to 9th level students [28].

A. Samples and procedures

The pilot study was performed with two nonequivalent experimental classrooms, 9A and 9B, taught by A. S. Another classroom from the same school, 9C, taught by a different teacher was used as control. All the groups had exactly the same teaching time on electric circuits. The lesson planning and the preparation of experimental activities were discussed beforehand by all the physics and chemistry school teachers. Every student used all the experimental settings proposed on the manual and solved

TABLE I. The three classroom samples and their different treatments.

	Classroom A experimental	Classroom B experimental	Classroom C control
Number of students (masculine + feminine)	26 (12 + 14)	25 (11 + 14)	25 (14 + 11)
Average age	14	14	15
Repeating students	0	3	4
	Treatments:		
Pretest	Yes	Yes	Yes
Use of analogy	Yes	No	No
Orientation to problem solving	Yes	Yes	No
Post-test	Yes	Yes	Yes

the same manual problems. These can be considered the common control conditions.

Table I contains information on the samples and on the different classroom treatments. The 9A classroom was the only one attributed to A. S. from the beginning of the academic year: since the first lesson of the electric circuits unit its students were deeply exposed to the analogy, being oriented to solve specially designed problems promoting their cognitive enrollment finalized by the presentation of reason and comments for the produced conclusions. Some problems had to be solved as homework. The 9B classroom was only attributed to A. S. one week after starting the theme electric circuits with a different teacher (this substitution was previously planned). Hence, 9B students were not exposed at all to the analogy, following closely the Curricular Guide's recommendations on a "hands on" approach. However, when taught by A. S., they were oriented to solve the same specially designed problematic situations, some as homework, and to produce the same sort of justified answers as classroom 9A students. Students from the three classrooms answered the same pretests and post-tests (identical to each other) just before initiating studies on electric circuits and completed the same assessment tasks.

B. Results

We discuss results for three questions serving as examples of the pretest and post-test challenges [29]: Q2, a short answer one, just asking for the result of cognitive effort; Q4, a multiple choice question; and Q9, a multiple choice question asking for reasons for the chosen hypothesis. Tables after the questions present the students answers both on pretests and post-tests. For each classroom (table lines) the digits appearing on the left and above the diagonal line indicate the number of pretest answers corresponding to the different types of classification defined on each column; to the right and below the diagonal line one can see the corresponding number of answers on the post-test.

Q2: *"If one introduces a metal wire on a plug, one suffers an electric shock; however, that does not happen when using a cotton thread."* Please explain why.

The analysis of Table II evidences a reasonable learning for the three classroom students after the development of the teaching activities, in what concerns the choice of the correct option (from 85% up to 100% in 9A, from 80% up to 96% in 9B, and from 24% up to 84% in 9C). However, if one considers the ability to explain the chosen answers, a characteristic of meaningful learning, progressions are markedly different: 42% in 9A, 8% in 9B, and 0% in 9C.

Q4: Observe the following electric circuit and select the correct option (see Fig. 7).

(a) Electric current intensity diminishes as it passes through the several circuit components.

(b) Electric current intensity maintains the same value along all the circuit.

(c) Electric current intensity maintains the same value from the generator up to the lamps, diminishes when passing through the lamps, and afterwards it increases again.

TABLE II. Students' answers to question Q2 for both pretests and post-tests.

		Correct and explained	Correct	Incorrect	No answer provided
Classroom A	Pretest	1	21	4	0
	Post-test	11	15	0	0
Classroom B	Pretest	1	19	0	5
	Post-test	2	22	1	0
Classroom C	Pretest	0	6	11	8
	Post-test	0	21	2	2

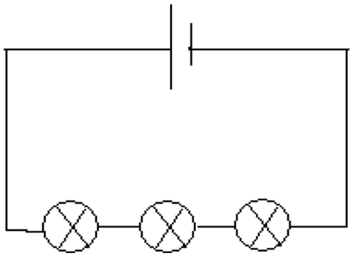

FIG. 7. Question 4.

(d) Electric current intensity is continuously augmenting along the circuit.

As in the previous question, one can see in Table III that the number of correct options after school learning is significantly higher than on the pretest. According to the pretest results it is possible to conclude that students perspectives on electric current, before school contact with the subject, were very similar in terms of correct options chosen: 23%, 20%, and 16% (the difference is only one answer), respectively, for classrooms 9A, 9B, and 9C. On the post-tests these values change to 96%, 88%, and 64%. It is curious to notice that misconceptions (a) and (c) are very strong at the beginning of the studies; misconceptions (c) and (d) are completely eliminated; however, misconception (a) still remains for 13 of the total number of 76 students, although being almost totally eliminated in classroom 9A and more persistent in classroom 9C.

Q9. In the following circuit (see Fig. 8), with an open switch after the lamp, one can say that

(a) the lamp is lit,

(b) the lamp is not lit.

Explain your option.

Again, one can notice that initial students' knowledge influenced a strong choice of the incorrect option (see Table IV). Correct and well-justified answers on the pretest amounted only to 15%, 20%, and 12% for classrooms 9A, 9B, and 9C, respectively. After school learning, correct options and adequate justifications increase to 100%, 92%, and 64%. Similarly to the previous question, 11 of the 76 students still maintain the initial misconception, which was totally eliminated in the 9A classroom, being more persistent in 9C one.

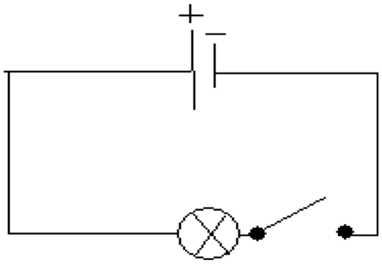

FIG. 8. Question 9.

TABLE III. Students' answers to question Q4 for both pretests and post-tests.

		Option (a)	Option (b) (correct)	Option (c)	Option (d)
Classroom A	Pretest	14	6	4	2
	Post-test	1	25	0	0
Classroom B	Pretest	5	5	13	2
	Post-test	3	22	0	0
Classroom C	Pretest	13	4	5	3
	Post-test	9	16	0	0

TABLE IV. Students' answers to question Q9 for both pretests and post-tests.

		Option (a)	Option (b) (correct and correctly justified)
Classroom A	Pretest	22	4
	Post-test	0	26
Classroom B	Pretest	20	5
	Post-test	2	23
Classroom C	Pretest	22	3
	Post-test	9	16

TABLE V. Classroom average classification, absolute gain, and normalized gain.

	Average Pretest R_1 (%)	Average Post-test R_2 (%)	Absolute gain G (%)	Normalized gain g
Classroom 9A experimental	49	92	43	0.84
Classroom 9B experimental	46	80	34	0.63
Classroom 9C control	39	65	26	0.43

Through a very simple statistical analysis, only justified by the dimensions and characteristics of this pilot study, it is possible to compare the different levels of learning by the three student samples, based on the total test classifications; for every test these were calculated through the attribution of adequate values to correct and incorrect answers, considering also the reasons presented by the students whenever asked for.

The average classification values for each of the three classrooms were calculated both for the pretests, R_1, and for the post-tests, R_2. Table V also presents the values for each classroom absolute gain $G = R_2 - R_1$, as well as for its normalized gain $g = G/(M - R_1)$, where $M = 100$ [30].

C. Conclusions

The results obtained in this study point out the following evidences:

Before specific school learning, experimental classrooms 9A and 9B did not seem very different as far as understanding electric circuit' behavior, both being slightly better than control 9C.

Solving specially designed problems to induce cognitive development in students (to produce reasons for answers and option choices) appears to have had a positive impact on both 9A and 9B students' learning.

Cumulatively, using the proposed analogy as a way to favor students' deep understanding of electric circuits and problem solving orientations in order to further develop cognitive skills seems to have produced excellent consequences on 9A classroom students (average value of 92% on post-tests); furthermore, a very large majority of these students consistently correct initial misconceptions, justifying adequately their scientific choices.

As far as factors eventually responsible for the differences occurring on the three classroom's assessment, one can point out the following:

Differences in student capacities: in fact pretest results point to classroom 9C as being slightly weaker than the two others. However, if one considers misconceptions, for instance, as revealed in the three example questions, all the three classrooms are very similar.

Different teachers: electric circuits were dealt with by the same teacher for both classrooms 9A and 9B, whose pretest results are very similar.

Different teaching methods: the better results (global and referring to correction of misconceptions) of classroom 9A can only be attributed to their understanding and efficient use of the proposed analogy.

This result is not surprising, as the proposed analogy fulfils several positive conditions indicated in the literature [13,15,16]: the base system belongs to the students' reality (it is intuitive) and is easily personalized (students can "see themselves" within it, which can trigger motivation to use it); furthermore, the analogy is fairly complete (it contains a lot of bridging correspondences). Moreover, upon exploring the base system and the correspondences with the scientific analogue, students solved several problematic situations designed to improve meaningful learning [2] of the scientific concepts.

V. FURTHER STUDIES

Having in mind the results of this preliminary study, several Portuguese teachers from different schools have already agreed to contribute to a deeper and wider verification of the efficacy, in practice, of the introduced pedagogical methodology of teaching electric circuits with rational fundaments, using explicitly the proposed analogy. The replication of this study in different countries would be most interesting.

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