The relationship between theoretical concepts in electrodynamics and experimental activities: A study on students' citizenship training

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ABSTRACT
This article investigates the relationship between theoretical concepts in electrodynamics and experimental activities, focusing on the citizenship formation of students. Electrodynamics, a branch of physics that studies the movement of electrical charges in circuits, is often considered abstract and distant from everyday reality. The teaching of science, in particular electrodynamics, often faces the challenge of making theoretical concepts accessible and relevant to students, as well as promoting a citizenship education that prepares them to face the challenges of the contemporary world. In this context, the central question arises: how does the integration of experimental activities in the teaching of electrodynamics influence students' understanding of theoretical concepts, their ability to apply these concepts in everyday situations, and their development as critical and responsible citizens? The general objective is to: analyze how students relate theoretical concepts to experimental activities and everyday circumstances, collaborating for their citizenship formation and, specifically: to investigate the performance of experimental activities in electrodynamics; evaluate the students' application and analyze the impact of integration. The methodology adopted in this study was based on the application of data and used a qualitative method. UD (Didactic Units) were used, which consist of a series of orderly, structured and articulated activities, carried out to achieve the proposed objectives. Activities included oral reading of the dissemination text, group discussions, and knowledge tests. The results reveal that students need more interlocution to be able to develop with more intimacy to the knowledge of Physics and, as a conclusion, students interact with the systems. Activities whose accomplishment evidenced the investigation procedures and the way science is developed, socioeconomic-culturally contextualized, were provided with the opportunity to provide students with the appropriation of the procedures they used to create the numerous physical theories, in order to understand in the same way how science is done.

Keywords: Theoretical Concepts, Didactic Unit, Electrodynamics, Citizenship training.

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INTRODUCTION

By exploring how students relate the theoretical concepts of electrodynamics to experimental activities and everyday situations, and how this integration contributes to their citizenship formation. And, by conducting classroom observations and interviews with students, teachers use it to investigate how they apply the concepts learned in everyday situations, such as the operation of electrical appliances, environmental and technological issues.

According to Santos (2023), the teaching of science, in particular electrodynamics, has been the target of growing interest from educators and researchers due to its importance in the academic and civic education of students.

Electrodynamics, a branch of physics that studies the movement of electric charges in circuits, presents particular challenges for educators, since many theoretical concepts in this area are complex and abstract, becoming distant from the everyday reality of students.

According to Lima & Heidemann (2023), the integration of experimental activities in the teaching of electrodynamics has been widely explored as a strategy to bring theoretical concepts closer to practice, promoting a deeper and more meaningful understanding of scientific principles.

Conducting experiential activities contributes to the development of cognitive and social skills in students, including critical thinking, problem-solving, and ethical decision-making.

In addition to the academic benefits, it is important to consider the role of experiential activities in the citizenship formation of students. Citizenship training involves not only the development of technical knowledge, but also the promotion of ethical values, social responsibility and environmental awareness.

The teaching of science, in particular electrodynamics, often faces the challenge of making theoretical concepts accessible and relevant to students, as well as promoting a citizenship education that prepares them to face the challenges of the contemporary world. In this context, the question arises: how do students relate the theoretical concepts in electrodynamics to experimental activities and everyday circumstances, contributing to their citizenship education?

The central question is: how does the integration of experimental activities in the teaching of electrodynamics influence students' understanding of theoretical concepts, their ability to apply these concepts in everyday situations, and their development as critical and responsible citizens?

The general objective is: to analyze how students relate theoretical concepts to experimental activities and everyday circumstances, collaborating for their citizenship formation. And the specific objectives are: to investigate how the realization of experimental activities in electrodynamics influences the students' understanding of theoretical concepts, analyzing whether practical experimentation facilitates the internalization of scientific principles; evaluate how students apply the concepts learned in experimental activities in everyday situations, examining whether they can establish connections between the theory studied in the classroom and everyday practice, and analyze the impact of the integration of experimental activities on the development of students' citizenship education, verifying whether the reflection on ethical issues, environmental and social issues related to electrodynamics contribute to their awareness and engagement as responsible citizens.

The justification lies in the need to better understand how the relationship between theoretical concepts in electrodynamics and experimental activities can contribute to the citizenship formation of students. By investigating this relationship, one can identify teaching strategies and practices that promote not only the understanding of scientific principles, but also the development of values such as responsibility, respect, collaboration, and environmental awareness.

It is relevant to investigate how students relate theoretical concepts in electrodynamics to experimental activities and everyday circumstances, and how this integration can contribute to their citizenship formation.

This study adopted a qualitative approach to investigate the relationship between theoretical concepts in electrodynamics and experimental activities, focusing on students' citizenship education. The research was conducted in a high school, involving final-year students.

The structure of the article is composed of an introduction that highlights the points of equivalence to the instructive commands of the study, followed by the theoretical foundation, then the methodology with the description of the stages of the study, followed by the results and discussions, final considerations and references.

THEORETICAL CONCEPTS IN ELECTRODYNAMICS AND EXPERIMENTAL ACTIVITIES

The conceptual relationship in electrodynamics and experimental activities seeks to establish the connection between the theoretical concepts studied in this area of physics and the experimental practices carried out in the classroom.

Knyppe (2021), highlights that through experimental activities, students have the opportunity to experience the principles of electrodynamics in practice, allowing a more complete and deeper understanding of the concepts covered.

The experimental activities also help in the development of practical skills, such as handling equipment and taking measurements, contributing to a broader citizenship education and providing students with an experience closer to reality.

According to Pereira (2022) and Da Silva & Lira (2022), this relationship between theoretical concepts and experimental activities aims to enrich the teaching-learning process, making it more meaningful and promoting the integral development of students.

The students' learning and the difficulties encountered in teaching electrodynamics are factors that deserve to be highlighted. For this, according to Siqueira (2022), it is necessary to explore various theoretical and practical perspectives, with the aim of understanding the learning processes of students in this area of Physics.

By discussing the main difficulties faced by students, such as lack of familiarity with theoretical concepts, difficulties in problem solving and low motivation to study the subject.

Silva (2023) points out that by investigating students' previous conceptions about electrodynamics, to identify possible obstacles in the learning process, it leads to fundamental reflections to support the construction of more efficient pedagogical strategies that are appropriate to the needs of students

Citizenship education in the educational context demands a reflection on the expectations of teaching. In this sense, Pereira (2022) emphasizes that it is essential to consider the importance of developing skills and competencies in students that make them active and critical citizens.

Through the teaching of theoretical concepts in electrodynamics and experimental activities, it is possible to promote the citizenship training of students, providing them with scientific and technological knowledge necessary to understand and act in society.

According to Máximo (2022), it is expected that the teaching of Physics will also contribute to the formation of values, such as ethics, social responsibility, and sustainability, preparing students to face present and future challenges.

The relationship between citizenship education and education expectations is fundamental for the construction of a more just and egalitarian society.

De Carvalho et al (2022) highlight that Physics plays a fundamental role in the creation and modeling of new methodologies for access to electrodynamics.

Through the application of the theoretical concepts of the discipline, it is possible to develop innovative approaches that allow a deeper and more meaningful understanding of electrical and magnetic phenomena.

According to Batista (2023), these methodologies may involve the use of technological resources, such as computer simulations and virtual experiments, which provide students with the opportunity to explore and interact with concepts in a practical and visually stimulating way.

Physical modeling allows the construction of simplified representations of phenomena and the elaboration of hypotheses and predictions, contributing to the development of students' scientific thinking.

These new approaches not only facilitate the understanding of concepts in electrodynamics, but also promote the active participation of students and stimulate critical and creative thinking.

Innovation and inclusive education have been increasingly relevant themes in the teaching of Physics. Innovation seeks to use new pedagogical approaches, technological resources and methodologies that can arouse the interest and participation of all students, promoting a more meaningful and pleasurable learning.

Picanço et al (2021), cite that inclusion is a fundamental principle, as it aims to ensure the participation of all students, including those with disabilities or learning difficulties.

When considering innovation and inclusive education in Physics, it is necessary to think of strategies that enable the adaptation of content and activities, making them accessible to all students.

Batista & Ustra (2021) points out that creating a welcoming and inclusive environment is crucial for students to feel valued and motivated to actively participate in Physics classes, contributing to their citizenship education.

THE STUDY OF ELECTRODYNAMICS IN HIGH SCHOOL

In basic education in public and private schools, the teaching of physics content, such as electrodynamics, has many deficiencies, for example: the number of courses available is small, the training and remuneration of teachers are low, and the irrefutable lack of resources. Of course, this situation usually promotes the development of education without motivation and is far from the recommendations of the PCN:

> [...] The study of electricity should focus on concepts and models of Electrodynamics and electromagnetism, making it possible, for example, to understand why appliances that serve to heat consume more energy than those used for communication, to size and execute small residential projects, or even to distinguish a generator from an engine. It will also be essential to understand where the electrical energy we use comes from and how it propagates in space (BRASIL, 2002, p. 24).

Taking into account that a significant portion of the current discourses on science teaching are focused on the following themes: student-centered teaching, shortening of theory and practice, use of technical resources in the field of education, problematic teaching, interdisciplinary nature, etc.

According to Moreira (2013), part of the classroom is based on traditionalist methods, that is, based on the use of textbooks.

Therefore, when teaching the content of electrodynamics, because the number of physics classes is small, this is not always possible, so it is basically the teacher who teaches the content verbally and classifies the exercises in the textbook, this causes the teaching to be unmotivated, boring and little used, this factor is determinant in the student's demotivation with physics.

THE STUDY OF ELECTRICAL CIRCUITS BY MEANS OF THE PHYSICAL QUANTITIES OF ELECTRODYNAMICS

The field of physics responsible for the study of electric charges in motion is electrodynamics. Therefore, in order to conduct such research, it is necessary to understand the basic concepts of electrostatics, as electrodynamics is built around them.

The broad field of electrodynamic research covers almost all electrical phenomena that people experience every day. Therefore, it was decided to perform this work through the understanding and manipulation of four quantities: current, potential difference, resistance and Ohm's law.

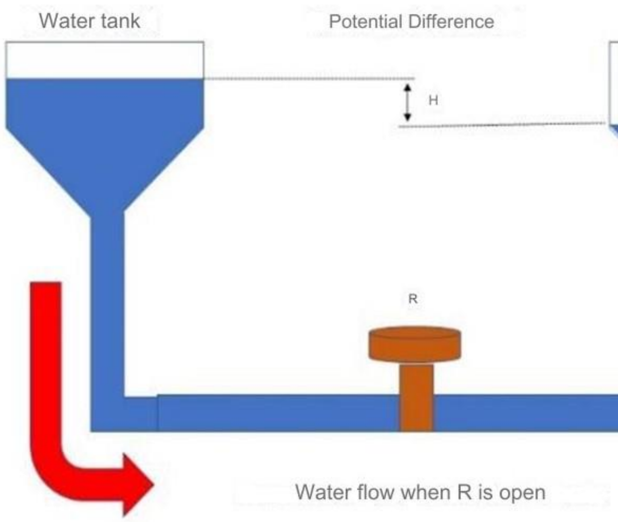
The reason for this choice lies in the theoretical orientation on which the behavior is based, since the selected content allows a diversity of activities that not only provide learning through the socialization of knowledge, such as debates about problematic situations, in the school environment and in the behavior of high school students.

Electric Current

The electric current must be understood as the ordered flow of the charge carriers, moreover, for this flow to occur, there must be a potential difference between the terminals of the network. However, not every flow of electrical charge will produce current. For example, free electrons or conductive electrons within a metal conductor move randomly and continuously in various directions. However, when you look closely, you can see that there is no orderly movement of the load in the defined direction, that is, when you study the lateral area inside the conductor, you will see that their number is about the same. Electrons crossing the plane in a certain direction and in the opposite direction cannot establish an orderly motion of charges.

One way to better understand the current is to analyze the following analogy: As shown in Figure 1, design a hydraulic system composed of two water tanks "X" and "Y" interconnected by pipes, with a register "R", you can open or close the connection between the water tanks. It is observed that in the water tank, there is a difference between the water level "h", that is, there is a difference in the gravitational potential energy between the water tanks, if the "R" register is opened at this time, then the water flow from the water tank "X" to "Y" will be established, and the water flow will be established until the water level is equal, that is, until the gravitational potential is no longer different (HEWITT, 2015).

Figure 1 - Hydraulic system composed of two water tanks and connected to each other by a pipe.

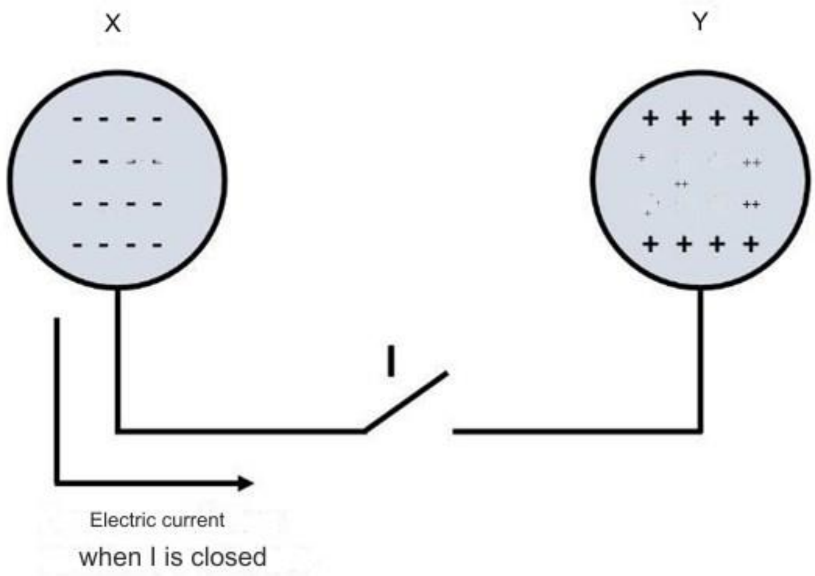


Source: Oliveira (2020).

Figure 2 shows a system consisting of two spheres X and Y. These are loaded. X is positively charged and Y is negatively charged. So there is a potential difference between the balls.

The wire connects the two spheres via an I-switch, allowing the connections to be established and undone. When the I switch is closed, i.e. when a connection is established between the spheres, the charged particles, which in this case are electrons, flow immediately from sphere X to sphere Y, thus establishing the stability of the current to the potential (HEWITT, 2015).

Figure 2 - System composed of two spheres charged and connected to each other by a conductive wire.



Source: (2020)

By analyzing the systems in Figures 1 and 2, it can be pointed out that there are some similarities between the two, so that the concept of current can be verified. The motion of water molecules moved by the gravitational potential difference forms a water flow, and the motion of charged particles moved by the potential difference forms an electric current.

In metal conductors, the particles that move around the charge are electrons because they are fixed inside the atom, the proton, and together with the neutron establish the nucleus. In this context, they are called conduction electrons or free electrons, since in conductive fluids, the charges are charged by ions.

Although this analogy is used, it is necessary to emphasize the importance that, in this case, students need to be aware of the difference between these examples, in order to avoid making conceptual errors.

In early electrical research, it was speculated that positive particles moved from a higher potential to a lower potential to form an electric current. However, it is now known that it refers to the movement of negative particles from a smaller potential to a larger potential. However, traditionally, the first idea related to the current direction continues to be used, because according to Halliday, Hesnick and Walker (2016, p. 139),

> We can use this convention because, in most situations, assuming that positive charge carriers are moving in one direction has exactly the same effect as assuming that negative charge carriers are moving in the opposite direction. (In cases where this is not true, we abandon convention and describe the movement as it actually happens.) (HALLIDAY; HESNICK; WALKER, 2016, p. 216).

However, in some cases, if well understood, the process needs to be described as it actually happens (HALLIDAY;HESNICK; WALKER, 2016). For example, the behavior of certain semiconductor components is analyzed.

Current (i) can be defined as the charge (dq) moving in the reta part of the conductor, whose load (dq) passes through that part in the time interval (dt) (HALLIDAY, HESNICK and WALKER, 2016).

$$i = \frac{dq}{dt} \qquad (1)$$

The International System of Units (SI) defines the unit of current as the Coloumb (C) per second (s), called ampere (A). The ammeter is the tool used to perform the current measurement.

$$1A = \frac{C}{s} \qquad (2)$$

In conductive materials, the actual motion of free electrons is arbitrary. However, when a potential difference is applied to these materials, it will be noticed that the electrons tend to move towards their own tissue and move towards the maximum potential.

In addition, it can be observed that when passing through the body of the material, the current produces some effects that can be observed in it or around it. Therefore, the main effects are:

a) chemical effects, which are mainly caused by chemical reactions caused by currents;

b) Magnetic effects, which are generated by the magnetic field generated by the current passing through the conductors;

c) Physiological effects, commonly known as electric shock; d) Thermal effect, namely Joule effect, usually seen/acted upon in electric showers.

In addition, current can be classified as direct current (DC) or alternating current (AC). The first is the motion that moves the load in a single direction. Secondly, the electron first moves in a certain direction and then moves in the opposite direction, alternating left and right around the set position, as shown in Figure 3 (HEWITT, 2015).

Figure 3 - Graphs of DC and AC currents as a function of time.

Source: Oliveira (2020)

According to Hewitt (2015, p. 436), "the main use of electric current, whether DC or AC, is to transfer energy from one place to another quickly, flexibly, and conveniently."

Current Density

Based on the study by Halliday and Hesnick (1996), when one is interested in studying the current i in a conductor in a more specific way, that is, when studying the flow of charge through the straight part of the conductor at any point in the circuit, it is necessary to use the density of the current J that is used to describe this flow; and if the charge is positive, it has the same direction and the same direction as the velocity of the charge that constitutes the current; If the charge is negative, the direction is opposite.

For each component of the straight part, the modulus J of the current density is equal to the current divided by the area of the component. The current flowing through the area component can be written as: J.dA; where dA is the area vector of the component, perpendicular to the component. Therefore, the total current flowing through the surface is

$$i = \int \vec{J} \cdot d\vec{A} \quad (3)$$

If the current is uniform across the surface and parallel to $d\vec{A}$, then $\vec{J}$ it will be in the same way uniform and parallel to $d\vec{A}$. Therefore, the previous equation will become

$$i = \int J\, dA = J \int dA = JA, \quad (4)$$

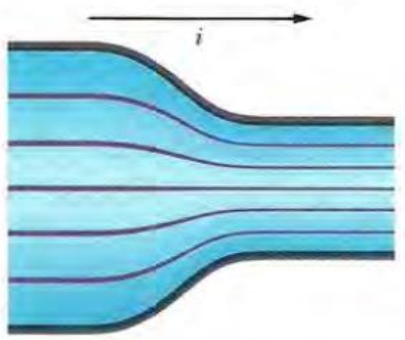
Therefore

$$J = \frac{i}{A} \quad (5)$$

Where A is the total area of the conduction surface. Based on the previous equations, the unit of current density in the SI is the ampere per square meter (A/m²).

As is well known, electric fields can be represented by field lines, because the higher their concentration, the greater the strength of the electric field. Figure 4 shows that current density can also be represented by lines commonly referred to as current lines.

Figure 4 - Representation of current density.



Fonte: Halliday e Hesnick (1996).

The left-to-right chain in Figure 4 transitions from the widest conductor on the left to the tapered conductor on the right. Once the load remains in the channel, the amount of charge and current cannot be changed. In this case, what changes is the current density, which is higher in conical conductors. In addition, the spacing of the chain lines is inversely proportional to the current density.

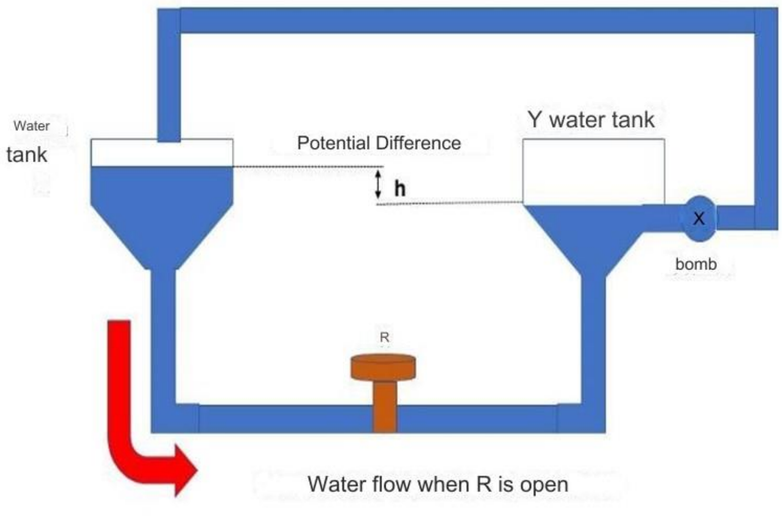
Potential Difference

The potential difference, also commonly referred to as voltage, is the difference in potential energy per unit load. The International System of Units (SI) defines volts as a unit of measurement for potential differences, which is a respect to Alessandro Volta, the coiner of the term voltage, to describe the same magnitude. A voltmeter is a tool used to measure voltage.

By analyzing the hydraulic system in Figure 2.1 again, it can be determined that the water tank will remain at the same level in a short time, that is, there will no longer be a difference in gravitational potential between them. However, if there is a pump that drains the water from tank Y and dumps it into tank X, as shown in Figure 4, by accurately measuring the amount of water entering tank Y, the potential difference and the water will be maintained and its existence will continue.

In this case, the function of the pump will become a potential source as it increases the gravitational potential energy of the water while keeping the system running.

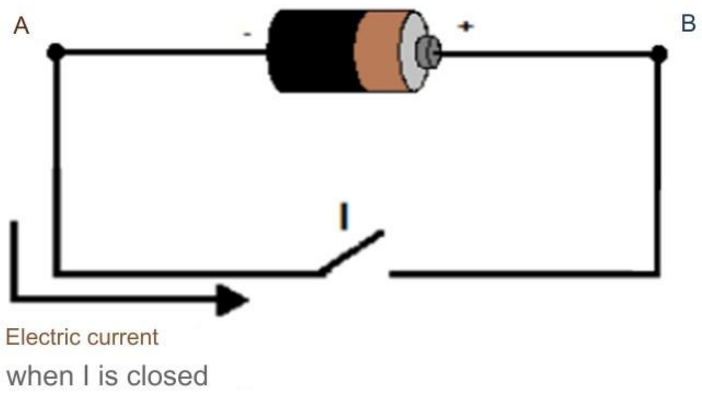
Figure 5 - Hydraulic system using a pump to maintain the unevenness between the water tanks and the current in the pipes.



Source: Oliveira (2020)

According to the hydraulic system analyzed in the past, it needs a device, i.e., a pump, which can increase the gravitational potential energy of the water, i.e., it can generate a gravitational potential difference to keep the hydraulic current of the system flowing in the system as shown in Figure 6. A suitable device, a battery that can generate a potential difference, is needed to maintain the flow of current.

Figure 6 - Electrical system using a battery to produce a potential difference and, consequently, electric current in the conductor



Source: Oliveira (2020)

The equipment used to generate the potential difference is usually referred to as a voltage generator, voltage source, or even voltage source. For example, there are batteries, electromagnetic generators, and various types of batteries. The task of such tools is to move negative charges away from positive charges (HEWITT, 2015).

Just like current, voltage can also be divided into continuous and alternating. A signal generated by a signal source that does not change its polarity over time is called a continuous signal, and a signal signal generated by a signal source whose polarity is constantly reversed is called an alternating signal.

As shown in Figure 6, a system that provides a path for current flow is called a circuit. However, in Figure 6, this circuit is not represented correctly because it still requires another size of interference, called resistance, which will be analyzed in the next section.

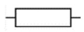
Electrical Resistance

When an equal potential difference is applied to the ends of two bars of the same size, very different results are obtained, one bar is conductive and the other is insulating. Therefore, it can be said that resistance is the aspect that establishes this difference in results. Therefore, in order to measure the resistance between two points of the conductor, it is necessary to apply a potential difference between these two points and measure the resulting current i. According to Halliday and Resnick (2016), resistance R is

$$R = \frac{V}{i} \qquad (6)$$

According to equation (6), the unit of resistance in the SI is the volt per ampere. The incidence of this arrangement is so common that the ohm (Ω), which is a special unit, ends up being used to represent it. Like so

$$1\ ohm\ =\ 1\Omega\ = 1\ volt\ por\ ampère \\ = 1\ V/A. \tag{7}$$

A resistor is a conductor whose task in a circuit is to insert a resistor. In electrical circuit diagrams, a resistor is represented with the symbol  or . When you write equation (6) in the form

$$i = \frac{V}{R} \tag{8}$$

It should be noted that in fact the name "resistance" is a great choice. The current will be, for a given potential difference, to the extent that the resistance is greater. The resistance of a conductor depends on the way the potential difference is applied.

According to Halliday and Resnick (2016), it is always necessary to use prisms instead of equipment to focus more on the materials. Therefore, the focus is not on the potential difference V between the two ends of a given resistor, but on the electric field E, which is a vector field composed of vector distributions, one at each point in the area around the electric field.

Therefore, one works with the current density instead of dealing with the current $\vec{J}i$ in the resistor, at the point under analysis. Instead of dealing with the resistance *R* of a device, it deals with the **resistivity** ρ of a material, since it is a measure of the opposition of a material to the flow of electric current:

$$\rho = \frac{E}{J} \tag{9}$$

Based on equation (8), by combining the units *E* and *J*, we obtain the ohmmeter (Ωm), for unit of ρ:·

$$\frac{unidade\ de\ (E)}{unidade\ de\ (J)} = \frac{V/m}{A/m^2} = \frac{V}{A} = \Omega \cdot m \tag{10}$$

In addition, equation (8) can be written in a vector manner:

$$\vec{E} = \rho\vec{J}. \quad (11)$$

Equations (9) and (11) are only valid for isotropic materials, that is, materials that have properties that are identical in all respects.

In the same way, we can talk about the *conductivity* σ of a material, which is the inverse of resistivity:

$$\sigma = \frac{1}{\rho} \quad (12)$$

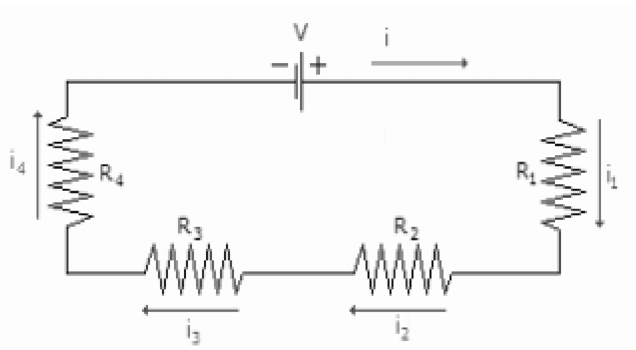
In SI the unit of *conductivity* is the corresponding ohmmeter, $(\Omega \cdot m)^{-1}$. At times, this unit is called mho per meter. Using the definition of σ (12), equation (11) can be written in the form:

$$\vec{J} = \sigma\vec{E}. \quad (11)$$

Association of resistors in series

A series connection is formed when two or more resistors are associated in which the electric current is the same at the time it is moving through them.

Figure 7 - Schematic representation of a circuit connected in series.



Source: Oliveira (2020)

In image 7, resistors R1, R2, R3, and R4 are connected in series. Since there is no accumulation of charge at any point in the conductive material, under the action of a constant current, if the charge ΔQ passes through R1 within a certain period of time, there is no other direction to go except to move continuously through R2 in the above time interval, then continuously through R3, and so on. In this case, the resistor will conduct the said current i.

As long as it is swapped out for a resistor, which has an equivalent resistance Req, circuit analysis with resistors in series can be simplified, by carrying the same current i, this will result in a similar voltage drop.

By adding up all the voltage drops of each resistor, the absolute voltage drop can be obtained as follows:

$$V = i.R_1 + i.R_2 + i.R_3 + i.R_4 = i.(R_1 + R_2 + R_3 + R_4) \quad (12)$$
$$V = i.R_{eq}$$

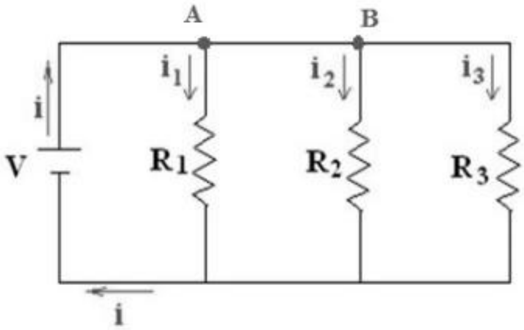
Therefore, it can be concluded that the equivalent resistance must be exactly equal to the sum of the values of the resistances of each resistor for the construction of a circuit with resistors in series.

$$R_{eq} = R_1 + R_2 + R_3 + R_4 \quad (13)$$

Association of resistors in parallel

Two or more resistors are connected in parallel at the moment when they cause a similar drop in potential.

Figure 8 - Schematic representation of a circuit connected in parallel.



Source: Oliveira (2020)

In image 8, it can be seen that the resistors at both ends are connected by negligible resistance wires. It is important to note that upon reaching point A, the current coming out of the voltage source will be interrupted, and upon reaching point B, the current will break again. Therefore, it can be concluded that all the circuit current derived from the voltage source is the sum of all the individual currents, all the resistors with parallel connections.

$$i_{total} = i_1 + i_2 + i_3 \quad (14)$$

Since one end of the parallel resistor is connected to the (+) terminal of the voltage source via a negligible resistance line, and the other end is connected to the (-) terminal of the same voltage source via the same sequence of lines, it can be concluded that each resistor will have a voltage drop of the same value and similar to the voltage drop of the power supply.

Whereas:

$$i_{total} = i_1 + i_2 + i_3 \quad (15)$$

We have

$$i_{total} = \ ; \ ; \ ; \frac{V}{R_{eq}} i_1 = \frac{V}{R_1} i_2 = \frac{V}{R_2} i_3 = \frac{V}{R_3} \quad (16)$$

In exchange we will have:

$$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \quad (17)$$

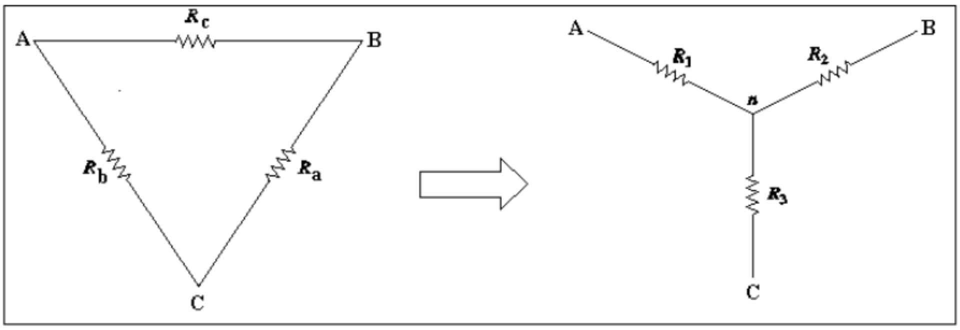
Thus, in each resistor the voltage drops are igauis, thus remaining the expression to calculate the value of the equivalent resistance of resistors associated in series as follows:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (18)$$

Triangle-star (ΔY) and star-triangle (YΔ) association

Figure 9, below, illustrates the triangle-star (ΔY) transformation:

Figure 09 - Schematic representation of the triangle-star transformation (ΔY)



Source: Oliveira (2020)

In order to establish the relationship between the resistors, it is possible to start by equating the following equivalent resistances:

$$R_{AB} = \frac{(R_a+R_b)R_c}{R_a+R_b+R_c} = R_1 + R_2 \quad (19)$$

$$R_{BC} = \frac{(R_b+R_c)R_a}{R_a+R_b+R_c} = R_2 + R_3 \quad (20)$$

$$R_{AC} = \frac{(R_a+R_c)R_b}{R_a+R_b+R_c} = R_1 + R_3 \quad (21)$$

By solving the system of equations that follow from 1 to 3, you can achieve:

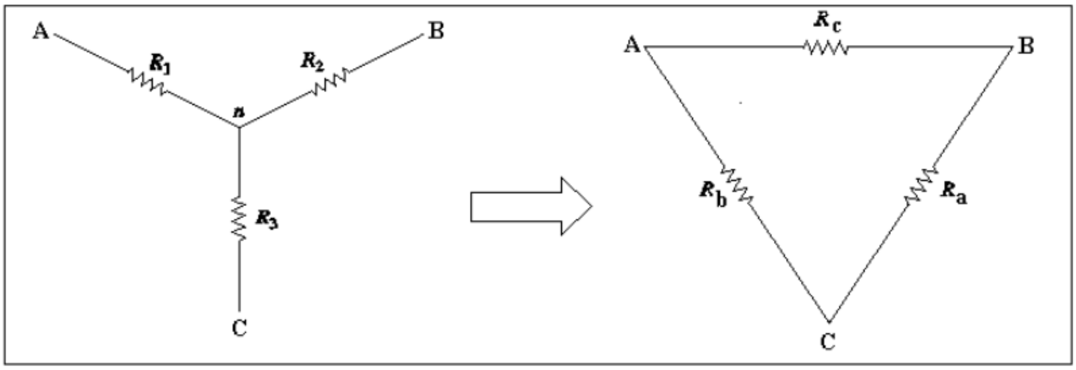
$$R_1 = \frac{R_b R_c}{R_a+R_b+R_c} \quad (22)$$

$$R_2 = \frac{R_a R_c}{R_a+R_b+R_c} \quad (23)$$

$$R_3 = \frac{R_a R_b}{R_a+R_b+R_c} \quad (24)$$

Figure 10, below, demonstrates how to do the opposite transformation, i.e., the star-triangle (YΔ) transformation:

Figure 10 - Schematic representation of the star-triangle transformation (YΔ)



Source: Oliveira (2020)

To put the function into an equation, we start in the same way, that is, as in the previous transformation (ΔY), obtaining the following equations as a result:

$$R_a = \frac{R_1R_2+R_2R_3+R_1R_3}{R_1} \quad (25)$$

$$R_b = \frac{R_1R_2+R_2R_3+R_1R_3}{R_2} \quad (26)$$

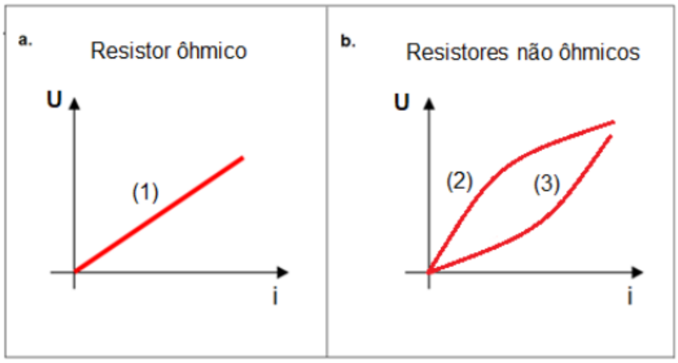
$$R_c = \frac{R_1R_2+R_2R_3+R_1R_3}{R_3} \quad (27)$$

Lei of Ohm

According to Halliday and Resnick (2016), Ohm's law can be conceptualized as "the statement that the current through a device is always proportional to the potential difference applied to the device". However, today this position is correct only in certain circumstances, but for historical reasons, it is still called "law."

Figure 6 shows two diagrams. Figure 6.a shows the diagram of the difference between the electric potential of the resistor and the current according to Ohm's law; in Figure 6.b, in this regard, for the two resistors that do not obey Ohm's law, the same as before is noted. The graph is an ohmic resistance line, i.e., the resistance remains the same regardless of the current and voltage values.

Figure 11 - a. Graph U x i for one ohmic resistor; b. Graphs U x i for two non-ohmic resistors.



k

Source: Oliveira (2020)

Also according to Halliday and Resnick (2016), "If the resistance of a device does not depend on the absolute value or polarity of the applied potential difference, it must obey Ohm's law". Therefore, a much-repeated misunderstanding should be avoided that V = iR is a mathematical expression of Ohm's law. In this case, in addition to being applied to any device that is allowed to conduct current (including devices that are not subject to Ohm's law), you also have an equation to determine the concept of resistance.

METHODOLOGICAL PROCEDURES

The research was conducted based on the formulation and implementation of Didactic Units (UD). According to Zabala (1998), UD are "a series of ordered, structured and articulated activities carried out to achieve certain educational objectives". The study aimed to explore the relationship between theoretical concepts in electrodynamics and experimental activities, with emphasis on the citizenship formation of students.

To this end, didactic units were structured based on Vygotsky's theoretical teachings on the zone of proximal development and Davidov's educational principles for the cognitive and moral development of students. The activities were implemented in a private school in Manaus, Amazonas, using the didactic material of the integrated education system adopted by the institution.

The study involved a second-grade high school class of 23 students who participated voluntarily. The classes were held after the school, lasting fifty minutes each. The students were divided into five groups to carry out the activities, and each group remained together until the end of the UD. All students had access to the experimental equipment used in the activities.

The research adopted a qualitative approach, which considers the data presented and the understanding of the phenomena under analysis. The experimental field took place between December 2019 and December 2020. To assess whether the research objectives were achieved, the activities performed by the students during the use of the UD were analyzed, using as a data source the activities collected by the teachers and the field diaries recorded by the researchers.

Data analysis was performed using the content analysis method, as proposed by Bardin (1997). This method allowed a qualitative analysis of the meaning attributed by the students to each activity carried out in the UD, emphasizing the students' ideas and enabling the verification of the hypotheses established for the research.

RESULTS AND DISCUSSION

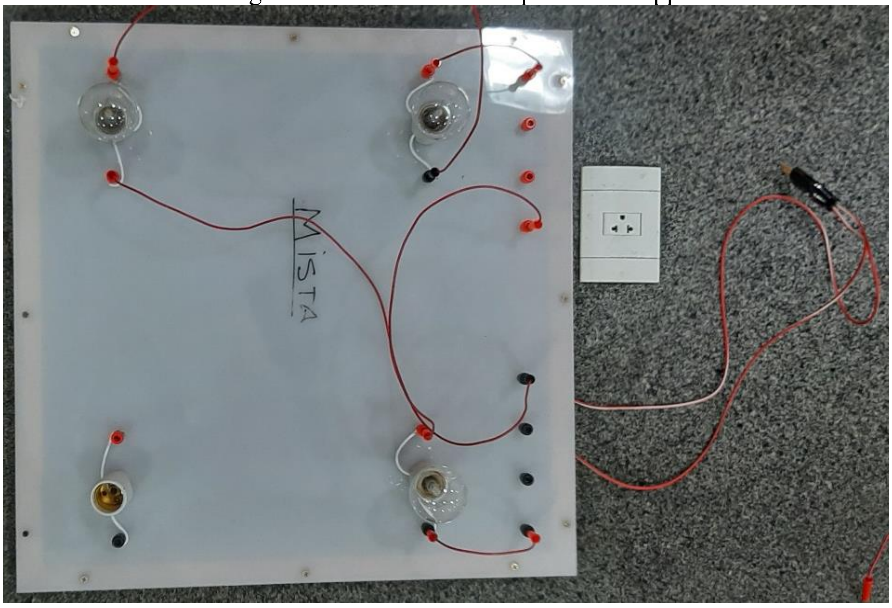
Experimental classes were carried out, here the mixed circuit experiment class stands out. **Mixed circuit experiments.** This class was organized with the second experimentation activity, focused on electrical circuits in parallel, in teams. Not only in this part of the experiment but also in the others, experimental activities were used that are categorized as laboratories with degree of freedom II, according to Carvalho (2010).

For this lesson, the following objectives have been established:

1. Identify if the students are able to recognize in the experimental activity the contents worked on in the previous classes.
2. Verify if students can relate the content worked with everyday situations.
3. Investigate how students behave in the face of experiments in the laboratory;
4. Discuss the results found by the teams about the problems proposed in the investigation script.

To achieve these objectives, an experiment was carried out over a time of 50 minutes, and this activity was carried out in five teams of no more than five students out of a total of twenty-two students who participated in this class. During this class, an experimental apparatus was used, consisting of a 50x50cm acrylic plate, with four 40W and two 60W incandescent lamps, four banana nozzles, 10mm cable, electrical tape, wire clippers, screwdriver and screws.

Figure 16 - Misto circuit experimental apparatus



Source: Oliveira (2020)

An investigation script containing six questions was used as a guide for the experiment, which are described and analyzed below.

During the class, the students were notified that they could not consult any materials other than those of the teacher's guidance, so that the verification of the answers concerning objectives 1 and 2 would not be difficult.

Tables are presented below with the students' responses to the investigative script of this experimental class. Table 1 shows the answer to question 1.

Table 1 - Answers to item (a) Use the materials on the workbench to set up an electrical circuit with two 40W bulbs in series and a third 40W bulb in parallel.

E1	You created the circuit correctly.
E2	You created the circuit correctly.
E3	You created the circuit correctly.
E4	You created the circuit correctly.
E5	Created the partially correct circuit.

Source: Oliveira (2020)

The results of this question were recorded in the teacher's field diary, in the face of an exploratory question focused on analyzing the independence of the teams in the assembly of the experiment. Therefore, it was noted that only the E5 team presented difficulties in assembling the experimental apparatus, requiring the help of the teacher.

In addition, it was clear that the teams became familiar with experimental lessons, absorbing the way the electric current behaves in the circuit, as well as the potential difference over the lamps. Table 2 shows the answers to item b.

Table 2 - Answers to item (b) Before we start the experiment, do you think the bulbs will show the same brightness? Try to justify it.

E1	No. Lamps in series will have less intense brightness than the lamp in parallel.
E2	No. The lamp in parallel will have greater brightness than the lamps in series.
E3	No. The brightness of the lamp in parallel will be greater because it will have greater electrical current.
E4	No. Lamps associated in series will have greater resistance, therefore lower electrical current. Therefore, lamps in series will have lower brightness than lamps in parallel.
E5	No. Lamps in series will shine less.

Source: Oliveira (2020)

The teams, without exception, correctly predicted the intensity of the lamps' brightness. However, it was noticed that there were minimal conceptual variations among the teams to justify their answers. The E3 team relied on the concept of electric current to explain the higher brightness of the lamp in parallel. On the other hand, the E4 team used the concept of resistor association and Ohm's law. On the other hand, the E5 team did not use any form of concept to explain their answer, which demonstrates that this team did not properly appropriate the concepts worked on in the previous classes. Table 3 shows the answers to item d.

Table 3 - Answers to item (d) Using the concept of electrical power, describe in detail what you observe when we connect the circuit set up on the bench.

E1	The lamps in series are not dissipating 40W.
E2	Lamps associated in series have lower brightness than those in parallel. Therefore, the lamps in series are not dissipating 40W and the lamp in parallel is.
E3	Lamps in series have lower brightness.
E4	Although all lamps are 40W, the lamp in parallel is dissipating an electrical power of 40W, while the lamps in series a lower value of 40W.
E5	The power in series lamps is lower.

Source: Oliveira (2020)

The teams, without exception, described in detail what they observed. It should be noted that the E3 team did not use the concept of electrical power to justify their observation, this shows that the team did not associate the brightness of the lamps with the power dissipated by them. It should be noted that the E5 team associated the brightness of the lamps with the concept of electrical power, since they use the term power to describe the brightness between the lamps in the circuit. Table 4 shows the answers to item e.

Table 4 - Answers to item (e) What are the voltage and current in a light bulb connected in parallel? And for the bulbs in series? Calculate.

E1	Parallel: Voltage =120V. Current = 0.33A. Series: 60V for each lamp and the current in both is 0.16A.
E2	The voltage across the lamp in parallel is 120V and its current is 0.33A. The voltage in the lamps in series is 60V each, having the same current of 0.16A.
E3	The voltage in the parallel association is 120V. And in series association, there are identical 60V lamps for each. The electric current in the lamp in parallel is 0.33A and in series association this current is half 0.16A.
E4	In the lamp connected in parallel, the voltage is 120V and the electric current is 0.33A. In series association, the electrical voltage is 60V in each lamp, and the electrical current is approximately 0.16A.
E5	The lamp in parallel has a voltage of 120V and the lamps in series have 60V. The lamp current in parallel is 0.33A and in series a lower value.

Source: Oliveira (2020)

When checking the justifications of the teams, it is noted that teams E1, E2, E3 and E4 obtained the correct values of what was requested in the question. However, it is observed that E5 did not present the value of the electric current in the series association, in addition, it should be noted that when presenting the value of the electrical voltage (60V) in the same association, the team failed to justify that this value would be that of each lamp, which could lead to later errors, such as calculating the electric current with wrong values. Table 5 shows the answers to item f.

Table 5 - Answers to item (f) Using the same circuit as in the previous question, what do you think will happen to the lamp in parallel, which is 40W, if we connect a third lamp, which is also 40W, in series? And what do you think will happen to the other 40W bulbs connected in series?

E1	The lamp in parallel continues with the same brightness. They will have less brightness than before.
E2	It will continue to dissipate the same power. The other lamps in series begin to dissipate an even lower power.
E3	Paralelo continues with the same shine as before. Series changes brightness, becomes smaller.
E4	If we associate a third lamp in series, it will not interfere with the brightness of the lamp in parallel. But in series association the resistance will increase and consequently the current will decrease, causing the brightness to decrease.
E5	This lamp will have the same brightness as before. The other lamps will lose brightness.

Source: Oliveira (2020)

It can be seen that all teams got the question right. However, it can be seen that the E2 team appropriated the concept of electrical power to justify the intensity of the brightness of the lamps. Thus, it was observed that E4 used the concept of association of resistors in series and Ohm's law to justify the difference in brightness (dissipated power) of the lamps in the circuit. Table 6 shows the answers to item g.

Table 6 - Answers to item (g) In which everyday situations do we find mixed associations?

E1	Electronic devices.
E2	Cell phone, video game, television.
E3	Electronic devices.
E4	Electronic devices.
E5	Cell phones.

Source: Oliveira (2020)

The teams, without exception, related the experiment to everyday situations. However, it was possible to notice that the examples given by the teams were the same as those provided by the teacher in the regular course classes.

According to Guimarães (2023), the study of mixed circuits in electrodynamics represents a fundamental integration between electrical and electronic components, providing a comprehensive understanding of the functioning and interaction of elements such as resistors, capacitors, and inductors.

Mixed-circuit analysis in electrodynamics is crucial for the integration between electrical and electronic devices, offering a thorough understanding of the behavior and interconnection of elements such as resistors, capacitors, and inductors.

According to Schettino (2016), mixed circuits are essential for the analysis of complex electrical systems, where direct and alternating current components coexist, allowing the application of theoretical principles of electrodynamics in real-world situations.

Mixed circuits play a key role in the evaluation of highly complex electrical systems, in which direct and alternating current components are present simultaneously. This makes it possible to apply the theoretical principles of electrodynamics in real-world scenarios in practical terms. Chart 1 highlights the categories according to the analysis of the responses.

Chart 4 - Categories drawn up according to the analysis of the teams' responses to the items in the investigative script for the first experiment.

	E1	E2	E3	E4	E5
They created the correct or partially correct circuit.	x	x	x	x	x
They made correct predictions and provided adequate justifications.	x	x	x	x	x
Presented appropriation of the concept of electrical power	x	x		x	x
They found the correct values.	x	x	x	x	
They correctly or partially predicted what would happen.	x	x	x	x	x
They related the experiment to some everyday event.	x	x	x	x	x

Source: Oliveira (2020)

The verification of the categories presented in Chart 1 shows that the objectives of the class were achieved. The students demonstrated independence in the organization of the experimental apparatus, although the E5 team had difficulty in this activity. In addition, it was noticed that the teams made correct predictions of the problems contained in the investigation process.

It was noted that the students appropriated the concept of electric power, with the exception of the E3 team, which showed difficulties in associating the brightness of the lamps with the power, which in turn led to a wrong answer to the question.

The teams, without exception, understood the meshes of the mixed circuit, as well as the appropriation of the concepts of electric current and electric voltage, to justify the values of the latter and the former. Thus, it is possible to notice that the students performed better when making predictions in the development of the experiment in this class.

CONCLUSION

The study on the relationship between theoretical concepts in electrodynamics and experimental activities revealed important contributions to the citizenship formation of students. By integrating theory and practice, it has been possible to provide a deeper understanding of scientific principles while promoting the development of ethical, social, and environmental values.

During the implementation of the didactic units, students demonstrated a high level of engagement and participation in the experimental activities, evidencing a broader understanding of the theoretical concepts when applied in practice. Reflection on ethical and social issues related to the experiments stimulated critical thinking and responsible decision-making.

Through the analysis of the collected data, it was possible to observe that the proposed educational objectives were achieved, with the students demonstrating not only a greater mastery of the electrodynamics contents, but also a greater awareness of the impact of their actions.

The research carried out on the influence of experimental activities in electrodynamics on students' understanding of theoretical concepts revealed significant results. Hands-on experimentation proved to be fundamental to facilitate the internalization of scientific principles, providing students with a deeper and more concrete understanding of the concepts covered in the classroom. Through the experimental activities, the students were able to experience the studied phenomena in practice, which contributed to a more effective and meaningful learning.

The analysis of the way students apply the concepts learned in experimental activities in everyday situations revealed the students' ability to establish connections between the theory studied in the classroom and everyday practice. Students demonstrated knowledge transfer skills, applying the principles learned in real-world contexts and recognizing the importance of electrodynamics in their daily lives.

The study also showed the positive impact of the integration of experimental activities on the development of students' citizenship education. Reflection on ethical, environmental and social issues related to electrodynamics contributed to the awareness and engagement of students as responsible citizens.

By promoting discussion on relevant topics, such as the sustainable use of energy and the environmental impacts of electricity, the experimental activities encouraged students to reflect on their role in society and to adopt more ethical and responsible behaviors.

Thus, it is evident that the integration of experimental activities in the teaching of electrodynamics not only improves the understanding of theoretical concepts, but also contributes to the development of conscious, critical citizens committed to collective well-being.

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