Multidimensional Perspective about Resistors Association in Electric Circuits: Part I - Investigating Non-Scientific Conceptions and Instructional Materials

Perspectiva multidimensional sobre a associação de resistores em circuitos elétricos: Parte I - Investigando concepções não científicas e materiais instrucionais

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ABSTRACT
The main goal is evaluating and analyzing non-scientific conceptions and learning difficulties in electric circuits. Reflections and instructional considerations will be admitted among researches in literature and some textbooks focusing topological representation. The study was carried out prioritizing the main concepts of equivalent resistance and association between resistors, including the perception of foundational and auxiliary concepts. A verifying of causal elements for intuitive reasoning on series and parallel circuits were analyzed. Is was found that understandings involve a complex linguistic and symbolic context. They had showed essential for bringing out a perspective about multidimensional representation. Findings characterize this as an active area where confusions appear when non-conventional diagrams are explored or due the visual homogeneity in textbooks, didactic choices or scientific books.

Keywords: conception, electric circuit, multidimensional, resistors association, topology.

RESUMO
O objetivo principal é avaliar e analisar concepções não científicas e dificuldades de aprendizagem em circuitos elétricos. Reflexões e considerações instrucionais serão admitidas entre as pesquisas na literatura e alguns livros didáticos com enfoque na representação topológica. O estudo foi realizado priorizando os principais conceitos de resistência equivalente e associação entre resistores, incluindo a percepção de conceitos fundamentais e auxiliares. Uma verificação de elementos causais para raciocínio intuitivo em circuitos em série e paralelo foi analisada. Verificou-se que os entendimentos envolvem um contexto linguístico e simbólico complexo. Eles se mostraram essenciais para trazer à tona uma perspectiva sobre representação multidimensional. Os resultados caracterizam isso como uma área ativa em que surgem confusões quando diagramas não convencionais são explorados ou devido à homogeneidade visual em livros didáticos, escolas didáticas ou livros científicos.

Palavras-chave: concepção, circuito elétrico, multidimensional, associação de resistores, topologia.
1 INTRODUCTION

Non-scientific conceptions have been documented in the study of Electric Circuits in several countries at different times, markedly in the last four decades (BRNA, 1988; McDermott & Shaffer, 1992; Engelhardt, 1997; Pesman, 2005; Azevedo & Gitirana, 2017). They are a natural part of student learning and understanding. In this sense, it is important evaluating conceptions associated with the basic learnings of resistive circuits, including equivalent resistance, parallel and series configurations. Abstract concepts together with interdisciplinary elements pose challenges and reflections. This content is key in the Physics curricula for high school, technical and higher courses.

1.1 CONCEPTUAL CONSTRUCTION

The application of Ohm's and Kirchhoff's Laws or techniques which unfold from them (Node Voltage, Mesh Current, Thévenin/Norton Theorem) is preceded by meaning of how the resistors, sources and another components are connected (series, parallel, \( Y / T, \Delta / \pi \)). In an initial highlight, this is a condition for understanding the schematic representation, for evaluating the interpretative elements of the circuit topology. In a complementary way, the analytical application or algebraic determinations require preliminary steps, reasoning structures which, notably, may not depend exclusively on the basic concepts.

Inaccuracy in the process of conceptual construction is described in several papers. This affects not just the basic solution of problems, mental models about current or voltage (Stocklmayer & Treagust, 2007; Burde & Wilhelm, 2017; Pramesti & Setyowidodo, 2018), students at different school levels (Garnet & Treagust, 1992; Küçüközer & Kocakülah, 2007; Turgut et al., 2011; Smaiill et al., 2011), teachers’ conceptions (Önder et al., 2017; Moodley & Gaigher, 2019), but also the appropriation of new concepts (André & Ding, 1991; Turgut et al., 2011). The recognition of schematic diagrams, which are used in the knowledge representation, is another relevant issue for interpreting circuits, part of general aim in this paper. For instance, about image representation, researchers have described or suggested that:

- circuit analysis instruction should integrate equations into circuit diagrams to avoid the split-attention effect (Ozogul et al., 2012).
- can be examine strategies for diagram labeling in conjunction with representation transitioning (Johnson et al., 2014).
- through including physical circuits into assessments, educators could identify more accurately if students have the deep seeded misconception of sequential reasoning or other language of concept gaps (Desportes et al., 2016).
These studies have reported on evaluating the effects of labels and equations’ integration in the electric diagrams, the conceptions about electric current, voltage and power. Here there will be focus on linguistic constructions and the imagery vocabulary about connections, diagrams and associations. From this, relationships will be established for conceptual learning difficulties, including didactic elements. Another difference is the perception of the consequences linked to technological resources at didactic and professional context.

1.2 STUDY SETTINGS

The investigation here is focused on the following questions: Why intuitive reasoning about the connection between electrical components is closed to false interpretations? Why students have difficulty in the physical or digital assembly of an electrical circuit? What influences the student’s decisions to classify connections or when analyzing a diagram, a functioning electrical circuit? Evidences were found that a qualitative perspective for prospecting answers to these questions is to understand the topological reasoning.

There are difficulties for understanding and applying some scientific concepts. Those which form the theory basis (voltage, current, resistance, power) are linked with others (electrical node, branch, mesh), auxiliary, essential in the phenomena interpretation. Then, the first step will be to discuss conceptual difficulties, presenting a bibliographic synthesis, mainly highlighting ideas about non-scientific reasoning, resistance and connections between components.

Recognizing that learning requires coherent representation due to the demands of cognitive processing, and admitting the broad educational and technological spectrum, a developed didactic outline will be presented. Particularities of research mapped in the international literature were considered as well as the way in which the concepts are constructed by Brazilian textbooks and by technical-scientific books used in several countries.

2 BACKGROUND

The Electric Circuits education often involves several forms for representing concepts: the natural language, mathematical expressions, diagrams (sketch, formal representation, freehand drawing, empirical images), digital and analog labs. Each one has a fundamental role. The first three are more associated with the semantic approximation that should be made from the scientific concept to abstraction. The last is related with didactic and professional applications (experimental benches, electronic components, digital resources, instruments, industrial equipment). Through them it is possible to communicate the scientific concept in written or verbal form, exposing words, signs, a symbolic language. It also proves appropriate with an iconic representation to build, read and interpret.
diagrams, standards and datasheets. Numerical results can be obtained through mathematical formulation and operations with equations which seek to explain the modeling of phenomena.

In the case of Technological Professional Education (TPE) in Brazil, labs activities are central. Therefore, a didactic environment of empirical resources can be added, which is used for simulation and/or physical construction. Real-world applications are previously addressed to exercises and simulations carried out in digital programs, “hands on” with prototype assembly (breadboards, double sided or impress circuit boards), electronic sources and resistors, as well as instruments for measuring electrical quantities (ammeter, voltmeter, ohmmeter). Ideally, all of this is related to the content in the classroom, respecting each academic level / desired objective.

From de preliminary ideas, schematic diagrams, language, models and technological applications provide the resizing of case studies between representation and practical realization (in both directions), adjusting abstract and concrete. They also take another stage, with new faces and possibilities: the main (founding) concepts start to show objects, elements of professional practice, and are also highlighted by these applications; subliminal concepts come to be expressed not just by iconic representations, but also by material elements.

There are several artifacts in the didactic laboratories of technical schools, science institutes and universities. They are most often seen in those organized for professional learning, aimed at training technicians, technologists and engineers. The context requires a detailed assessment, in which it has unconventional representations, variations of traditional didactic approaches. They can provoke an interpretive effort, which is mobilized by the students, liable to decline during the teaching-learning process, distancing them from the scientific concept. This can happen in a scenario different from the theoretical plane experienced or in some empirical processes.

Among the research objectives, conducted at the doctoral studies through the Postgraduate Program in Mathematical and Technological Education (EDUMATEC) of the Federal University at Pernambuco (UFPE), it is intended to show difficulties by students on basic electrical circuits and researchers’ indications in the literature, prominently about the association between resistors.

3 ABOUT CONCEPTIONS AND LEARNING DIFFICULTIES

The student's first contact with the context of Electric Circuits usually occurs with a symbolic set. This approach results immediately in the appreciation of abstract elements, which seek to give meaning to scientific concepts. From there, it is observed that the signs assume a central role on the knowledge's construction and would be strongly connected to the subject's conceptions about the theory. Thus, the idea about the term "conception" stands out.
3.1 STARTING WITH NON-SCIENTIFIC CONCEPTIONS

With regard to the idea of conception, in the paper this term will refer to the understanding structured by the subject, the act of imagining a concept, in the interaction of what is understood or that is being structured towards representations or objects. This requires a state of balance between what the student knows and his new experiences, in which here we also highlight the environment in which the subject is inserted, notably in Physics: the classroom, physical and digital laboratories. Here, it should be referred to the conception of an electric concept. Thus, it is predisposed to understand what affects the structuring in a diversified symbolic scenario.

In an attempt for learning new concepts, the student is challenged to effective circuit representation. However, their conceptions cannot be in accordance with the scientific scope. In a complementary way, the transition between theoretical knowledge and the empirical framework in both directions is not simple. Understanding’ processes associated with the non-scientific conception are related to several aspects: conceptual difficulties, informal ideas, conflicting interdisciplinary knowledge, lack of students’ skills, language confusion, incorrect pattern of response. The “Misconception” term is commonly mentioned in literature (ANDRE & DING, 1991; ENGELHARDT & BEICHNER, 2004; SENCAR, YILMAZ & ERYILMAZ, 2001; GORIS, 2016; WIDODO et al., 2018), although it has acquired different meanings (pre-conception, alternative conception, misunderstanding). What stands out in the theoretical core about the Electric Circuits analysis is that non-scientific conceptions (previous, alternative) affect learning due to some ideas “which students have incorporated into their cognitive structures and that they use to understand or make predictions” (ANDRE & DING, 1991, p.303) or even, which can be induced in this process of dynamic balance of each subject with the learning environments.

About theoretical principles, researchers in many countries carried out that students have a lack of knowledge articulation. This is more directly related to the concepts of Electric Current and Voltage, emphasizing incorrect responses, proposing diagnosis’ instruments (ABEL, 1995; ENGELHARDT, 1997; PESMAN & ERYILMAZ, 2010), emphasizing drawings (GOUVEIA, 2007; FRANZONI et al., 2010), evaluating experiments in learning (TAVARES & DA SILVA, 2019), referring on the persistence of these misconceptions (DE ANDRADE et al., 2018), confrontation (BRNA, 1988; FLORÊNCIO et al., 2019), describing curricular proposals (SHAFFER & McdERMOTT, 1992). Just exemplifying about resistors association, a basic error is an initial tendency to focus on the number of circuit elements rather than on the configuration (McDERMOTT & SHAFFER, 1992). There is also a resilience in spontaneity for activities which involve different circuits mainly in non-congruent cases (AZEVÊDO & GITIRANA, 2017).

There are two gaps in line with the introductory aspects:
• The way of interpreting the connections between components and the constructed linguistic and symbolic context.

• The learning about the concept of equivalent resistance and its related approaches (underlying concepts) to the typological classification of connections.

3.2 A REPRESENTATION PROBLEM

Learning difficulties do not have a fixed address. In different education systems, with different curricular proposals and teaching methodologies, non-scientific conceptions are mobilized by students. Its amplitude in Physics stands out in relation to the circuits:

An active area of research on misconceptions in physics is the subject of simple electric circuits. Research on students’ understanding of science has shown that they have a wide range of misconceptions in the field (SENCAR, YILMAZ & ERYLMAZ, 2001, pp.113-114).

Mestre (1989) defends that Misconceptions are a problem for two reasons:

First, they interfere with learning when students use them to interpret new experiences. Second, students are emotionally and intellectually linked to these misconceptions because they have been actively building them (MESTRE, 1989, p.2).

Notably, we extend the previous perception (in Mathematics) to Physics. Introductory courses in high school, in Physics or Engineering courses contemplate abstract concepts and a didactic sequence naturally involving new diagrammatic, linguistic elements and equations. Together, they form the representation core of scientific knowledge (Figure 1).

Figure 1. Core for abstract representation of electrical circuits.

![Diagram showing the core of abstract representation of electrical circuits](source: elaborated by the authors)

Formal diagrams give meaning to associations through images. Spoken expressions and written words are used to characterize constituent elements of circuits, types of connections. Graphs can express results of Ohm’s law; mathematical equations describe models and can allow to estimate results through calculations. In addition, everyone can expose correspondence.
Learning difficulties could occur due to the educational system in which the student is immersed, their textbooks, or even in the cognitive process of each one during the conceptual construction at class. Vocabulary can be confusing, difficulties can arise during operations with equations, in basic laws’ application, or even connections’ production in an electric diagram. According to literature, these non-scientific conceptions can occur after formal instructions, being common among students who have had formal instructions with relevant material (McDERMOTT & SHAFFER, 1992, p.995).

However, the way in which the content is presented could provide a more robust analytical insight. Then, diversifying scenarios and assessing how the theory appears in books is essential. This can be an alternative for expanding a diagnostic perspective by teacher. Also, the student’s difficulties about types and nature of the situations which they face will likely to emerge in exercises, tests, lab activities. A criticism occurs when there is a standardized correspondence between the content of the book and its proposed exercises. Otherwise, difficulties may remain:

Typically, these erroneous models are expected to disappear as a result of formal instruction on the operating principles of a simple electrical circuit. Numerous studies show that learners resorting to spontaneous explanations whenever the context of questioning differs from that of the problems at the end of the chapter in their textbook (MÉTIOUI, 2012, p. 4202).

Previous contents reinforce the need to address the causes of these conceptions, raising a look at the way in which the contents have been approached. Can any analogy be the source of a non-scientific conception? This may be a question whose answer depends on the analytical deepening of the teacher. With this, it is intended to warn that teachers are not safeguarded from non-scientific conceptual interpretations (MOODLEY & GAIGHER, 2019). Then, they need remain alert about challenges and responsibilities for mapping conceptions.

Exclusively theoretical support is not always enough to provide training which allows an integrated look at the knowledge representation and experimental demands. Objects and their relationship with signs and concepts commonly differ from conventional symbolic representation:

[...] although many students can solve theoretical questions, few are able to solve practical questions that require experience. Thus, the need for laboratory activities must also be taken into account (SENCAR, YILMAZ & ERYLMAZ, 2001, p.119).

In a study carried out with 286 students from four (04) Brazilian public universities (USP, UFSCar, UERN, UESPI), Costa & Catunda (2008) evaluated the reasoning developed by students regarding the analysis of simple electrical circuits composed of lamps and batteries. It was noticed that few students manage to develop a conceptual, qualitative reasoning:
The problem can be solved (...) in a qualitative way. Therefore, it is necessary that students have assimilated the basic concepts of electric current, electric potential, potential difference, resistance, equivalent resistance and electrical circuits in series and parallel. (...) we observe the great need for numerical values (COSTA & CATUNDA, 2008, p. 3).

There are concerns about the concept of equivalent resistance. We highlight this still at the paper of Costa & Catunda (2008), in which they observe algebraic-conceptual confusions by students, something which occurs at preference over the qualitative abstraction of cases:

Another concept which is not clear is equivalent resistance. Some students, in order for ranking the luminosity of the lamps, first calculated the equivalent resistance of each circuit, and noting that the luminosity is directly proportional to the power, they replaced the value found for the equivalent resistance in the power formula (COSTA & CATUNDA, 2008, p. 8).

However, algorithmic teaching makes calculation procedures prevail even when it is not necessary to solve problems qualitatively. Therefore, identifying connections must be a previous need which aims to provide student support for understanding diagrams and situations.

Equivalent resistance must be perceived as a relevant concept in introductory learning about Electric Circuits, but also in more advanced situations at this curricular component or at others, when it is necessary to reduce complex electrical circuits or power systems which have many electrical nodes. It is appropriate to highlight that underlying concepts - node, mesh, open and short circuit - are decisive for identifying types of association (series, parallel, Δ, Y,...) or obtaining equivalent resistances from the simplest cases to for Thevenin and Norton theorems. About difficulties, in this core, some notes were raised in the literature (Table 1):

| Authors | Interpretative Difficulties |
|---------|-----------------------------|
| McDermott e Shaffer (1992) | a) Focus on the number of circuit elements instead of the configuration.  
| | b) do not distinguish between the equivalent resistance of a network and the resistance of an individual element. |
| Abel (1995) | c) believe that the equivalent resistance always increases when the number of resistors increases in a circuit. |
| Engelhardt e Beichner (2004); Dorneles, Araújo & Veit (2007); Gouveia (2007) | d) do not easily identify series and parallel connections. |
| Hussain et al. (2012) | e) have alternative conceptions about open and short circuit. |
| Azevêdo & Gitirana (2017); Widodo et al. (2018) | f) think that the type of circuit depends on how the resistors are placed with each other. |

Source: elaborated by the authors.
In the assessment of exams or teachers’ daily routine, part of these difficulties can be attributed to algebraic errors or to the lack of understanding Ohm's law or Kirchhoff's laws. However, the diagrams presentation mode and the number of components can apparently cause disorientation in relation to scientific concepts because many students are unable to decompose circuits with four or five resistances in series and parallel connections, especially when the circuits are designed in an unconventional way (McDERMOTT & SHAFFER, 1992, p.999).

When authors report on unconventional drawings, they recognize the abstraction inherent in diagrams and their multiple possibilities, and whose approach is rare in most books (Figure 2).

Figure 2. A single circuit drawn in different ways.

![Circuit Diagrams](source: Nahvi e Edminster (2014)).

Note that nodes (A, B, C), branches (AB, BC, CA) and meshes (ABA, ACBA) can be represented using different images. Some of these can, somehow, generate visual turbidity, which incurs the need to understand each connection point, paths between points, open and closed circuits, relative positions, even observing short circuits ($R_s$ at Figure 2). Thus, another observed element refers to symbolism and connections of electrical diagrams. Although treated in a secondary way in the researches, data from the literature in this regard were collected (Table 2):

| Authors                      | Interpretative Difficulties                                      |
|------------------------------|------------------------------------------------------------------|
| McDermott & Shaffer (1992)   | a) To recognize that a circuit diagram represents only electrical elements and connections, and not physical and spatial relationships.  
                               | b) To treat instruments as part of the circuit and recognize the implications for their construction and making the connections. |
| Abel; Azevêdo e Gitirana (2017) | c) Regarding the series concept: it has a connotation of sequentially instead of a specific type of connection.  
                                | d) In relation to the term “parallel”: it is thought in terms of its geometric property and not its electrical property. |
Figural elements employed at class are so important. Furthermore, a morphological status seems to be present in Electric Circuit studies. Then, students must interpret and design a variety of circuit parts. “Parallel” and “series” terms would be linked to reasoning of a positional nature.

3.3 ABOUT SCIENTIFIC AND NON-SCIENTIFIC CONCEPTION

In the literature (McDERMOTT and SHAFFER, 1992; ELGELHARDT & BEICHNER, 2004; PESMAN & ERYILMAZ, 2010), common nonscientific conceptions are (Table 3):

| Model         | Characteristics                                                                 |
|---------------|---------------------------------------------------------------------------------|
| Sink          | The single connection of a conductive wire between a device and a power source allows the operation of the electrical circuit |
| Attenuation   | The electric current which circulates along an electrical circuit in one direction gradually decreases due to the consumption of this current as it “crosses” the devices |
| Local reasoning | When changing a part of an electrical circuit, what happens at another point is ignored. There is an emphasis on the local part instead of global analysis |
| Sequential reasoning | The change in a section of the electrical circuit affects it in the direction of the current ("forward"), not "backward" |
| Empirical Rule | The further away a lamp is from the power supply, the lower its brightness |
| Short circuit | Wires which interconnect points that do not have connected components are ignored |
| Parallel circuit | Resistors are considered obstacles to current circulation. Increasing the number of resistors connected in parallel would result in an increase in the total equivalent resistance of the circuit |

From a scientific perspective, some aspects are mentioned:

- Resistance is a property of an object or material, which marks the relationship between voltage and electric current from Ohm's Law in those components whose behavior “$v \times i$” occurs in a linear manner.
- If more elements are added until they form “$n$” combined resistors:
Equivalent resistance in series increases: \( R_{eqs} = \sum_{k=1}^{n}(R_k) \);

Equivalent resistance in parallel decreases: \( R_{eqp} = \left[\sum_{k=1}^{n}(1/R_k)\right]^{-1} \).

- It is necessary to identify nodes, branches and meshes in order to identify the type of association and the circuit operation (voltage and electric current):
  - Two resistors directly connected in series share a single electrical node.
  - Two resistors connected in parallel share two pairs of electrical nodes.
  - The electric current is the same at resistors connected in series (at branch), the voltage will be divided between resistors (at mesh) according to Kirchhoff's Law for Voltage (KLV).
  - The electric current is divided at resistors connected in parallel (at branches) according to Kirchhoff's Law for Current (KLC); there will be the same voltage at the resistor terminals.

From the classical conceptions manifested in learning, the classification (Table 3) is closely linked to voltage and electric current, as well as the resistors or lighting devices distributed throughout a circuit. From the scientific perspective, auxiliary concepts were highlighted. Some students, for example, believe that in a series association with different resistors, the one with the highest resistance will have the lowest electrical current (BILAL & EROL, 2009). Another difficulty refers to recognizing and dealing with the interpretation or application of serialization and parallelism concepts (McDERMOTT & SHAFFER, 1992; SMAILL et al., 2011). It is possible to suggest here that the detailed discussion of auxiliary concepts can help a counterpoint to non-scientific conceptions, something to be discussed at the following section.

Also, it is known that part of the cognitive structure associated with the students' conceptions stems from the process of building knowledge and teaching (HÄRTEL, 1985; NIEDDERER & GOLDBERG, 1995). Some teachers even expose non-scientific conceptions (GAIGHER, 2014). The relationship between connections, forms and written / spoken language would be an additional point in the analysis, but it is not dealt with in detail in the literature. Another perspective is about empirical situations. Marshall (2008) attends that a fundamental characteristic of circuit diagrams is that they show that electrical connections exist but not how they are made physically, so the standard symbol was not enough. The empirical context must be seen also emphasizing how basic and auxiliary concepts physically appear, how the circuits are formatted and the requirements for measurement using analog and digital instruments.
4 ANALYZING REPRESENTATION: CONCERNS AND PERSPECTIVES

Starting studies on electricity, the association of resistors supports circuits simplification. Decisions about the components' connection are urgently needed for solving problems. As was pointed out, in circuit diagrams there is a “geometrization” of representations. Was there an element rooted in linguistic construction or in the classroom approach that would induce this perspective? How the terms "series" and "parallel" are interpreted? It will be admitted that there is a mistaken administration, by students, of the semiological mechanism which structures the interpretation of concepts and problems.

Although they can solve numerical problems quickly, many students are not able to arrive at a correct qualitative solution in circuit analysis (DORNELES, ARAÚJO & VEIT, 2006). Experimentally, there are also several difficulties in associating diagrams with activities. When using digital programs, for example, students are very motivated, receptive and active to information, preferring illustrations to texts and their difficulties are often attributed to memorization elements inherent to some school contexts (FRAGA & CASTRO, 2004). It is worth noting, in a complementary way, that empirical resources (simulators, hardware, applications in general) are rich in symbolic elements.

Many of the analog devices in science and engineering laboratories are not dealt with in detail as to the presentation of the theoretical framework on Electric Circuits. A set of diagrams can represent the same circuit, in which a conceptual assessment is required. Engelhardt and Beichner (2004) indicate that errors associated with the circuit physical aspects may occur because they lack the necessary declarative knowledge to understand the physical nature of the diagram and its associated elements. Thus, new schemes offered to the student, different from those understood by him as “standard” for a certain object, can generate a reason for global change in the typology pre-classified by him. Therefore, difficulties may arise in the interpretation of cases that do not have a symbolic scheme like the subject's conception.

Components layout as if on parallel and perpendicular lines values geometrization in scientific thinking, being extensively explored in textbooks. Consequently, they are explored in admission exams for Universities and Federal Institutes like National High School Exam (ENEM) in Brazil (Figure 3). Visual representations are fundamental for communicating about electrical circuit knowledge. However, there is a spatial overvaluation in the components’ arrangement. Likewise, this occurs in the abstract representation of connecting wires.

We highlight the choices about how the components are connected to each other. In an electrical circuit or in the simple arrangement between electrical resistors, different layout of components may
exhibit equivalent electrical topology just as equivalent spatial distributions may not be electrically equivalent from a topological perspective.

Figure 3. Question with components spatially arranged through vertical and horizontal lines.

Many smartphones or tablets no longer need keys, since all commands can be given by pressing the screen itself. Initially this technology was provided through resistive screens, formed basically by two layers of transparent conductive material that do not touch until someone presses them, modifying the total resistance of the circuit according to the point where the touch occurs. The image is a simplification of the circuit formed by the plates, where A and B represent points where the circuit can be closed by means of the tank.

Source: National High School Exam (ENEM, 2018).

Perceptions expressed through drawings could be a great source of data to understand how the student understands concepts (PACCA et al., 2003; LABURÚ et al., 2009). Thus, it’s interesting the study of topological equivalence through situations with iconic/diagrammatic data which could reveal concepts linked to the way the circuit is visually communicated.

In attempting to formalize the comparative analysis, Dorf and Svoboda (2008) indicate that two diagrams A and B represent the same circuit if the following conditions are met:

i. There is a two-way correspondence between the nodes in diagram A and the nodes in diagram B. The nodes position is not important.

ii. There is a one-to-one correspondence between the components of diagram A and the components of diagram B.

iii. The same components are connected to the same nodes in the two diagrams.

Analyzing two-way correspondence, the authors say that “the position of the nodes is not important”. Thus, they warn that the spatial arrangement is irrelevant to define equivalence. It is implied that the reference of the electrical topology is essential in this significant demarcation. The appropriation of appearance can be an obstacle for perceiving topological structuring. Laburú et al. (2009) pay attention to the symbology, emphasizing the complexity of this scope:

Among the contents of Physics which use symbols, explored in high school, those about electrical circuits stands out in quantity. We can see several codes and signs which are distant from the things they conceive. [...] In the case of electrical wires, they are figured as straight
lines almost always symmetrically associated, connected at ninety degrees and converging at a single point or node, depending on the convenience and symmetry of the symbolic scheme (Laburú et al., 2009, p. 33).

There is an interpretive naivety which can distance the student from the scientific concept. Electrical nodes have several visual possibilities, often shaped by means of wires or straight lines. An aspect of these imagery schemes is that it implies, on the part of students, an attempt at abstraction, to reproduce the physical-geometric characteristics of a model (MARSHALL, 2008; AZEVÊDO & GITIRANA, 2017; FLORÊNCIO et al., 2019). Thus, it is fruitful to explore aspects of the organization of the form and content of this knowledge.

Learners are faced with multiple diagram and connection representation. At basic DC Electrical Circuits, moving between different forms of representation admitting scenarios of conflicting conceptions would perhaps be another important didactic alternative. It is crucial to assess the connection between the components, which can be represented in different ways. Note that we bring here the need for the study of meaning invariants (rotation, reflection, component sliding in the branch), very close to the studies on symmetry, strengthening relations between Mathematics and Physics. Some variations of planar representations are exposed in Figure 4: in series, in parallel, in π or Δ format.

Figure 4. Some topological variations to represent the connection between resistors.

(a) Series

(b) Parallel

(c) π / Δ

Source: elaborated by the authors.

This action could oppose visual homogeneities that subsidize static knowledge, revealing reasonings that generate certain behaviors.

Authors commonly create rigid aspects between formal terms and representations in textbooks (Figures 5, 6 and 7). Alone, however, they tend to generate morphological reasoning. Thus, it is necessary to explicitly link different representations, whether of a symbolic or empirical nature (analog, digital). Multiple representations are likely to create a valuable relationship about spatial
distribution of the components, creating perception on electrical topology. From this, the possibility of dynamic situations would be a next interesting step.

Figure 5. Resistors association: textbook “Understanding Physics - Electromagnetism and Modern Physics”.

![Resistors association: textbook “Understanding Physics - Electromagnetism and Modern Physics”.](image)

Source: Gaspar (2013, p.107)

Visual representation of series and parallel concepts are very similar in the Figures. In Figure 5 there is only a positional reference of the connections, an arrangement. In Figure 6, the idea that current is the same at series resistors or that voltage is the same at parallel resistors is explicit. Nodes are represented by points which refer to electric solder or union of the resistor’s terminals. In Figure 7, in addition to the ideas explicitly referenced at Figure 6, it is added a notion that voltage is divided between the resistors connected in series at the mesh and that current is divided at the branches with
parallel resistors. In addition, there is reference in the image about the idea of equivalent resistance, without algebraic details.

In some technical-scientific books, the notion of alignment can be avoided from the way of drawing the resistive arrangement like a loop (Figure 8), but it creates a sequentially sense.

Figure 8. A series circuit in books (A) “Introduction to Electric Circuits” and (B) “Electric Circuits”.

![Figure 8](image)

**FIGURE 3.3-1**
Single-loop circuit with a voltage source $v_v$.

Sources: (A) Svoboda & Dorf (2014, p.63); (B) Nilsson & Riedel (2011, p.58).

However, the notion of alignment or sequence can also be reinforced through the chosen visual model to suggest the measurement of equivalent resistance (Figure 9), certainly affecting novice students. In Figure 9 there is also a reference to the node as an electronic solder between the components or connection of the alligator terminal (from ohmmeter) with the resistor.

Figure 9. Measuring equivalent resistance ($R_T$) in book “Introductory Circuit Analysis”.

![Figure 9](image)

**FIG. 5.4**
Series connection of resistors.

**FIG. 5.11**
Using an ohmmeter to measure the total resistance of a series circuit.

Source: Boylestad (2007, p. 134)

This highlights the importance of labels in the diagrams, while generating a concern: the intuitive reasoning. In the learning process, if students need to store electrical typologies with an exclusive exploration of the formats above - just individual and homogeneous attention - the ideas of alignment and superposition (series circuit) or parallel lines (parallel circuit) will be in their mental representations. It will probably be evoked in intuitive reasoning for situations which, diagrammatically, remember these initial representations. The referential connections will be strongly linked to a limited imagery set. A learning obstacle can be stablished.
5 CONCLUSIONS

In relation to works in the literature, the international character of groups and researchers who have been studying the learning difficulties in the Electric Circuits theory is noted. A second point is the inclination of research to: more prominently the modeling of activities whose purpose is to identify the students' conceptions (mainly related to the concepts of voltage and electric current) and, less frequently, to the construction of situations that promote favorable conditions for the identification of conceptions about diagrams and connections.

A third aspect to highlight, in which we observed a trend in the last decade and a half: the attempt to improve teaching with the development of proposals mediated by technologies, considering the diversity of materials and experimental environments (digital simulators, physical laboratories), but without the perception about non-scientific conceptions, about dynamic operators linked to topology, as well as without appreciation of transition requirements between semiotic and non-semiotic representations. Sometimes the connections between components are neglected, so that a correct interpretation of the object does not materialize. In students who are part of introductory Physics courses, morphological reasoning should prevail, which is constituted by the historicity and use of terms, in addition to the visual set induced by the books (series - alignment and sequence; parallel - parallel lines, geometric reference).

AUTHORS NOTE

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