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Looking at the theoretical relations of the teaching of electromagnetism based on the theory of developmental teaching[+*]

Daniel Trugillo Martins Fontes[1]
Doctoral Student - Interunit Post-graduate Program in Science Teaching
University of São Paulo
São Paulo – SP
André Machado Rodrigues[1]
University of São Paulo
São Paulo – SP

Abstract

This paper aims to investigate which theoretical relations could form a model for teaching electromagnetism based on Davydov's theory of developmental teaching. In this sense, this work fits into a theoretical analysis on the content of teaching electromagnetism by addressing issues of its foundation, and not of its methods. As a result, we present an initial synthesis of the essential concepts that structure the classic electromagnetic phenomena, namely: movement, variation, and interaction. We also propose an activity to analyze these concepts, concretizing them in the generation, transmission and use of electrical energy. We highlight as this work's main conclusions the possibility of dialogue between Davydov's theory and the teaching of Physics to promote theoretical thinking, as well as the outline of a theoretical model.

Keywords: *Physics Teaching; Electromagnetism; Developmental Teaching; Davydov.*

[+] Um olhar para as relações teóricas do conteúdo de ensino de eletromagnetismo fundamentado na teoria do ensino desenvolvimental

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[1] E-mails: daniel.truga@gmail.com; rodrigues.am@usp.br

I. Introduction

This paper aims to analyze the content and present a theoretical model for the teaching of classical[2] electromagnetism, the result of the master's thesis by Fontes (2020) from a cultural-historical perspective, particularly focused on the theoretical contributions of the theory of developmental teaching. Therefore, we divided this article into two main parts: up to item IV, we present data from the literature regarding the teaching of electromagnetism and Davydov's theory of developmental teaching. From this, we justify the need to elaborate a theoretical model for Science Teaching in general, and particularly for electromagnetism. From item V onwards, we present a dialogue with the developmental theory and discuss a first proposal for a theoretical model (DAVYDOV, 1990; HEDEGAARD; CHAIKLIN, 2005) based on the work of electrical energy. A literature review (FONTES, 2020) shows that there are no proposals for the analysis of content on electromagnetism from the perspective of the developmental teaching theory and, considering any content in physics, there are only two Brazilian works (MARENGÃO, 2011; BORGES, 2016) aimed at classical mechanics. Fontes and Rodrigues (2020, p. 4) suggest a justification to the lack of works in Physics teaching that use the Davydovian theoretical framework: "the main researchers dedicated to the study of Davydov's theory do not have academic training – undergraduate or postgraduate – in the field of Physics or Physics teaching".

Research on the teaching of electromagnetism has reported that students have great difficulty in studying electrical and magnetic systems (SILVA, 2012). According to Casperson and Linn (2006), students have difficulty in topics such as electrostatics, since such topics involve ideas and experiences that incur in a disconnection between the macroscopic and microscopic spheres related to the same phenomenon, while physicists tend to integrate both perspectives to understand the investigated phenomenon. In addition to electrostatics, Colin and Viennot (2001) show that the conceptual understanding of the wavelike behavior of light is difficult to assimilate, even among university students.

Stocklmayer (2010) highlights the fact that students with various degrees of academic education lack a deep understanding of the physical model of electric current and electron motion. Still on this topic, Scarinci *et al.* (2009), in a didactic experiment aiming to demonstrate the conduction and generation of electric current, notices that students showed difficulty to interpret what occurs inside wires, batteries and lamps. Sağlam and Millar (2006, p. 545), when investigating the understanding of electromagnetism by students in the final

[2] Similar to Bezerra (2006), we use the term *classical* to refer to non-quantum electromagnetism. We also understand that textbooks often divide the content of electromagnetism into different sections, such as electrostatics, electrodynamics, magnetostatics, electromagnetism and radiation. In this article, we have a broad use of the term *electromagnetism*, to encompass all these didactic separations. Specific cases will be explained appropriately.

years of high school, showed that few students "seem to have an integrated perspective or can present their understanding through the application of concepts in new situations”.

Regarding Physics teaching, there is extensive literature on the development and use of methodologies for teaching certain contents or concepts. Several literature reviews, such as those conducted by Fávero and Sousa (2001); Ribeiro and Verdeaux (2012); Jardim and Guerra (2017b); Müller et al. (2017), and Oliveira, Araujo and Veit (2017) explore how different methodologies are present in different contents within Physics teaching. Henderson, Dancy and Niewiadomska-Bugaj (2012) also developed a list of twenty-four different methodological strategies found in research in Physics teaching. When reviewing the teaching of electromagnetism at all levels of education in the last two decades, Fontes and Rodrigues (2021) highlighted that the solutions adopted by teachers focus mostly on the use of experimentation or on the adoption of technological resources, such as virtual simulators.

However, from our perspective, perhaps the problem of the teaching of electromagnetism is even more complex, and there might be a lack of reflection that can direct the questioning about which theoretical relations (CHAIKLIN, 1999) could become the core of teaching, considering the intellectual development of students. Fontes and Rodrigues (2021) analyzed forty-six articles on the teaching of electromagnetism and observed that 70% of this total is guided by a theoretical framework. Notwithstanding, of the fourteen different adopted references, none is used as a basis for analysis of the content that is being taught.

Developmental teaching, as proposed by Davydov (1988a, 1998), allows us to rethink content and structuring aspects of the teaching of electromagnetism – and of Physics teaching – from a teaching standpoint that strives for a greater intellectual development. In other words: classical electromagnetism involves a solidified and systematized type of content (laws, definitions, concepts); developmental teaching suggests that we need to analyze the theoretical structure behind these contents. One of the products of this analysis is the elaboration of a *theoretical model* – also called “genetic model” (LAGO; ORTEGA; MATTOS, 2020, p. 130) – which identifies the essential, central, and nuclear relations, thus allowing the use of the model as a tool for *theoretical* studies, in opposition to *empirical* studies of the relationships that compose the appearance of the object (HEDEGAARD; CHAIKLIN, 2005).

II. Specifying the research question based on *electromagneticity*

To deepen our understanding on the development of theoretical thinking in electromagnetism teaching, imagine the following situation to contextualize the issue: imagine a conversation between two people, João and Maria, who like birds. While at the park, Maria questions herself on what makes a bird a bird. She assumes that there are things –

what we call *theoretical relations*[3] – that are present in all phenomena, and thus, that would not be different for birds. João offers a suggestion: let us observe all birds and then we may say what makes a bird a bird, we will reach a *birdity*.

Maria understands João's point and together, they start to write down all they can observe in birds: feathers, wings, beaks, colors, etc. During this process, they find under a tree some excerpts of *Dialectical Logic: Essays on its history and theory*, written by Ilyenkov (1977, p. 115):

> *The universal can be better expressed externally in the shape of differences, even when opposed, which make separate phenomena complement each other, the components of a whole, of something real, an organic aggregator, and not an amorphous plurality of unities grouped together due to being more or less attributed to it [...] on the other hand, the universal, which manifests itself precisely in the peculiarities, in the individual characteristics of the components of the whole without exception also exists alongside other individuals that derive from it [...] the genetically understood universal does not simply exist, naturally, in the abstract plane, in the elements of words and ideas, and existence in no way disregards the reality of its modifications in the singular characteristic that derive from it and depend on it.*

After noticing João's confusion, Maria adds to her words: this excerpt criticizes what we were doing. Even if we recognized that universality – the theoretical relations, in this case *birdity* – will manifest itself in each of the birds that we see, it is not through the analysis of the classification of characteristics that we select such as feathers, wings and beaks that we will reach a *birdity*. The *birdity* exists as part of the particular and of the individual, as the relation between the reduced form *feathers* and the universality *birdity*. João, still intrigued, poses the question: and what are those conditions? Maria answers: I do not know; the text does not express that. It seems that we will have to find for ourselves in the process of investigation.

Similarly, we are interested in an *eletromagneticity*. We emphasize that *eletromagneticity* is not a new term or concept that would abandon the definitions, laws, and concepts that we have within electromagnetism, but a new delimitation of what the theoretical relations of this subject could be. In other words, we are interested in the conceptual relations that allow asked to express theoretical elements of electromagnetism.

[3] In Davydovian literature, there are different terms to express this idea: theoretical relations, basic relations, essential relations, central relations, nuclear relations, universality, among others (FONTES, 2020, p.14-18)

III. Developmental teaching and Davydov's contributions

Our delimitation of *eletromagneticity* is based upon the theory of developmental teaching, which is a consequence of historical-cultural psychology. Such theoretical basis starts with the contributions of Vygotsky (2007) to the understanding of human development from dialectical-materialist principles (LIBÂNEO; FREITAS, 2006). Prestes, Tunes and Nascimento (2017, p. 68) summarize that the challenge of Vygotsky and his collaborators was that of "creating an innovative approach for the psychological processes there are strictly human and given in psychology materialist bases". Throughout the decades, many other psychologists and pedagogues joined this work group formed in the 1920s.

From the theoretical standpoint of the historical-cultural theory, Davydov and his collaborators established the theory of developmental teaching. His theory is not a rupture with Vygotskyan traditions since they share the same assumptions, particularly the comprehension that there are different types of concepts, and each possesses different characteristics and peculiarities.

Vygotsky (2007) differentiates the concepts that are produced in school teaching (scientific) and enable the process of generalization and theoretical abstractions; and the empirical or daily concepts that are based on the concrete actions of the child in his or her daily life. Additionally, Vygotsky (2007) defends that the development of superior psychic functions is due to an active phenomenon of interiorization and appropriation of the outside world, mediated by language and by culture, through a dialectic process. Furthermore, that means that knowledge occurs primarily in the social world, filled with signs that become the individual knowledge of the child. Rosa, Moraes and Cedro (2016, p. 174) show that Davydov would still add an assumption: "students, by understanding the general principles one type of knowledge, will know how to deal with particular variations, with few interventions from the other".

Libâneo and Freitas (2017, p. 336) highlight that to enable mental development, the learning process must be organized and correctly systematized, in which the basis "for intellectual development in children is the content of a simulated knowledge". Chaiklin (2002) argues that analysis and working with content are the preconditions in the conception of developmental teaching. We adopt the position presented by Dias and Souza (2017, p. 185-186) on the potential of the appropriation of content:

> *When we apprehend said [theoretically structured] content, the individuals also apprehend a way to organize universal thinking that is present in the structures of the superior levels of thinking. Such developments are not acquired empirically, through daily actions connected to the empirical levels of thinking, because they are connected to theoretical thinking and depend on teaching processes that are institutionally organized, in which the historically created meanings are reproduced.*

In this context, Libâneo and Freitas (2017, p. 361) explain the didactic proposal of Davydov from three basic premises of Vygotskyan theory:

> *The first is that the psychic functions are rooted on the social historical ways of human existence, that is, on the cultural instruments developed by humanity and accumulated socially and historically. The second is that the constitution of an individual as a human being implies in him or her apprehending these cultural instruments, internalizing them, turning them into the means of their own activity. The third is that this apprehension implies in a complex activity of human consciousness, which is the generalization and creation of concepts, aiming to overcome the limits of immediate sensory experience.*

The model promoted by Vygotsky (2007) references instruction and learning as sources of psychic development, in which instruction should prepare and motivate the child to participate actively and creatively in the existing social practices. From that, the development of psychic functions such as logical thinking, attention, memory, generalization, and abstraction, which were still not completely developed, would occur.

Based on this, Davydov and his collaborators created their own conception of organization off school teaching, focusing on the appropriation of theoretical concepts and in the intellectual skill of working with the object in a critical and autonomous way striving to obtain the ability of theoretical. In other words, Davydov (1982) understands that theoretical knowledge should be the essence of teaching because it is due to its apprehension that theoretical thinking is developed in the child, which leads to their psychic development.

Davydov (1982, 1990) acknowledged at least two types of social knowledge: empirical and theoretical, which are connected and possess distinct specificities to the development of science (HEDEGAARD, 1996). One of the aims of Davydov and Elkonin – his main collaborator – was to ensure that children would obtain control over the subjects that they would learn in the classroom, in other words, that children would be able to deal with those subjects in an autonomous way (HEDEGAARD; CHAIKLIN, 2005). The importance of working with content to plan the teaching process is fundamental in the theory of developmental teaching (CHAIKLIN, 1999). Therefore, we notice the objective of organizing and systematizing teaching in a way that enables the learning of theoretical concepts, with the potential of developing theoretical thinking. Libâneo and Freitas (2017, p. 332) summarize Davydov's theory:

> *It offers a good theoretical-methodological basis that brings together psychological principles in terms of pedagogical and didactic goals for the development of theoretical-scientific thinking in students. He argued in favor of a type of teaching that is more compatible with the contemporary world of science, technology, the media, and culture, one that is committed to the personal and social transformation of the student, which helps him or her to develop the analysis of the objects of study*

> *in abstract, generalized, dialectical ways [...] the basic concepts of his theory were: human and teaching-learning activities, generalization and development of concepts, developmental teaching and the act of studying.*

IV. On the characteristics of theoretical thinking and knowledge

The relationship between knowledge and thinking used by Davydov (1990) derives from the positions of Vygotsky (2007) and of the Soviet Marxist philosopher Ilyenkov (2007). Therefore, Davydov sees an inseparability between theoretical thinking and theoretical knowledge, opposing interpretations that distinguish thinking and knowledge (HEDEGAARD; CHAIKLIN, 2005). According to Ilyenkov (2007), thinking is the ability to work with the object in an intelligent manner, that is, in agreement with its nature and not from the individual's fantasies. Ilyenkov's assumption that thinking and knowledge are psychological faculties which are so tightly connected that an analysis cannot separate them without mutilating them is vital to the development of theoretical thinking. Ilyenkov (2007, p. 76) highlights that thinking occurs in relation to an object:

> *And when people say (and they frequently say) that someone has knowledge but is incapable of "applying" it to reality, they are making an absurd statement, half of it completely cancels its other half. How can someone know an object – and be incapable of connecting this knowledge (knowledge of the object!) with the object?! This paradoxical situation happens because the person does not truly know about the object but knows something different. What? Sentences about the object. Words, terms, formulas, signs, symbols.*

To Ilyenkov (2007), the essence of the conception of thinking is in the autonomous, critical, and creative manipulation after content by the individual. In other words, the individual must be capable of creating and generating his or her own actions in relation to different objects.

Ilyenkov (2007) limits the problem of thinking independently in a way that allows us to ask: what must a child have to allow him or her to autonomously deal with an object? Davydov (1990) focuses on this issue and explains the role of theoretical and empirical generalizations. In developmental teaching, we understand that empirical generalization does not grant enough skills for the individuals to deal autonomously with an object. With this process of generalization, the student selects distinct characteristics there are captured through the senses, separating the repeated qualities or common attributes of an object. For example, when observing birds, the child would select characteristics such as: the presence of feathers, beaks, eyes, among other features, and this process reflects an empirical generalization. The students lack the control of the theoretical relations that allow the existence of the object, which allows them to work with a constant wavering abstract and concrete elements. Teachers and students spent time developing empirical knowledge that has little to no value to the intellectual development of the child.

While empirical knowledge uses categories to represent the observed reality (HEDEGAARD; CHAIKLIN, 2005), theoretical knowledge reflects the relationship between universal-abstract and empirical-apparent – between the *birdity* and the feathers, between *eletromagneticity* and warmed food – and gains consciousness of its transformations and properties (DAVYDOV, 1988a; PANOSSIAN; MORETTI; SOUZA, 2017). The Davydovian proposal suggests that instead of investigating the world directly, we could conceive a model of relations as explanations for phenomena, that is, the belief that the knowledge of the objects would result from lower relationships between their actions, which diverges from an Aristotelian interpretation, for example. In the Aristotelian understanding of mechanics: "a rock falls because there is an intrinsic purpose within it to go, as seen, to the center of the universe, which is its natural place" (PEDUZZI, 1996, p. 50). This Aristotelian understanding of the world takes the study of phenomena to specific objects, in this case, the rock. However, this could hinder or put a stop to our classic understanding of gravity not as an intrinsic property of an object, but as relationship between bodies. Full understanding of theoretical relations allows the students to work with an infinity of concrete cases.

Thus, we refine what we mean by having theoretical knowledge of a phenomenon: we refer to the processes of being or nonbeing[4] of an object, that is, its relationships, due to being theoretical, are present in all concrete cases. Such relationships are necessary to understand the behavior or nature of a certain object, explaining its genesis and its development.

In summary, in Davydov's theory of developmental teaching, the development of thinking is sought in a way that reflects essential relationships in the phenomena. The theoretical relationships relate to universality, that is, with its presence in all concrete cases. Therefore, seeking the theoretical relationships of electromagnetism means looking for the relationships that explain the genesis and the development of electromagnetic phenomena. The ascension to the concrete and from the concrete to the abstract is understood as theoretical thinking.

With the presentation of our theoretical references, we can enrich our research question: (i) we understand that school teaching should strive to develop theoretical thinking in the students; (ii) to do so, we should work with the theoretical relationships in the chosen content. Thus, we rephrase the question, now solidified under the Davydovian referential: what can these theoretical relationships be in the context of teaching electromagnetism? What can be the theoretical model of these relationships?

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[4] Lenin's expression "being and nonbeing" (DAVYDOV, 1990, p. 126) refers to Hegel. Throughout Davydov's work (1990), the term "appearance" is used. We understand it as having two appropriate meanings: it means both the way in which an object appears to us and the what the object becomes. Therefore, the term is a symbol of both the appearance of the object to our senses and becoming in essence.

V. Models in the perspective of developmental teaching

We are interested in expressing *eletromagneticity* in a theoretical model, because in this format, operations with an object allow us to express the properties that are not revealed when operating empirically. Davydov (1990) recognizes the potential of using models for teaching when conceiving them as a symbolic tool that allows the organization of knowledge over certain objects. Based on Shtoff, Davydov (1900) highlights that the conditions to the development of a model should allow the theoretical relationships to create a determined structure that would allow both the reduction to the concrete and the ascension to the abstract. Based on Gaspar (1997) we may ask: how could someone who does not know the atomic model and the movement of charges explain what happens with pieces of paper that are attracted to a rod after we rub it against a handkerchief?

The model is understood both as a starting and an ending point to the activity of investigation. Being universal, the theoretical relations create "the original model (prototype) and the scale to evaluate the things which an individual encounters empirically" (DAVYDOV, 1988a, p. 130), those being a fundamental way of thinking in the theory of developmental teaching, in the tradition of theoretical knowledge (HEDEGAARD, 2002; HEDEGAARD; CHAIKLIN, 2005). Cunha (2014, p. 98) summarizes the functions of theoretical models in the developmental perspective:

> *These models work as a connection between the abstract concept (general, universal) and the global concretion of the object, there is, the concrete object that is present in social reality with several ways of manifesting itself. It is important to know that under this theoretical perspective, working with models does not mean molding a way of thinking and of acting with the object, but enabling the individual to engage in the cognitive process of the creation of the semiotic model the represents the reeling concrete object, including its transitions and transformations, in its real movement, and not in a fixed and static way.*

Therefore, we understand that a theoretical model consists in the identification and possibilities of using the theoretical relations. Works in Physics teaching that are based on Davydov have determined as a conceptual nucleus: "the idea of movement" in the subject of mechanics (MARENGÃO, 2011, p. 45) and "resistance to the variation of the state of movement; the relationship between resultant force, mass and acceleration; opposed forces" in the subject of Newton's Laws of Motion (BORGES, 2016, p. 107). However, most academic works connected to Davydov relate to mathematical subjects, as shown by Khidir (2006), Rodrigues (2006), Cunha (2014), Rosa and Damazio (2017), among others.

Davydov (1990, p. 80-81) shows at least three different work layers related to the elaboration of a theoretical model for teaching. The first consists of a logical-epistemological work that describes the content, its principles, and theoretical relations. The second consists of the study of the psychological mechanisms that allow the development of theoretical thinking in students, a description of intellectual activities of the child that allow them to apprehend theoretical thinking. The third is the creation and use of didactic methodological strategies that create possibilities for the students to work with the theoretical relations. In this work, we will discuss the first layer, the delimitation of the theoretical relationships in the teaching of electromagnetism from dialectic principles in the construction of knowledge.

VI. A proposal of a theoretical model for *eletromagneticity*

By considering that scientific concepts are consequences of logical, historical, and cultural developments, analyses for the understanding of the essence of concepts in the theory of developmental teaching demands a logical and historical study of the genesis and development of concepts (BORGES, 2016). From the standpoint of the organization of subjects, it is noticeable that many scientific concepts, laws, definitions, and applications of the electromagnetic theory are found when analyzing different didactic manuals, such as the collection by Machado (2000, 2002, 2006) or books such as Purcell (1970), Hewitt (2002), and Young and Freedman (2009).

We may thus ask if every concept of *scientific origin*, such as electron clouds, skin effect, capacitance, electromotive force, etc. is *theoretical* – in a Davydovian sense – in relation to electromagnetism. In other words, the didactic manuals do not help us to steer the investigation towards which theoretical relationships they might be, since these manuals present and discuss as much as possible. Therefore, we analyzed papers and post-graduate works that intended to elaborate a conceptual model for electromagnetism, regardless of the theoretical basis adopted by the authors. We found several examples of conceptual maps for electromagnetism (CUDMANI; FONTDEVILA, 1989; BAGNO; EYLON, 1997; MOREIRA, 2006; LABAS, 2016;) for electrostatics (SALÉM, 1986), for Maxwell's equations and for electromagnetic waves (GRIGORE; MIRON; BARNA, 2013).

Through this, we understand that some concepts of scientific origin appear more frequently or with more relevance. They are the concepts that refer to *electric charge, electromagnetic field, electric force, electric potential, electric current, electromagnetic induction, and electromagnetic waves*. As discussed previously, the theory of developmental teaching demands us to limit the theoretical relationships if we want to create a model. Therefore, we must question ourselves on whether there are relationships that would hold these concepts together, how they could be, and how they could come true. In a previous work, Fontes (2020, p. 60-78) shows and discusses the genesis and the process of development of these concepts that were selected to be analyzed. Towards the end, the author suggests that throughout the historical development of electromagnetism, from ancient China to the beginning of the 21st century, the different explanations that focused on the study of electromagnetism while based on the relationships of *movement, variation,* and *interaction*.

To exemplify the analysis, we draw from Fontes (2020) a few elements that led to the creation of the properties of what we currently call *electric current*. In ancient Greece, around 570 BC, there are records that amber rubbed against certain objects would influence them (PESSOA JUNIOR, 2010). At the time, rubbing some materials would transfer certain virtues (TONIDANDEL; ARAÚJO; BOAVENTURA, 2018). The idea of transferring virtue would lose popularity and in the 16th century, Jerome Cardan would note that amber has attraction qualities, acting over matter (ROLLER; ROLLER, 1957). The notion that electricity was a property of bodies would continue with William Gilbert, who divided materials between electrical and non-electrical based on whether they attracted light bodies (CHAIB; ASSIS, 2007; PESSOA JUNIOR, 2010; TONIDANDEL; ARAÚJO; BOAVENTURA, 2018). Pessoa Junior (2010) highlights that electricity would be material, acting through invisible effluents. Therefore, attraction would no longer be a property of the body, but would fill the space around it, similar to fluids (SIQUEIRA; PIETROCOLA, 2004).

The idea of electrical fluid obtained different interpretations: Benjamin Franklin suggested one electrical fluid, while Charles Du Fay saw two types of electrification (BELÉNDEZ, 2008). With the invention of the Leyden jar, electricity could be stored (JARDIM; GUERRA, 2017a) and released afterwards, thus presenting a *movement* through shiny sparks. With the voltaic pile, the *movement* in electricity was observed through the contact of metallic pairs in series. The diverse ways to observe the movement of electricity – produced via electrification by friction or by galvanic phenomena – was the source of disagreements in relation to the nature of electricity (MARTINS, 1999), where the only consensus was the existence of movement.

The understanding of electricity as one electrical fluid gave way to the existence of two different electrical fluids, as defended by Coulomb and by Oersted (DARRIGOL, 2000; GARDELLI, 2008). With Oersted, electricity and magnetism became known as related, yet distinct phenomena. Wilhelm Weber suggested the reduction of all electric phenomena to the mechanic movement of electrical fluids. The notion of electrical fluid would not convince Faraday, who systematically avoided this interpretation and would visualize electromagnetic phenomena with the help of lines of force, that would become more complex with time and eventually culminate in the term tubes or force. Maxwell used the term *tube* to refer so Faraday's induction law. Therefore, instead of using Faraday's term *lines of force*; Maxwell, Poynting and others also used *tubes of force* (DARRIGOL, 2000). A strong rejection of electrical fluids would be seen in the electrodynamic theory of Heinrich Hertz, since for him, the *ether field* would be the theoretical foundation from which derived the other concepts (DARRIGOL, 2000, p. 258). Other developments happened with Wiechert, J.J. Thomson, Lorentz, until we reached the concept of corpuscle, the precursor to the current notion of electron in classical electromagnetism.

What we wish to highlight in the mentioned excerpt is: even if the agent has been identified and interpreted through different names and meanings (virtue, single fluid, fluids, lines of force, ether, particles), they seem to be built on conceptions connected to *movement*, be it transference, passage, transport, among other interpretations. For instance, describing the movement of a magnetized needle when there is a passage of an electric current. The notion of electric current was once interpreted as a single fluid, as invisible fluids, the interaction between ions, or as invisible particles, until it reached the modern concept of electron flow. Although the agents changed due to the language used by different researchers (DARRIGOL, 2000; BEZERRA, 2006), the appeal of the idea of the *movement of something* or the *passage of something* was present in different argumentations, from different subjects throughout the historical development of the concept of electric current. Fontes (2020) conducted a similar analysis to assert that the same can be said towards the notions of *variation* and *interaction.*

Thus, we propose an initial model for the teaching of electromagnetism from the theoretical relationships of *movement*, *variation,* and *interaction* there are the basis of the laws and concepts that we have. We comment on Maxwell's equations on Section 8 of this paper, when we suggest that *movement* and *variation* should be explicitly separated in the model for simplicity. Furthermore, Fontes (2020, p. 76-78) suggests that the result predicted by Gauss' law may be postulated to part of the model, given that "Gauss' law is not *yet another* physical law of electrostatic interactions, but it is equivalent to Coulomb's law" (SALÉM, 1986, p. 86).

From developmental teaching, the model is directed to a specific organization of thinking and of the knowledge of an object, event, or phenomenon. Thus, it is destined to the understanding into the explanation of events and concrete situations in the life of the students (DAVYDOV, 1988b; HEDEGAARD; CHAIKLIN, 2005). A model also needs to explain how these relationships come true in certain cases. To do that, we use example of generation, transmission, and use of electrical energy.

VII. Conceiving the use of the model: how come I have electricity at home?

At this point, we propose a reflective activity that could guide the planning of activities in teaching electromagnetism. We emphasize that the following discussion was not applied in the classroom.

Many stages must take place before a person living in a big city can warm their food in a microwave. The first stage in this wide context of electrical energy is generally divided in generation, transmission, and distribution (CAMPOS, 2017). According to the National Agency of Electrical Energy, the state of São Paulo has forty-eight different Hydroelectric Plants. Considering that hydroelectric plants are responsible for over half of the production of electrical energy in São Paulo, we opted to use them as an example. Even though the details of the production of electrical energy may vary according to the type of plant, all of them have as a goal the production of electrical energy through the hydraulic potential that exists in rivers or dams.

Throughout our discussion, we will use Image 1, developed by Lago, Ortega and Mattos (2020) to exemplify the continuous movement between the abstract and the concrete from the theoretical relations.

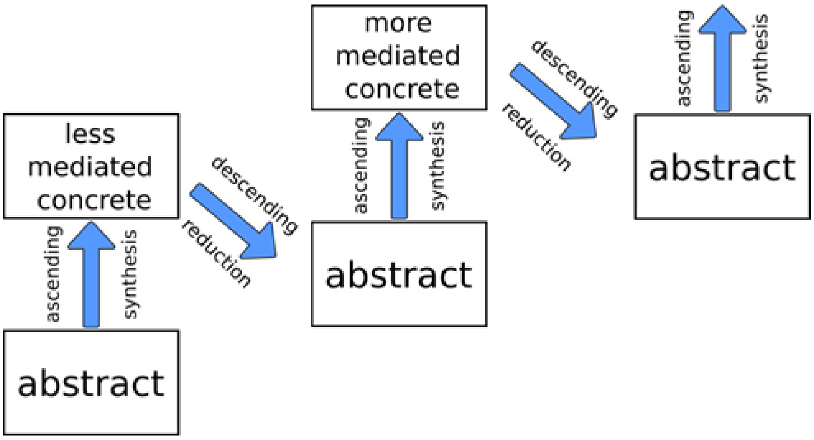

Image 1 – Multiple movements of descension and ascension in the process of creation and understanding of concepts. Source: Lago, Ortega and Mattos (2020, p. 127).

By posing the question "how can I warm my food at home with a microwave?" we could start with the notion of *movement* "something happens for electrical energy to reach my home." With the help of the teacher, we may work with the abstraction of the concept of movement in a wide manner, with different examples in electromagnetism, to then apply it to the investigated problem "in our case, what is moving?" First, *movement* happens in the notion of the conversion of mechanical energy in the water flow to electrical energy in the turbines that are connected to an electric generator.

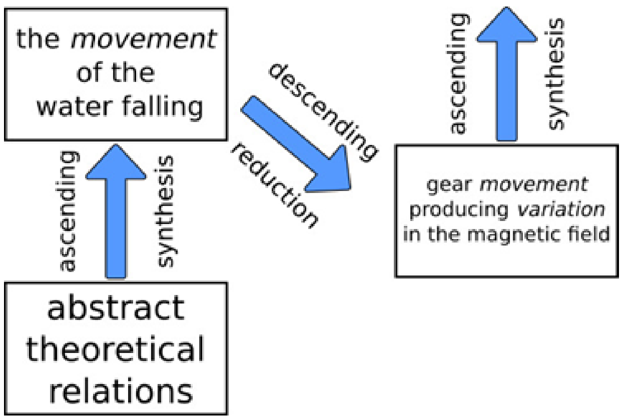

Image 2 – part of the movements of descension and ascension in the process of understanding heating food with the microwave.

However, we notice that not any kind of movement interests us, only the type that can produce a variation. Variation of what? Of the magnetic field or the electric current in a conductor. At this stage, again with the help of the teacher, we ascend to a more general abstract level: “what does varying a magnetic field or an electric current mean? Varying in space? In time? In intensity? In angle?”

In the context of the generation of energy in hydroelectric plants, especially for transmissions, the production of alternate currents has more economic advantages. In the production of alternate current, there is a *second variation of the magnetic flow* that goes through a coil connected to a circuit that leads to a transformer. Generally, the production of electrical energy happens away from urban centers. That means that electricity generated in hydroelectric plants travels long distances in a complex transmission system, due to the use of transformers. We will simplify the transmission process, focusing on the physical phenomenon related to the propagation of electromagnetic energy in the cables.

The *transmission* of energy is only possible because there is an *interaction* between the electric and the magnetic fields. Some interaction between the fields would need to exist, since it is not possible to have a purely electrical wave traveling through space, that is, a wave that is composed only of an electric field. This impossibility is because a purely electrical wave would have a varying electric field. This varying field would not necessarily generate a magnetic field; therefore, a purely electrical wave is impossible (YOUNG; FREEDMAN, 2009). The opposite is also true: a purely magnetic wave does not exist.

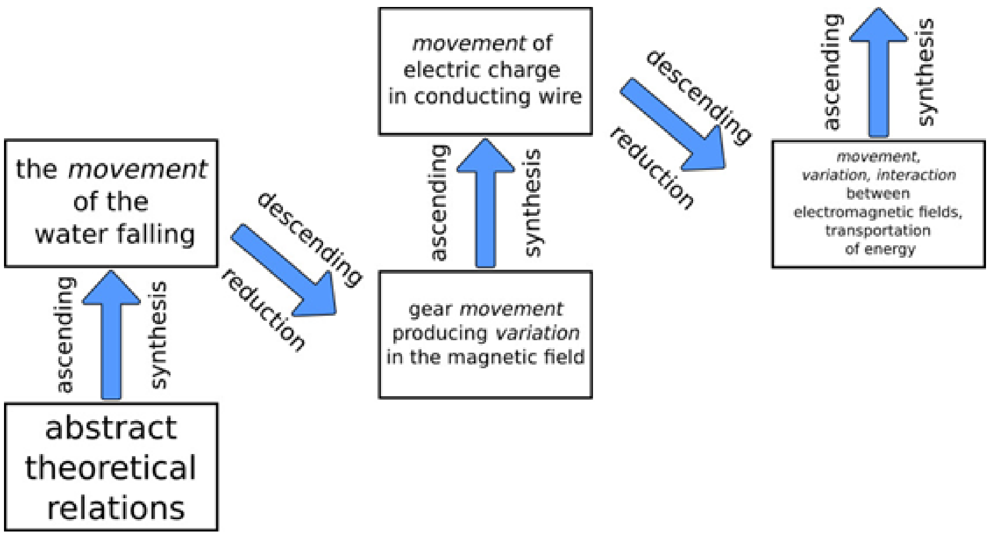

Image 3 – continuation of Image 3, considering more stages of the process.

Towards the end of this process, we have access to electrical energy. With that, we can have electrical lighting and plug in different electrical appliances. The appliance that concerns us is the microwave.

This electrical oven can produce electromagnetic waves with frequencies between 300 MHz and 300.000 MHz and is composed of three parts: the *magnetron*, the waveguide, and the cavity (SOUZA; NOGUEIRA; RASSINI, 2002). Both the waveguide and the cavity are composed of reflecting walls and built to direct the microwaves that are produced in the *magnetron* to the cavity to avoid loss of energy.

A sample is warmed in the microwave because there is an *interaction* between the molecules of the sample and electromagnetic radiation. The absorption of the radiation from the microwaves by dissolved ions and solvents and occurs because of two mechanisms: dipole rotation and ionic migration (SOUZA; NOGUEIRA; RASSINI, 2002).

The dipole *rotation* mechanism references the characteristic of the water molecule, which is polar. That is, the water molecule has a positive and a negative pole, creating an electrical dipole. Therefore, it can align with the external electric field of the microwaves, which varies with time. With this process, the polar molecules that compose the food tend to align with the field. Their constant attempts to align with the electric field results in the increase of kinetic energy in the molecules and consequently the increase in temperature of the food.

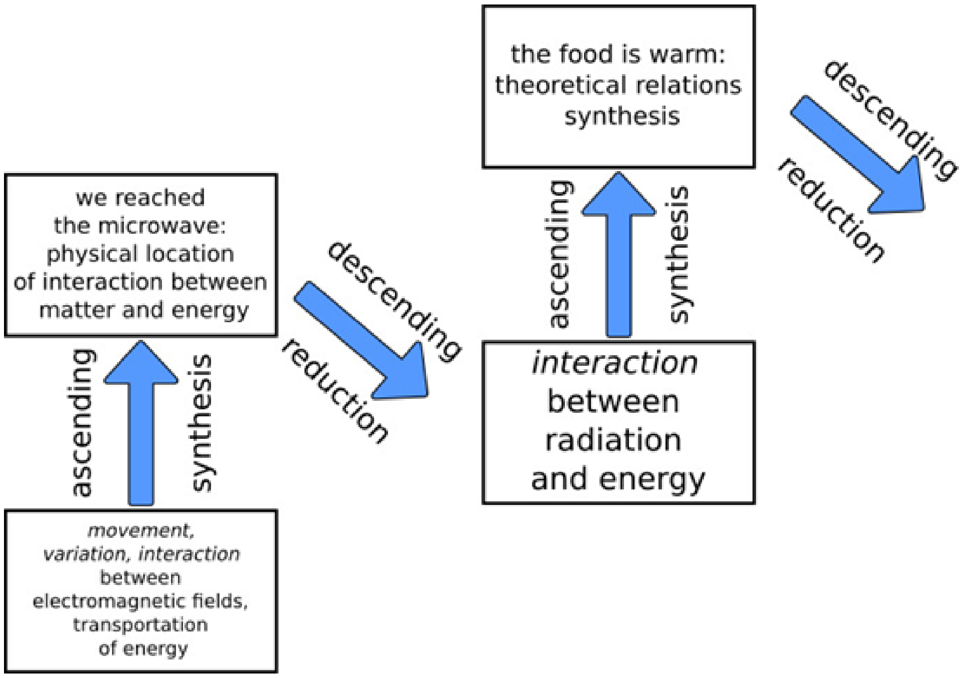

Image 4 – sequence of image 3, considering more stages of the process. We kept the last arrow of descension/reduction to illustrate that the movement of ascension and reduction is permanent.

Thus, we can see how this process presents new concrete elements, which summarize the abstract theoretical relations. For each summary, the students should be led to think and produce, autonomously and creatively "what appliance producers one specific variation? How can I [the student] improve this appliance or conceive a different one? What are some of the challenges of engineering? What were the historical processes culminated in the creation and use of this appliance in modern society? Why was this appliance not invented earlier in the history of humanity? What did we need and what was altered in our knowledge? What is the benefit cost ratio of the appliances that we have? Why is my food not warm? Are there other blinds that generate electrical energy in less damaging ways? Do different societies and cultures use the same appliances? How do the appliances of a certain place or society work? How do the theoretical relationships come to be in these appliances?" To understand the processes that involves the creation and the use of appliances in daily life, we need full understanding of the theoretical relations presented. It is evident that the depth of the investigation and the autonomy of the students should be based on the level of instruction and the objective of the learning activity

This hypothesis shows that the theoretical model allows us to work with all the different concrete examples. Students may now pose other questions: "how do wireless connections work (*Bluetooth, wi-fi*)?" And now? Where does the investigation start? Well, why not start investigating the theoretical relations, the ways in which they come to be in this case? Is it true that to understand wireless connections, we need the concept of variation? Or would it be interaction? Or a combination of both? How are they combined is there a predominant relationship? What is it?

Once the initial concept(s) of analysis has(have) been chosen – here we are dealing with the abstract – then, we pose the question: how does this new concept relate to this new case of wireless connection? Does something interact with another thing? What and how? How can I investigate this relationship? Do we have enough to understand the phenomenon? What do we know about it? And here, back to the concrete, a new, amplified and complexified concrete (MATTOS, 2014; LAGO; ORTEGA; MATTOS, 2020). This movement that comes and goes is perpetual and characterizes the theoretical thinking that we expect of education in general, and particularly of Physics teaching.

From the movements between theoretical relations and social practices that involve electromagnetism, we build and promote the intellectual development of students, allowing them to act autonomously in relation to the objects, which is a crucial point of the Davydovian theory of developmental teaching.

VIII. Some summaries on *eletromagneticity*

We emphasize that the theoretical relationships that form the model are closely related and are often mixed, added and materialized in diverse ways in research and teaching activities. Changes in any of the concepts reflect changes throughout the theoretical model

(HEDEGAARD, 1996). In this section, we discuss some summaries on the issue of theoretical relationships.

1) On the distinction between *movement* and *variation*. Let us take as an example Faraday's law, that in the case of a closed coil, can be enunciated as "the electromotive force induced in a closed coil is given by the variation rate of the magnetic flow, with the negative sign, through the space of the coil" (YOUNG; FREEDMAN, 2009, p. 283). Classical electromagnetism understands electric current as an orderly stream of electrons. As we know, the orderly stream of electrons may be constant; that is, a given amount of charge that crosses a cross-section of a conductor over a period of time may be a scalar. What we are suggesting is that the notion of electric current is built upon a notion of movement; however, to have the effect of electromagnetic induction we need the current – which we already understand as a movement – to vary with time. In other words, *the induced current* in a nearby circuit depends on the *variation* of the inducting current. It is notable that the same result would happen with the nonuniform relative movement between the two coils. Therefore, to understand Faraday's law, two different concepts are used: movement and variation.

We may also look at Ampère’s circuital law: $\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$. The terms μ_0 and ϵ_0 are constants that relate to the environment and do not modify the following analysis: the first term represents the conduction current, the second represents the variation of density of charge through time. Notice that, in this equation, we have both a notion of *movement* (expressed by $\vec{J}$) and of *variation* $\left(\frac{\partial \vec{E}}{\partial t}\right)$. In the case of displacing a constant amount of charge in a given region of space, this last term would be void. Thus, Ampère’s circuital law shows that magnetic fields are created both by electric currents (*movement*) and by the *variation* in the density of the charges.

Certainly, the theoretical model could be presented with only *movement* and *interaction* if the notion of movement is amplified to encompass the notion of variation. we question whether amplifying the notion of movement to encompass variation is useful since Ampère’s circuital law and Faraday's law already distinguish these concepts.

2) On the electromagnetic field. The electromagnetic field is a particular expression of the theoretical relations in the model. More exactly, the electromagnetic field is a way of implementing the theoretical relationship of *interaction*.

Currently, classical electromagnetism uses the notions of field and Maxwell's equations – with notable improvements and contributions by Helmholtz, Heaviside, Lorentz, and others – to interpret and explain its phenomena. However, even in modern times, the definitions of electric (or magnetic) field are varied and there is no clear consensus beyond mathematization. As an example, Rocha (2009, p. 1606) refers to field as “a type of ‘electromagnetic substance’ with a single structure”, while Hewitt (2002, p. 380) understands it as “a kind of aura that extends through space”. According to Oliveira (2019, p. 15), the electric field "can be seen as a 'field of invisible lines', in which the center of it is the very charge that created it".

Serway and Jewett (2004, p. 685) prefer a more pragmatic description: "an electric field exists in a certain place if a charged test particle that is racing in this place experiments an electrical force". Based on this interpretation, Bezerra (2006) adds that the dispositional property is necessary, yet insufficient to characterize the electromagnetic field, given that this property is also present in other mathematical constructs, such as potentials.

When analyzing the concept of field in different textbooks, Silva and Krapas (2007) and Krapas and Silva (2008) highlight the multiple attributions given to the term depending on the book and the author, namely: the field is a region; the field is a vector; the field is an alteration of space; the field is a curvature of space; the field holds energy; the field interacts with particles and mediates the interaction between them; the field propagates itself, it supports the propagation of energy; the field fills the space. Purcell (1970, p. 17) summarizes the discussion on field:

> *Perhaps you still want to ask: what is an electric field? Is it something real or is it merely the name of a factor in an equation, which must be multiplied by something else to give us the numeric value of the force we are measuring in an experiment? Two observations might be useful here. The first one: since it works, it makes no difference. This is not a frivolous answer, but a serious one. The second: the fact that the vector of electric field in a point in space is all we need to know to calculate the force in any charge in that point is not, in any way, trivial. It could be otherwise!*

Thus, our theoretical model does not explicitly discuss the electromagnetic field, because we consider that even with its varied interpretations, when applied in the context of social[5] practices involving electromagnetism, the concept of field can be understood with the examination of the proposed theoretical relationships. Therefore, we suggest the following: from a concrete point of view, the things that can be said about the field can also be approached from the perspective of an appropriate relation between movement, variation, and interaction. From an abstract point of view, what is the field but its relationships?

3) From the theory of developmental teaching, the teaching activities on electromagnetism that aim at the development of theoretical thinking in students should be organized by having the theoretical relationships both as a starting point and as an arrival point. According to Davydov (1990), theoretical thinking exists in two basic forms: i) a theoretical generalization is made from the structure of the content, in which the essence of the object in question is established. In other words, the theoretical generalization is expressed in the form of theoretical relationships, *of electromagneticity.* Real data related to electromagnetism is analyzed along with problems involving social practices. The second

[5] In this paper, *social practice* is analogous to *societal practice* or *social situation of development* or yet *practical problems*, respectively discussed in Chaiklin (2002), Hedegaard and Chaiklin (2005), and Davydov (1998).

basic form ii) takes place in the exposition of the contradictions of the theoretical relationships and in determining their applicability in concrete cases.

We should note that the essence related to the ideas of *movement, variation*, and *interaction* remains, the distinct aspects are the ways in which they summarize concrete elements, which change according to the social and cultural contexts of each school, student, and teacher. Although we understand theoretical thinking in two basic forms, theoretical thinking does not come in halves.

4) The theoretical model offers a way to organize the conceptual relationships that affect each of the areas and, in addition, it offers a suggestion of how to conceptualize the different teaching activities (CHAIKLIN, 1999).

We do not know of a similar organization in literature, and we believe it to be a necessity: we need to work with the essential relationships to develop theoretical thinking; fantastic, but what can these relationships be, if we consider the teaching of electromagnetism? The next step, which should ideally occur simultaneously, is asking: how do these relationships happen in different contexts and teaching activities? The ways in which they occur will necessarily modify the initial theoretical model, expanding it and assigning meanings to it. Image 6 shows that, although there are different processes to which the theory of developmental teaching refers, these processes are part of a whole that is connected and dialectically influenced.

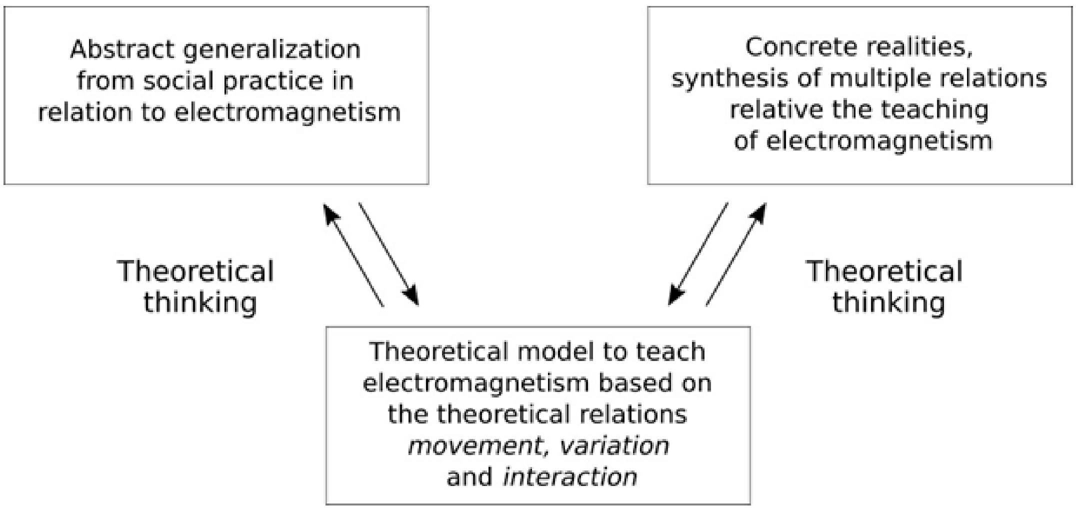

Fig. 5 – Dynamics between the abstract generalization of content, the theoretical model, and its occurrences in different contexts. Every process, represented by arrows, is mediated by theoretical thinking and the theoretical model in the theory of developmental teaching.

Chaiklin (1999, p. 191) summarizes the process illustrated in Image 6 in the following terms:

> *A typical recommendation is starting with the basic relationships, investigating some variations of these relationships, trying a synthesis through the model that captures the essential aspects, applying the model to new and related cases and then evaluating the adequacy of the theoretical model.*

We highlight this excerpt from Chaiklin (1999), "starting with the basic relationships". Highlighting and justifying what such relationships could be is just the first step in a lengthy process. The last word on the adequacy of a theoretical model is the teacher's, along with his or her student, because he or she is the only one who knows the contexts they are immersed in contexts and their concrete material realities. What we suggest is that the teacher should structure the teaching activities by being aware of theoretical relationships, and he or she should allow students to discover and investigate the relationships and manifestations of these general laws that created *electromagneticity* in different concrete examples. This is the way by which the theory of developmental teaching points to a greater chance of the development of intellectual personality, particularly of theoretical thinking and knowledge. This happens because the appropriation of content and the intellectual development occur in an inseparable and simultaneous process, transforming and expanding each other.

IV. Final considerations

This paper presents a theoretical reflection centered on the question of "what" could comprise the core of the teaching of electromagnetism. There is extensive research in the literature that suggests different "hows", based on the most diverse theoretical references (FONTES; RODRIGUES, 2021). We made a possible summary of a theory from the field of psychology in relation to a theory from the field of physics. The theory of developmental teaching, based on pillars of the historical-cultural theory elaborated by Davydov (1988a, 1990) and his collaborators defends that a central task of school education is the development of theoretical thinking in students. For this, Davydov (1988a, 1990) argues that there are certain theoretical relationships that are critical and necessary to the understanding of the current state of an object and the changes that it may suffer, and that it is through the acquisition of theoretical knowledge that the generation of theoretical thinking and consequently the psychological development of the child is structured. By choosing as an object of analysis the theoretical relationships in the teaching of electromagnetism, we identified the relations *of movement, variation,* and *interaction.* As explained, these are not formal abstractions and only gain meaning when occurring concretely. Thus, we described a proposal to various movements between the abstract and the concrete, based on the theoretical model, which we also call *electromagneticity.*

As a result, we suggest that it is not because electromagnetism involves a solid body of knowledge that all these concepts would be essential for an understanding that strives to lead towards theoretical thinking. In other words, it is not because the concepts are of scientific origin that they are the theoretical relationships to which developmental teaching refers, and research in the field of physics teaching is necessary.

Thus, we consider that an important discussion that would contribute significantly to this area of research is that, on the one hand, A) it is known, due to diverse theoretical foundations, that the concept of mediation of the previous knowledge of students, among other factors, is important to the students' effective learning. On the other hand, B) in textbooks, literature or in academic training, we observe the presence of several concepts of scientific origin. Is it enough to choose a concept in B) and then create classroom conditions that stimulate interaction between students? Based on the theory of developmental teaching, we believe that it is not, because the problem is more complex than that.

In basic education, the teaching of electromagnetism deals with several concepts such as electromagnetic field, electrical potential, capacitors, Kirchhoff's law, among many others. However, certain concepts are discussed by assigning to them a value *per se.* In this work, we advocate that such concepts can be selected and constructed from meaningful uses of the theoretical relationships that constitute the discussed model. Our proposal does not seek to reduce all knowledge and possibilities regarding the teaching of electromagnetism to the theoretical model. However, assuming that there is limited time in basic education, educators need to make some decisions about what the focus of their teaching should be.

There is much be done, and different research and multiple perspectives are needed when the object of research is the development of a theoretical model for the teaching of electromagnetism or of other areas of Physics. The next step that would continue the discussion is understanding how these three theoretical relationships come true in educational work in the classroom. In other words, our study points to the investigation of conceptual relationships that allow us to express theoretical contents in the teaching of electromagnetism. We can say that theoretical relationships do not exist in the abstract plane, since they unfold and complement each other in an organic aggregate, revealing themselves in the movements of ascension to concrete and descension to the abstract. The ways of implementing the proposed model will modify it, since it will gain new meanings when it is assessed.

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