# The ‘state of art’ of the research on Magnetic field teaching: A review of Physics education literature between 1995 and 2015

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**ABSTRACT**

In this paper, we present a review of the Physics Education literature on the topic of Magnetic Field. We investigated eleven renowned national and international journals in the field over a period of twenty years, collecting papers that involve situations where magnetic field is present. Items collected were categorized within a qualitative literature perspective and three categories emerged naturally. It was noticed that students’ difficulties in understanding this concept is somewhat linked to their inability to visualize three-dimensional situations involving the magnetic field. The use of computer simulations was suggested as a possible means of addressing this. Despite criticism/suggestions made by various authors regarding the use of Computer Simulations to teach this concept, there are few investigations theoretically and methodologically grounded on the educational applications of computer simulations to teach Magnetic field in the curricula of courses where this concept is deemed as important.

**Keywords:** Literature Review. Magnetic Field. tridimensional imaging. Physics Teaching.

## Campo magnético: uma revisão da literatura no período 1995-2015 sobre o estado da arte deste conceito em ensino de Física

**RESUMO**

Apresentamos uma revisão da literatura da produção na área de ensino de Física sobre o tópico de Campo Magnético. Investigamos onze periódicos nacionais e internacionais de renome na área durante um período de vinte anos, coletando os artigos que apresentassem palavras-chave que envolvessem situações onde o Campo Magnético está presente. Os artigos coletados foram categorizados dentro de uma perspectiva de pesquisa bibliográfica qualitativa, e três categorias emergiram naturalmente. Percebeu-se que as dificuldades de entendimento, por parte dos alunos, circundam a impossibilidade de visualizar tridimensionalmente as situações que envolvem o Campo Magnético, sendo isso possível de ser feito por intermédio de Simulações Computacionais. E apesar das críticas/sugestões feitas por vários autores com relação ao uso de Simulações Computacionais

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para esta visualização, existem poucas investigações, teoricamente e metodologicamente fundamentadas, sobre as aplicações didáticas de simulações computacionais no sentido da larga utilização dessa poderosa ferramenta, nos currículos de cursos de Física e/ou áreas que possuem o Eletromagnetismo em seu currículo.

**Palavras-chave:** Revisão de Literatura. Campo Magnético. Visualizações Tridimensionais. Ensino de Física.

## INTRODUCTION

This article aims to present the results of a literature review made to build the 'state of the art' of the research on the concept of magnetic field, and situations that involve the teaching of physics. To build this review we searched for articles published in leading scientific Science Education journals in Brazil and worldwide. The research was done using Google Scholar, the system of CAPES, the ERIC system and specific journal sites of the field. We consider only journals with Qualis A1 and A2 (the top-tier ranked journals within Brazilian CAPES ranking), and twenty-nine articles in the following magazines: Science & Education; Enseñanza de las Ciencias; International Journal of Science Education; Research in Science Teaching; Journal of Research on Science Education; Research in Science Education; Enseñanza de las Ciencias; Science & Education; Science Education; Journal of Physics Teaching; Caderno Brasileiro de Ensino de Física.

The first step of the literature review process was the enumeration of the papers. In this phase we read the summaries published in all the numbers of enrolled magazines. The search within these journals' site was done using the search fields by entering keywords such as Magnetic Field, Electromagnetic Induction, Magnetism, and Faraday. The second stage was the reading and classification of items in categories. This step aimed to construct a framework of knowledge published in the field, important both to contextualize the research proposed here as to the pointing new contributions to research in teaching the concept of magnetic field.

With all collected papers in hand, we proceeded to the analysis. Our first step was the establishment of categories within which we could place each paper. During this process, three categories emerged from a subject analysis. The first category is of the paper that discuss students' conceptions on Magnetic Field, specially their alternative conceptions or difficulties when solving problems that used the concept of Magnetic Field. The second category deals with criticism and/or suggestions that some authors offer regarding the usual approaches to teach magnetic field. The third category consists of papers that somehow have proposed and made didactic interventions for teaching magnetic field.

### Students' conceptions

This first category groups up the paper that discussed students' ideas with respect to the concept of field and electromagnetic induction. Regarding the concept of Field, articles were selected that discussed ideas exposed by the students about the general image of field. We subdivided those papers and selected those that discussed student's ideas on Electric and Magnetic Field.

Students' conceptions regarding 'field' concept will be addressed here, as they are a prerequisite that students must master to properly interpret electromagnetic induction phenomena (ZUZA; ALMUDÍ; GUISASOLA, 2012).

Therefore this category of articles that deals with students' conception on electromagnetic induction (Faraday's Law) was divided into three items which are the electric field, the magnetic field and electromagnetic induction. These three items have, of course, an evolutionary ordering in a conceptual reading. To sum up the discussed results, we have organized in Table 1 below the categories that were discussed in this paper, their characteristics and how each category relates to students'conceptions that were discussed in literature.

TABLE 1 – description of student's conceptions and characteristics of each of the concept investigated in the literature.

| Categories | Characteristics | Students' conceptions |
|---|---|---|
| Electric Field | Tridimensional force field caused by electric charges | Newtonian model, magnetic flux, electric flux, distance action, Coulombian profile |
| Magnetic Field | Show tridimensional, closed and concentric field lines | Newtonian force, electric field, difficulties in the source of the magnetic field |
| Electromagnetic Induction | Relative motion between the inductor and the induced, may be represented in 3D | Coulombian and Maxwellian profile of induction, difficulties in relating the flux variation and induction |

Source: Authors.

## Electric field

Five papers were found that fit in this category. The selected papers were Furio & Guisasola (1997), Furió & Guisasola (1998), Guisasola et al. (2008), Araujo, Veit & Moreira (2007), and Park et al. (2001). The work of Furió & Guisasola (1997) is about the evolution of the formation of the concept of electric field. First, the authors show the "Coulomb" profile of the electric field that would be similar to a Newtonian view, which is often introduced in a manner analogous to the gravitational field.

Another category of the field profile, these authors report, is the "Maxwellian" which, according to the authors, surpass the Newtonian and Cartesian cosmologies and extends the entire surrounding space of the charge. Thus, after this evolving nature of the formation of concepts and scientific theories have been accepted, the authors comment that "[...] the acquisition of the first conceptual profile is a necessary prerequisite for the second profile.". In addition, they assume that "students show real difficulties in understanding the second conceptual profile [...]" (FURIO; GUISASOLA, 1997, p.517.).

The authors Furio & Guisasola (1998), through questionnaires applied to high school students and college students which, in turn, had already taken Electromagnetism classes, identified some students' conceptions – or difficulties – of the electric field. They are: (a) Students can not differentiate clearly the magnitude of electrical force (F) and electric field intensity (E) and that the students did not come to dominate the Maxwellian electric field profile. And yet (b) students support the immediacy of the transmission of electrical interaction between charges and (c) when they should interpret complex electrostatic interactions, as in "Faraday's cage", they most likely will use the Coulomb conceptual profile, paying attention to changes and distance, and ignoring the environment in which they are and their geometry.

In short, the authors'' conclusions allow us to say that most students do not use the "Maxwellian" field concept in problematic situations of cognitive conflict, and persists in a reasoning based on the Newtonian model of "action at a distance". Even college students who have extensive training in electromagnetism interpret the concept of electric field from the theoretical basis Coulomb (FURIO; GUISASOLA, 1997, 1998).

Another students' conception of electric field reported by Guisasola et al. (2008), are that the explanations of the students to phenomena involving electric field are based on the literal description of a formulae that is often seen to be an incorrect analysis of it. In many cases, students do not conceive the electric field associated with a region of space. One point that Guisasola et al. (2008) also cite is with respect to students disregard the normal vector to the Gaussian surface when it comes to electric field.

In this sense, Guisasola et al. (2008) and Araujo, Veit and Moreira (2007) – that uses the Vygotskian and Ausubelian theoretical frameworks reach a consensus when discuss that students often mix up Electric Field and Electric flow. And, in turn, Park et al. (2001) commented on the difficulty of students when they think that insulators do not generate Electric fields because there is no current in them.

## Magnetic field

With regard to the conceptions presented by the students in understanding the concept of magnetic field, four articles were selected in this research. The selected texts were Furió & Guisasola (1998), Guisasola, Almudí & Zubimendi (2004), Martin & Solbes (2001) and Brandamante & Viennot (2007).

Thus, various techniques have been used to probe the students' conceptions. Different techniques were used to yield different results: Guisasola, Almudí & Zubimendi (2004) used phenomenography. The authors justify the use of this technique, because it aims to describe and explain the variation in students' conceptions regarding a topic. This technique is an empirical approach that aims to identify the different qualitative ways that different people perceive and understand the phenomena.

In this framework, Guisasola, Almudí & Zubimendi (2004), using this technique, identified some categories on students' conceptions about the Magnetic Field. The authors comment that one of the identified categories was that although most students have an appropriate declarative knowledge on the subject, a significant portion of them refuses to accept the existence of an immobile magnetic field, which does not manifest itself by a perceptual behavior.

In a second category, it was identified that for the magnetic phenomenon and its interpretation, even if identified, there is a “naive realist” interpretation by the students. In this category the magnetic phenomenon is identified, and the actual entity is attributed to the interaction of the magnetic field lines that occurs as a result of “attraction” and “repulsion” of the field lines.

The other category of students’ conception, regarding the magnetic field that Guisasola, Almudí & Zubimendi (2004) identified, was called “Electric”. This category refers to the interpretation that the students give the source of the magnetic field from the electric charge. Students identify the source of the magnetic field from the electric charge, whether in motion or at rest, and even identify that the magnetic interactions are explained by a central force Coulomb.

The last category that the authors used to explain the views of the students was called “Ampere”. This category has allowed students the correct identification of the source of the magnetic field with the moving rates, they found that moving charges give rise to the magnetic field. And they used the model of Ampère to explain the relationship between magnets and solenoids as magnetic field sources.

In the same sense, Martin & Solbes (2001) also proposed to find some views of students regarding the concept of Magnetic Field and comment that most students still think in terms of force and don’t modify their previous ideas on the subject; thus the field is remains seen as a force.

In the same train of thought, Martin & Solbes (2001) conclude that students confuse the Newtonian theory of interactions between particles with the field theory. Therefore, students can not relate the field theory with its many technological applications, nor do they know the impact this has had on science and society, unaware of its advantages for the development of physics.

Brandamante & Viennot (2007) conducted a focused research on the concepts of magnetic fields and gravitational fields. Thus, only a minority of students involved in this research can differentiate the two types of interactions. The authors comment that the idea of a mere attraction remains dominant and can show the idea of orientation.

With that in mind, Brandamante & Viennot (2007), with respect to the understanding of the magnetic field ontology, conclude that students mix up the Magnetic with the Gravitational Field and attribute Magnetism to a “magic” substance intrinsic to magnets.

Based on these arguments, it is seen that students’ difficulties revolve around some common aspects. Among these are the problems of referring to the magnetic field sources (FURIO; GUISASOLA, 1997; 1998; 2004), the operational understanding of the magnetic field (FURIO; GUISASOLA, 1998; 2004), difficulty in understanding ontological aspects of the Magnetic Field (BRANDAMANTE; VIENNOT, 2007; PARK et al, 2001), difficulty distinguishing Magnetic and Electric fields (FURIO; GUISASOLA, 2004).

Based on these facts, it is clear that the greatest difficulties of students with respect to the understanding of the field, is the confusion of this with force (FURIO, GUISASOLA, 1997; 1998; MARTIN; SOLBES, 2001; BRADAMANTE; VIENNOT, 2007) and the lack of association of the field with a region in space (GUISASOLA, ALMUDÍ; ZUBIMENDI, 2004).

Thus, the representation of the magnetic field takes the form of a vector field, and this view is made possible through some Computer Simulations due to the fact that the magnetic field is a human abstraction.

Moreover, knowing that many of the students' difficulties is to distinguish the concept of field from the force, it is expected to design the magnetic field with "Maxwellian" characteristics and, therefore, we intend to use simulations that reproduce the Magnetic Field representation containing its main features in a three-dimensional worldview, as the aforementioned authors make an open question: tridimensional views of the Magnetic Field can help in the learning of electromagnetism concepts?

## Electromagnetic induction

By consulting 32 scientific papers in the field of Science Education and Physics Education between 2000 and 2012, Martin & Garcia (2012) reach the same conclusions of Araujo & Veit (2004), which also consulted studies that relate to the use of computer technologies in teaching physics at secondary and university level from the 1990, to highlight the emphasis on the research on mechanics in teaching physics.

With this, we realize that electromagnetism teaching was very little studied in Brazil. The consensus of these authors (ARAUJO; VEIT, 2004; MARTINS; GARCIA, 2012) is that the teaching of classical mechanics is the most well researched.

Electromagnetic induction (EI) – Faraday's Law – is a fundamental topic in the physics curriculum of medium and also higher levels. It is not surprising that this theory constitutes a specific chapter in high school curricula and also many university courses.

For this review, we selected different papers on alternative conceptions of students, both in their last year of high school and higher education with respect to EI. Off all articles selected for this category, three are from the research group coordinated by Guisasola that are Zuza, Almudi & Guisasola (2010, 2012, 2013) and other are the contributions of Thong & Gunstone (2008) and Mauk & Hingley (2005).

Thong & Gunstone (2008) carried out the exploration of the concepts of university students of the second year on some aspects of electromagnetism. The students had already done an introductory course of electromagnetism in their first year of course and, at the time, were doing laboratory investigations of Electromagnetic Phenomena.

The authors identified, through interviews, three main misconceptions about the topic demonstrated by students. These misconceptions were: 1. The magnitude of the induced current was directly proportional to the magnitude of the current in the solenoid coil at the side; 2. There must always be contact between the magnetic flux and external coil for any induced shows in the coil; 3. The Coulombian or electrostatic potential difference is the same as a induced e.m.f.

Mauk & Hingley (2005) also proposed to investigate the views of students regarding the Electromagnetic Induction, comparing a group that studied standard Electromagnetism of the school curriculum, and found that less than half of the surveyed students properly used Faraday's law in academic contexts and also that these students usually associated EI with the magnetic field and not with the variation of the magnetic flow.

Zuza, Almudi & Guisasola (2010) also investigated the views of students regarding EI in the first and third years of engineering. The question that guided the authors for this research was: What are the concepts and ways of thinking of university engineering students on electromagnetic induction?

The authors found that a significant percentage of responses related the lines of the magnetic field passing through the circuit with the cause of producing the electromotive induced force confusing thereby the field lines through the circuit with the variation of the magnetic flux through this.

Another observation made by Zuza, Almudi & Guisasola (2010) was that when students analyze electromagnetic induction experiments involving motion, the vast majority tends to mix up the circuit integration area with Faraday's Law interaction area.

The idea that students do not distinguish between the interpretive-macroscopic levels (Faraday's Law) and microscopic (Lorentz Law), of the electromagnetic induction phenomenon is included in Zuza, Almudi & Guisasola (2010; 2013).

Thus, some aspects regarding the difficulties pupils are better understood as follow: problems in associating the variation of the magnetic flux and the electromagnetic induction (THONG; GUNSTONE, 2008; MAUK; HINGLEY, 2005; ZUZA; ALMUDÍ; GUISASOLA, 2010, 2013); the idea that students make confusion between interpretations by Coulomb and Maxwell concepts involving Electromagnetism (ZUZA; ALMUDÍ; GUISASOLA, 2010, 2013; THONG; GUNSTONE, 2008), and not understanding that an induced electric current can be created when we vary the intensity of an electric current in a coil near the circuit (ZUZA; ALMUDÍ; GUISASOLA, 2010, 2013).

According to our assessment, the concepts presented by the students, involving the teaching and learning of electromagnetic induction, happen in the key ideas of this scientific theory. Overall, the analyzed studies show that most students do not have an understanding of the EI model, or Faraday's Law. A significant number of students does not explain the phenomenon this law helps to describe or uses the knowledge presented inconsistently.

Students' difficulties happen in the interpretations made by Coulomb and Maxwell's magnetic field and Faraday's Law. As proposed here, the use of a computer simulation that depicts three-dimensionally the magnetic field, is also proposed in case of the Faraday's Law. We argue that the representation of the magnetic flux present in Faraday's Law has strong similarities with the representation of the magnetic field.

The authors Silva et al., (2014, p.227) comment that "the magnetic induction $\overline{\mathrm{B}}$ is commonly called magnetic field", and that "the total number of induction lines that traverse a surface, in turn, is known as magnetic flux."

Likewise the representation of the magnetic field, the representation of the magnetic flux also is made through a three-dimensional vector field. Therefore, it is intended to use three-dimensional computer simulation of Faraday's Law, in that also contain the need for visualization of magnetic field lines in 3D form.

Thus, as the authors who treat the concepts of field of students, these authors did not comment on the three-dimensional visualization of magnetic flux as possible tools to aid the understanding of Faraday's Law.

One issue here is also open: Do three-dimensional view of the Magnetic Flux help in the learning of Faraday's Law?

As much as for the magnetic field, as for the magnetic flux and Faraday and Lorentz laws, in short, much of the magnetic phenomena, a three-dimensional view of the representations created by physics is necessary for an understanding of these concepts. Well, Wu & Shah (2004) have already established that visualization is of great importance for the understanding of scientific concepts in many domains, and this becomes a truly complex problem when the visualization is necessarily three-dimensional. Thus, we use the the Cognitive Networks Mediation Theory (CNMT) as theoretical framework, indicating that a substantial improvement in three-dimensional apprehension should result from the use of computational tools that represent the electromagnetic phenomenon with three-dimensional representations of the field. The use of such tools will help students develop internal representations and *drivers* that consequently should help in meaningful learning of these concepts (WOLFF, 2015).

## CRITICISM TO DISCIPLINES

Using the same criteria of search and selection of papers described, in this category, four articles that have some sort of criticism and/or suggestions for disciplines were selected, that address Electromagnetism. The selected articles were: Silveira & Marques

(2012), Dias & Martins (2004), War, Kings & Braga (2004) and Guisasola, Monteiro & Fernandez (2008).

In this category, Silveira & Marques (2012) aimed to present two induction motors which can be easily constructed in a laboratory. The authors criticize the curricula, surprised that induction motors are not present in general physics books both in high school and higher education and also are not usually found in physics teaching labs. In addition to the undeniable importance of this type of engine in the daily lives of students, the authors explain that the use of the induction motor in the didactic laboratory of an elementary course of electromagnetism allows the discussion of various topics such as:

> […] application of Faraday's law, Lenz, magnetic torque in one loop or on a coil with electrical current immersed in the magnetic field, the phasing that normally exists between the electric current and the voltage in reactive systems, the composition of oscillating fields to produce a rotating field, and the use of resistors or capacitors associated with coils to change the phase of the electric current. (SILVEIRA; MARQUES, 2012, 123p.)

The authors Dias & Martins (2004) conducted a study on the experimental work regarding electromagnetism conducted by Michael Faraday in the early nineteenth century. The authors found some elements that could be used in science education. Thus, the authors advocate the use of historical knowledge on the experimental work of Faraday and the reasons that led to the discovery of electromagnetic induction as a significant unit in the paper provide students a more adequate conception of the science development.

In this context, Dias & Martins (2004, p.528) conclude that "important elements for a discussion of science should be brought into the classrooms, along with the appreciation of the experimental work." These authors corroborate the arguments of Silveira & Marques (2012) to include in the curriculum experiments related to Faraday's Law.

The other paper discussed was Guerra, Reis & Braga (2004). In this article the authors construct a curriculum proposal for Electromagnetism teaching in high school and highlight the application of this proposal in a concrete school reality.

The authors' proposal is a curriculum explicitly designed with a historical-philosophical bias that covers the first phase of electromagnetism, from 1820 to 1832, and is divided into four units which are Unit I: Background of the electromagnetism; Unit II: The Birth of Electromagnetism; Unit III: electromagnetism after Faraday and Unit IV: electrical circuits.

By applying the discussion of these units in a four-month course, the authors concluded that, in general, students showed up highly motivated to work and discuss the development of this first phase of electromagnetism in the classroom, that not only creates room for reflecting on science, it also made possible understanding of internal technical issues to science because:

> As the development of electromagnetism was discussed, students were confronted with philosophical ideas and scientific theories, learning in the process, the current status of the studied science without unquestionable truths being presented. (GUERRA; REIS, BRAGA, 2004, p.244)

The work Guisasola, Monteiro and Fernandes (2008) also takes into account the history of science regarding the Electromotive Force (e.m.f.). These authors consider this tool to be helpful to identify where the problems were in the construction of concepts and theories and, therefore, indicate that epistemological barriers had to be overcome that allowed the progress of the historical evolution of the concept of e.m.f.

Thus, it is observed that some authors propose the discussion in the classroom on the historical evolution of the concept of electromotive force as a way of better understanding this concept. Guisasola, Monteiro and Fernandes (2008) describe seven criteria for Comprehensive Learning this concept, after showing its evolution and the multiple contexts of theories within the Electromagnetism in which fits the idea of e.m.f.

They highlight five periods of the concept of construction:

- ✓ Between the eighteenth and nineteenth centuries, when scientists like Coulomb, Lagrange, Poisson and Laplace had established the basis for action at a distance;
- ✓ In the nineteenth century, when Volta proposes the galvanic fluid to explain electricity as associated with a force exerted in order to separate charges and keep them separate;
- ✓ In the nineteenth century, when developing the study of electrodynamics, with Ohm making use of the ideas of electroscopic forces and Kirchhoff (1847) proposing the introduction of the concept of energy to explain the operation of electrical circuits;
- ✓ In the nineteenth century (mid – late), when Maxwell (1865) works the idea of Fields and the idea of Energy;
- ✓ Throughout the eighteenth and nineteenth centuries, when the concept of Electromotive Force evolves from an unknown force to a Work per Electrical Charge unit, related to a non-conservative electric field.

Regarding the Comprehensive Learning indicators, Guisasola, Almudi & Furió (2005) suggest the following indicators:

- ✓ Understanding Electrical current as generated by a voltage;
- ✓ Understanding the separation of Electric Charges as a cause of DDP;
- ✓ Understanding the separation of charges arising from chemical processes as related to e.m.f.;
- ✓ Acquisition of scientific experimental how-to.

It can be said that the work Guisasola, Monteiro and Fernandes (2008) contributes to the research, because it reiterates the distinction made in the concept of Electromotive Force regarding the concept of potential difference.

In this view, one can also conclude that, with respect to physics curricula, the experimental work on electromagnetism, in these curricula, is defended by the authors selected here (SILVEIRA; MARQUES, 2012; DIAS; MARTINS, 2004; GUISASOLA; ALMUDÍ; FURIO, 2005; GUISASOLA; MONTEIRO; FERNANDEZ, 2008).

Likewise, War, Kings & Braga (2004) also corroborate towards the physical education curricula have a historical and philosophical bias to the concepts of physics are built by students.

These items contribute to the proposed research, it is intended here to investigate the use of computer simulations as a proposal in the teaching of electromagnetism, and this aspect has not been discussed as an alternative by the authors cited here.

Even before the time of use of technology in which we live today, because there was no criticism or suggestion to be included in educational curricula of physics using computer simulations. These items fall into this category, but none of them proposes to use computer simulations to solve electromagnetism problems.

Therefore the research on how to use computer simulations to help in the learning of electromagnetism concepts and problem solving is a question to be answered.

Based on these facts, there has been an increase in the interest in approaches that take into account the historical and contextual aspects (which directly influence motivation) and three-dimensional aspects (directly influencing cognition) (RAUPP, 2015) in order to undertake a learning integral concepts in science. In this paper we just aim to dissect the cognitive aspects.

## TEACHING PROPOSALS

Using the same search criteria mentioned above we have grouped in this session papers from authors who have too the effort to write some kind of didactic proposal related to the teaching of concepts involving the magnetic field. We found several articles on this subject, so they were divided into three subcategories:

- ✓ educational proposals involving experiments;
- ✓ educational proposals involving the use of Computer Programs;
- ✓ Other educational proposals.

## Educational proposals involving experiments

Several articles related to proposals for practical experiments aimed at understanding issues involving the magnetic field were found during this literature review. We selected seven articles dealing with this subject: Araújo & Angels (2006), Araújo & Müller (2002), Pimentel et al. (2004), Pimentel & Zumpano (2008), Silva & Laburú (2009, 2013) and Silveira & Varriale (2009).

Araujo & Anjos (2006) built a Helmholtz coil proposing the determination of the sensitivity of other sample coils placed close to it. The proposed study was able to provide values for sensitivity tests coils very close to those obtained from calculations involving the generic parameters of such coils. The authors consider that – due to the intrinsic nature of physics – this is "an area of science that allows both the practical and theoretical aspects of reality" (ARAUJO; ANGELS, 2006, p.286.).

The work of Araujo & Muller (2002) proposed the use of a device based on a transformer in order to illustrate the phenomenon of "magnetic levitation" produced by inducing an electric current in a conductor metal ring placed as the transformer secondary.

In this scenario, the authors conclude that:

> The illustration of this phenomenon can serve as a starting point and support for the discussion of some important aspects involved with electromagnetism, as Faraday's Induction Law, the Law of Ampere and Lenz's Law. (ARAÚJO; MÜLLER, 2002, p.113)

Pimentel et al. (2004), and Pimentel & Zumpano (2008) also proposed in their papers experiments dealing with Faraday's law, but the two have used as material a computer hard drive (hard disk – HD) that is no longer used.

First, Pimentel et al. (2004) suggested some educational applications for existing permanent magnets inside the computer hard drives. Thus, the authors described four experiments that can be prepared: magnetic linear accelerator; random magnetic pendulum; pendulum immersed in a magnetic field and also a Magnetic Brake.

Through these experiments the authors propose the study, observation and qualitative verification of laws involving mechanics and electromagnetism. Among these laws, Faraday's Law.

Therefore, Pimentel & Zumpano (2008) indicate the experimental exploration of the action of Foucault currents by means of a rotor magnetically coupled to a computer hard disk. This assembly, according to the authors argumentation, "allows the qualitative observation of the effects of the currents that arise due to movement of an electrical conductor in a region where there is a magnetic field" (PIMENTEL; ZUMPANO, 2008, p.194.).

Thus, the authors agree (PIMENTEL; ZUMPANO, 2008; PIMENTEL et al., 2004) that the illustration of the laws of physics has a didactic value, if proposed to instigate electromagnetism students, and allow them to make new uses for computer hard drives.

Silva & Laburú (2009) developed an assembly of the Faraday induction motor including its two variants (one with a mobile rod and fixed magnet and another fixed rod and mobile magnet) and due to the dimensions and weight of the equipment developed, according to the authors, this is more appropriate for non-formal educational setting such as science and technology museums or teaching laboratories that provide internal visits to enjoy a demonstration.

The same authors showed a compact version of that engine, the first of the aforementioned variants (SILVA; LABURÚ, 2009), but differs in size and weight of the previous proposal, being easy to transport and use in the classroom. The authors have proposed not to explain the operation of the engine or the laws involving its operation, but suggested that "educators interested in the demonstration can more easily do it in the classroom whenever they deem convenient" (SILVA; LABURÚ, 2013, p.394).

The experiment of this engine can be used both to explain Faraday's law in the experimental way or also to use this experiment in a way to design a class with a philosophical historical bias as proposed by Guerra, Kings & Braga (2004).

Silveira & Varriale (2009) address another application of Faraday-Lenz's law which is to have magnet cylinders rolling on an aluminum ramp. In this experiment the electromagnetic braking phenomenon happens in these magnets rolling on the ramp due to currents induced on the ramp, a phenomenon that involves Faraday's Law.

Moreover, the authors comment that in addition to use this experiment to teach Faraday's law, "the experimental study of this type of movement is of interest in disciplines that include Mechanics in higher education" (SILVEIRA; VARRIALE, 2009, p.4303-5).

As can be seen, some authors propose the use of experiments for classes in physics, but as these experiments really help the process or improve the teaching and learning process is not addressed by the authors, especially with regard to problem solving.

## Didactic Proposals that involve the use of computer programs

This category is for items that have some kind of modeling and computer simulation related to situations involving magnetic field.

It was noticed that there are few articles based on the pre-established search criteria. The low presence of articles in this area was also observed by Araujo & Veit (2004) and Martin & Garcia (2012).

Araujo & Veit (2004) consulted, since 1990, studies which refer to the use of computer technology in teaching physics at secondary and university levels. The articles were classified in terms of computer usage modalities and Physics topics being covered. For electromagnetism, the authors found a grand total of five articles, however, none of these articles addresses the use of computer software related to Faraday's Law.

Martins & Garcia (2012), similarly, consulted scientific papers in the field of Science Education and Physics Education between 2000 and 2012. The authors selected papers that presented results of research that have been developed, or applied, in the use of software in physics teaching. They found only two articles referring to electromagnetism, but only one has the Faraday's law as part of the study, in for it, this article is part of this review.

Articles selected for this review were: Macedo, Dickman & Andrade (2012), Alves, Amaral & Medeiros Neto (2002) and Dorneles, Araújo & Veit (2012).

Macedo, Dickman & Andrade (2012) reported, in their work, the process of developing and implementing an Activity Roadmap, aimed at high school teachers, in which computer simulations are used for teaching selected topics of electromagnetism. Computer simulations used by the authors were developed by the Technology project in Physics Teaching (PhET) from the University of Colorado in the United States.

The authors sought to develop activities in which students must necessarily interact with the simulations, exploring thus its various aspects, to answer the questions proposed in the pre- and post-tests.

Because of this interaction, they used simulations characterized as interactive where the user can adjust various parameters of the simulation, exploring the physical situation depicted by checking the implications of changes in the behavior of the studied phenomenon.

Among the simulations used by the authors, there is the "Electromagnetism Laboratory". This simulation shows situations involving basic concepts of electromagnetism in two dimensions. High school students were the sample used and the authors conclude that:

> [...] You can display basic contents of Electromagnetism in an attractive and illustrative way, providing thus a greater involvement of students in physics classes. The use of simulations, when properly conducted by the teacher, provides a

> stimulating environment, motivation and involvement, thus improving the process of teaching and learning. (MACEDO; DICKMAN; ANDRADE, 2012, p.609.)

The analysis of these arguments arises a question: how would the proposed use of simulations in two dimensions, involving "advanced" concepts of electromagnetism as Faraday's law, represented in various ways as the relative motion of a magnet near a coil or in the form of a transformer or even so; the different ways of representing the Ampere's Law, where the representation of these situations occurs in the three-dimensionally?

The other two articles deal with other electromagnetism concepts, not Faraday's law, but because of their relevance in the matter, some comments of the authors will be transcribed here.

Alves, Amaral & Medeiros Neto (2002) report the experience of using computer algebra (CA) as student learning tool in a basic course in electromagnetic theory. The software chosen by the authors to perform the simulations was Maple.

The authors' goal was to motivate the application of a programming technique via algebraic computation, to those interested in computer use in education. One response by means of a graph in a Maple section view shows the potential of a charged ball and the graphic can be rotated allowing thus its viewing from various angles.

A fact noted by the authors is the response or computing of the program, that show results in real time, almost instantaneously, allowing focus in a short period of time, a large number of calculations to such simulations, showing, in this way, several results.

Even knowing that the authors do not propose to investigate the "teaching effectiveness" of the use of programming via algebraic computation, they found that:

> [...] With this rapid accumulation of results it notably helps the development of the "intuition" of students in relation to the studied subjects. This rapid development of intuition in seemed unusual compared to what occurs on average in learning cycles that do not include the programming of the concepts taught. It also looked above average interest in the subject content, as well as precision in the use of mathematical language. (ALVES; AMARAL; MEDEIROS NETO, 2002, p.212.)

It is easily seen here the importance of three dimensional simulations in the study of electromagnetism and the need for more research in the area of the cognitive impact of the use of this type of computer simulation.

The work Dorneles, Araújo & Veit (2012) proposes the integration of the didactic proposal to use experiments in Physics teaching, argued by some authors before, and the proposed computational activities such as electromagnetism teaching in general physics, suggested by Macedo, Dickman & Andrade (2012), and Alves, Amaral & Medeiros Neto (2002).

The results of Dorneles' work, Araújo & Veit (2012) point out that this suggested integration can provide students with a more appropriate epistemological view on the role of theoretical models in physics and computational and experimental activities in the learning process, and also promote interactivity and their engagement in their own learning. Another interesting result of this research is that

> [...] Students who used computer simulations instead of laboratory equipment performed better in solving conceptual questions about simple circuits and, surprisingly, have developed greater skill in handling real components. (DORNELES; ARAÚJO; VEIT, 2012, p.101)

Computer simulations used by the authors were displayed in two dimensions, involving situations of basic electromagnetism concepts.

Based on the discussed above, we see few research on the use of Computer Simulations in Physics teaching involving topics of electromagnetism, and especially how these computing resources can assist in the teaching and learning process.

Even though this is a subject little studied, the authors mentioned here are in favor of the use of computational resources. This meets the need for further research on the subject and the use of theoretical frameworks that support the use of such resources.

## OTHER PROPOSALS FOR TEACHING

The articles selected for this category were Alves et al. (2011) and Oliveira, Veit & Araujo (2015). These two articles do not fall into the two categories mentioned above, but address educational proposals involving electromagnetism.

Alves et al. (2011) conducted a study that proposes an individualized teaching methodology, widely used in the 70s, which is the Personalized System of Instruction (SPI), of Fred Keller. The authors used this methodology in an introductory course on electromagnetism with students of the third semester of an undergraduate course in physics.

According to the authors' argumentation, the development of courses using this methodology requires more effort, as there is a definitive need in providing a systematic feedback to student performance. Thus, in the analysis of the use of this methodology, the authors comment that:

> In the execution point of view, if no monitors are available to provide systematic feedback, the teacher can take on such a task, requiring adjustments to such. (ALVES et al. 2011, p.11)

With respect to these adaptations the authors point out that:

> Such adjustments may take into account the use of new technologies to create mechanisms to facilitate the preparation and correction of assessments, especially in disciplines where assessments involve long calculations to be checked. (ALVES et al. 2011, p.11)

Also in order to present a proposal for alternative education teachers on the issue of electromagnetism, Oliveira, Veit & Araujo (2015) present an educational experience in teaching basic concepts of Electromagnetism in high school, using Peer Instruction, associated with Just-in-Time Teaching.

Regarding this experience report, the authors consider that:

> [...] It has been a successful experience as students demonstrated: involvement in teaching activities that have been proposed and motivation to learn; They appreciated the changes introduced in the classroom and learned physics concepts taught at a higher level to that achieved by traditional classes, as shown by comparing the normalized gain between groups. (OLIVEIRA; VEIT; ARAUJO, 2015, p.199.)

Faced with a dissatisfaction with the low efficiency in terms of learning by means of traditional teaching methods characterized by almost exclusively a focus on the transmission of information, the authors argue in the sense that the report of his educational proposals are better as compared to traditional teaching, however, the real impact or changes that occur in cognitive structure, when these methods are used for the teaching of electromagnetism, is an open question that excites researchers.

Thus, we can see that there are reports of educational applications experience in the electromagnetics simulation software are used as the main tool or aid to classroom activities or laboratory and also practical activities reports proposals by some authors, and also the integration of the use of experiments in teaching physics with the computational activities (DORNELES; ARAÚJO; VEIT, 2012).

In most studies reporting the use of software, the results achieved by students are better than those that would be expected without the mediation of the computational tool.

Nonetheless, were not found among the chosen parameters in our literature review, publications indicating investigations towards the use of these tools in an integrated manner in the curricula of physics courses and / or areas that have the electromagnetism as a base.

Moreover, it is observed that there are very few published research in Science Teaching on computer simulations in teaching electromagnetism in physics, which is contrary to other areas such as mathematics education, where it is possible to find a more advantageous discussion.

The field of Physics Education could benefit from research theoretically and methodologically based on the educational applications of computer simulations in the sense of the wide use of this powerful tool in the curricula of physics courses and / or areas that have electromagnetism as a main disciplinary subject analyzing thereby the impact during the process of teaching and learning. Naturally, this process must consider teachers' initial training and in-service training as well.

## FINAL CONSIDERATIONS

After the discussion of the state of the art of the research on electromagnetism teaching in major journals in the field, it is possible to locate and justify the contribution that further research should bring to the field of Physics Education.

However, these contributions do not go deep in the use of a computer program that represents the phenomena and electromagnetic concepts in three dimensions, and, according to many theoretical frameworks an external mediation mechanism that makes use of three-dimensional representations is able to help in the process of internalization of three-dimensional representations by students.

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