Didactic Simulations for Electromagnetism Based on an Element Oriented Model

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Abstract—The web has spurred our imagination as to how education can be drastically transformed and improved through the adoption of Information and Communications Technology (ICT) and the use of simulations quickly became a wildly disputed topic. This kind of simulations are considered as a significant pedagogical innovation especially in the electromagnetics course where it is possible to concretize, via a set of interactive simulations, some experiments that are inaccessible in real life. The aim of interactive simulations is to enhance the student's understanding by providing him a meaningful insight into the studied notions, phenomena, concepts, laws and models. The design of didactic simulations is constrained by both technological choices, learning theories and numerical models which should guarantee a minimal execution time, a better stability and an acceptable precision. Our goal in this work is to design didactic simulations for electromagnetism using a numerical Element Oriented Method (EOM). The proposed EOM meets the needs of speed, accuracy and ensure better dynamical and visual interpretations of the basic laws of electromagnetic. Moreover, these applications are not only available for traditional training in the classroom but also for new training platforms provided by digital technologies such as web-based training, e-learning and m-learning.

Keywords—Didactic simulation; e-learning; virtual laboratory; electromagnetism; element-oriented method

1 Introduction

The introduction of ICT (Information and Communication Technology) in schools and universities has produced significant transformations in educational systems. Indeed, many research studies show that the appropriate use of these technologies in teaching can bring multiple benefits [1-4]. In other words, the successful integration of ICTs in education can contribute to improve the quality of teaching/learning, increase the success rate, motivation and perseverance and efforts made by learners. The contribution of ICT is more observable in scientific subjects where the relationship between real and theoretical models is particularly strong. For example, the teaching of physics focuses on the use of computer tools for data processing, implementation, computer-assisted experimentation and experiment simulations.

Experiment simulations are one of the most attractive additions brought by ICT. Didactic simulations main concern is the relationship between models and theories. The possibility of making these models operational constitutes a concretization of the theoretical knowledge that the learner must acquire: the relations between physical quantities and their representations are no longer abstract signs contained in books but entities that are manipulated. While it is clear that instrument manipulation is essential for the acquisition of empirical knowledge, it must be admitted that the manipulation of the models is also beneficial to the acquisition of theoretical knowledge.

Learning physics has always faced problems of lack of conceptualization and visualization among learners. This is especially true in learning electromagnetism. The theory of the electromagnetic field is most often exposed by the deductive method: one always starts from Maxwell's equations, which are theoretical postulates, to arrive at particular classes of phenomena. This theory is postulated by equations linking abstract concepts to mathematical operators [5]. In addition, this discipline deals with the notion of "fields", an abstract concept that is often difficult to grasp. Learners generally feel overwhelmed by the theory and, as a result, lose interest in learning.

The present work is part of a didactic research in physics which focuses on didactic simulations. Thus, we propose in this article some interactive simulations in electromagnetism that can be described as "simulated experience". These simulations are exploitable by web-based training, by mobile platforms (smartphones and tablets) as well "traditional" courses in classrooms. They offer to learners the opportunity to have a systematic reflection on the theoretical models, to obtain evolutionary representations in real time and to develop a better conceptual intuition of associated phenomena.

2 Difficulties in Teaching / Learning Electromagnetism

The theory of the electromagnetic field is most often exposed by the deductive method: one starts from Maxwell's equations, theoretical postulates, to arrive at particular classes of phenomena. This theory is postulated by equations linking abstract concepts to mathematical operators [6]. Students often use it in a procedural way rather than a reasoned one. As a result, ambiguities and difficulties arise at the level of teaching and learning of this discipline. In addition, the concept of field or electromagnetic field is the basis of this theory. The term "field" is defined ambiguously; it follows that the concept of field is equivocal. Most often, it is used to describe a certain physical characteristic that manifests itself in every point of space (actually space and time). In this case, the notion of field only has a descriptive value.

In addition to the difficulties of the continuous notion of field and the mathematical operators on the vector functions which define the field, in the mathematical sense, the teaching of electromagnetism proves difficult for three other additional reasons:

- The student can easily get the idea that this theory is based solely on mathematical entities. By using the mathematical tool, the student can easily consider this physical branch as a mathematical branch.
- Few examples are solved on the board and, in the best cases are still idealized; witch further minimize the meanings and the physical aspects.
- In the introduction of this theory, it seems that raising the motivation of students by real or practical examples as support is not always easy and will, most likely, be accompanied by additional difficulties. It should be noted here that some applications (which are still relevant) do not raise students' curiosity, except perhaps for their more media aspects such as antennas, satellites and radars or their commercial and consumable aspects such as mobile phones or RFID.

The difficulties of teaching/learning the electromagnetism theory are rarely addressed by researchers and educationalists. In the analysis of the students reasoning using the basic concepts of electromagnetism, Venturini [7] points out the scarcity of works in electromagnetic didactics that deal with learning difficulties encountered in the understanding and use of the magnetic field and associated concepts. He studied "the reasoning implemented by bachelor’s students in physics, when they mobilize the basic concepts of electromagnetism in different situations, by referring to the theory of the conceptual fields". In this way, he identifies the used operating invariants and the organization of their behaviors. It appears to him that "the students questioned are very few to control the relevance and the coherence of their remarks, that the operating invariants are used in a non-contextualized way and very often without any physical sense associated to them". In another article [8], the same author analyzed the interpretations of the similarities and differences in the conceptual mastery of students in electromagnetism from their relation to knowledge. From a questionnaire, he showed that the majority of students have difficulty in giving a physical meaning to the basic electromagnetic concepts involved in simple situations, and that they use the associated mathematical tools in a more procedural than reasoned way. However, he finds that some students have a more successful conceptual mastery. A review of classical knowledge reveals that students do not consider scientific knowledge as important to learn, whether for themselves as individuals or as future professionals. This lack of value in scientific learning is one of the elements, among others, that can be related to the difficulties that have appeared for the majority of them in the operationalization of concepts.

Other articles [9-13] address the teaching of electromagnetism. In a similar way, they identify the same difficulties mentioned above. They introduce the electromagnetism course either by the inductive method or by the deductive method. They also discuss the issues and problems to which electromagnetism can provide solutions in an unavoidable way. Finally, they propose ways to improve its teaching.

3 Solutions: From Modeling to Simulation

Nowadays, numerical computation models are developing faster and faster, which enhance the idea of using simulations or virtual laboratories in a teaching/learning perspective. We mean by simulation any simplified re-production of a phenomenon that allows us to model a situation in which we can manipulate parameters without wary of the potential intervention of parasitic variables. It tries to bring modern conceptions of didactic resources of production and maintenance. The simulation then takes all its values of interest, as soon as the electromagnetism concepts and notions that the student is supposed to construct are abstract teaching objects. The simulations are well solicited by teachers and students especially when the practical realizations are delicate, even impossible to conceive. In general, despite all the coherent theory developed by physicists to model phenomena such as the electromagnetic wave from its production and its spread till its reception, and all the arsenal of equipment designed to measure quantities, the students can easily lose the string of associations of their ideas and learning during a phenomenological description. It is therefore necessary to design didactic simulations to help students in getting a good mental picture of a phenomenon. This is the role of the didactics (figure 1). It must facilitate the transposition of scholarly knowledge to a taught knowledge. Thus, step by step, the student reconstructs his image of knowledge. Subsequently, one finds oneself in the case of a teaching favoring the evolution of learner's conceptions towards a more scientific one. Gyselinck and al. [14] show that pictorial information enhances the learning process and suggest that the visual and the spatial components of visuospatial working memory should be considered separately.

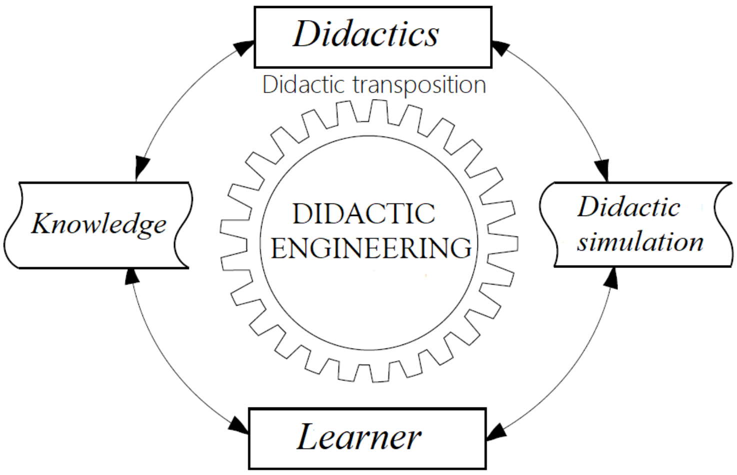

Fig. 1. Didactic engineering is based on scientific knowledge (scholarly knowledge) submitted to a control in order to reach appropriate tools to design didactic simulations (taught knowledge).

Many research works focus on applications dedicated to the teaching / learning of electromagnetism. Some authors offer very simple applications that does not require too much resources, but with a very poor graphic quality. Sevgi [15] discuss the problem of teaching electromagnetic compatibility to future engineers and the challenges and perspectives brought by new technologies. Osaci, Hirano, Patil and many other authors [16-21] used the well-known Matlab software to develop didactic applications. Selleri [22] was the first to introduce and present a new computer tool now called ‘frameworks’ using Matlab. The most important utility of a framework is certainly the help it brings to application developers through its organization as libraries. For this purpose, it aims at the maximum productivity of the programmer. Nevertheless, frameworks are, in principle, dictated by the type of program and the target architecture for which they are designed. Iskander explored the issue of web technologies and their interests and benefits in teaching electromagnetism [23-24].

We note that most of the didactic simulations designed by their authors are essentially based on the FDTD (Finite Difference Time Domain) method, which is widely used for solving electromagnetic problems. However, other works make use of other techniques such as the finite element method, the finite volume method, and so on.

We also noticed that most of the cited applications are designed not to experiment with electromagnetic phenomena, but to simulate analytical results. These simulations are of a confirmatory nature. They help the student to check calculations and to note the influence of certain parameters on the different electromagnetic phenomena. The number of these simulations can only be limited, since it is known that algebraic solutions only exist for well-known canonical problems. Nevertheless, they are of great importance from a didactic point of view as long as they help the student to rediscover, in a visual and interactive way, analytical solutions written in the form of mathematical equations. This remark leads us to define the functions of a simulation. Indeed, it may have a strictly exploratory or strictly confirmatory function. It has an exploratory function when it is difficult to priori develop hypothesis or assumptions that would predict the observed results, which may later be useful for the development of hypotheses. It has a confirmatory function when used to verify the veracity of a hypothesis. In fact, we can consider a simulation device as a research plan that can be used to confirm the expected results according to a theory (confirmation and deduction) or simply to explain results by induction (exploration). Moreover, since the model is eclectic, the realization of a simulation is very complex. In some cases, the model is so complex that the computers in our reach are not powerful enough to consider the design of a realistic simulation.

Based on these remarks, we present in the following the new "Element Oriented Model" (EOM) in electromagnetism [25]. This model allows us to formalize the electromagnetic equations in a similar way as object-oriented numerical computation. For that, and based on a topological approach, we identify spatio-temporal geometric objects or elements on which we define conservative equations. Therefore, we can identify the properties and behaviors of basic electromagnetic elements. In addition, this new model allowed us to prove the foundation of the nonstandard FDTD method (NS-FDTD).

4 Electromagnetics Modeling

Electromagnetism has introduced a set of physical and conceptual novelties. The electromagnetic field is the key concept of this theory; it was forged in the 19th century to describe, in a unified way, electrical and magnetic phenomena. In 1865, James Clerk Maxwell formulated the basic equations governing the theory of electromagnetism. In his treatise of 1881 [26] Maxwell modified his original equations of 1865. In addition, he introduced the quaternions notation by rewriting his equations in a new form. However, he never really made calculations with quaternions. He gathered the scalar and vector notions in a more compact form [27]. Since that time, the equations of electromagnetism are still subject to multiple modifications that sometimes affect the form (at the level of notation or relations) and sometimes act directly on the formalism level. It is especially this second type of modification which extends the classical interpretations of the electromagnetic phenomena to new and more radical interpretations. They may even give rise to new physical entities. These modifications enrich the theory of the electromagnetic field by opening new perspectives on both formalism and interpretations levels. Some of them are more suitable for the resolution of some specific cases than others, they seem simpler to use, and therefore more appropriate for a given level of education. The complete set of equations established in 1865 by Maxwell is a mathematical tool that describes the electromagnetic theory. It is considered the basic postulate of this theory. This set is defined on 20 variables called field variables. It was Olivier Heaviside and Williams Gibbs the first to have transformed these equations into an easier to use vector shape; this formulation is the best known nowadays.

Moreover, we noticed that the topology is not fully exploited in electromagnetism. Indeed, although the topology has been recognized by Leibnitz, Gauss and Maxwell to play a pivotal role in the electromagnetic theory [26], it is not exploited enough as a modeling and calculation tool. Recently, several researchers have been studying this axis [28-31]. For some optimization problems, this approach seems to be effective. Indeed, the topology provides an essential framework of connection between electromagnetic entities and geometry.

Furthermore, the topological approach allows us to establish new dynamic visualizations of the basic laws of the electromagnetic theory [25] which is, from a didactic point of view, very important, these representations root the theory and make it assimilation simpler. This approach is the basis of our proposal for the object-oriented model. This modeling uses the Object-Oriented Programming (OOP) paradigm. This method describes electromagnetic objects that include the topology and the usual entities of electromagnetism. These objects have properties or "data members", methods or "function members" as well as "events". Properties define the objects identity and their states as internal variables. As for the methods, they define the interface and condition the behavior of the object. This method allows us to enjoy all the advantages of the OOP (abstraction, encapsulation, modularity, hierarchy, polymorphism and persistence). Therefore, we looked for objects by describing their properties. In this proposal, the links and interactions between objects were clearly formulated. The individual behavior of each component is considered as an entity with its own properties, history and actions. And since each of these objects uses identical schemas, Element Oriented Modeling (EOM) is strongly favored to produce exploratory simulations.

4.1 The element-oriented model

The integral form of the Maxwell's equations distinguishes integrable electromagnetic entities on geometrical objects such as, for example, the electric field E on a line, the density on a surface or the volume charge ρ on a volume. However, these equations do not clearly reflect the orientation of these geometric objects. The distinction between a geometrical object without orientation and an oriented geometrical object is very important. In electromagnetism, all geometrical objects are oriented. Maxwell pointed out at least four geometrical objects with internal or external orientation to correctly represent the natural laws of electromagnetic field theory. For continuous or discontinuous media, and in a Euclidean frame, we list four basic geometrical objects: Point, line, surface and volume. They can have either internal or external orientation.

If we extend the analysis of spatial 3D geometrical objects into space-time 4D geometrical objects, a first idea is to consider space-time as a single 4D space. We can then apply and extend the previous definitions to 4D geometrical objects. However, the fourth dimension, time, is of a different nature from other spatial dimensions. As a result, we will consider the workspace as a Cartesian product of the usual 3D space by the time (space × time). The time domain will then include objects of zero dimension (instant t) and objects of first dimension (time interval or duration). We can then combine these two objects with the 8 spatial objects to obtain 16 temporal spatial objects. An example of a temporal geometrical object is shown in figure 2.

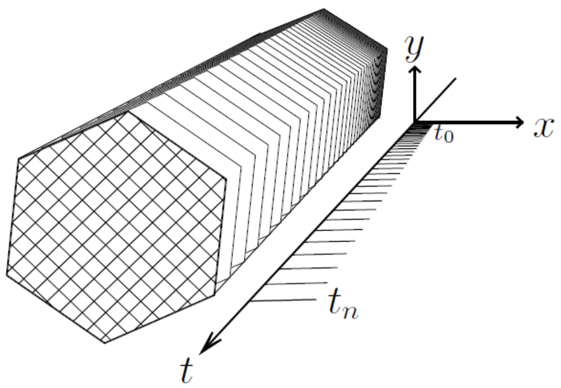

Fig. 2. Example of a space-time geometrical object - here a volume S × I

Using this kind of space-time objects and knowing that Maxwell's equations contain a certain number of symmetries and conservation laws that could be broke or modified by discretization, we propose a set of equations where conservation laws remain preserved in a discretized zone when they are formulated near the borders of this region. Thus, they do not depend on the space metric and are invariable under homeomorphism (for more details on the calculation process, readers can refer to [25]).

$$\Phi^e + \Phi^d = 0^3 \tag{1}$$

$$\widetilde{\Psi}^h + \widetilde{\Psi}^d = \widetilde{Q}^j \tag{2}$$

$$\langle c_2^{i,2}, \Phi^b \rangle = \langle c_2^{i,1}, \Phi^b \rangle \pm \sum_{j=1}^{n_2-2} \alpha_{i,j}^{3,2} \langle c_2^j, \Phi^e \rangle \tag{3}$$

$$\langle \tilde{c}_2^{i,2}, \widetilde{\Psi}^d \rangle = \langle \tilde{c}_2^{i,1}, \widetilde{\Psi}^d \rangle \pm \sum_{j=1}^{n_2-2} \tilde{\beta}_{i,j}^{3,2} \langle \tilde{c}_2^j, \widetilde{\Psi}^h \rangle \pm \langle \tilde{c}_3^i, \tilde{Q}_i^3 \rangle \tag{4}$$

where

- $\Phi^2 = (\Phi^b, \Phi^e)$ is the electromagnetic flux associated to primal surface S. Φ^2 is a pairing of Φ^b with Φ^e where Φ^b is the magnetic flux associated with the object $S \times \delta I$ and Φ^e is the electric flux associated with $\delta S \times I$ (δ is the boundary operator)
- $\widetilde{\Psi}^2 = (\widetilde{\Psi}^h, \widetilde{\Psi}^d)$ is the electromagnetic charge-current potential associated to dual surface $\tilde{S}$. $\widetilde{\Psi}^h$ is the voltage impulse associated with $\delta\tilde{S} \times \tilde{I}$ and $\widetilde{\Psi}^d$ is the electric flux associated with $\tilde{S} \times \delta\tilde{I}$
- $\widetilde{Q}^3 = (\widetilde{Q}^\rho, \widetilde{Q}^j)$ is the electromagnetic charge associated to dual volume $\widetilde{V}$
- $(\alpha_{i,j}^{3,2}, \tilde{\beta}_{i,j}^{3,2})$ are the incidence numbers of the cell c_3^i(or $\tilde{c}_3^i$) on the cell c_2^j (or $\tilde{c}_2^j$)

The first two equations are exact equations: they prove that the laws of electromagnetism contain an intrinsic discretization while the later equations use cochains as discrete representation to describe the electromagnetic objects behavior.

The computation of the fluxes on the cells of any mesh is obtained by injecting a local distribution function on these cells. This method leads us, depending on the chosen local function, to the Yee algorithm of both standard (FDTD) and nonstandard (NS-FDTD) Finite Difference Time Domain methods. In the same way, two new NS-FDTD algorithms have been developed by using adequate local distribution functions which allow the correction of spatial and temporal truncation errors. This correction is beneficial for the numerical calculation since it contributes to reduce the discretization errors.

4.2 Results and comparison

To compare the results of the two new nonstandard algorithms NS-FDTD (1) and (2), we used the diffraction problem commonly known as "Mie scattering" problem. This is a well-known testing problem for electromagnetics algorithms. In general, diffraction problems are posited as boundary conditions for electromagnetics equations. Very few analytical solutions are known for simple diffraction bodies such as cylinder and sphere. These exact solutions are of great interest for the validation of numerical schemes. For this problem, we consider a parallel wave hitting a cylinder of diameter D comparable to the wavelength of the incident wave λ. We seek the spatial and temporal distribution of the total field (incident + diffracted). We chose to be on the observation plane parallel to the axis of the cylinder where the error of the numerical anisotropy is maximal (angles ±π/2). The incidence field E_z is a plane wave and the exact solution of the Mie scattering problem is known [25].

Figure 3 shows the new NS-FDTD methods relative error in the L_1 standard and compares them with the classical FDTD, NS-FDTD and Finite Element (FEM) methods, as a function of the mesh density N_λ. The algorithm NS-FDTD (2) shows better results and is more accurate than the others for the lower mesh steps (between 6 and 12). When the mesh becomes very thin, the errors of the different methods are approximately the same.

For computational times, a slight increase in the computation time of the nonstandard methods is noted. By comparing the Cole algorithm with the second nonstandard algorithm NS-FDTD (2), we note that for any precision, the latter has a better computation time; and for any computation time, it has a better accuracy. Comparing these results with those of the finite element method, we notice that the NS-FDTD (2) algorithm is more accurate when it comes to finer mesh densities (from 6 to 12) and for all densities, the computation time of the finite element method is much larger.

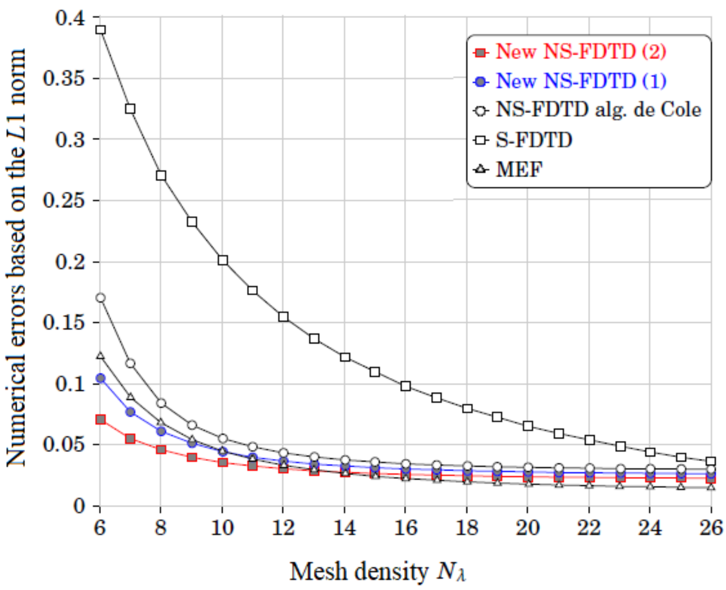

Fig. 3. Relative error (L1 norm) of the methods: finite elements, S-FDTD, NS-FDTD Cole algorithm and the two proposed NS-FDTD algorithms (1) and (2) in terms of the mesh density.

5 Didactic Simulations

Didactic simulations as a phenomenon model or an educational activity intended for learners, takes full advantage of technological advances. Simulations as didactic means are required as soon as the performed experiments in laboratories are impossible or difficult to design for reasons of feasibility, safety or prohibitive cost. In these cases, the use of simulation is the most accessible means for students to apprehend and understand difficult, complex or abstract notions.

We note that the complexity of any simulation is always proportional to the complexity of the problem, the representation, the tools and the simulation methodology. Indeed, the procedures for designing a simulation contain a rather large number of parameters:

- The theory behind the phenomenon
- Mathematical techniques and numerical computing
- Choice of parameters, initial conditions and boundary conditions
- The reduction of degrees of freedom
- Ad hoc models
- Computer algorithms
- Graphical system
- Evaluation of the reliability

From the perspective of our research strategy guided by the didactic approaches and the frame of references discussed in the sections above, we developed some applications and simulations that best meet the expectations of researchers, teachers and learners. In addition, the Element-Oriented Model facilitated the task of designing exploratory and interactive simulated experiments. Indeed, the manipulation of interactive graphic objects allows students to activate, complete and structure their knowledge [33]. The implementation of some applications is based on our non-standard FDTD algorithms that meet our criteria of precision and execution time speed imposed by current technologies. In the following, we present some of those simulations.

5.1 Simulations in electrostatics

The main goal in designing these simulations for teaching/learning is to shape the concepts of field and electric potential in a graphical and interactive way. By examining most of the manuals of electromagnetics theory and electrostatics in particular, we realize that we are already undertaking a capital concept relating to the notion of electric field. This field is customarily defined through the mechanical concept of forces on a test charge. This definition is not very questionable except that it does not generate clear explanations of the notion of field. Indeed, the learner can quickly believe that it is about the interactions between charged objects and that the idea of field is only a simple mathematical computational formalism. However, this notion is more than that, it defines in itself a whole natural concept that plays an important role in modern physics; it is as "real" as material objects. The electric field is a modification of the space created by the presence of electric charges. It is a physical vector entity - mathematically speaking - that takes values and directions in a continuous way in all space.

Given the conceptual significance introduced by electrostatics, we developed experiential simulations in ActionScript Flash while adopting a new numerical scheme based on the object-oriented programming paradigm. We used a regular and equidistant rectangular mesh for the study domain D. Each spatial element is a "medium" object with geometrical and physical properties and a behavior function that updates the field calculation as a result of any charge detection or displacement in the D domain. We also consider that the charge is an object endowed with properties of position and electric charge q. The electric field produced by a unit charge at a distance r-less than or equal to the largest dimension of the D domain is calculated beforehand. Taking advantage of the spherical symmetry, we only need to do the calculation on one line. These field values are stored as an array vector in the "charge" object itself in order to reduce the computation time of simulations. As a result, we provide the user with better interactivity when moving charges in the study domain. An appropriate algorithm for drawing equipotential lines is implemented in each "medium" object as an action function. Examples are shown in figures 4 and 5.

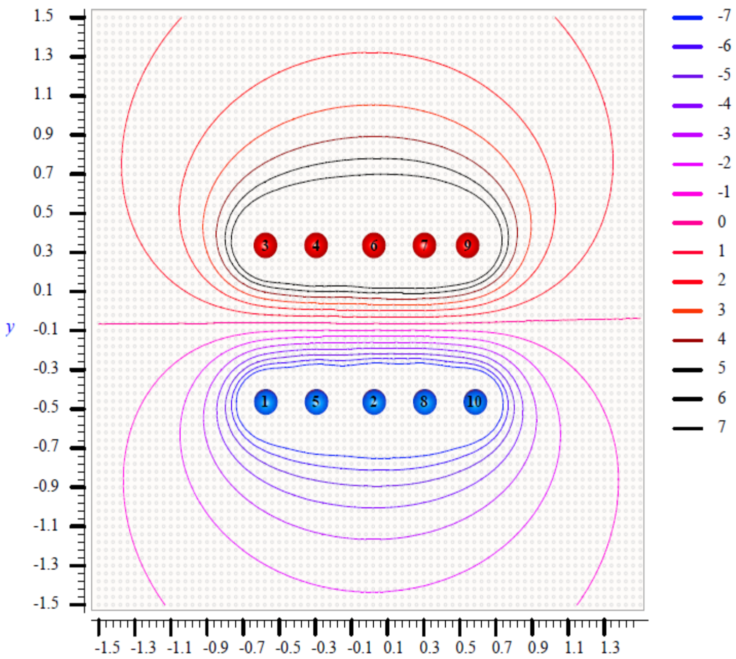

Fig. 4. Example of a didactic simulation in electrostatic. Ten "charge" objects of opposite signs are instantiated by the program to simulate a planar capacitor

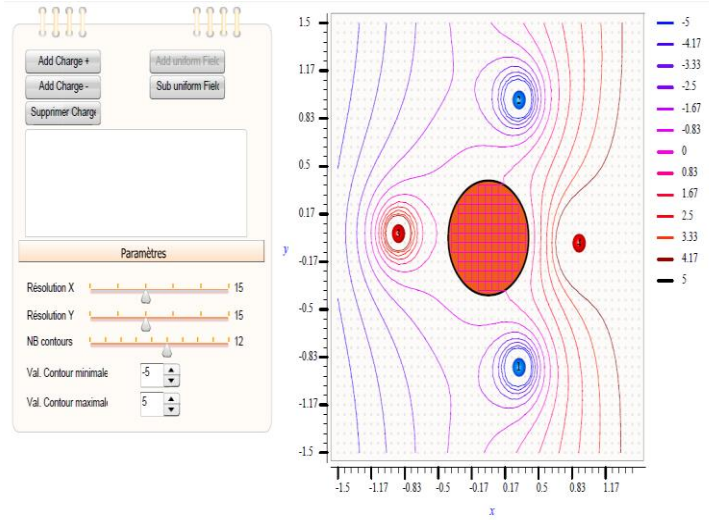

Fig. 5. Another example of the electrostatic web-lab showing some electrostatic phenomena.

5.2 Wave propagation and transmission lines

Based on the new Element Oriented Model, many applications have been developed for the teaching/learning of transmission lines and the propagation of electromagnetic waves in different mediums. From a didactic point of view, the transmission lines course overwrites the classical theory of electric circuits in quasi-stationary mode where lines do not induce any changes to the propagation process. The introduction of microwave concepts can be assisted by visualizations of the propagation of a TEM wave along a transmission line while varying the wavelength parameters. Such educational scenarios integrating these simulations will not only facilitate the introduction of the course, but will also allow problem-based situations to be integrated throughout the course.

For wave propagation, we propose an interactive application allowing, thanks to numerous didactic simulations, to visualize the spatiotemporal evolution of an electromagnetic wave in different mediums. The learner will be able to choose between three types of sources:

- A sinusoidal signal: characterized by its amplitude and frequency that can be modified using two horizontal potentiometers (figure 6)
- A Gaussian signal: generates a Gaussian signal centered on t_0 and with a width determined by a “spread” parameter. The peculiarity of this signal is its Fourier transform which is also in Gaussian form. Hence the usefulness of this type of signal in different simulations

- A rectangular signal: or unit pulse which is also rich by its discontinuous spectrum. This signal is determined by its rising edge at the instant t_{on} and its falling edge at the instant t_{off}

A first simulation shows the propagation of an electromagnetic wave in free space as well as its evanescence in the absorption cells at the edges, thanks to the PML (Perfectly Matched Layer) absorption technique. In addition, the user can manipulate the various excitation parameters related to the signal nature and its characteristics as well as the position of the excitation point. Thanks to the power of the new element-oriented model, the computing results are displayed in real time and any parameter modification will be taken into account instantly. Another variant of this simulation makes it possible to study the propagation of an electromagnetic wave across three mediums (figure 6). Each of the three medium is characterized by its relative permittivity and conductivity (in this example, we present parameters independent of frequency and temperature), which allows the study of a large number of known materials. Also, for wave propagation in frequency-dependent media, we propose the case of a plasma medium (figure 7) which has a dielectric model of complex permittivity:

$$\varepsilon^* = 1 + \frac{\omega_p^2/\vartheta_c}{j\omega} - \frac{\omega_p^2/\vartheta_c}{\vartheta_c + j\omega} \tag{5}$$

Where ω_p is the plasma natural frequency; and ϑ_c is the electron collision frequency.

Figure 6 shows the wave propagation simulation in a plasma with the properties of silver: $f_p = 2000\text{THz}$ and $\vartheta_c = 57\text{THz}$. This kind of simulations allows to highlight the filtering properties of plasma mediums. Indeed, any frequencies lower than the plasma frequency do not propagate in the medium while frequencies higher than the plasma frequency completely pass through the medium. Plasma behaves as a high pass filter for electromagnetic waves.

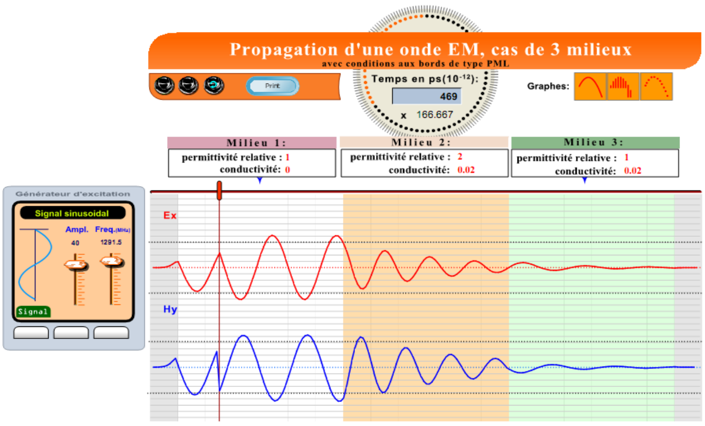

Fig. 6. Propagation of a sinusoidal electromagnetic wave of 1.29GHz frequency in three different mediums each having a configurable permittivity and conductivity

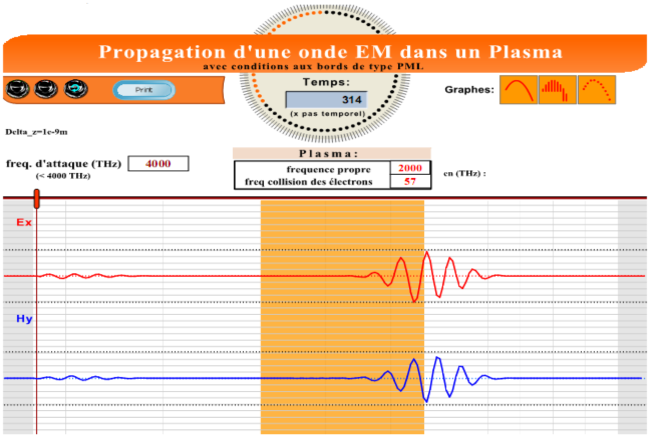

Fig. 7. Wave propagation of a 4000 THz electromagnetic signal in a plasma

6 Conclusion

Simulation plays an important role in the understanding and perception of electromagnetic and electronic phenomena. Visualization is a very useful tool in electromagnetism teaching. The introduction to subjects such as fields, wave propagation, transmission lines and Smith chart are more easily illustrated by visualization and simulation. The affirmation of the mathematical model through simulation can also strengthen the student confidence. In addition, they stimulate student motivation and increase their participation. These applications are an excellent teaching tool where learners can explore the solutions through their own efforts and in great detail, thus deepening their understanding of the subject.

In this perspective, we developed a variety of interactive applications in electromagnetism dedicated to web-based training and didactic engineering. Due to their virtual and animated mode of representation, the impact of these applications on teaching is of great interest. Indeed, this kind of teaching gives students the experience of questioning, idea gathering and association, self-appropriation of knowledge, highlighting and analysis of scientific processes.

7 References

[1] Machin, S., McNally, S., & Silva, O. (2007). New technology in schools: Is there a payoff? The Economic Journal, 117(522), 1145-1167. https://doi.org/10.1111/j.1468-0297.2007.02070.x

[2] Falck, O., Mang, C., & Woessmann, L. (2018). Virtually no effect? Different uses of classroom computers and their effect on student achievement. Oxford Bulletin of Economics and Statistics, 80(1), 1-38. https://doi.org/10.1111/obes.12192

[3] Ferraro, S. (2018). Is information and communication technology satisfying educational needs at school? Computers & Education, 122, 194-204. https://doi.org/10.1016/j.compedu.2018.04.002

[4] Salmi, K., Magrez, H., & Ziyyat, A. (2016). Interactive applications in HF electronics for mobile learning. In International Conference on Information Technology for Organizations Development (IT4OD), (pp. 1-5). IEEE. https://doi.org/10.1109/it4od.2016.7479270

[5] Darrigol, O. (2016). Models, structure, and generality in Clerk Maxwell's theory of electromagnetism. The Oxford Handbook of Generality in Mathematics and the Sciences, 345. https://doi.org/10.1093/oxfordhb/9780198777267.013.12

[6] Temes, J. B. (2003). Teaching electromagnetic waves to electrical engineering students: an abridged approach. IEEE Transactions on Education, 46(2), 283-288. https://doi.org/10.1109/te.2002.808275

[7] Bagheri-Crosson, R., & Venturini, P. (2006). Analyse du raisonnement d'étudiants utilisant les concepts de base de l'électromagnétisme. https://doi.org/10.4267/2042/23952

[8] Venturini, P., & Albe, V. (2002). Interprétation des similitudes et différences dans la maîtrise conceptuelle d'étudiants en électromagnétisme à partir de leur (s) rapport (s) au (x) savoir (s). Aster, 2002, 35" Hétérogénéité et différenciation". https://doi.org/10.4267/2042/8803

[9] Ferreira, G., Lima, C., Cardoso, G., Vukovic, A., & Thomas, D. (2017). Teaching Electromagnetics in an Electrical/Electronic Engineering undergraduate course: the hybrid option.

[10] Roussel, H., & Hélier, M. (2012). Difficulties in teaching electromagnetism: an eight year experience at Pierre and Marie Curie University. Advanced Electromagnetics, 1(1), 65-69. https://doi.org/10.7716/aem.v1i1.59

[11] Maaskant, R., & Rosen, A. (2016). Teaching and Learning Electromagnetics: An Analytical Problem-Solving Approach [Education Corner]. IEEE Antennas and Propagation Magazine, 58(2), 75-83. https://doi.org/10.1109/map.2016.2520401

[12] Furse, C. M., & Iskander, E. T. (2018). Electromagnetics Education: Past, Present, and Future Directions. In The World of Applied Electromagnetics (pp. 655-675). Springer, Cham. https://doi.org/10.1007/978-3-319-58403-4_25

[13] Furió, C., & Guisasola, J. (1998). Difficulties in learning the concept of electric field. Science Education, 82(4), 511-526. https://doi.org/10.1002/(sici)1098-237x(199807)82:4<511::aid-sce6>3.3.co;2-#

[14] Gyselinck, V., Ehrlich, M. F., Cornoldi, C., De Beni, R., & Dubois, V. (2000). Visuospatial working memory in learning from multimedia systems. Journal of Computer Assisted Learning, 16(2), 166-176. https://doi.org/10.1046/j.1365-2729.2000.00128.x

[15] SEVGİ, L. (2014). Electromagnetic compatibility engineering education: problems, challenges and perspectives. Turkish Journal of Electrical Engineering and Computer Science, 17 (3), 273-280. Retrieved from http://dergipark.gov.tr/tbtkelektrik/issue/12078/144419

[16] Osaci, M. (2018). Numerical Simulation Methods of Electromagnetic Field in Higher Education: Didactic Application with Graphical Interface for FDTD Method. International Journal of Modern Education and Computer Science, 10, 1-10. https://doi.org/10.5815/ijmecs.2018.08.01

[17] Hirano, T., & Hirokawa, J. (2017, August). Education materials of electricity and magnetism using MATLAB. In Radio-Frequency Integration Technology (RFIT), 2017 IEEE International Symposium on (pp. 16-18). IEEE. https://doi.org/10.1109/rfit.2017.8048275

[18] Sevgi, L. (2015, July). Teaching electromagnetics via virtual tools. In Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2015 IEEE International Symposium on (pp. 1021-1022). IEEE. https://doi.org/10.1109/aps.2015.7304898

[19] Patil, S., Kelagadi, H. M., Kumar, P., & Shettar, R. B. (2018, December). Technology Enabled Active Learning for Electromagnetic Waves and Theory. In 2018 IEEE Tenth International Conference on Technology for Education (T4E) (pp. 225-226). IEEE. https://doi.org/10.1109/t4e.2018.00062
[20] Apaydin, G., & Sevgi, L. (2017). A MATLAB-Based Virtual Tool for Simulations of Wave Propagation Inside a Parallel-Plate Waveguide [Testing Ourselves]. IEEE Antennas and Propagation Magazine, 59(4), 100-105. https://doi.org/10.1109/map.2017.2707324
[21] Qingqing, Z., Jin, W., Jin, L., & Lei, Z. (2015). Application of ElecNet software in teaching of Electromagnetic Field and Electromagnetic Wave course. Experimental Technology and Management, 6, 035.
[22] Selleri, S. (2003). A MATLAB experimental framework for electromagnetic education. IEEE Antennas and Propagation Magazine, 45(5), 86-90. https://doi.org/10.1109/map.2003.1252814
[23] M. F. Iskander, "Technology-based global revitalization of electromagnetic education," 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, 2015, pp. 1019-1020. doi: 10.1109/APS.2015.7304897 https://doi.org/10.1109/aps.2015.7304897
[24] M. F. Iskander, "Multimedia- and Computer-Based Engineering Education," 1999 29th European Microwave Conference, Munich, Germany, 1999, pp. 90-92. https://doi.org/10.1109/euma.1999.338417
[25] Magrez, H., & Ziyyat, A. (2012). A new element-oriented model for computational electromagnetics. Progress in Electromagnetics Research, 36, 193-220. https://doi.org/10.2528/pierb11050102
[26] Maxwell, J. C. (1881). A treatise on electricity and magnetism (Vol. 1). Clarendon press.
[27] Majernik, V. (1999). Quaternionic formulation of the classical fields. Advances in Applied Clifford Algebras, 9(1), 119. https://doi.org/10.1007/bf03041944
[28] Stern, A., Tong, Y., Desbrun, M., & Marsden, J. E. (2015). Geometric computational electrodynamics with variational integrators and discrete differential forms. In Geometry, mechanics, and dynamics (pp. 437-475). Springer, New York, NY. https://doi.org/10.1007/978-1-4939-2441-7_19
[29] Jazebi, S., Zirka, S. E., Lambert, M., Rezaei-Zare, A., Chiesa, N., Moroz, Y. & Narang, A. (2016). Duality derived transformer models for low-frequency electromagnetic transients—Part I: Topological models. IEEE Transactions on Power Delivery, 31(5), 2410-2419. https://doi.org/10.1109/tpwrd.2016.2517327
[30] Salmi, K., Magrez, H., & Ziyyat, A. (2014). Interactive simulation as a virtual tool in electromagnetics for online education. In Third IEEE International Colloquium in Information Science and Technology (CIST), (pp. 192-195). IEEE. https://doi.org/10.1109/cist.2014.7016617
[31] Han, J. H., Ju, S. H., Kang, N. W., Lee, W. S., & Choi, J. S. (2018). Wideband Coupling Modeling Analysis by Arbitrarily Incoming Source Fields Based on the Electromagnetic Topology Technique. IEEE Transactions on Microwave Theory and Techniques. https://doi.org/10.1109/tmtt.2018.2876221
[32] Magrez, H., Salmi, K., & Ziyyat, A. (2016). Interactive simulations for teaching and learning differential equations. In International Conference on Information Technology for Organizations Development (IT4OD), (pp. 1-5). IEEE. https://doi.org/10.1109/it4od.2016.7479266
[33] Tibola, L. R., Pereira, C. E., & Tarouco, L. M. R. (2014). Improving performance to engineering students through virtual labs and its monitoring in cockpit. International Journal of Engineering Pedagogy (iJEP), 4(4), 43-50. https://doi.org/10.3991/ijep.v4i4.3957

[34] Drigas, A., & Kontopoulou, M. T. L. (2016). ICTs based Physics Learning. International Journal of Engineering Pedagogy (iJEP), 6(3), 53-59. https://doi.org/10.3991/ijep.v6i3.5899

[35] Choi, C. (2013). Teaching Electromagnetic Interference on Microcontrollers through Lab Experiments. International Journal of Engineering Pedagogy (iJEP), 3(2), 4-8. https://doi.org/10.3991/ijep.v3i2.2252

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