

## High school students' interpretation of the conceptual issues relating to electromagnetic waves

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**Summary.** — A questionnaire about electromagnetic waves was submitted to 194 high school students after they completed the study of electromagnetism. The questionnaire consists of 6 multiple choice questions —each one with 5 options— also asking for a justification of the answer. They investigate the main conceptual issues and learning difficulties emerging from the literature about the time-dependent electromagnetic field. The answers' analysis was carried out through an iterative categorization process, aimed at verifying the consistence between the selected options and the motivations provided by the participants. The results show which are the most common learning difficulties (*e.g.*, the interpretation of the wave profile representation and the relationships between the velocity and the other quantities characterizing electromagnetic waves, such as frequency, intensity and the propagation medium) and how they are related to each other, providing implications for teaching.

### 1. – Introduction

This study is part of a larger research aimed at elaborating a learning path about electromagnetic waves in the framework of the Entangled Research Method (ERM) [1]. It is based on the Model of Education Reconstruction revisited by focusing on disciplinary fundamental concepts of the selected topic, aiming at conceptual change with respect to the knots that differentiate common sense from scientific ideas. According to this framework, this step of the research was carried out in order to identify those conceptual knots on which the conceptual change will have to act. As there is not a large body of literature about this topic, we chose to carry out this identification by submitting a questionnaire to a sample of the target population. It investigates the main learning objectives that are related to the generation, propagation and reception of electromagnetic waves, as we will show in the next sections. According to ERM, the teaching-learning path will provide several strategies and methods of conceptual change to overcome the conceptual knots we identified analysing the answers of this questionnaire.

The main conceptual aspects on which the learning proposal will be based are the same we are going to investigate through the questionnaire. Thus, the same instrument may be also used to investigate the learning difficulties about electromagnetic waves, insisting on the learning objectives that are usually considered in traditional teaching for the target population. In order to provide insights of the larger context of the research, in the next section we are going to illustrate some of the conceptual aspects which the learning path will be based on.

## 2. – Theoretical framework

The system of Maxwell's equations provides the link between the electromagnetic field and its sources, while the Lorentz force provides the link between the electromagnetic field and the charges on which it acts. Thus, they represent the synthesis of the classical electromagnetism. Secondary school students are not yet introduced to the mathematical formalism which allows these equations to be written in differential form, thus obtaining the wave equation for the electric and magnetic fields. Nevertheless, it is possible to adopt an approach which allows to infer some characteristics of the propagating electromagnetic field starting from the integral form of Maxwell equations. In particular, we can obtain the velocity of the electromagnetic field propagation reasoning about the expression of the electric field associated to the variation of the magnetic flux over time, and vice versa. Hypothesizing that the fields are not propagating instantly, it is possible to calculate the velocity of electromagnetic waves in vacuum. In our approach, we refer to a plane distribution of currents to implement this reasoning. In this way it is also possible to recognize that the directions of the oscillating electric and magnetic field form a vector-oriented triad with the direction of propagation. Furthermore, the oscillation in phase of the electric and magnetic field arises from this reasoning. Finally, the Hertz's experiment provides the real context in which electromagnetic waves are produced and detected, through an oscillating circuit providing the wave frequency. As this approach is embedded in free space and we can take into account the energy of the electromagnetic field, the only characteristic that we have not demonstrated is the specific wave form according to which it is oscillating. It depends on the specific source, and it could be demonstrated using the differential approach. Thus, we provide the case of plane monochromatic wave, whose representations and characteristics is the focus of the second part of our TLS. Furthermore, some of the main relationships between the quantities characterizing the electromagnetic waves —*i.e.*, the wavelength ( $\lambda$ ), frequency ( $f$ ), propagation velocity ( $v$ ), intensity ( $I$ ) and the medium— may be proved at this level. We are going to analyze the one-to-one relationships which characterize the nature of the electromagnetic radiation.

From the study of mechanical waves, students already know that the relationship  $v = \lambda f$  is valid, and also that the propagation velocity depends on the medium. On the other hand, when dealing with visible light as portion of the electromagnetic spectrum, they learn to associate both the frequency and the wavelength to the color of light [2]. But these two quantities represent different properties, as the frequency —differently from the wavelength— does not change when the propagation medium is changing. For instance, this explain why the color of light does not change when changing the medium, but also why the velocity depends on the medium: the path changes according to the refraction phenomenon, so that we can define for each medium a specific refraction index. On the other hand, every portion of the spectrum will propagate with the same velocity in the same medium, and it will not be affected by the relative motion between the source

and the observer: this aspect represent a link with the postulates of Einstein's theory of relativity.

Another link with modern physics is represented by the relationship between the intensity and the frequency. Indeed, differently from mechanical waves, the intensity of electromagnetic waves is independent of the their frequency according to the classical theory. Only the quantum interpretation of the photoelectric effect will make evident that the photons' energy increase when the frequency increase.

There relationships characterize among others—for instance, the transversality of the electric and magnetic field with the propagation velocity—the propagation of electromagnetic waves. On the other hand, their generation is characterized by the quantities of the field which do not depend on the medium—*i.e.*, their oscillation frequency. Furthermore, the characterization of accelerated charges as microscopic sources of electromagnetic waves deserves a special treatment, as it involves several misleading conceptual aspects: the time dependence of the fields generated by charges in uniform motion and the force of “radiation reaction” [3].

Finally, the last phase involving the waves is their reception. Of course the radiation-matter interaction would require a quantum description, but the mechanism of an antenna receiving a signal may be simply described in terms of the action of Lorentz's force [4, 5]. Thus, the implications of this mechanism involve the concept of resonance, the set for having the best signal's reception and the validity of Lorentz's force for non-static electric and magnetic fields.

### 3. – Research questions

The aim of this study is to analyse the conceptual content knowledge of Italian high school students about the classical theory of the time-dependent electromagnetic field, at the end of their curriculum. Following the structure of the instrument we are going to describe in the next section, the specific research questions that guided our study are the following:

- 1) Which relationships do students identify between the electromagnetic waves and their sources?
- 2) Which relationships do students identify between the characteristic quantities of electromagnetic waves (*e.g.*, wavelength, frequency, velocity, intensity) in their propagation in free space or in matter?
- 3) How do students explain the interaction of electromagnetic waves with matter that allow their reception?

As in the items some representations of electromagnetic waves are included, the analysis will also provide information about students' interpretations of these kind of images. Furthermore, a specific question about the interpretation of the profile of plane and monochromatic waves propagating over space and time. Since it is recognized as a key aspect of the learning process about this topic by the literature [4, 6], we also included the following research question:

- 4) How do students interpret the profile of plane electromagnetic waves?

Finally, It is worth noting how these research questions cover a large part of the electromagnetic field theory, and almost all the aspects that are usually reported in the

school textbooks, as they represent the three phases of the waves' nature: generation, propagation and reception.

#### 4. – Methods

4.1. *Sample.* – We carried out the analysis with a sample of 194 high school students (18 years old), which attended the last year of the curriculum in two schools in the north of Italy. All the students experienced the same physics' curriculum, that is mandatory for everybody according to the national plan of the ministry of education. The convenience sample included 10 full classes. The students were submitted the questionnaire after they completed the study of electromagnetism with their teachers. The participation was on a voluntary basis, and it took place through an online form.

4.2. *Instrument and data analysis.* – The instrument we submitted was developed by us, since there is not a large body of research literature about this topic. Thus, we carried out an epistemic review of the classical theory about the electromagnetic field in order to identify the key ideas that characterize the conceptual steps in its evolution. Then, we declined each key idea into one or more learning objective for the target population, and we elaborated an item for each objective. The final structure of the instrument consists of 6 multiple choice questions, which also ask for a justification of the options selected. Each item has 5 options: just one is correct, while the others are related to possible learning difficulties of the target population of students. We defined these learning difficulties as “possible” since some of these issues emerged in literature [7-9], while others are plausible learning obstacle considering the experience of teachers we discussed the topic with, and also considering the typical content knowledge presented in school textbooks that may reinforce these misconceptions.

In fig. 1 the 6 questions are reported in the English version, while the original questionnaire was submitted in Italian. Question No. 1 was reformulated from a similar version in a previous instrument of Ambrose *et al.* [4].

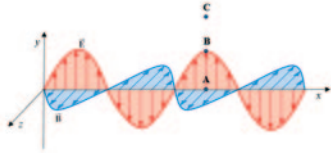
The data analysis was carried out through an iterative process of categorization of the open answers provided by students for each item, aimed at checking the consistence between the options selected and the underlying explanations. Indeed, as the items are not yet validated, this check will provide useful information to investigate if categories other than those identified in the response options emerge, or whether possible mix of existing categories emerge.

#### 5. – Results

5.1. *RQ1: Which relationships do students identify between the electromagnetic waves and their sources?.* – To answer the first research question we took into account the analysis of question No. 2, that is related to the identification of accelerated charges as the microscopic sources of electromagnetic waves. Our analysis of students' open answers show that the emerging categories are reduced to 3 —instead of the initial 5 options— as fig. 2 reports. Indeed, the only emerging difference is between the group of students stating that the motion of the source does not influence the time trend of the electromagnetic field (41.3%) and those that identify a casual relationship between these two factors (57.1%). Finally, a small group (1.6%) do not find enough information to answer the question.

**Question 1**

The figure shows an electromagnetic wave at instant  $t = 0$ . Both the electric and magnetic fields assume the same values in all points belonging to a plane parallel to the  $y$ - $z$  plane.



Given the period of the wave  $T$ , which of the following options represents the order of the intensities of the electric and magnetic fields in the points A, B, C at instant  $t = T$ ?

1.  $E_B > E_A = E_C$  and  $B_A = B_B = B_C$
2.  $E_A = E_B = E_C$  and  $B_A = B_B = B_C$
3.  $E_A > E_B > E_C$  and  $B_A = B_B = B_C$
4.  $E_A > E_B > E_C$  and  $B_A > B_B > B_C$
5. None of the previous alternatives.

Briefly explain your answer.

**Question 3**

Consider the following cases:

1. An electric field  $\vec{E}_1(t)$  propagates in a simple dielectric medium D with an oscillation frequency equal to  $f_1$ .
2. An electric field  $\vec{E}_2(t)$  propagates in a simple dielectric medium D with an oscillation frequency equal to  $f_2 > f_1$ .
3. An electric field propagates in empty space with an oscillation frequency equal to  $f_3 < f_1$ .

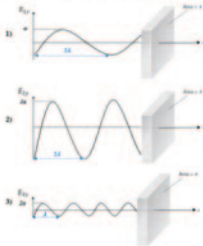
The three fields are generated in the same point O, having the same direction of propagation, and are detected in the point P. Given the time intervals  $t_i$  necessary for the fields  $\vec{E}_i$  to be detected in P, which of the following options will be verified?

1.  $t_1 = t_2 = t_3$
2.  $t_2 > t_1 > t_3$
3.  $t_2 < t_1 < t_3$
4.  $t_2 < t_1 < t_3$
5. None of the previous alternatives.

Briefly explain your answer.

**Question 5**

Consider the following 3 figures. They represent the components in the direction of propagation of three electric fields, which vary over time with a sinusoidal trend. They invest an area  $A = 1 \text{ m}^2$  lying in the  $y$ - $z$  plane. The amplitudes of the three fields are  $a$ ,  $3a$  and  $2a$  respectively, while the wavelengths are  $3\lambda$ ,  $2\lambda$  and  $\lambda$  respectively.



Given the amount of energy  $I_i$  that invests the surface A in 1 second, which of the following alternatives will be verified?

1.  $I_1 > I_2 > I_3$
2.  $I_2 > I_3 > I_1$
3.  $I_1 = I_2 = I_3$
4.  $I_2 > I_3 > I_1$
5. None of the previous alternatives.

Briefly explain your answer.

**Question 2**

Four students discuss the states of motion that a point electric charge has to assume with respect to an inertial reference frame S, to generate an electromagnetic wave detectable in all inertial frames.

Student A states: "An electric charge at rest in S is able of generating an electromagnetic wave".

Student B replies: "I disagree, because a charge at rest does not generate time-varying electric and magnetic fields. Thus, we need the charge to move in uniform motion."

Student C replies: "I disagree, because even in this case the generated fields are constant. Thus we need an accelerated charge".

Student D replies: "I disagree, because even a charge in uniform motion is able to generate time-varying fields, but not in all inertial frames. For this reason we need an accelerated charge".

Who do you agree with?

1. With student A.
2. With student B.
3. With student C.
4. With student D.
5. With none of the students.

Briefly explain your answer.

**Question 4**

An observer at rest in a reference frame S, equipped with a portable radio, receives a signal from a radio wave source. Consider the following three cases:

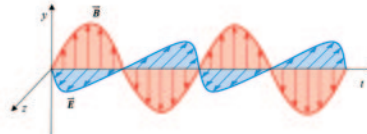
1. The source is at rest in S.
2. The source moves away from the observer with uniform motion with respect to S.
3. The source approaches the observer with uniformly accelerated motion with respect to S.

Given the propagation velocities  $v_i$  of the radio signal measured by the observer, which of the following alternatives will be verified?

1.  $v_1 = v_2 = v_3$
2.  $v_3 > v_2 > v_1$
3.  $v_1 > v_2 > v_3$
4. There is not enough information to answer.
5. None of the previous alternatives.

Briefly explain your answer.

**Question 6**



The figure illustrates the time trend of an electromagnetic wave. An observer is equipped with a portable radio which he can detect this signal with. In which direction should the antenna of the portable radio be oriented to get the best possible reception?

1. In the direction of the  $y$ -axis.
2. In the direction of the  $z$ -axis.
3. In the direction perpendicular to the  $y$ - $z$  plane.
4. The direction of best reception varies over time, so it is not possible to determine it.
5. None of the previous alternatives.

Briefly explain your answer.

Fig. 1. – Items of the questionnaire (English version).

5.2. RQ2: Which relationships do students identify between the characteristic quantities of electromagnetic waves (e.g., wavelength, frequency, velocity, intensity) in their propagation in free space or in matter?. – To answer the second research question we took into account the analysis of the questions Nos. 3,4,5, that are related to the

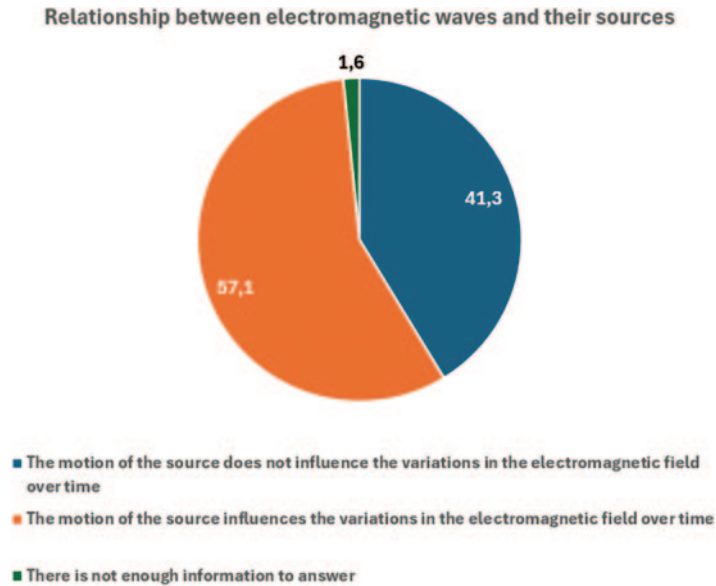


Fig. 2. – Categories emerging from the analysis of question No. 2 and their frequencies (%).

identification of the relationships between the quantities characterizing the propagation of electromagnetic waves. Figure 3 reports the emerging categories for all the questions. In all the three cases, four categories emerge, except for those named as “other”, where we included all the answers that cannot be grouped with the others and are not interesting for the research question.

The relative majority of students recognize that the propagation velocity of the electromagnetic field only depends on the medium, while it is independent of the oscillation frequency (38.5%) and of the relative speed between the motion and the observer (52.1%). On the other hand, almost all the other combinations of relationships are reported in the answers, with percentages that cannot be neglected, as they are reported with examples that show fundamental alternative conceptions of students. For instance, 27% of the sample state that the propagation velocity increases when the relative speed of the observer with respect to the source increase, while 46.3% of the participants identify a linear relationship between the propagation velocity and the wavelength or the frequency, reporting the different parts of the spectrum as having different orders of magnitude in the characteristics of the propagation.

**5.3. RQ3: How do students explain the interaction of electromagnetic waves with matter that allow their reception?.** – To answer the third research question we took into account the analysis of question No. 6, that is related to the identification of the mechanism of reception of electromagnetic waves through the Lorentz force. Figure 4 reports how only three final categories emerge from the analysis. While 8.1% of the sample state that there is not enough information to provide an answer, the main difference is given by the time trend of the direction of the signal’s best reception. Indeed, despite the large majority of students (64.5%) state that this direction coincides with that of polarization —namely, the direction along which the electric field oscillates— there is a not neglectable percentage of students (27.4%) considering that this direction changes

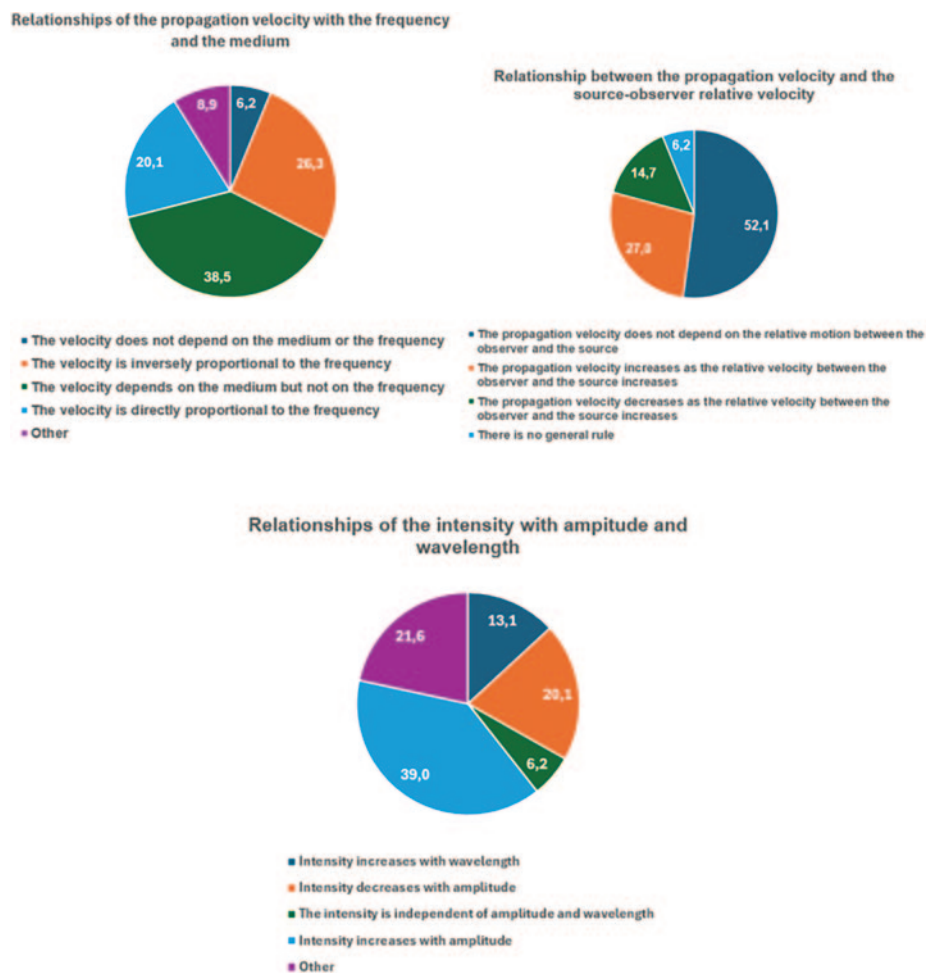


Fig. 3. – Categories emerging from the analysis of question Nos. 3,4,5 and their frequencies (%).

over time following the oscillation of the electric and magnetic fields. Their answers suggest that a misinterpretation of the representation provided in the question for the signal plays a role in their analysis of the reception. Furthermore, in the larger group of students, most of them provide an explanation of the phenomenon in terms of the force due to the electric field—that is parallel to the field itself—while making implicit or explicit the fact that the magnetic contribution may be neglected.

**5.4. RQ4: How do students interpret the profile of plane electromagnetic waves?.** – To answer the fourth research question we took into account the analysis of question No. 1, that is related to the interpretation of the profile of plane waves. This aspect is crucial, as we also noticed in the last paragraph, as students have to deal with a three-dimensional representation illustrating both the electric and magnetic field changing over time or propagating over space. Furthermore, much of the information about the symmetry of the wave is not made explicit in the representation. Another confusing factor is given by the fact that the fields' trend in time and space often appear to be the same—namely, sinusoidal—in the cases presented in school textbooks. This is the reason why we chose

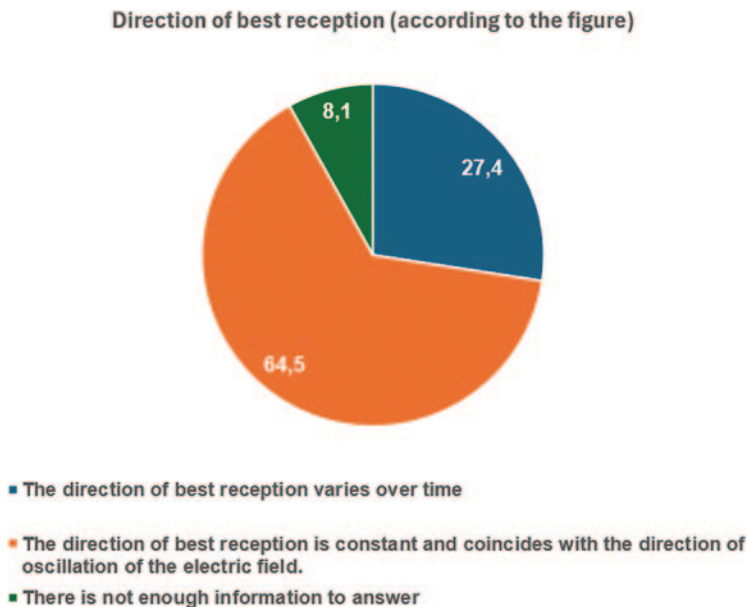


Fig. 4. – Categories emerging from the analysis of question Nos. 6 and their frequencies (%).

to include both these aspects in the same question, asking to determine the rank of the electric and magnetic fields' intensity in three points lying in the same plane, after a time interval equal to the period of the wave has passed after the snapshot reported in the illustration.

Figure 5 shows the four emerging categories from the analysis, even though there is a large group of students (32%) providing answers that cannot be grouped with the others. The relative majority of students recognize that both the fields assume the same values in all the three point. They provide the correct interpretation of the representation, also making explicit that the representation will not change after a period has passed. On the other hand, the other groups confirm some of the misconceptions that were also found in [4]: 11.6% of students state the electric field assume increasing intensity when moving to the propagation axis, but a similar percentage (9.7%) consider that the electric field is zero on that axis. Furthermore, the majority of students do not identify that the electric and magnetic fields are oscillating in phase, so they have to assume the same value in the same point. The interpretation of the answers are not made explicit by students, but we may refer to [4] to provide a more detailed explanation, as our discussion will suggest.

## 6. – Discussion

In this section we are going to discuss the main results we reported in the previous section, in order to answer the four research questions.

Among the students who identify a casual relationship between the motion of the source and the generation of the electromagnetic field, almost half of them (about 30% of the sample) identifies accelerated charges as sources of electromagnetic waves, but they do not distinguish the periodic waves from the general case of the time-dependent electromagnetic fields. Thus, the students may interpret them as a generic case in which the electric and magnetic fields vary over time. Following this interpretation, also a single

**Order of the intensities of the electric and magnetic fields in the points shown in the figure at the instant T**

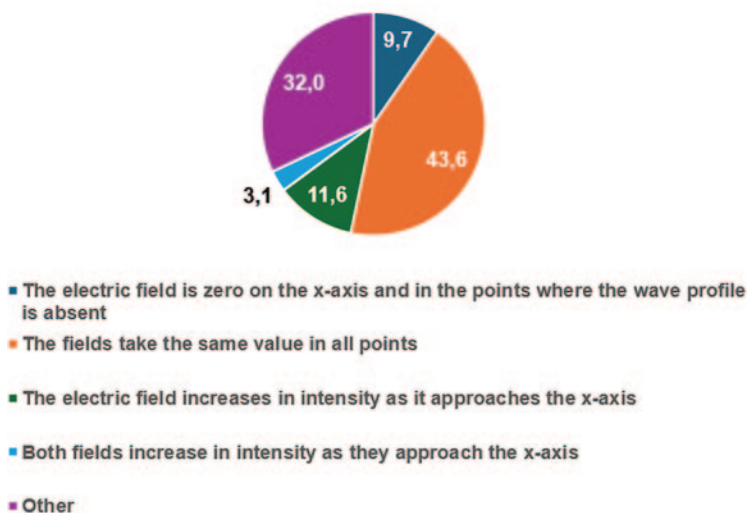


Fig. 5. – Categories emerging from the analysis of question No. 1 and their frequencies (%).

charge in uniform motion is able to generate non-static fields —even though not in all inertial reference frames. Furthermore, this aspect is usually not made explicit in the school textbooks, and it could produce a fundamental misinterpretation.

Coming to the analysis of the waves' propagation, less than 40% of students recognize the independence between the propagation velocity and the frequency of electromagnetic waves. Their answers suggests that the relationship providing the propagation velocity  $c = \lambda f$  — cause this misinterpretation, as it provides a linear link between these two quantities. To confirm this we report that the same alternative conception was found in the literature about mechanical waves [10], but there are many other aspects which the electromagnetic waves differ from the mechanical ones about. For instance, we can argue that the missing link in the traditional teaching between the wave equation and Maxwell's equations may lead to an incomplete understanding of the relationship between the velocity of the electromagnetic waves and the relative speed between the observer and the source. Indeed, although about half of the students characterize them as independent, they do not clarify the difference with other wave phenomena. Furthermore, another difference with mechanical waves concerns the independence of intensity from wavelength, that is identified by less than 40% of students.

About the reception of electromagnetic waves, we observed that almost 65% of students correctly identify the invariance over time of the interaction between a plane electromagnetic wave and free charges in matter by means of the Lorentz force: despite this, only half of them, provide a correct interpretation of this interaction.

Finally, we analyzed the students' interpretation of the electromagnetic waves' profile. We found that about 44% of the students correctly interpret the representation of the profile of a plane wave, while the other answers confirm the alternative conceptions found in the literature: for instance, the axis of propagation may be identified as the location of the source of the wave, or the fields may be implicitly considered as absent in the region above the wave profile.

## 7. – Conclusions

In this study we investigated how high school students deal with the interpretation of the main conceptual issues relating to electromagnetic waves. We focused the research in Italy, since in many other countries this topic is not included in the physics curriculum, or it is not mandatory. The final aim of the larger research is to develop a learning path about electromagnetic waves for this target population, and the results we got in this study provide useful information to understand which conceptual aspects have to be emphasized, according to the ERM framework.

A remarkable limitation of this study is represented by the fact that the instrument we used was basically developed by us, so it is not already validated. This is the reason why we chose to implement a mixed formulation of the questionnaire, both with multiple-choice questions and open answers to get insight of the students' interpretations. The analysis revealed that the final categories may be rearranged differently from the options presented in the items, but the validity of the instrument would need further steps to be confirmed with larger groups of students.

Finally, we got confirmation about the crucial role that representations plays about the interpretation of the phenomena involving electromagnetic waves. The Italian school textbooks usually report illustrations that are similar to that we used in question Nos. 1,5,6, except for some details—for instance, sometimes the arrows representing the fields under the wave profile are not reported. Interestingly, another step of our research about the textbooks revealed that no significant differences emerge between the kinds of representation used to illustrate different phenomena involving waves—for instance, interference, diffraction, polarization, etc. Thus, the wave fronts or fields' lines are almost absent in the chapters dealing with electromagnetic waves, while literature show how the transition between different kinds of representation would help to extract more information and in interpreting the phenomena in this context [6]. This is a crucial aspect we will take into account in developing the proposal for the learning path, together with the main learning difficulties emerged from these studies about the three phases of the waves' nature: generation, propagation and reception.

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