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# Scientific explanations in Greek upper secondary physics textbooks

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**ABSTRACT**

In this study, an analysis of the structure of scientific explanations included in physics textbooks of upper secondary schools in Greece was completed. In scientific explanations for specific phenomena found in the sample textbooks, the *explanandum* is a logical consequence of the *explanans*, which in all cases include at least one scientific law (and/or principle, model or rule) previously presented, as well as statements concerning a specific case or specific conditions. The same structure is also followed in most of the cases in which the textbook authors explain regularities (i.e. laws, rules) as consequences of one or more general law or principle of physics. Finally, a number of the physics laws and principles presented in textbooks are not deduced as consequences from other, more general laws, but they are formulated axiomatically or inductively derived and the authors argue for their validity. Since, as it was found, the scientific explanations presented in the textbooks used in the study have similar structures to the explanations in internationally known textbooks, the findings of the present work may be of interest not only to science educators in Greece, but also to the community of science educators in other countries.

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## Introduction

In this study, an analysis of the structure of scientific explanations included in physics textbooks of upper secondary schools in Greece was completed, and the findings were used to recommend methods for use in teaching scientific explanations, which methods have the potential to enhance students' ability to understand, construct, and apply scientific explanations.

In recent years, one of the main goals of science education is the active involvement of students in the practices of science. An intrinsic part of these practices is the construction of scientific explanations about physical phenomena, which is quite a demanding goal (Berland & Reiser, 2009; Brewer, Chinn, & Samarapungavan, 1998; Horwood, 1988; McNeill & Krajcik, 2009; McNeill 2011). To achieve this goal, students would need to be supported both by their teachers and by the content of their science textbooks. By using appropriate teaching strategies, teachers can engage students in scientific

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explanations (McNeill & Krajcik, 2008), and science textbooks can help students to become acquainted with scientific discourse (Koulaidis & Tsatsaroni, 1996), an integral part of which are the explanations given about various phenomena. Thus, since the authors of science textbooks attempt to transform scientific knowledge into school knowledge, it would be interesting to trace and analyse the way in which the authors structured scientific explanations to explain phenomena.

The aim of the present work is the analysis of the structure of scientific explanations included in physics textbooks of upper secondary schools in Greece. The possible implications of the empirical findings for the teaching of physics are discussed.

It should be noted that well-known textbooks (e.g. Serway, 1990; Young, 1992) that have been translated into Greek are among the sources in the sample (G-TBs). In fact, these sources have been recommended to students in introductory physics courses in the Greek universities for many years. We thought that it would be useful to study the structure of scientific explanations in these internationally known university textbooks (U-TBs) and trace whether the authors of the G-TBs follow similar reasoning in constructing scientific explanations as do the authors of U-TBs. In this way, we will have an indication that the way the authors of the G-TBs construct scientific explanations is not confined to the science education community defined by the culture of a small country, but in fact reflects a general practice developed by the science education community internationally. Thus, the findings of this work might be of interest to science education researchers. For this reason, four well-known university textbooks (U-TBs) (Halliday, Resnick, & Walker, 2008; Ohanian, 1989; Serway, 1990; Young, 1992), and eight chosen cases of scientific explanations were compared with the corresponding cases found in G-TBs.

## Models of scientific explanations

In everyday life, whenever we use the term 'explanation', we mean an answer to the question 'why' something (e.g. a fact) has happened or, in other words, what the cause of the fact is. In contrast, in science the term 'explanation' is used in a broader sense because scientific research goes beyond 'a mere description of its subject matter by providing an explanation of the phenomena it investigates' (Hempel & Oppenheim, 1948). For many philosophers and scientists 'it is not enough for scientific theories to describe the world as it is, they should also tell us why it is that way' (Ladyman, 2002, p. 198). However, the literature in the field of the philosophy of science suggests that no single definition of explanation can account for the range of information that can satisfy a request for an 'explanation' (Berland & Reiser, 2009). According to Salmon (1992, pp. 8–9) we can say that 'scientific explanation' is

> … an attempt to render understandable or intelligible some particular event (such as the 1986 accident at the Chernobyl nuclear facility) or some general fact (such as the copper colour of the moon during total eclipse) by appealing to other particular and/or general facts drawn from one or more branches of empirical science.

Salmon (1992) notes that the above attempt to somehow define the term should be considered as an indication of what we mean by the term 'scientific explanation' and not as a strict definition, because terms such as 'understandable' and 'intelligible' are as much in need of clarification as is the term 'explanation'.

A scientific explanation consists of two parts: The *explanandum* and the *explanans*. The *explanandum* is the 'fact' to be explained. This 'fact' may be a particular fact, such as the collapse of a specific bridge, or a general fact, such as the Law of Conservation of Linear Momentum. The *explanans* is that which does the explaining. It consists 'of whatever facts', particular and/or general, are used to explain the *explanandum* (Salmon, 1992, p. 10). In 1948, Hempel and Oppenheim published the essay 'Studies in the logic of explanation', in which they formulated 'with great precision' one pattern of scientific explanation that is 'central to all discussions of the subject' (Salmon, 1992, p.14). It came later to be known as the 'deductive–nomological' (D–N) model of scientific explanation (Salmon, 1989, p. 3) or the 'covering law' model (Braaten & Windschitl, 2011). An explanation of this type explains by subsuming its *explanandum* under a general law. The *explanandum* must be a logical consequence of the *explanans* which contain at least one general law (Hempel, 2002, p. 47; Salmon, 1992, pp. 14–15).

This model explains both particular events and general regularities by deduction from more comprehensive universal generalisations. For example, Kepler's Laws hold as they are special consequences of the Newtonian Laws of Motion and Gravitation (Hempel, 2002, p. 47; Salmon, 1989, pp. 9–10).

At this point, it would be useful for the discussion which follows to mention that the D–N pattern can also be used for the prediction of a phenomenon. Explanations and predictions have exactly the same structure; the only difference between them is 'that, in the case of an explanation we already know that the conclusion of the argument is true, whereas in the case of a prediction the conclusion is unknown' (Ladyman, 2002, p. 205). Salmon (1992, p. 22) refers to a characteristic example:

> … From the present positions of the earth, moon, and sun, using laws of celestial mechanics, astronomers can predict a future total eclipse of the sun. After the eclipse has occurred, the very same data, laws, and calculations provide a legitimate D-N explanation of the eclipse … .

In addition to the D–N model presented above, a second type of scientific explanation has been proposed. Since statistical laws play an important role in virtually every branch of contemporary science (Salmon, 1992, p. 23), Hempel proposed a different type of scientific explanation, the 'probabilistic explanation'. In this type of explanation, some statistical laws are included in the *explanans*, and the '*explanans* does not logically imply the *explanandum*, but only confers a high likelihood upon it' (Hempel, 1965, 2002).

We will briefly mention three additional types of explanation which are products of a philosophical discussion about the aforementioned two models: the 'causal explanation', the 'pragmatic view of explanation', and the 'explanatory unification view of scientific explanation' (Braaten & Windschitl, 2011).

In 'causal explanation', emphasis is given to causation as a key attribute of explanatory power (Braaten & Windschitl, 2011). According to Ladyman (2002, p. 199) 'It is widely thought that functional explanation is only legitimate when a plausible casual mechanism is available, even if only in outline'. Salmon claims that 'we can explain effects by citing their causes', and states that in cases where two effects of a common cause are correlated with one another, we cannot explain the one effect by means of the other. Along these lines, in the above example of a solar eclipse, Salmon notes that by using the same data to predict the eclipse, 'astronomers can retrodict the previous occurrence of a solar eclipse', but that it is not sufficient to invoke later conditions to explain earlier facts (Salmon, 1992, pp. 21–23).

For philosophers who support a 'pragmatic view of explanation', 'the context surrounding the request for an explanation determines whether or not a response "counts" as a satisfactory explanation' (Braaten & Windschitl, 2011). Van Fraassen (1980) states that there are two factors which play an important role in a satisfactory explanation:

(1) The clarification of the question seeking explanation. For example, for the question 'Why does the Moon orbit the Earth?' the emphasis can be placed on the Moon (i.e. Why 'the Moon' and not another body?), on the orbit (i.e. Why 'orbit' and not another movement?), or on the Earth (i.e. Why 'the Earth' and not another body?).
(2) The knowledge and intellectual level of the person requesting the explanation. For example, an explanation that makes reference to the non-Euclidean structure of space is inappropriate for schoolchildren (Salmon, 1992, pp. 36–37).

Finally, according to the 'explanatory unification view of scientific explanation', the value of an explanation lies in fitting things into a universal pattern, or a pattern that covers major segments of the universe (Salmon, 1992). Indeed, the unifying theories of Newton and Maxwell are excellent examples of the fact that a large number of specific regularities can be unified into one theory with a small number of assumptions or postulates. This view of scientific explanation was elaborated by Friedman (1974) and later by Kitcher (1989). They assert that our understanding of the physical world is increased as the number of independently required assumptions is decreased.

## The 'scientific explanation' in science education

In science education, guiding students to construct scientific explanations is considered to be very important because through this process, students are engaged in an authentic scientific practice (Berland & Reiser, 2009; Horwood, 1988; McNeill & Krajcik, 2008). As a result, they can increase not only their ability to reason, but also their understanding of the content of science (McNeill & Krajcik, 2007, 2009).

In science education, the term 'explanation' is often used in a broader sense than in science, and this is a topic of discussion in the science education community. According to Braaten and Windschitl (2011), the common uses of 'explanation' in science education are the following:

(1) Explanation as explication. Students are asked to provide clarification for the meaning of a term, or 'explication of reasoning about a problem'.
(2) Explanation as causation. Students are asked to explain an observable effect by emphasising cause–effect relationships.
(3) Explanation as justification. Students are asked to construct an argument based on evidence to support their claim. It is worth mentioning that selecting the appropriate 'evidence' to support their explanation is a difficult process for students (McNeill & Krajcik, 2007).

Osborne and Patterson (2011) state that the terms 'explanation' and 'argument' are frequently used in science education without a necessary distinction. A defining feature of the explanation is that the *explanadum* is not in doubt, and 'facts derived either from observables, laws, or theories are provided as the premises of the reasoning that makes plain what is being explained'. In an argument, however, there is the goal of justifying a claim: the coherence of an explanation can be judged by arguments which support it (Thagard, 1989). According to Osborne and Patterson (2011)

> … the essential difference between the two linguistic acts – argument and explanation – lies in their epistemic function. One, explanation, seeks to make plain, to generate that sense of increased understanding, whereas the other, argument, seeks to justify a claim to knowledge or to persuade …

Along these lines, Brigandt (2016) indicates the differences between explanation and evidence-based argumentation, noting that the aim of a scientific explanation is 'to provide understanding of why a phenomenon occurs', whereas the aim of an argument 'is to convince someone that a claim is true'. According to the same author, standards of explanatory adequacy 'correspond to what counts as a good explanation in a science classroom, whereas a focus on evidence-based argumentation can obscure such standards of what makes an explanation explanatory'.

Berland and McNeill (2012) agree that argumentation and explanation are distinct scientific practices that are often treated as one in science education, but they question what 'this implies about the distinctions made for students' in secondary education classrooms. According to Berland and Reiser (2009) the practices of explanation and argumentation are complementary, since explanations are developed through argumentation. Scientific explanations 'can provide a product around which the argumentation can occur', and argumentation creates a context in which 'robust explanations' are valued. Also, McNeill and Krajcik (2007) developed an instructional model for evidence-based scientific explanations, and they use it as a tool for 'both classroom practice and research'. This model uses an adapted version of Toulmin's (1958) model of argumentation, and takes into consideration the research on students' construction of scientific explanations and arguments. McNeill and Krajcik (2009) 'combine the goals of explaining scientific phenomena and constructing individual arguments' because, as they state, they refer to this complex practice as 'scientific explanation' since the 'phrase aligns with the national and state standards'.

As previously mentioned, the structure of a scientific explanation can be the same as that of a prediction (Salmon, 1992, p. 22). For example, a physicist who has never seen a performance of a skater could be asked what will be happen if she folds in her arms and legs close to her body. The prediction may be that the angular velocity will increase, and the argumentation will be identical with the one that another physicist, who actually watches the performance of the skater, has made to explain the phenomenon. This fact may explain the reason why in science education, the term 'scientific explanation' is also used in cases of questions or predictions, e.g. 'Write a scientific explanation that states whether a chemical reaction occurred when … ' (McNeill & Krajcik, 2009). That is to say, in science education, the term 'scientific explanation' is used to refer not only to the explanation of an undoubted fact, but also in cases in which students have to first set out a claim and then justify it.

## The study

The research consisted of two phases: the study of the explanations traced in the G-TBs, and the study of a number of chosen examples of explanations of the U-TBs and the comparison of the way the authors of G-TBs and U-TBs construct these explanations.

### The study of explanations traced in G-TBs

To conduct this phase of the study, based on the literature referred to in the two previous sections, we took into consideration the following:

(i) The aim of familiarising students with the scientific way of thinking concerns all future world citizens (Braaten & Windschitl, 2011); thus we investigated physics textbooks that were addressed to all students, and not only to those who planned to pursue a career in the hard sciences (e.g. physicists, biologists, etc.).
(ii) We studied the explanations of specific phenomena and of regularities (i.e. physics laws, principles and rules) which are considered 'undoubted' according to the reasoning of Osborne and Patterson (2011).
(iii) For the analysis of the structure of the detected explanations, the schema of *explanandum–explanans* was followed, and the detected explanations were categorised according to the type of *explanandum* (e.g. specific phenomenon–regularity) and reasoning (e.g. logical derivation–induction) (Salmon, 1992).
(iv) The school scientific knowledge involved in each type of explanation was recorded. The terminology we used for this content knowledge (e.g. theory, law, rule) is the one explicitly referred to in the textbooks. If a specific terminology was not referred to, we adopted the terms used in teaching related to the nature of science: A 'law' is a descriptive generalisation about how some aspects of the natural world behaves under stated circumstances whereas a 'theory' in science is a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses (*Teaching about evolution and the nature of science*, The National Academies Press, 1998, p. 5). Finally, in science, a 'rule' is a statement which specialises a scientific law.

The research sample consisted of three physics textbooks (listed in Appendix) used in Greek upper secondary education (grades 10–12). The content of these textbooks corresponds to the mandatory Physics curriculum taught to students in each grade of upper secondary education. (It should be noted that in Greece, for every school subject and for each grade level, only one textbook is officially approved by the Ministry of Education (i.e. one Physics book for grade 10, one for grade 11, and one for grade 12) and is distributed free to all students.)

The scientific explanations used by the textbook authors in each of the sample books were traced and analysed according to the following procedure:

- The first step was to detect the instances in the texts where the authors 'explain' not only specific phenomena, but also regularities (i.e. physics laws, principles, and rules). For the detection of the appropriate extracts, the main criterion was that the fact to be explained is considered to be undoubted and for which a rationale had been developed to explain it. The *explanandum* was not a claim that needs justification, but rather it 'is generally presumed to be true' (Osborne & Patterson, 2011). Thus, the following cases were excluded:

- Predictions of physical phenomena or situations.
- Arguments for the introduction of a fundamental or a derived physical quantity. For example, the argumentation for the definition of the average velocity as the displacement divided by the corresponding time interval.
- Formulas that are derived directly from definitions of physical quantities or a combination of definitions. For example, the definitions of electric current ($i = q/t$) and of potential difference ($V = w/q$) lead to the formula of electrical energy ($E = w = Vit$).

- In the second step, once each explanation had been detected, three aspects of it were recorded: (i) the *explanandum*, (ii) the statements that form the *explanans*, and (iii) the reasoning that was developed.



Moreover in the second step, to clearly present the structure of each explanation found, we rephrased the corresponding text by removing those extra details, descriptions, and clarifications whose main purpose was to make the text more attractive to students and/or to help them better understand the particular item.

Following is an example of the way the data was collected and analysed.

First, we used a recorded excerpt of the text that referred to the explanation which describes the model of ideal gas, and to explain that a quantity of a gas in a container exerts force on every wall of the container. Specifically, the translated text (from Greek to English) is:

(1) In the case of gas, we consider the molecules as solid balls that move randomly in all directions. The distances between molecules are large compared with their dimensions; thus, we conclude that forces are exerted on molecules only during the collisions between them or with the walls of the vessel in which they are contained.
(2) Consequently, they (i.e. the molecules) have only kinetic energy, and force is required in order to change their velocity.
(There is a figure in the textbook that represents a vertical cylindrical container containing gas, and it is closed at the top with a movable, heavy piston which is balanced.)
(3) How can we explain the balance of the piston despite the empty space between molecules?
(4) Consider a molecule that moves directly to the surface of the piston and is then deflected in the opposite direction.
(There is a figure in the textbook that represents the vector of the force $F$ exerted on the molecule by the piston during the collision, and the opposite force $F'$ of the molecule to the piston.)
(5) The force $F$ is the force that causes the change of the momentum of the molecule,
(6) and thus an equal and opposite force $F'$ exerted by the molecule to the piston.
(7) If we consider the fact that a very small amount of gas (i.e. the amount contained in a space which is the size of the head of a pin) contains $10^{17}$ molecules (i.e. 100,000 trillion), the number of molecules in the container is unimaginably large. The molecules within the container collide with each other and also with the walls of the container.

As a result, at any given moment, some of the huge group of molecules collides with the walls of the container.

(8) The resultant force of all the forces acting on the piston by the molecules is the one that balances the piston's weight …

(9) Gases have the capacity to exert force on every wall of the vessel within which it is contained.

Second, the *explanandum*, i.e. the statements that form the *explanans* and the reasoning underlying them, were identified and concisely rephrased.

Specifically, as can be seen in Table 2:

- The *explanandum* corresponds to excerpt (9) above.
- The statement M1 is concluded from excerpts (1) and (7).
- The statement S1 is formulated considering excerpts (2) and (4).
- The laws L1 and L2 correspond to excerpts (5) and (6).
- Excerpts (3) and (8) are helpful for the reasoning process.

### The study of examples of explanations found in the U-TBs

After analysing the explanations in the G-TBs, eight scientific explanations found in the G-TBs were chosen according to the criteria presented in the 'Findings' section below and in the subsection referring to U-TBs. The next step was to investigate the manner in which these eight explanations were presented in the four U-TBs (referred to in the last paragraph of the 'Introduction'). For the analysis of the structure of explanations in the U-TBs, the same process described above for the analysis of the G-TBs was followed. Furthermore, we investigated whether the authors of the four U-TBs used similar reasoning to construct explanations, and then compared the U-TB explanations with the corresponding G-TB explanations to find the extent to which they had the same structure.

## Findings

### The study of explanations traced in G-TBs

Sixty-four cases in which the textbook authors explain an 'undoubted fact' were detected and analysed. These cases were classified into three categories: K1, K2, and K3, as follows.

- K1: Explanation of a particular fact (29/64).
- K2: Explanation of a regularity (e.g. a law or rule) by deduction from more general physics laws or principles (23/64).
- K3: Reason for the validity of a law which is not derived from a more general one (12/64).

As has already been stated above, for the categorisation of the detected explanations, the type of *explanandum* (specific phenomenon–regularity) and reasoning (e.g. logical derivation–induction) were taken into consideration. The three categories K1, K2, K3 are the result of such an analysis, and the findings for each category are presented analytically below.

*Category K1.* In the cases within this category, the *explanandum* refers to a particular phenomenon/event (e.g. a skater spinning, the recoil of a gun, etc.) or the function of a particular piece of equipment (e.g. a potentiometer). The word 'particular' can refer to a specific case (e.g. a gun with specific mass) or to a case in general (e.g. the recoil of any gun). The *explanans* are formed by statements concerning a specific case or specific conditions (e.g. 'no external forces act on the system' or 'a series combination of two resistors'), as well as school knowledge that has already been taught. More specifically, 'school knowledge' refers to:

- Definitions (e.g. "the acceleration defined as the ratio Δυ/Δt")
- Models (e.g. ideal gas, Bohr's model of the atom)
- General regularities, such as laws (e.g. Newton's Law of Gravitation), principles (e.g. conservation of energy), rules (e.g. Kirchhoff's rules), mathematical/geometrical propositions (e.g. Pythagorean Theorem), and general physical phenomena (e.g. the explanation of a rainbow as a consequence of the phenomenon of dispersion).

Furthermore, the reasoning presented by the textbook authors contains justifications of the statements that hold in the specific case (e.g. justification of why a physical system is considered as isolated). The two examples provided (Tables 1 and 2) illustrate this.

In the above cases, elements of scientific knowledge (e.g. laws, principles, rules, or models) are included in the *explanans*. This knowledge is presented in Table 3. It should be noted that the thematic topics 'gasses', 'electric charge', and 'radiation' mainly used



**Table 1.** Category K1: explanation of a particular event (the recoil of a cannon).

| | |
|---|---|
| *Explanandum* | When a cannon fires, it recoils in the opposite direction from the direction of the projectile. |
| *Explanans* | Definition (D1): The momentum of an object is a vector quantity, and it is defined as the product of the mass and the velocity of the object. |
| | Law (L1): The total momentum of an isolated system of objects is conserved. |
| | Specific case (S1): The system cannon-projectile is isolated because the net external force is considered zero (weight and normal force are opposite vectors). |
| | Specific case (S2): The cannon was initially at rest, i.e. the initial momentum of the system is zero. |
| | Specific case (S3): Immediately after being fired, the projectile gains velocity (and hence momentum) and moves to the right. |
| Reasoning | S1 ensures that the L1 can be applied in the specific case. S2 in combination with L1 lead to the conclusion that after being fired, the cannon gains opposite momentum from the momentum of the projectile, that is (taking into consideration S3) the cannon recoils to the left. |

**Table 2.** Category K1: explanation of a particular event (gas exerts forces on the walls of its container).

| | |
|---|---|
| *Explanandum* | Gas exerts force on every wall of its container. |
| *Explanans* | Model (ideal gas) (M1): Gas is composed of a huge number of molecules that move randomly and undergo elastic collisions with the walls of the container. |
| | Specific case (S1): When a molecule strikes and rebounds from a wall of the container, the direction of the velocity changes, and hence its momentum (vector quantity) changes. |
| | Law (L1): The wall exerts force on the molecule equal to the rate of change of the momentum (Newton's Second Law). |
| | Law (L2): If the wall exerts force on the molecule, then the molecule exerts opposite force on the wall (Newton's Third Law). |
| Reasoning | Taking into consideration M1, a huge number of molecular collisions with the walls of the container should happen per second. Thus, taking into consideration L1 and L2, there must be a huge number of forces exerted by the molecules on every wall. The result is that at the macroscopic level, the gas exerts force to every wall. |

**Table 3.** Scientific knowledge used for the explanation of particular events.

| Topics | Scientific knowledge used for the explanation | Number of explanations |
|---|---|---|
| Mechanics | Newton Laws (First and/or Second and/or Third) | 4 |
| | Conservation of momentum | 2 |
| | 'Laws' of friction and centripetal force | 1 |
| Gasses | Model of ideal gas (and Second, Third Newton Laws) | 1 |
| Electric force/field | Atomic model/conservation of electric charge | 3 |
| Electric current | Kirchhoff's rules (First and Second) and Ohm's Law | 4 |
| Magnetism | Magnetic domain theory | 2 |
| Light-radiation | Bohr model of the atom | 3 |
| | Laws of phenomena (reflection–refraction–dispersion) | 4 |
| | Absorption of radiation | 1 |
| | Work-energy theorem and energy of photons | 1 |
| | Joule's Law and energy states | 1 |
| Nuclear physics | Coulomb's Law and strong nuclear force | 1 |
| | Law of radioactive decay | 1 |

'models' for the explanations, whereas this does not happen in the thematic topic 'mechanics'. Also, when five of the laws or rules listed in Table 3 were referred to in the textbooks for the first time, they were explained as consequences of other, more general laws (K2 category). Specifically, the conservation of momentum is explained from Newton's Third Law, Kirchhoff's (two) rules from the principles of conservation of energy and of electric charge, the work-energy theorem as a consequence of the conversation of energy, and finally Joule's Law from the conversation of energy and Ohm's Law.

*Category K2.* Each *explanandum* in this category is a regularity (e.g. a law or rule or a relationship) that is derived from general physics laws or principles. For example, conservation of momentum is a consequence of Newton's Third Law (action–reaction). The general regularities used in each topic are presented in Table 4.

The structure of the *explanans* and the reasoning provided by the textbook authors for the Category K2 cases are similar to those of Category K1. Two typical examples are presented in Tables 5 and 6.

It should be mentioned that in Categories K1 and K2, four cases are included (i.e. two of the kinetic theory of gases and two of radioactive decay) in which the laws used in the *explanans* are statistical laws. Despite this, the structure of the explanations was the same as in the other cases of Categories K1 and K2. For example, the result of a radioactive dating is considered accurate without discussion of the statistical nature of the corresponding law.

**Table 4.** Scientific knowledge used to explain regularities.

| Topic | Scientific knowledge used for the explanation of regularities | Number of explanations |
|---|---|---|
| Mechanics | Laws (Newton Laws) | 6 |
| | Principles – Theorems of Physics (Principle of Independence of Motion, Work-energy theorem) | 2 |
| | Relationships between physics quantities and Mathematical propositions (Pythagorean Theorem) | 6 |
| Gasses | Model of ideal gas and Newton's Second Laws | 1 |
| Electromagnetism | Principles (conservation of energy/electric charge) and/or Laws (Laplace and Biot–Savart, Ohm) | 4 |
| | Model (Free electron model) | 3 |
| Nuclear physics | Law of radioactive decay | 1 |

**Table 5.** Category K2: explanation of a law based on a general physics law (conservation of momentum).

| | |
|---|---|
| *Explanandum* | The total momentum of an isolated system of objects is conserved. |
| *Explanans* | Specific case (S1): An isolated system of objects A, B is under consideration (the net external force is zero). |
| | Law (L1): The net force that is exerted on a system of objects is equal to the rate of the momentum change of the system (Newton's Second Law). |
| | Law (L2): If the object A exerts a force on the object B, then the object B exerts an equal force, oppositely directed, on the object A (Newton's Third Law). |
| Reasoning | From S1, it can be deduced that the only forces that are exerted on A and B are those from the interaction between them, the result of which (according to L2) is zero. In that case, from L1 it can also be deduced that the rate of change of the momentum of the system is zero. Thus, the total momentum of the system is constant/is conserved. |

**Table 6.** Category K2: explanation of a physics rule based on a general physics law (Kirchhoff's First Rule).

| | |
|---|---|
| *Explanandum* | The sum of the electric currents entering any junction equals the sum of the currents leaving that junction. |
| *Explanans* | Specific case (S1): A junction in an electric circuit is under consideration. |
| | Definition (D1): An electric current is equal to the ratio of the charge that passes through a cross-sectional area of a wire to the corresponding time interval. |
| | Principal (P1): The total electric charge of an electrically isolated system is always conserved (electric charge conservation). |
| Reasoning | From P1, it can be deduced that per second, the total charge entering the junction equals the total charge leaving the junction (i.e. a charge cannot build up or disappear at any point of the circuit). From D1, it can be deduced that the charge per second is the current, thus the sum of the currents entering the junction equals the sum of the currents leaving the junction. |

*Category K3.* As previously mentioned, 12 (out of 64) cases were detected in which the authors argue for the validity of physics laws that are not deduced from more general laws. Two main cases of their relative argumentation for the validity of the laws were recorded.

(a) *The law is axiomatically formulated*

The law is axiomatically formulated, and in order to prove the validity of the law, the authors

(i) appeal to the 'authority' of science/scientists, such as the authority of the scientist who discovered the law, the confirmation of the law by the scientific community, and the fact that there have not been any cases of the falsification of the law to date.
A characteristic example is the presentation of Newton's Law of Gravitation. The authors present the formula, and they appeal to the authority of Newton and to the fact that the law has been confirmed by the scientific community.
(ii) present some specific cases or experiments that verify the validity of the law.
A characteristic example is the presentation of Newton's Third Law (action–reaction). The authors formulate the law and then present experiments using dynamometers for the verification of the law.

(b) *The law is inductively derived*

The law is inductively derived from the generalisation of the result of one or more experiments. For example, the textbook authors present an experiment in which the

**Table 7.** Category K3: presentation of fundamental laws.

| Presentation of the law | Topic | Number of cases |
|---|---|---|
| The law is axiomatically formulated and the authors appealing to the 'authority' of science/scientists | *Mechanics* (Law of Gravitation-parallelogram rule) | 2 |
| | *Electromagnetism* (Coulomb's Law) | 1 |
| | *Nuclear Physics* (Law of Radioactive Decay) | 1 |
| The law is axiomatically formulated and the authors present an experiment for verification | *Mechanics* (Newton's Third Law – addition of forces in one dimension) | 2 |
| | *Light* (Law of Reflection) | 1 |
| The law is inductively derived from the generalisation of the result of an experiment | *Mechanics* (Newton's First and Second Laws – Independence of Motion) | 3 |
| | *Electromagnetism* (Law of Laplace –properties of electric charges) | 2 |

acceleration of a body is measured when the net force increases two or three times. The acceleration also increases two or three times, and the authors generalise the result: 'The acceleration of a body is proportional to the force that is exerted on it'. Also, in another case, the authors present a multiflash photograph which shows two golf balls released simultaneously from the same point. The one is released without initial velocity, and the other is projected horizontally. Based on the study of the photograph, the authors deduce the 'Principle of Independence of Motion'.

In other cases, a law is inductively derived not only by generalising the result of a real experiment, but also of a thought experiment. For example, the authors perform a thought experiment by considering a body that is projected so that it moves on a horizontal floor and stops because of friction after having travelled some distance. They repeat the thought experiment by eliminating the friction so that the body moves with constant velocity and never stops. Then, the authors generalise the result of the thought experiment and formulate the Law of Inertia.

The K3 category cases are briefly presented in Table 7. It should be noted that cases in which the laws are referred to as 'a given' without any argument are not recorded.

It is worth noting that in the cases of the K3 category, in contrast to K2, authors do not use a physics 'theory' to explain a regularity. Also, the laws which occur in Category K3 cases are included in the *explanans* of the explanations of K2 category cases. In other words, authors argue for the validity of general laws which they then use to explain specific phenomena or regularities. Earman and Salmon (1992, p. 42), in the introduction to their work 'Confirmation of Scientific Hypothesis', state that 'If we are to be able to provide an explanation of any fact, particular or general, we must be able to establish the statements that constitute its explanans … '. Thus, we can characterise the cases in the K3 category as arguments for the validity of a physics principle or law and not as scientific explanations.

### *The study of examples of explanations found in the U-TBs*

Eight examples of scientific explanations found in G-TBs were chosen, and the way these explanations were presented in the four U-TBs (Halliday et al., 2008; Ohanian, 1989; Serway, 1990; Young, 1992; translated into Greek) was studied. The eight explanations were chosen so that they would correspond to the K1, K2, and K3 categories of explanations, which are the examples presented in the 'Findings' section (relating to the G-TBs). Specifically:

- From the Category K1, two examples were selected from different chapters. These are not specific examples found only in one or two textbook, but common examples included in all the textbooks studied. The chosen examples are 'The recoil of a cannon' and 'Gas exerts force on every wall of its container'.
- From the Category K2, two regularities were selected from different chapters. These regularities are basic in teaching physics, and thus they are referred to in all of the textbooks. Specifically, the 'Conservation of Momentum' and 'Kirchhoff's First Rule' were selected.
- From the Category K3, four examples of laws were selected. These laws cover all of the cases of the Category K3 and they constitute the pillars of a physics theory, i.e. the theory of the Newtonian mechanics. Specifically, Newton's First, Second, and Third Laws and the Law of Gravitation were chosen.

The results are presented below.

(1) The recoil of a cannon (K1 category)

The authors of the four U-TBs follow identical reasoning; the only difference is in the type of the weapon. The structure of their explanations is the same as the structure found in the G-TB (Table 1).

(2) Gas exerts force on every wall of its container (K1 category)

The structure of the explanations is the same in all the U-TBs analysed. The same statements are used (*explanans*), and only small differences in the mathematical processing occur in one of them (Young, 1992) because of the type of container used. Specifically, the example in this latter U-TB considers an amount of an ideal gas in a cylindrical area, while in the other U-TBs, the gas is contained in a cube. The reasoning of the explanation identified in the respective G-TB (Table 2) is the same as that of the U-TBs, except for the level of the mathematical formalism.

(3) Conservation of momentum (K2 category)

The explanations used by the U-TB authors are identical to those presented in Table 5 for the corresponding G-TB. However, one of the U-TBs (Halliday et al., 2008) considers the case of a physical system which is comprised of a large number of particles rather than a system with only two particles, as occurs in the other three books.

(4) Kirchhoff's First Rule (K2 category)

The explanations in the four U-TBs have exactly the same structure as the explanation that was found in the corresponding G-TB (Table 6). Small differences were noticed only in the presentation of this rule. Specifically, in three of the four U-TBs, the rule is formulated first, and then it is explained as a consequence of the principle of electric charge conservation, while in the other U-TB (Halliday et al., 2008), the authors started from electric charge conservation to conclude and formulate the rule. Also, in one of the U-TBs (Serway, 1990), the author additionally uses analogies with pipes of water.

(5) Newton's Law of Gravitation (K3 category)

As in the G-TBs analysed, the authors of the four U-TBs axiomatically formulate the specific law. In three of them, some historical data are mentioned and the authority of Newton is invoked. Also, the authors report the Cavendish's experiment for the verification of the validity of the law.

(6) Newton's First Law – The Law of Inertia (K3 category)

In one of the U-TBs (Young, 1992) the law is axiomatically formulated, then argumentation is developed to reveal the reasons why the law seems to be in contradiction with everyday experience, and finally a thought experiment is 'performed' to confirm the law. In Ohanian's (1989) book, real experiments are performed (e.g. by using an air table) and the law is formulated by generalising the results of these experiments. In the other two U-TBs (as in the G-TBs analysed), a thought experiment is 'performed', and the law is formulated by generalising the result of this thought experiment. Additionally, in all the books (except Young, 1992), historical data and scientific views from the era of Galileo are referred to, and the authors appeal to the authority of Newton and Galileo.

(7) Newton's Second Law – $\boldsymbol{F} = m\boldsymbol{a}$ (K3 category)

In one of the four U-TBs (Ohanian, 1989), the law is axiomatically formulated, and then some experiments are described for verification. In the other three U-TBs (as in the G-TBs analysed), specific experiments are described, and the law is formulated by generalising the results of these experiments.

(8) Newton's Third Law – action–reaction (K3 category)

The presentation of the specific law in the four U-TBs is similar to that of the corresponding G-TB. That is, the law is axiomatically formulated and then experiments are referred to for verification and application.

It should be noted that the specific editions of the studied U-TBs are those which have been translated into Greek and are cited as references by the authors of the G-TBs. A comparison with more recent editions of the U-TBs (Ohanian & Markert 2007; Serway & Jewett, 2008; Young & Freedman, 2008) did not reveal any significant changes in the way the explanations in question were constructed.

## Conclusions – discussion

There is a strong indication that in order students develop the ability to understand and construct a scientific explanation, they need to be acquainted with various aspects of the nature of science. Furthermore, such an ability is one of the key points of scientific literacy and can be considered as a valuable life skill, since it would enable our future world citizens to actively participate in the public discourse about science matters and socioscientific issues. In the science education literature, a number of studies referring to students' scientific explanations can be traced (some of them have been discussed in section 'The "scientific explanations" in science education' above). In this work, an attempt has been made to analyse the explanations found in science textbooks, which constitute a powerful dimension in the educational process, and possible implications to be discussed. The findings revealed that the authors of both the U-TBs and G-TBs to a great extent follow similar reasoning in constructing explanations of phenomena and of regularities. The findings of a study on how the forms of scientific explanations in Greek school textbooks relate to forms of explanations used in internationally known university textbooks could be an indication of possible correlation between the explanations of school textbooks and university textbooks, but they cannot be generalised. Also, from these findings, no general conclusions can be drawn about the structure of scientific explanations in school textbooks used internationally. However, the findings do provide an indication that the way the authors of the G-TBs construct scientific explanations reflects a general practice developed by the science education community internationally, and for this reason, the findings of the present work may be of interest to the international science education community.

In brief, the findings of the study indicate that:

(A) In scientific explanations presented in textbooks for specific phenomena, the *explanandum* is a logical consequence of the *explanans*, which include in all cases some school science knowledge previously presented (e.g. law, principle, model, rule, etc.), as well as statements describing the particular facts.

(B) The regularities (e.g. physics laws, rules, relationships) in the sample textbooks are presented in two ways:
   (a) Many of them are deduced by using explanations which the authors derive deductively from statements that are true in the cases under consideration, and also from at least one more general law or principle of physics that had been previously introduced.
   (b) A number of the physics laws and principles are not deduced as consequences from other more general laws; rather, they are:
      - formulated axiomatically, and then their validity is supported by appealing to the authority of scientists and/or to the fact that these laws are accepted by the scientific community and they have not yet been falsified. Also, in some cases, the authors formulate the laws first and then describe experiments for their validation.
      - inductively derived by generalising the results of specific experiments.

As previously mentioned, a primary goal of science education is to familiarise students with the procedures and practices of science, an important part of which is to explain phenomena (McCain, 2015). For this reason, students should be given more opportunities to practice constructing scientific explanations, mainly for specific phenomena (Category K1). Research shows that students have difficulty in constructing scientific explanations, and especially as regards providing appropriate evidence and the necessary scientific laws for this purpose (Kampourakis & Zogza, 2008; McNeill & Krajcik, 2007). Students' ability to construct scientific explanations can be improved when the content and the structure of scientific explanations are presented explicitly to them. To this end, the role of teachers in organising learning environments that will support students in their efforts to construct scientific explanations is important (McNeill & Krajcik, 2008, 2009). However, the everyday routine in science classrooms often leads to the teaching of scientific content in a superficial manner, rather than emphasising the practices which the scientific community uses to construct the realisation of this content. We believe that the findings of the present work could be used in training seminars to help science teachers deepen their knowledge of the scientific content which should be conveyed to their students, to become better acquainted with the practices of science (and in particular scientific explanations), and to empower their students do the same. The theoretical and empirical part of this study could be a means to help educators teaching physics go deeper into the subject so that they will (a) realise the real potential of scientific explanations, (b) analyse the 'organic parts' of scientific explanations, (c) differentiate scientific explanations from predictions and arguments, and (d) organise learning environments which would enhance their students' ability to understand and construct scientific explanations.

As regards scientific explanations in textbooks, the present work could provide a guide for

- their detection (i.e. their differentiation from predictions and arguments),
- their rephrasing, and
- their analysis to identify the constituent parts of which they are comprised

in order to use them as models in instructions that aim to develop students' ability to construct scientific explanations.

The analysis of textbook explanations reveals that the school science knowledge needed for the explanation of both particular 'facts' (as they have been defined in the present work) and the majority of scientific regularities demands the use of only a few general laws and principles (Category K3). Thus, by following basic accounts of the nature of scientific knowledge, the authors of TBs explain specific phenomena and most of the regularities with logical derivation from a limited number of general laws and principles, as is shown in Figure 1.

Therefore, as regards explanations, when designing their lesson on a thematic entity, science teachers should answer questions like:

- What kind of physical phenomena and events should the students be able to explain?
- What kind of necessary school science knowledge should the students know in order to explain the above-mentioned physical phenomena and events?
- Which of this knowledge could be extracted with logical induction from more general laws and principles?
- Which are the laws and principles that could be taught, without using other more general laws and principles?
- Which of the techniques used by the textbook authors would be useful to adopt when teaching more general laws and principles (e.g. induction, axiomatic formulation, and examples for validation)?

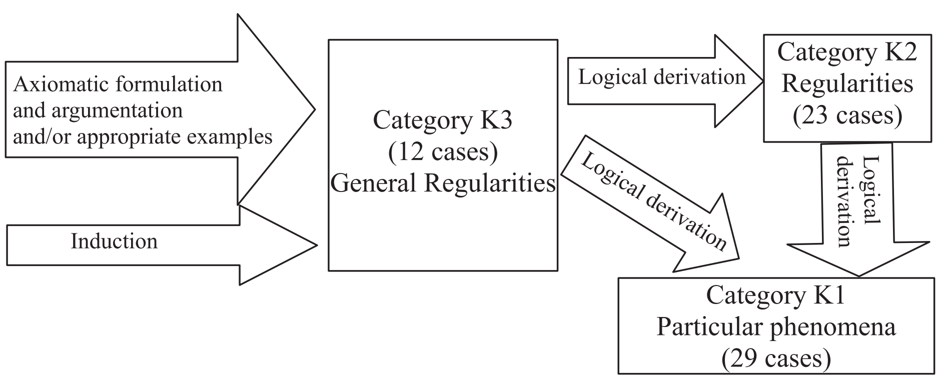


**Figure 1.** The construction of textbooks' explanations.

Moreover, it is useful to note that: (a) in Category K1 (explanation of specific phenomena), students have to explain a specific event (e.g. The recoil of a cannon); (b) in Category K2 (explanation of a regularity), students should invent (or rely on) an abstract situation (e.g. an isolated system of bodies); whereas (c) in Category K3 (reason for the validity of a law), students have to argue for the validity of a law. It is obvious that the degree of difficulty in constructing an explanation increases from Category K1 to Category K3. Thus, the training of secondary students in the construction of scientific explanations should primarily focus on the explanation of specific phenomena, while special attention should be given to developing students' ability to select the appropriate laws and principles needed, since the latter usually poses a great deal of difficulty to students.

It should be noted that in science education, the term 'scientific explanation' is used not only when 'the *explanandum* is generally presumed to be true' (Osborne & Patterson, 2011), but also when a student is asked to justify a claim, as for example, in the case of a prediction or of a question about the result of an experiment (McNeill & Krajcik, 2009). In such cases, the student's expected 'scientific' justification of the claim would have the same structure as that of a scientific explanation. However, the question remains whether it is in fact important for students to be aware of this difference (Berland & McNeill, 2012; Osborne & Patterson, 2011). In our view, the answer to the question depends on the age of the students and the target of the specific teaching (e.g. the differentiation between the two is important in a lesson that focuses on science processes). It is very important for secondary school students to be able to use the appropriate school scientific knowledge (i.e. law, principle, rule, model, etc.) in their explanations (McCain, 2015; McNeill & Krajcik, 2007). For example, for the claim: *S suffers from the disease M*, the argument *because the distinguished doctor D diagnosed it* cannot be considered as a scientific explanation (Govier, 1987, p. 165).

The findings of the present study show that the physics textbooks used in upper secondary education in Greece contain a number of well-structured scientific explanations. Teachers could use this material to provide practice for their students in understanding the characteristics of scientific explanations. The schema of explanandum–explanans would be a useful strategy within the teaching repertoire of physics teachers. Likewise, authors of physics and other science textbooks could use the explanadum–explanans in graphics and textual material. Excerpts of scientific explanations from the textbooks could be given to students, who could then be asked to identify the *explanandum*, the set of sentences that constitute the *explanans*, and the reasoning that leads deductively to the *explanandum* from the *explanans*. A proposed future study would be the evaluation of such a procedure for the improvement of students' ability in constructing scientific explanations of phenomena.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## References

Berland, L., & McNeill, K. (2012). For whom is argument and explanation a necessary distinction? A response to Osborne and Patterson. *Science Education*, *96*(5), 808–813.

Berland, L., & Reiser, B. (2009). Making sense of argumentation and explanation. *Science Education*, *93*, 26–55.
Braaten, M., & Windschitl, M. (2011). Working toward a stronger conceptualization of scientific explanation for science education. *Science Education*, *95*(4), 639–669.
Brewer, W., Chinn, C., & Samarapungavan, A. (1998). Explanation in scientists and children. *Minds and Machines*, *8*, 119–136.
Brigandt, I. (2016). Why the difference between explanation and argument matters to science education. *Science & Education*, *25*, 251–275.
Earman, J., & Salmon, W. (1992). The confirmation of scientific hypotheses. In M. Salmon, J. Earman, C. Glymour, J. Lennox, P. Machamer, J. McGuire, & K. Schaffner (Eds.), *Introduction to the philosophy of science* (pp. 42–103). Indianapolis/Cambridge: Hackett Publishing Company.
Friedman, M. (1974). Explanation and scientific understanding. *The Journal of Philosophy*, *71*, 5–19.
Govier, T. (1987). *Problems in argument analysis and evaluation*. Dordrecht: Foris.
Halliday, D., Resnick, R., & Walker, J. (2008). *Fundamentals of physics*. Hoboken,NJ: John Wiley & Sons. Extended version, 8th ed.
Hempel, C. (1965). *Aspects of scientific explanation and other essays in the philosophy of science*. New York: Free Press.
Hempel, C. (2002). Two models of scientific explanation. In Y. Balashov & A. Rosenberg (Eds.), *Philosophy of science. Contemporary readings* (pp. 45–55). London: Routledge.
Hempel, C., & Oppenheim, P. (1948). Studies in the logic of explanation. *Philosophy of Science*, *15* (2), 135–175.
Horwood, R. (1988). Explanation and description in science teaching. *Science Education*, *72*(1), 41–49.
Kampourakis, K., & Zogza, V. (2008). Students' intuitive explanations of the causes of homologies and adaptations. *Science & Education*, *17*, 27–47.
Kitcher, P. (1989). Explanatory unification and the causal structure of the world. In P. Kitcher, & W. Salmon (Eds.), *Scientific explanation, Minnesota studies in the philosophy of science* (pp. 410–505). Minneapolis: University of Minnesota. Vol. XIII.
Koulaidis, V., & Tsatsaroni, A. (1996). A pedagogical analysis of science textbooks: How can we proceed? *Research in Science Education*, *26*(1), 55–71.
Ladyman, J. (2002). *Understanding philosophy of science*. London and New York: Routledge.
McCain, K. (2015). Explanation and the nature of scientific knowledge. *Science & Education*, *24*, 827–854.
McNeill, K. L. (2011). Elementary students' views of explanation, argumentation, and evidence, and their abilities to construct arguments over the school year. *Journal of Research in Science Teaching*, *48*(7), 793–823.
McNeill, K. L., & Krajcik, J. (2007). Middle school students' use of appropriate and inappropriate evidence in writing scientific explanations. In M. Lovett & P. Shah (Eds.), *Thinking with data* (pp. 233–265). New York, NY: Taylor & Francis.
McNeill, K. L., & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. *Journal of Research in Science Teaching*, *45*(1), 53–78.
McNeill, K. L., & Krajcik, J. (2009). Synergy between teacher practices and curricular scaffolds to support students in using domain-specific and domain-general knowledge in writing arguments to explain phenomena. *Journal of the Learning Sciences*, *18*(3), 416–460.
Ohanian, H. C. (1989). *Physics* (2nd ed. expanded). New York: W.W. Norton.
Ohanian, H. C., & Markert, J. T. (2007). *Physics for Engineers and Scientists* (3rd edition). New York - London: W.W. Norton & Company.
Osborne, J., & Patterson, A. (2011). Scientific argument and explanation: A necessary distinction? *Science Education*, *95*(4), 627–638.

Salmon, W. (1989). Four decades of scientific explanation. In P. Kitcher, & W. Salmon (Eds.), *Scientific explanation, Minnesota studies in the philosophy of science* (pp. 3–219). Minneapolis: University of Minessota. Vol. XIII.
Salmon, W. (1992). Scientific explanation. In M. Salmon, J. Earman, C. Glymour, J. Lennox, P. Machamer, J. McGuire, & K. Schaffner (Eds.), *Introduction to the philosophy of science* (pp. 7–41). Indianapolis/Cambridge: Hackett Publishing Company.
Serway, R. A. (1990). *Physics for scientists & engineers*. Philadelphia: Saunders College. 3rd ed.
Serway, R. A., & Jewett, J. W. (2008). *Physics for scientists and engineers with mondern physics* (7th Edition). Belmont: Thomson-Brooks/Cole.
Thagard, P. (1989). Explanatory coherence. *Behavioral and Brain Sciences*, *12*, 435–502.
Toulmin, S. (1958). *The uses of argument*. Cambridge: Cambridge University Press.
Van Fraassen, B. C. (1980). *The scientific image*. Oxford: Clarendon.
Young, H. (1992). *University physics*. New York: Addison-Wesley. 8th ed.
Young, H. D., & Freedman, R. A. (2008). *University physics* (12th edition). New York: Pearson - Addison Wesley.

## Appendix

The authors and titles (translated from Greek to English) of the three textbooks used in Greek upper secondary schools ('lyceum') are:

Vlahos, J., Grammatikakis, J., Karapanagiotis, V., Kokkotas, P., Peristeropoulos, P., & Timotheou, G. (2003). *Physics for the first class of the lyceum* (10th grade).

Alexakis, N., Ampatzis, S., Gkougkousis, G., Kountouris, V., Moshovitis, N., Ovadias, S., Petroheilos, K., Samprakos, M., & Psalidas, A. (2009). *Physics for the second class of the lyceum* (11th grade).

Georgakakos, P., Skalomenos, A., Sfarnas, N., & Christakopoulos, J. (2012). *Physics for the third class of the lyceum* (12th grade).