

## **Exploring physics teachers' NOTSs (Nature Of The Sciences) conceptions and discussing their relation to the current domain-general NOS (Nature Of Science) agenda**

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### **Abstract**

The present study elaborates on a domain-specific approach to NOS (Nature Of Science) and employs a NOTSs (Nature Of The Sciences) agenda to investigate how Greek in-service physics teachers understand the unique features of school physics and biology. Our theoretical framework focuses on the notion of worldview and important differences that exist between the Newtonian and the neo-Darwinian worldviews, whereas our methodology involves questionnaires and mainly individual interviews. The empirical findings indicate that participants understand the nature of the sciences from the perspective of how they understand their own science and tend to share homogeneous NOTSs conceptions that mostly stem from how they have assimilated positivistic tenets. As a result, they have serious misunderstandings regarding (a) the nature of biology because they project upon biology epistemological characteristics that biology does not possess and (b) several NOS items because they erroneously consider domain-specific NOS (or NOTSs) conceptions to be domain-general and disregard important NOTSs conceptions that underpin the understanding of domain-general NOS items. The implications of all such findings for synergies that may exist between the NOTSs agenda and the current domain-general approach to NOS are also discussed.

*Keywords:* misconceptions, Nature Of The Sciences, neo-Darwinian worldview, Newtonian worldview, in-service teachers, preconceptions.

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### **Introduction**

Students' understanding of the Nature Of Science (NOS) is currently considered an important educational objective worldwide (Cofré et al., 2014; Lederman, 2007; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003), and its achievement presupposes teaching personnel that is able to provide effective NOS instructions. A necessary but insufficient condition for promoting such instructions in the classroom is that the teachers themselves have informed views of NOS (Abd-El-Khalick & Lederman, 2000); for this reason, a large number of research studies have explored what teachers know about NOS. Most of these studies have been carried out in the Anglo-Saxon educational context (e.g., King, 1991; Lederman, 2007; Pomeroy, 1993) rather than

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other cultural contexts (e.g., Lin & Chen, 2002; Liu & Lederman, 2007; Ma, 2009; Yalvac, Tekkaya, Cakiroglu, & Kahyaoglu, 2007; Vázquez-Alonso, García-Carmona, Manassero-Mas, & Bennassar-Roig, 2013), and their focus is more on pre-service teachers (e.g., Abell & Smith, 1994; Aguirre, Haggerty, & Linder, 1990; Hanuscin, Akerson, & Phillipson-Mower, 2006; Lin & Chen, 2002; Liu & Lederman, 2007; Mellado, 1998; Tairab, 2001a; Yalvac et al., 2007) and less on in-service teachers (e.g., Ma, 2009; Rubba & Harkness, 1993; Tairab, 2001b).

The overwhelming majority of these studies have compared what teachers actually know about NOS with what researchers wish teachers to know. The latter often involves seven general aspects of NOS (Abd-El-Khalick, 2005; Akerson, Morrison, & McDuffie, 2006; Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002), which have been considered informed and have been emphasized by an increasing number of international science education standards (Kaya, 2012; McComas, 2008). These aspects include the empirical basis (based on and/or derived from observations of the natural world), the subjectivity (theory-laden) and tentativeness (subject to change) of scientific knowledge, the role of human inference, imagination and creativity (i.e., the notion that scientific knowledge is partly the product of such matters), the social and cultural embeddedness of science, the absence of a universal step-by-step scientific method, and the function of and relationship between scientific theories and laws (i.e., scientific laws are descriptive statements about discerned patterns of natural phenomena, while scientific theories are inferred explanations of those phenomena).

The results of these studies show that teachers possess a fluid, mixed and naive understanding of NOS and often hold alternative conceptions about most of the aforementioned NOS aspects (Buaraphan, 2009; Lederman, 1992). For example, teachers believe in the objectivity of science (Haidar, 1999) and consider scientists' observations and interpretations to be dissociated from theoretical loadings (Abd-El-Khalick & BouJaoude, 1997; Dogan & Abd-El-Khalick, 2008; Palmquist & Finley, 1997); they overlook the role of creativity and imagination in scientific practices (Murcia & Schibeci, 1999; Thye & Kwen, 2003); they view science as a stable or static practice (Craven, Hand, & Prain, 2002; Murcia & Schibeci, 1999) that aims primarily at accumulating scientific facts (Tairab, 2001b); they view the scientific method as a lock-step and a universal step-wise procedure (Abd-El-Khalick & BouJaoude 1997; Craven et al., 2002; Dogan & Abd-El-Khalick, 2008) in which experiment is a necessary prerequisite for validating scientific theoretical constructs (Thye & Kwen, 2003); they identify scientific models with exact representations of empirical phenomena (Abd-El-Khalick & BouJaoude, 1997; Dogan & Abd-El-Khalick, 2008; Soulios & Psillos, 2016); and they believe in the hierarchical relationship between hypotheses, theories and laws, viewing laws as more credible than and superior to theories (Abd-El-Khalick & BouJaoude, 1997; Dogan & Abd-El-Khalick, 2008; Jain, Abdullah, & Lim, 2014).

To the best of our knowledge, however, no studies have explored teachers' NOS conceptions with a focus on epistemological differences between the natural sciences. This gap in the literature may be attributed to the attitude of current NOS researchers towards the question of what science is. Most NOS researchers answer this question from a domain-general perspective, and the instruments they use focus more on a universal view of science and less on specific features of individual natural sciences (e.g., physics, chemistry, and biology). Interestingly, several critics consider this

domain-general approach to NOS to be insufficient and rather misleading (Allchin, 2011; Duschl & Grandy, 2013; Hodson, 2014; Irzik & Nola, 2011; Matthews, 2012; Rudolph, 2000; van Dijk, 2011) and support a different approach that emphasizes differences between the various natural sciences. However, the suggestions of these critics have not been employed in empirical research.

The purpose of this study is to conduct such research by employing an alternative domain-specific NOS or Nature Of The Sciences (NOTSs) agenda, aspects of which have been presented in Schizas, Psillos, & Stamou (2016). In particular, we aim at exploring how in-service physics teachers address the unique features of Newtonian physics and neo-Darwinian biology by focusing on the respective worldviews.

Our choice to focus on domain-specific epistemologies by using the notion of worldviews is grounded in the following assumptions: (a) sciences are related to the natural world via conceptual structures referred to as 'scientific fields'; (b) the specific epistemological features of separate sciences are associated with background ontological, methodological, and epistemological assumptions that play an important role in the constitution of each scientific field and shape the answers each field provides to the question of what science is (Baltas, 1986; Schizas, 2012); and (c) although these assumptions are characteristic for each scientific field, they often formulate general patterns of how the world is made up and operates, namely, 'scientific worldviews', which are used by scientists of one or more fields to identify, understand and explain the world of their scientific work.

Thus, elaborating on a NOTSs agenda, we employed the two dominant worldviews in the world of natural sciences; namely, the Newtonian and the neo-Darwinian worldviews. The former embraces all physical scientific fields that constitute the so-called classical physics, draws its assumptions from classical mechanics (Merchant, 2003) and is grounded on positivistic tenets, whereas the latter originates from neo-Darwinian synthesis and draws its assumptions from evolutionary biology (Smocovitis, 1992), thus providing an alternative understanding of the nature of science, which is predominately based on the techniques of hermeneutics and historical sciences.

Certainly, we recognize that physics and biology comprise many different fields, some of which present inconsistencies with assumptions that underpin the Newtonian and the Neo-Darwinian worldviews, respectively. Nevertheless, regarding physics, curricula in school science and K-12 settings often assume a Newtonian worldview because (Fischler & Lichtfeldt, 1992; Kalkanis, Hadzidaki, & Stavrou, 2003; Krijtenburg-Lewerissa, Pol, Brinkman, & van Joolingen, 2017; Mashhadi, 1996) (a) classical mechanics constitutes much of the knowledge taught in contexts of physics instruction internationally, (b) most taught physical fields share the epistemological standards of the Newtonian worldview, and (c) modern physical fields not consistent with these standards are still excluded from the curriculum or are misrepresented in textbooks.

Furthermore, regarding biology, many scholars (Dobzhansky, 2013; Mayr, 1997, 2004) and science educators (Alles, 2001; Athanasiou, Katakos, & Papadopoulou, 2016; Kloser, 2012; Rudolph & Stewart, 1998; van Dijk & Reydon, 2010) recognize that biological knowledge can only be captured in the light of evolution. Various

international textbooks have also begun to implement this insight when presenting numerous and diverse biology topics (e.g., Hoefnagels, 2012; Reece et al., 2014).

That epistemological assumptions of evolutionary biology underlie the nature of contemporary biology is grounded on the nature of biological entities and research object. Biological entities have an innate purposefulness and “exist” as constantly changing or historically defined realities only because they are open systems; they cannot be isolated from the specific environments in which they live and that consist of hierarchically stratified and interacting living systems. In the science of biology, thus, interaction and context (Lewontin, 1991, 2000), including the multi-level contextual embeddedness of living systems (Van de Vijver, Van Speybroeck, & Vandevyvere, 2003), are of essence, resulting in a structurally coevolved research object. Biological phenomena occurring at some organizational level depend on other phenomena occurring at lower and higher organizational levels and are fully captured when they are determined throughout their relations to these other phenomena. Therefore, biology always seeks coherency and succeeds in responding to this hermeneutical request by connecting all organizational levels throughout with central features underpinned by the assumptions of evolutionary biology and the neo-Darwinian worldview.<sup>1</sup>

Returning to research aspects of our study, the working hypothesis is that science teachers’ NOTSs (and NOS) conceptions stem from spontaneous philosophical ideas that are likely conveyed to them during their undergraduate science education and their own secondary experience of school science teaching. This hypothesis associates learners’ NOTSs (and NOS) conceptions with how they understand the peculiar ontological/methodological/epistemological features of scientific discipline-specific research objects or the particular background assumptions lying behind the respective scientific knowledge taught in school environments.

Testing this hypothesis and exploring its heuristic potential is not an easy task. Numerous empirical studies focusing on different target groups (i.e., primary education teachers, in-service/prospective physics and biology teachers and primary/secondary education students) are needed. Taking thus, an initial step towards this exploration, the present study focuses on a specific target group, namely, Greek in-service physics teachers, and investigates the following research questions: (a) Do physics teachers use homogeneity as a starting point in addressing the unique features of Newtonian (school) physics and Neo-Darwinian biology? (b) Do they share a kind of epistemological idiosyncrasy that results from how they perceive the Newtonian worldview or are their conceptions simply fluid, inconsistent and naive, as current NOS research demonstrates? (c) How do their NOTSs conceptions influence their views of NOS list items, and what are the implications for current NOS research?

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<sup>1</sup> Some fields or older versions of contemporary biological disciplines present inconsistencies with the assumptions that underpin the neo-Darwinian worldview. For example, the underpinnings of classical population ecology (Kingsland, 1995) and the assumptions of some historical models of the gene concept (Gericke & Hagberg, 2007) are closer to the Newtonian worldview. These inconsistencies, however, can be explained by the fact that the respective knowledge developed in a period during which “positivism” was the overarching epistemology used in academic circles, biology was considered an immature science, and “physics envy” was at its height (Smocovitis, 1992; Stamou, 1998).

Before embarking on the results of our study, it is necessary to present a short description of the main differences between the Newtonian and neo-Darwinian worldviews. This presentation is not exhaustive but focuses on epistemological issues that represent the crucial positivistic/historico-hermeneutical distinction between the two worldviews and help learners to understand not only the nature of school physics and biology but also significant aspects of declarative and procedural knowledge (Dagher & Erduran, 2014; Schizas, Psillos, & Stamou, 2016). These issues refer to scientific theories and laws, scientific methods, scientific predictions and scientific explanations.

### **Fundamental differences between the Newtonian and neo-Darwinian worldviews Scientific theories and laws**

Newtonian physics is predominantly nomothetic and is considered by positivism as the model science and the standard for all others (Frodeman, 1995). It possesses a mathematical theoretical structure consisting of interconnected universalities (i.e., scientific laws) and can only manage general phenomena; the concrete empirical phenomena that it grasps and addresses through the use of experimental methods are simple and interchangeable representatives of some general phenomenon (Baltas, 2004).

These features result from how natural phenomena are transformed into physical phenomena (Baltas, 1988). Newtonian physics strips the natural phenomenon of qualities taking no mathematical values and picks up a single particular aspect of the phenomenon that is both idiosyncratic to its conceptual system and compatible with deductive-nomological reasoning. As a result, (a) the seemingly heterogeneous entities involved in the natural phenomenon are transformed into material points that can only differ among themselves on the values of some characteristic variables (e.g., mass) and parameters, and (b) the seemingly heterogeneous environments within which the behaviour of these entities is manifested are transformed into different values of initial and boundary conditions.

On the other hand, biology cannot be a nomothetic science<sup>2</sup> and due to the complex, heterogeneous and foremost historical (Sober, 1993) nature of biological systems, it is forced to address the uniqueness and specificity of empirical phenomena. In contrast to Newtonian physics, biology is concerned with (a) the specific characteristics that comprise the identities of the entities involved in the phenomenon, (b) the particular characteristics of the environment in which the behaviour of these entities is manifest, and (c) the specific relations developed among the entities and their environment. Thus, different and various approaches are usually required for the articulation of robust theoretical frameworks, whereas biological theories very often contain concepts, hypotheses, etc. that are not expressed in mathematical terms (Korfiatis & Stamou, 1999) and are families of models (Stamou 2012), some of which are purely theoretical

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<sup>2</sup> There is an on-going debate among philosophers of science about whether biology has laws (Dagher & Erduran, 2014). To address this topic, scholars consider questions of meaning referred to qualities or attributes that the concept of law connotes. Thus, under one definition of 'law', it is true that biology possesses laws, while under a different definition, it is false. Nevertheless, this debate neither questions the fundamental differences that exist between biology and physics nor disputes the fact that biology lacks the kind of mathematical and universal statements that are widely recognized as 'Newtonian laws'.

and others of which are descriptive (i.e., involving descriptions of the relationships among observable phenomena), explanatory (i.e., involving inferred explanations for observable phenomena), qualitative, and quantitative.

These features result from how biology transforms natural phenomena into biological phenomena. A continuing and gradual movement occurs between the world of biological theories and the empirical world, which has no counterpart in Newtonian science: biologists are always forced to move back and forth from theoretical constructions to raw empirical data by employing hermeneutical processes and various kinds of models, which differ in their testability and play different roles in the frame of the biological field to which they belong (Stamou, 2012; Schizas, Psillos, & Stamou, 2016).

### **Scientific methods**

The fact that specific numerical values constitute the only identity items of the empirical world with which Newtonian physics may be familiar has a direct impact on methodology (Baltas, 2004). The steps followed are consistent with methodological reductionism and essentialism and include the isolation of the phenomenon under consideration from its environment and the elimination of all those qualitative characteristics (including historical aspects) that comprise the specific empirical identity of the entities involved in the phenomenon. Remarkably, to the extent that these steps are technically possible, all physical phenomena can be reproduced under laboratory conditions (Baltas, 2004).<sup>3</sup> Thus, each physical theory can be subjected to experimental testing, a matter that explains why positivism considers experimental implementation as the most appropriate scientific method.

Biology, on the other hand, cannot mimic Newtonian physics in constructing systems that are materially and conceptually isolated from their environment (Taylor, 2011). Biological phenomena are multivariate-multilevel in nature and can be grasped through focusing on the organizational and hierarchical stratification of biological systems (Van de Vijver et al., 2003), thus opening up questions regarding the heterogeneity and the multiple contextual embeddedness of their structure. Therefore, scientific practice in biology is pluralistic in the sense that it involves a variety of methodological approaches, such as reductionist-analytical methodologies, simulation models, general and specific models, qualitative and quantitative models, and holistic-synthetic methodologies (Korfiatis and Stamou, 1999).

### **Scientific explanations**

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<sup>3</sup> It is acknowledged that astronomy and cosmology study singular phenomena, which cannot be reproduced under laboratory conditions. However, the epistemological underpinnings of these physical disciplines are in principle consistent with the Newtonian worldview. All these phenomena would be treated as interchangeable representatives or 'instances' of general phenomena if there were more 'copies' of our solar system or galaxy and would be reproduced in laboratories if we had the technical ability to construct giant super-laboratories (Baltas, 2004). Additionally, there are aspects of molecular biology that are considered experimental but cannot be handled in the way in which Newtonian physics handles natural phenomena. As parts of a structurally coevolved research object, they cannot but obey the standards of the neo-Darwinian worldview.

Newtonian phenomena are deterministic and causally closed<sup>4</sup> and envisage 'formal' explanations. These explanations are based on the deductive-nomological model and consist of simultaneous functional relations among quantities, which describe the system and are all internal to the system (Besson, 2010).

Moreover, the Newtonian principle of decomposability and the resulting reductionism envisages mechanistic explanations. These explanations (a) focus on how a phenomenon occurs, (b) require the formulation of chains of causes and effects by which the parts of the systems under consideration are connected to each other (Lewontin, 2000), and (c) give rise to the notion of 'bathogeneous' explanations (Besson, 2010; Halbwachs, 1971), which consist of a lower-level underlying structure or a more general, deeper theory and assume that regularities at lower organizational levels explain regularities at higher organizational levels.

On the other hand, the contingency and causal openness<sup>5</sup> of biological systems imply that deductive reasoning and universal, non-contextual and law-like knowledge (Van der Vijver et al., 2003) are inappropriate for explaining biological phenomena. Thus, while biology focuses on causal mechanisms and descends organizational levels to answer questions of the 'how' type (i.e., proximate causality: Mayr, 1997), it considers these mechanisms as historically generated and ascends organizational levels to answer questions of the 'why' type (i.e., ultimate causality: Mayr, 1997). The latter explanations are evolutionary and make extensive use of narrative logic; i.e., they involve descriptions of historical and rather observable facts.

### Scientific predictions

If we keep in mind that the specific numerical values of the characteristic variables, parameters and conditions (both initial and boundary) not only constitute the unique identity elements of the Newtonian phenomena under consideration but also can be estimated with accuracy, then we can reach the positivistic conclusion that all behavioural aspects of these phenomena can be predicted with certainty (Baltas, 2004). Moreover, because of the reversibility of Newtonian systems, explanations can to some extent be equated with predictions.

Biology, however, does not involve certain and secure predictions because of discontinuities in the behaviour of biological systems, missing data resulting from their complex nature, and the dependence of the new states of biological systems on the historical succession of their previous states (Beatty & Desjardins, 2009). Needless to say, the past and the future of biological systems are not compatible with each other

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<sup>4</sup> Causal closeness implies that everything that explains a physical system is already contained within the mathematical equations that describe this system, and the system is not exposed to external influences.

<sup>5</sup> The contingency of biological systems implies that a biological fact does not necessarily occur because of the presence of another fact, as in determinism, but has a tendency to occur in a particular context (Ulanowicz, 1999). In addition, the causal openness of biological systems implies that (a) the action of a causal agent is interrelated with the effects of other causal factors that are found not only within but also outside the borders of the biological system under study, and (b) unexpected and unique events such as mutations and stochastic changes in environmental conditions result in discontinuities in the behaviour of the system.

because time is the relational sequence between events rather than the neutral background on which timeless laws of nature unfold (Kwa, 2010).

## Method

### Participants

Greek secondary science teachers are, to a great extent, single-subject university graduates who have studied their discipline for four years. Usually, they have a strong disciplinary background but, according to Greek legislation, they possess the appropriate qualifications to teach not only physics but also biology in secondary education schools. Moreover, during their undergraduate studies they have not taken any compulsory science education or nature of science courses and their further professional development as school science teachers does not involve institutional in-service courses on NOS because this knowledge is not included in school science curricula.

Fourteen acting physics teachers (8 males, 6 females) were purposefully selected out of a larger pool of physics teachers willing to participate in our research, and the resulting sample represents a range of individual and educational profiles. Their ages varied from 33 to 56 years, and their teaching experience ranged from 2 to 25 years; ten teachers had experience of more than six years; nine teachers taught in public schools, and the remaining teachers taught in 'private coaching' schools; six schools were located in rural or semi-rural areas, and eight were located in urban areas; one teacher held a Masters in Physics, and two others held PhDs in Physics and Science Education, respectively.

### Data collection and analysis

Our study is qualitative, and data were collected using questionnaires and mainly through individual interviews, which seem to be the appropriate research choice for studying learners' NOS views in depth (Lederman et al., 2002).

Prior to the interview sessions, each teacher was asked to complete a multiple-choice questionnaire, which was different from the usual questionnaires (VOSTS or VNOS for example; Lederman et al., 2002) employed in respective NOS studies. Rather than focusing on similarities among natural sciences, our questionnaire focused on differences between classical (Newtonian) physics and neo-Darwinian biology and, in its final version, involved 6 items concerning scientific theories and laws (Question 1), scientific methods (Question 2), predictions (Question 3) and explanations (Questions 4, 5 and 6).

The final version of the questionnaire resulted from a developmental procedure that involved several stages. Initially, the entire questionnaire and each separate item were discussed by a panel of experts consisting of two biology and physics professors with work in epistemology and two experienced teachers who hold PhDs in science education. During this process, some items were reworded, and one was excluded. The questionnaire was then addressed to two experienced science teachers who had taught physics and biology in school settings, and further revision resulted in additional rewording and the deletion of one more question.

Each item presented the respondents with bipolar agree–disagree statements or positions coupled with several reasoned viewpoints or justifications to choose from.

Each couple was classified as either an informed (I) or a non-informed (NI) NOTSs view, while the criteria used for this classification were drawn from the theoretical scheme discussed previously. Each item also involved only one informed position and justification, whereas the content of non-informed justifications involved homogeneous and differential aspects of the nature of the sciences inspired by positivism and pre-Darwinian thinking, respectively. Moreover, the questionnaire provided respondents with the option of expressing ideas or viewpoints that differed from those provided for each item. This option, however, was rarely used by the participants, and when it was used, the teacher-written responses were, in almost all cases, a combination of the choices provided for the various items.

The administration of the questionnaire was intended to trigger teachers' thinking of NOTSs, elicit their NOTSs views and create a context in which these views could be discussed. This discussion was carried out during in-depth individual interviews. All participants were handed their questionnaires and asked to explain their responses, clarify the meanings they ascribed to key epistemological terms, and provide specific examples to illustrate and contextualize their NOTSs views. Follow-up and probing questions were also used to clarify vague statements or seeming contradictions in the participants' responses.

The typical duration of the interviews was 60 minutes. Digressions were common, and we often reworded the questionnaires' questions and used many other questions to follow the participants' lines of thought. All the interviews were recorded verbally and fully transcribed afterwards. Interview transcripts were then content-analysed, with each participant treated as a separate case.

The determination of the unit of analysis, the formation of categories and the reliability of analysis are crucial features of this last stage of our research. As the unit of analysis, we took the answers of each participant to every questionnaire item. Our choice reflected the fact that each item helped us discuss a central theme or particular aspects of this central theme with participants during the interview session.

Content analysis categories resulted from a refinement of analogous categories employed in Schizas & Stamou (2005) as well as in Schizas, Papatheodorou, & Stamou (2017). Used as columns in tables of contents (see Table 1), these categories helped us to organize a large amount of descriptive data (Devetak & Vogrinc, 2013) involved in interview transcripts, develop participants' main ideas and detect misconceived NOTSs views, contradictions, missing information, inconsistencies, and inaccurate statements. The category "Subject" labelled the studied text material according to the headers of the epistemological issues discussed in the theoretical section; "Text" included the participants' responses to the questionnaire and interviewer's questions; "Vocabulary" referred to definitional and associated features that the participants attributed to epistemological concepts; and "Ideas" referred to participants' assertions and/or assumptions concerning philosophical or epistemological categories (e.g., the category of causation, the category of wholeness, and the category of time) that underlie the epistemological issues discussed in the theoretical section. The elements of all of the previous categories were merged in the column "Worldview" such that the participants' affinity to Newtonian or neo-Darwinian worldview could be determined. The verbal

material included in the category “Text” was horizontally analysed (separate content analysis was done for each table row).

Finally, the authors and one experienced science teacher analysed the data, and inter-rater agreement was considered necessary to be established before the analysis of the whole dataset. This was accomplished by a two-round analysis of randomly selected data sets. We checked the intercoder agreement by involving ourselves and an independent experienced teacher researcher in coding a random 20% sample of the data. Differences were discussed extensively and claims and interpretations were reciprocally revised and checked against the interview and questionnaire data for meaning until consensus was reached. This process resulted in 90% agreement during the second round of analysis, which used another random sample of the data set.

Table 1: Examples of content analysis

Subject	Text	Vocabulary	Ideas	Worldview
Scientific theories and laws	[P2]“ The law is a relationship in which if you have some characteristics you will have a certain result”	The definition of law is confused with the formula of deductive-nomological reasoning	Predisposition to deductive-nomological reasoning and influence of this type of reasoning on the definition of the concept of ‘scientific law’	
	[P1]“Social sciences are not sciences because they do not possess laws, mathematical background and predictability based on mathematical equations”		The presence or absence of mathematics and deductive-nomological reasoning is a crucial criterion for distinguishing sciences from non-sciences	Newtonian (affinity to the positivistic idea that Newtonian physics should be considered the appropriate model to judge scientific activities and understand the nature of science)
Scientific methods	[P13]“Experimentation is the bedrock of every natural science. It is the method we use to validate theories and laws”.		Experimentation is a necessary methodological step for the acquisition of validated scientific knowledge	Newtonian (affinity to the positivistic idea that scientific method should be experimental)
Scientific predictions	[P10]“if you can predict, then you can also explain”	The concepts explain and predict can be used interchangeably	There are no qualitative differences between the past, present, and future; time	Newtonian (consistency with the assumption that natural phenomena are irreversible)

			lacks the form of arrow.	
Scientific explanations	[P11]"Birds migrate because they want to live... otherwise they will die...there is a survival mechanism"		Explanation of an event by reference to the outcome or consequences of that event rather than an antecedent of the event. This causal reasoning is based on the assumption of a goal or purpose.	Pre-Darwinian (affinity to teleological reasoning)

## Results

The content analysis of the interview transcripts yielded the following results (the questions' numbering does not denote their sequential order in the questionnaire):

### Scientific theories and laws

**Question 1:** Do all natural sciences possess scientific laws?

All Participants (P) accept the questionnaire's non-informed position that all natural sciences possess laws and avoid selecting the informed position and justification that biology does not possess laws because biological systems are subordinated to evolutionary processes that create novel and unforeseen facts. Thus, all participants disregard the presence of non-nomothetic natural sciences.

In the interview session, the belief of many participants in the nomothetic character of the natural sciences takes normative dimensions and conforms to positivistic ideas that defend the necessity for sciences to possess laws. P2 and P12, for example, argue that the law is the base, somewhere to stand and agree with P3 who mentions that "it is not feasible to practise science without laws". P4 expresses similar ideas when he states that natural sciences must possess laws because nothing happens randomly. "All things follow some rule" he says, thus rooting the existence of laws in deterministic causality. Additionally, P1 argues that he could not imagine a lawless natural science because "laws are the pillars on which natural sciences are built"; P13 holds that "natural sciences would become chaotic without laws", whereas P11 and P5 go one step beyond P1 and P13, defending hard positivistic ideas. P11 mentions that the "social sciences are immature sciences because they have no laws", and P5 states, "social sciences are not real sciences because they do not possess mathematical laws and predictability based on mathematical equations."

Focusing further on the participants' responses to question 2, 8 out of 14 participants accept the non-informed questionnaire's justification that all natural sciences possess laws because they identify invariable sequences of facts that can be stated in the form of laws. Almost half of the participants (6 out of 14) select the other justification for the same position, namely that in each natural science, scientists make scientific hypotheses that, if verified, become scientific theories, which in turn, if there is more

evidence, become the higher order generalizations referred to as scientific laws. However, in the interview session, the former participants state that they also agree with this justification. As P14 puts it, “Laws are something indisputable, something you should follow...they have resulted from and are validated by many experiments and measures....they are superior to theories...theories are more easily questioned”.

The presence of the misconception about the hierarchical validity of scientific ‘laws’ and ‘theories’ in the participants’ mind motivates us to explore how they understand the distinction between these concepts along with how they understand the relation between the concept of law and the empirical world. Thus, P1 uses the concepts of ‘laws’ and ‘theories’ indiscriminately and interchangeably when he says, “The law is a general principle, that something results in something else....you say the law of mechanics, kinetic theory and [the principle of] kinetic energy. They are some principles.” In this context, P3 states that “the law is a theory capable of explaining some phenomena”. In our question of whether the concept of theory is identical to the concept of law, he answers that theory is based on law, but like P7 he also mentions that he probably does not understand the exact difference between these concepts. Responding to our call to focus on this difference, P11 and P13 restate aspects of the misconception about the hierarchical validity of scientific ‘laws’ and ‘theories’ (e.g., “theories are descriptive generalities, more general than laws and rather non validated yet”), whereas P5 and P6 agree with P11 and P13, stating also that theory may be the verbal expression of law and that law may be the mathematical equation. As P5 puts it, “the theory in regard to the first thermodynamic law is that “the heat is equal to the sum of the change in the internal energy and work, while the law is  $Q=\Delta V + W$ ”.

Misconceived views of “laws” are also present in how participants understand the relation between the concept of law and the empirical world. For example, P5 argues that “law is the mathematical formulation of a concrete empirical phenomenon”, P9 believes that laws can be inductively extracted from experiments, and P8 claims that laws meet exceptions because sometimes they are idealizations and appear discrepant with reality.

All these misunderstandings indicate more serious misunderstandings concerning the very nature of Newtonian science, which in turn make participants vulnerable to misconceived NOS views, such as those on the hierarchical validity of theoretical constructs. Participants erroneously presuppose that in the frame of Newtonian science, there is a distinction between scientific theories and laws and disregard the idea that theories are nothing more than interconnected and mathematically articulated laws. Remarkably, due both to the reasonable difficulties they encounter in finding or recalling physical theories independently of laws (thus resulting in misleading definitions of the concepts of ‘theories’ and ‘laws’) and their strong belief in the nomothetic character of natural sciences, they are forced to believe that laws are superior to theories.

Moreover, participants overlook the idea that scientific laws are primarily theoretical and ideal constructs that capture the universal essence of empirical phenomena and disregard the idea that concrete empirical phenomena are subsumed to these ideal generalizations after being transformed to physical phenomena. These deficiencies are reflected in how participants conceive the relation between ‘laws’ and the empirical world (e.g., that ‘laws’ may be inductively produced and empirically

tested as if they were non-ideal constructs) and establish in their mind an erroneous (hierarchical) continuum of testability among scientific hypotheses, theories and laws. Needless to say, this hierarchical continuum provides participants with plausible but misleading explanations of why laws are superior to theories.

Overall, it seems that participants make an indifferent and simultaneous appeal to the natural and scientific worlds and view the relation between them from a viewpoint that appears to accord with empiricism and naïve realism. The question thus arising is whether they erroneously accept the presence of a universal method that is supposed to handle this relation and make this handling 'scientific'. Apparently, this presence might help participants to distinguish the natural/empirical world from the scientific one and render the term 'science' meaningful.

### Scientific methods

**Question 2:** Do the natural sciences use a single method or many different methods?

Eight of 14 participants accept the questionnaire's position referred to as the myth of the scientific method (Lederman et al., 2002). Most of them (6 out of 8) accept the justification that in all scientific research, the scientist observes and records natural facts, provides explanations on the basis of those facts, and then tests whether these explanations are true or not through experiments. As P1 states, "scientific research must be carried out in this way", thus ensuring the normative dimension of this belief.

P2 and P3 agree with the myth of the scientific method but dispute the necessity of the observation step. This differentiation divides the participants into those who consider the formulation of scientific hypotheses to be based on empirical facts or inductive reasoning and those who consider such formulation to be based on mathematical logic (Apostolou & Koulaidis, 2010).

Despite differences regarding the scientific context of discovery, the participants are in strong agreement when treating the scientific context of justification. Almost all participants (12 out of 14) share the view of experiment as a necessary methodological step for the acquisition of validated scientific knowledge. Remarkably, this rather positivistic view (a) helps participants to determine the relation between the scientific and natural worlds and define the notion of scientific-ness, (b) complies with the ability of Newtonian physics to transform all natural phenomena into experimental phenomena, and (c) is accompanied by misunderstandings regarding what an experiment is.

Participants encounter difficulties in defining the concept of experiment as a technical means of reproducing the natural phenomenon under laboratory conditions because they lose sight of the transformations that are carried out during experimental implementation. This oversight may explain why P5 for example confuses not only experiment with observation but also the manipulation and control of experimental variables with their estimation. The dialogue below is indicative:

I: Suppose that a scientist studies a population living in a lake. He describes some population features and measures the population number. Is this a scientific research?

P5: Certainly, it is.

I: Does it involve experiment?

P5: Certainly, it does. Isn't the lake the experiment? Isn't the ecosystem the experiment?

I: What is exactly the experiment?

P5: You observe how the population behaves in this environment. Therefore, you can determine if your theory is true or not. For example, you can see why this population migrates. What is the cause? You find the cause.

I: Is this more an observation and less an experiment?

P5: Okay. This is a problem in biology. This is partly an experiment. If, for example, you say that the population migrates because there are many frogs, and if you observe that indeed there are many frogs [in the lake] and the population does not migrate, this means that your theory is erroneous. The ecosystem is indeed the experiment...you can determine if your theory is true or not.

I: If someone asked you to define 'experiment', what would you say?

P5: It is a process in which you rigorously determine the parameters that influence your system and determine if the law is true or not...

I: When you count the individuals of a population living in a lake, do you rigorously determine the parameters that influence this population?

P5: Certainly, you do. You say I have a lake that is so wide it has a particular population of birds and a particular level of pH in the water.

I: You can measure pH. Can you manipulate it?

P5: Do you mean to influence pH? Okay, this is a disadvantage of biology (laughing). You can't influence the water's pH. Yes, you are right.

I: If you can't influence it, is it an experiment?

P5: Okay, we used the lake as an example. Let's think drug investigation. Isn't the drug a biological research object? You influence everything.

Irrespective of these misunderstandings, all participants share a common viewpoint that can be inferred from the above passage and their respective definitions of experiment: the perception of experiment as any interaction of scientists with the empirical world that involves the comparison of some deduced state of affairs with some observed state of affairs. Thus, P5 considers the making of scientific hypotheses along with observation to be an experiment (and also ecological fields to be giant laboratories), P2 and P7 consider stimulations to be experiments and so on.

That deductive reasoning influences participants' thinking on methodological issues is also evident in their answers to our question of whether research studies could only involve descriptions. For example, P3 answers that "descriptive research without results or confirmed conclusions [as the deductive-nomological model wishes] cannot exist". Remarkably, deductive reasoning and testability go along with the belief in the importance of quantification. As P2 and P3 argue, "quantification allows more measurements, more experiments, more results and more conclusions".

Overall, most participants believe in the necessity for natural sciences to be nomothetic and experimental. Do they also accept the other positivistic tenet holding that the sciences should have high predictability?

### Scientific predictions

**Question 3.** Can the natural sciences make certain and secure predictions?

Most of the participants (13 out of 14) disagree with the positivistic view of predictability as an essential feature of every science and, of these participants, most

(11 out of the 13) note the informed questionnaire's position that the natural sciences do not have the same predictability. Explaining this position, they also note the informed questionnaire's justification that, in contrast to Newtonian physics, unforeseen events can occur both in biological systems and in their environment, making the forecasting of future events difficult. P1 makes this justification more concrete when he says, "How can you predict this event [that dinosaurs disappeared]? Suppose that something occurs and suddenly the population changes... Yes, [in biology we have random events] but not only in biology... we can also observe randomness in other sciences ... Let's say that biological systems are more influenced by their environment."

P1 presents an informed and mostly non-positivistic aspect of scientific prediction, while in response to the previous questions, he stated positivistic views that do not apply in the case of biology, such as the view that all sciences should be nomothetic and treated as deductive-nomological endeavours. This inconsistency forces us to discuss the issue of laws with P1 again:

I: Does the existence of laws imply high predictability?

P1: Yes, certainly yes.

I: You say, however, that biology has low predictability, although it possesses laws.

P1: Okay... [pause]... they [biological laws] could be more fluid, could change more easily...

P1 recognizes the contradiction between his ideas about prediction and his former positivistic conceptions about other NOTSs issues, but he does not question the soundness of using positivism in capturing the nature of biology. Because of his indisputable faith in the nomothetic character of the sciences, he attempts to face the resulting contradiction by making ad hoc hypotheses that unavoidably trigger new misconceptions. Thus, P1 associates the low predictability of biology with rather misleading NOTSs aspects, such as the notion that biology may possess fewer laws than physics or possess laws that are fluid, present exceptions, and change.

Analogous remarks could be made for P12 and P5, who have adopted most of P1's positivistic ideas. P12 agrees with P1 and mentions that "when there is no law, prediction is uncertain". In addition, when P5 is confronted with his own contradictions, he resorts to positivism and possesses the misconception that biological disciplines close to the physico-chemical organizational level behave similar to physics, while biological disciplines far away from that level, such as ecology, embody a different epistemology that degrades their scientific status. In his own words: "Things are more mathematical in biochemistry and the biology of DNA... I consider the part of biology that refers to population studies as blurred. It is a bit... pseudo-science."

Moreover, almost all the participants (11 out of 13) who maintain that biology cannot make certain and secure predictions fail to recognize this feature as a fundamental difference between biology and physics. Neither can they associate the unique and unforeseen events occurring in biological systems with evolutionary processes nor can they recognize that Newtonian physics is capable of making certain predictions due to how a nomothetic science is structured and how such a science studies empirical phenomena.

In many respects, participants assume that problems concerning prediction are common to both biology and physics. For example, P2, P3 and P9 maintain that predictability problems in biology are analogous to those in weather models where the parameters involved cannot be estimated with mathematical accuracy. Similarly, P10 claims that “biology is a microcosm applied to the macrocosm, and its low predictability is analogous to that of quantum physics”, whereas P11 mentions that “certain predictions are impossible because of the non-linearity of natural systems”.

This homogenization of predictability problems in the natural sciences brings forth the question of how participants perceive the notion of time. When we ask participants to tell us whether predictions and explanations are related, a significant number (6 out of 14) maintain that there is an inextricable linkage between them. For example, P1 argues that if we explain how a physical system behaves, then we can predict how it will behave in the future, whereas P10 similarly states that “if you can predict, then you can also explain”. Thus, participants consider the past to be compatible with the future and identify time as a neutral background on which timeless laws of nature unfold (Kwa, 2010), exactly as positivism and the deductive-nomological model wish. Does this adherence to deductive-nomological reasoning and the non-historical notion of time impede participants from viewing differences between biological and physical explanations?

### **Scientific explanations**

**Question 4.** A physicist and a biologist try to explain the behaviour of a particular pendulum within a specific environment and the behaviour of a population (e.g., a population change of a specific species within a specific environment), respectively. Does the physicist think in the same way as the biologist?

Only three participants (P1, P4 and P11) agree with the questionnaire’s positivistic position and justification that physicists think in the same way as biologists because in both cases, explanations are based on the deductive-nomological model. The remaining teachers agree with the informed questionnaire’s position and justification that physicists do not think in the same way as biologists because in biology there are no generalizations capable of explaining how each population will behave in each environment. However, they meet serious difficulties in providing informed explanations of their choice and lead themselves to develop misunderstandings. For example, P8 and P14 do not reject the idea that the deductive-nomological model can be applied to biological explanations and hold in parallel or complementarily with this type of explanation that there are teleological explanations based on the intentional or mental characteristics of organisms.

Before focusing on this last finding by examining the participants’ responses to the next question, it is worth mentioning that those teachers who disagree with the application of the deductive-nomological model to biological explanations do not approach aspects of the neo-Darwinian worldview better than the other participants. For example, P9 states that such application in biology encounters serious problems, which, rather than resulting from the unique epistemological features of biology, are in many respects similar to those that are sometimes encountered by physicists. In P9’s own words, “the deductive-nomological model cannot apply to biology because biologists cannot describe the initial conditions of their systems with accuracy, as sometimes occurs in the case of dynamical physical systems”.

**Question 5:** A physicist investigates the causes of a physical phenomenon, such as the expansion of metals in summer, and a biologist searches for the causes of a biological phenomenon, such as the migration of insectivorous birds from temperate to subtropical and tropical areas in the autumn. Does the physicist think in the same way as the biologist?

A few participants (P1 and P10) agree with the questionnaire's non-informed position and justification that physicists think in the same way as biologists because explanations concern how something occurs and thus they consist of mechanisms. At the same time, however, these participants do not disagree with both the informed position and the non-informed justification that physical and biological thinking are different because in biology, explanations occur that are not found in physics, such as those based on intentions and goals. Actually, P1 differentiates between physical and biological systems on the basis of mental characteristics. He argues that the migration of birds is a phenomenon whose explanation may involve the feature of memory, something which is not the case with metals. Thus, in an attempt to distinguish physical from biological entities, P1 abandons the materialistic framework of modern biology and flirts with anthropomorphism.

This flirtation with anthropomorphism and pre-Darwinian thinking is also present in participants who agree with the questionnaire's informed position and justification that physicists do not think in the same way as biologists because in biology, explanations exist that are based on narrations of evolutionary or historical events. For example, P6 justifies her response on the grounds that biology is more theoretical than physics and involves more verbal statements. However, in our question about why insectivorous birds eventually migrate, she covers her need to offer such statements by agreeing with other participants who share P8's view that "birds migrate to find food and to protect themselves from weather conditions that make it difficult for them to find food and survive."

The former example shows that physics teachers have considerable difficulties in clarifying how evolutionary history is associated with biological explanations. The cause of such difficulties is not only their ignorance of significant aspects of evolutionary theory (which is justifiable for physics teachers) or the misconception that in the frame of the natural sciences, teleological explanations are in principle acceptable and may distinguish biology from physics. Other important causes are (a) their belief in the nomothetic character of natural sciences and the resulting necessity for such sciences to involve universal explanatory statements containing quantitative data (e.g., P4 mentions that 'explaining a fact by means of mathematical symbols is more accurate, more correct and less controversial than explaining the same fact with words', while P8 expresses similar ideas when he says: "...mathematics is a tool with which we learn to read data in the same way...if someone says 3, it is 3, not 1 or 2.... you can't dispute it") (b) misconceptions about the concept of "qualitative data" (c) the adherence of participants to the Newtonian assumption of reversibility or the Newtonian notion of time, and (d) difficulties concerning how higher organizational levels are related to evolutionary explanations.

Specifically, regarding (b), participants encounter difficulties in distinguishing qualitative data from quantitative data. For example, P4 considers physical data to be both qualitative and quantitative: “first,” he says, “one describes the body’s motion, and then she quantifies it”. Most likely, trapped by the mathematical structure of physical theories, P4 cannot contemplate qualitative data as data that cannot take numerical values and erroneously equates qualitative data with the verbal description of (physical) phenomena that can be quantified. Apparently, this confusion distorts the nature of explanatory statements that are employed in biology (e.g., singular statements that are rich in qualitative data) and along with (a) and (c) may impede their understanding or create a negative disposition towards them. For example, P10 states that “Qualitative data are non-explainable data. Scientists who are based on such data remain at a superficial level; they cannot proceed deeper”. We will elaborate (d) during our analysis of the next question.

**Question 6.** Are scientific disciplines that study lower organizational levels (e.g., the subatomic/atomic or molecular level in regard to physics and molecular biology or genetics in regard to biology) more important than disciplines that study higher organizational levels (e.g., physics of liquids or gases and ecology, respectively)?

Almost all teachers (12 out of 14) agree with the informed questionnaires’ position that scientific disciplines focusing on lower and higher organizational levels are equally important. They also agree with the informed justification that in some natural sciences, such as biology, answering questions that focus on a concrete organizational level (e.g., questions focusing at the organism level, such as why a specific organism has a certain characteristic) requires knowledge from branches of biology that study lower (e.g., molecular biology and genetics) and higher organizational levels (e.g., ecology).

When, however, we ask these teachers to explain why they agree with this questionnaires’ justification, they overlook the notion of three organizational levels and focus only on two. Needless to say, participants are not familiar with explanations based on three organizational levels because such explanations are only met in biology and ignore the fact that systems at a higher level than that of the focus level are involved in determining ultimate causes, whereas lower level systems determine proximate causes.

Nevertheless, even if they were aware of biological knowledge, they would have serious difficulties in capturing the explanatory interplay of levels in biology. There are three main reasons for this. First, physics teachers are prone to the assumption of the ontological closeness of physical systems. For example, P5 states that ecosystem studies cannot involve events that occur at the level of biochemistry; to justify this postulate, he recalls physical studies: “when we study bodies’ motion”, he mentions, “we don’t study the spin of electrons”. Thus, it is rather hard for physics teachers to change this assumption in favour of another that lies behind the three-level biological explanatory scheme; namely, the ontological openness of biological systems.

Second, many teachers, probably influenced again by the epistemology of Newtonian physics, have reductionist ideas in their minds, which are not favourable to or appropriate for understanding how higher organizational levels than the focus level can afford explanations. For example, P10 claims that in biology, the microcosm (meaning biochemistry) is applied to the macrocosm; thus, he tends to believe that higher organizational levels cannot determine processes occurring at lower levels. P4 agrees with the notion that the proper scientific method is analytical, and P9 along with

P13 agree with P4's methodological reductionism when he says that "the deeper someone goes into the composition of matter, the more she knows about these facts". Apparently, these participants have conceptions about the scientific method that are opposed to the nature of the biological method and the resulting blending of reductionist and holistic insights in forming biological explanations.

Third, many teachers encounter serious difficulties in understanding the meaning of 'organizational level' and what this notion implies for the nature of explanations that employ relations among different levels. Certainly, these difficulties have also repercussions on how the Newtonian two-level explanatory framework is applied. Thus, when these teachers refer to theoretical constructs that are related to different organizational levels, such as Boyle's law (focus level) and the kinetic theory of gases (lower level), they mainly use the terms "macrocosm" and "microcosm" and argue that the occurrences in the microcosm and in the macrocosm are equally important. However, when we ask these teachers to tell us whether Boyle's law is somehow associated with the kinetic theory of gases, a few of them (e.g., P2 and P14) respond negatively, whereas others (e.g., P1, P3, and P5) overlook how explanatory reductionism works and share the view that Boyle's law explains the kinetic theory of gases and the latter explains the former.

Unavoidably, this confusion with reductionism makes it difficult for participants to understand the NOS tenet that scientific laws describe natural phenomena, while scientific theories explain those phenomena. P5, for example, argues that (a) Boyle's law explains the behaviour of gases in isothermal changes and describes the relationship between the pressure and volume of a gas and (b) the kinetic theory of gases describes and explains the behaviour of gases. P3 also agrees with most of the P5's ideas and, answering the question of what exactly Boyle's law explains, he states that this law explains the relation between the variables; i.e., "why if we reduce the volume, the pressure will be increased". Apparently, P5 and P3 along with other participants misconceive the current NOS distinction between scientific laws and theories because they use the terms 'describe' and 'explain' indiscriminately and interchangeably. This kind of use impedes participants from understanding the meaning of 'organizational level' and the causal relation between different organization levels and mostly results from the way in which Newtonian physics combines descriptive statements with deductive-nomological explanations. Participants are prone to these 'formal' explanations and have difficulties in understanding aspects of 'bathogeneous' explanations, which indicate differences between the terms 'describe' and 'explain'.

### **Conclusions and implications for science education**

Participants lack an elaborated knowledge of topics regarding the nature of the sciences and, although at the beginning of our research they admit their ignorance about biological topics, they do not hesitate to discuss NOTSs questions concerning biology. This is indeed feasible because most of the participants answer these questions from a rather normative viewpoint that favours essentialist and universalist NOTSs views (Fourtounis, 2005). In particular, the teachers focus on what a science should be if it is to be called 'science' and answer questions of what a science is by defining beforehand what can be referred to as 'essence' of science.

This priority given to the essence of science over the existence of specific sciences calls the participants to search for a priori criteria that may distinguish sciences from non-sciences in the science they know best; namely, Newtonian physics. Thus, while until now, research has shown that science teachers possess heterogeneous, fluid, incoherent and rather eclectic aspects of NOS (Abd-El-Khalick & BouJaoude, 1997; Apostolou & Koulaidis, 2010), our study demonstrates that behind these aspects may be found homogeneous NOTSs conceptions. In our case (i.e., the case of physics teachers), these conceptions stem from how participants understand the nature of school physics and have assimilated positivistic aspects of science, given that school physics promotes the Newtonian worldview and that positivism has flourished in academic circles worldwide (Caldwell, 1980; Frodeman, 1995).

Certainly, these findings do not imply that the participating teachers are rigidly committed to a coherent and consistent philosophical position. They fail to understand essential features of Newtonian science, possess many misunderstandings about key epistemological terms and are confronted with contradictions when their reasoning about some NOTSs epistemological topics does not comply with the use of positivism in capturing other NOTSs topics.

The fact that physics teachers understand the nature of the sciences from the perspective of how they understand their own science has two major consequences. The first consequence is that serious misunderstandings regarding the nature of biology are induced because participants project upon biology epistemological characteristics that biology does not possess. Remarkably, while the participants tend to erroneously equate the nature of physics with the nature of biology, they are not impeded from stating at least a few differences. On this point, two troublesome concerns appear. First, some teachers conceive these differences within an improper homogeneous framework. For example, while recognizing that biology possesses lower predictability than physics, they hold that both biology and physics face similar difficulties in forecasting future events. Second, some teachers consider the differences between physics and biology as radical. However, these teachers resort to a pre-Darwinian (non-scientific) way of thinking or have disparaging images of biology (e.g., the misleading view of biology as a soft science) that distort the very nature of biology and may have repercussions for their understanding of biological topics. The latter is important because Greek physics teachers are supposed to possess the appropriate qualifications to teach not only physics but also biology in secondary education schools. Needless to say, our research findings show these qualifications to be questionable.

The other major consequence resulting from the understanding of the NOTSs from the perspective of Newtonian (school) physics is the induction of serious misunderstandings concerning several NOS items. For example, the triptych deductive reasoning-testability-quantification embraces all of physical (Newtonian) knowledge, and participants' belief in this triptych underlies their misunderstanding that experiment is a necessary methodological step for the acquisition of validated scientific knowledge. Participants also encounter significant difficulties in understanding the distinction between qualitative and quantitative data because all physics data are quantitative; therefore, they are forced to believe that non-experimental research based on descriptive studies and qualitative data is non-scientific.

Domain-specific NOS conceptions that are erroneously considered domain-general may underlie learners' misconceptions about the current NOS items; in addition,

important domain-specific NOS conceptions that underpin the understanding of domain-general NOS items may not be present. For example behind learners' erroneous belief in the necessity of experimental implementation, and in the absence of descriptive research studies, there may be found learners' ignorance of how historic-hermeneutical scientific studies differ from Newtonian reasoning. Moreover, behind learners' difficulties in understanding that lower level generalities such as the kinetic theory of gases explain phenomena described by higher level generalities such as Boyle's law may be found misconceptions of how reductionism works in physics or a total lack of important insights regarding what organizational levels are and how they relate to each other in the frame of 'scientific explanation'.

In this light, we will discuss the implications of our research for the current state of the NOS field. Regardless of the intensity of the debate between domain-specific and domain-general researchers, the latter researchers admit that it is time for domain-specific NOS definitions to enter the NOS field and complement the current agenda (Kampourakis, 2016). In Abd-El-Khalick's words: "...the two approaches are complementary and synergistic... current consensual NOS aspects serve as foundational understandings that could be further refined and nuanced through context-specific explorations..." (Abd-El-Khalick, 2012, p. 365). A dialogue among NOS researchers has also been implicitly carried out, and essays have been published (e.g., Kampourakis, 2016) seeking a consensus on how domain-specific NOS definitions can be introduced into the current agenda and on what this may imply for instruction on NOS issues.

Our research focuses on how a domain-specific approach to NOS can be synergistic and complementary to the current domain-general one by elaborating on the insight of Schizas, Psillos, & Stamou (2016). that domain-specific or NOTSs definitions involve more thorough elaborations of the question of what is science than domain-general definitions and may supplement the NOS content knowledge of the latter definitions with causal knowledge. This insight proves beneficial in uncovering and treating learners' NOS conceptions because current NOS research is mostly descriptive, with rather weak explanatory power.

In some respect, Lederman recognizes this problem when he states that the mechanisms behind how learners' NOS conceptions change over time are unknown (Lederman, 2007) or when he introduces explanatory research questions into the critical lines of NOS research that need to be pursued in the future (Lederman, 2006). Additionally, the quest for explanations may lie behind the turn of current NOS research towards relating learners' NOS conceptions to demographic or social variables (e.g., Dogan & Abd-El-Khalick, 2008; Deng, Chai, Tsai, & Lin, 2014; Karaman, 2017; Ozkal, Tekkaya, Sungur, Cakiroglu, & Cakiroglu, 2011; Wen, Kuo, Tsai, & Chang, 2010).

More to the point, the current NOS research encounters difficulties in explaining why students and teachers have these or those NOS conceptions/misconceptions because the consensus (domain-general) NOS view upon which it is based is decontextualized from larger conceptual wholes and in the end isolated from modern sources that serve the explanatory requests of humanitarian/social sciences (Latour, 2012). Certainly, one such source is nature, defined in the frame of our research as the

peculiar ontological/methodological/epistemological features of the discipline-specific scientific research object or as the particular background assumptions lying behind the declarative and procedural scientific knowledge taught in school environments.

While this decontextualization or isolation lies behind critics against the domain-general NOS agenda, which pinpoint the individualistic/stereotypic character of the current NOS list items (Allchin, 2011; van Dijk, 2011), it should not be forgotten that the current NOS items are not simply treated as being parts of a list but are discussed in the frame of their instantiations in different disciplines (Schwartz, Lederman, & Abd-El-Khalick, 2012). Despite these beneficial features, however, the current NOS research agenda can hardly bring to light learners' misunderstandings about the specific nature of scientific disciplines. Thus, by employing a complementary NOTSS agenda, the NOS field will be able to uncover these misunderstandings and employ the important explanatory role of NOTSS definitions in the process of understanding learners' misconceptions.

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## Appendix

Three items comprising the questionnaire used in the present study are quoted below. These items focus on differences between the classical (Newtonian) physics and neo-Darwinian biology concerning the existence or absence of scientific laws (Question 1), the certainty of scientific predictions (Question 3) and the nature of scientific explanation (Question 5). Each item presents respondents with a statement (position) coupled with several reasoned viewpoints (justifications) to choose from. Additionally, following Abd-El-Khalick & BouJaoude, (1997) as well Dogan & Abd-El-Khalick, (2008), we complemented each item with an open-ended choice that allows respondents to express ideas or viewpoints different from those provided for each item. This additional position (not shown in the items below) is expressed as follows: "None of the above choices fits my basic viewpoint. My basic viewpoint is (please explain your viewpoint in the space provided below):" (Dogan & Abd-El-Khalick, 2008, p. 1108). Finally, the questionnaire's justifications were categorized as representing informed (I) and non-informed (NI) respondents' views.

**Question 1.** Do all natural sciences possess scientific laws?

Your position is

**All natural sciences possess scientific laws**

Justification:

(NI)A. Because all natural sciences identify sequences of natural facts, in which a fact results necessarily from another fact. These sequences are expressed in the form of generalizations called scientific laws (e.g. for each physical body or organism it is true that if A occurs then B will necessarily occur). As examples we could mention Newton's and Mendel's laws in physics and biology, respectively.

(NI)B. Because in each natural science, scientists formulate scientific hypotheses, which if they are proven to be true they are generalized and become theories, which in turn, if they are further proven to be true, are further generalized and become laws.

**There are natural sciences that do NOT possess scientific laws**

Justification:

(NI)C. Because some natural sciences are immature compared to nomothetic sciences such as physics. Biology for example does not involve laws because it is still an immature science.

(I)D. Because some natural sciences such as biology cannot formulate laws. This is because biological systems are subject to the process of biological evolution, which generates new and unexpected facts. Thus, there are no invariant sequences of facts referred to as laws that can be applied to all biological systems, such as cells, organisms and the like.

**Question 3.** Can natural sciences make certain and secure predictions?

Your position is

**Natural sciences can make certain and secure predictions**

Justification:

**(NI)A.** Because in each case prediction is based on explanation. For example, if we can explain how a physical or biological system behaves then we can predict how this system will behave in the future with certainty and security.

**(NI)B.** Because in each case the behavior of physical and biological systems is subordinated to physical and biological laws. If we know the initial state of these systems we can use these laws to predict their future states with certainty and security.

### **Natural sciences CANNOT make certain and secure predictions**

Justification:

**(NI)C.** Because in both classical (Newtonian) physics and biology non-predictable events can occur that change the predictive outcome.

**(ID).** It depends. For example, classical (Newtonian) physics can make certain and secure conditions because it knows everything concerning the physical system under study. Biology, however, cannot make certain and secure predictions because non-predictable and new events can occur in both the environment of the biological system and the biological system itself. Apparently, these events change the predictive outcome.

**Question 5.** A physicist investigates the causes of a physical phenomenon such as the expansion of metals in summer and a biologist searches for the causes of a biological phenomenon such as the migration of insectivorous birds from temperate to subtropical and tropical areas in the autumn. Does the physicist think like the biologist?

Your position is

**The physicist thinks similarly to the biologist.**

Justification:

**(NI)A.** Because the explanation in both cases concerns how these phenomena occur. Both the physicist and biologist seek for the mechanisms that cause the phenomena and attempt to describe a sequence of events that take place in the interior of the metal and the organism, respectively.

**The physicist does NOT think similarly to the biologist.**

Justification:

**(NI)C.** Because there are types of explanations in biology that are not present in physics. These explanations ascribe intentions and purposes to organisms. For example, insectivorous birds migrate from temperate to subtropical and tropical areas in the autumn because they want to find food, to overcome the unfavorable climate conditions, to reproduce, and so on.

**(ID).** Because biological explanations involve not only mechanisms that cause the phenomenon under study but also narrations of historical events. Thus apart from describing the mechanisms that underlie the behavior of migratory flight, the biologist should narrate a story in regard to how the insectivorous birds manifested this behavior in the past.