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Constructing Scientific Explanations: a System of Analysis for Students' Explanations

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Abstract This article describes a system of analysis aimed at characterizing students' scientific explanations. Science education literature and reform documents have been highlighting the importance of scientific explanations for students' conceptual understanding and for their understanding of the nature of scientific knowledge. Nevertheless, and despite general agreement regarding the potential of having students construct their own explanations, a consensual notion of scientific explanation has still not been reached. As a result, within science education literature, there are several frameworks defining scientific explanations, with different foci as well as different notions of what accounts as a *good* explanation. Considering this, and based on a more ample project, we developed a system of analysis to characterize students' explanations. It was conceptualized and developed based on theories and models of scientific explanations, science education literature, and from examples of students' explanations collected by an open-ended questionnaire. With this paper, it is our goal to present the system of analysis, illustrating it with specific examples of students' collected explanations. In addition, we expect to point out its adequacy and utility for analyzing and characterizing students' scientific explanations as well as for tracing their progression.

Keywords Scientific explanations · Students' explanations · System of analysis · Science education

Introduction

Science education literature and several reform documents on science education in Europe and North America have been addressing the importance of involving students in the construction of their own scientific explanations. Two main arguments are the importance of scientific explanations for improving students' conceptual understanding (Braaten and Windschitl 2011;

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McCain 2015; NRC 2012; Norris et al. 2005; Osborne and Patterson 2011) and the importance of involving students with authentic practices of science for facilitating learning about the nature of scientific knowledge (McCain 2015; NRC 2012).

However, despite general agreement regarding the potential of having students construct their own explanations, a consensual notion of scientific explanations has still not been reached (Braaten and Windschitl 2011; Brigandt 2016; McCain 2015; Osborne and Patterson 2011). As a result, within science education literature, there are several frameworks defining scientific explanations (Rönnebeck et al. 2016). They have different foci as well as different notions of what accounts as a *good* explanation. Some of these frameworks use explanations as artifacts to assess students' conceptual ideas and students' reasoning (e.g., Jördens et al. 2016; Taber and Watt 2000; Watson et al. 1997; Yan and Talanquer 2015). Other frameworks use explanations and argumentation interchangeably. In such studies (e.g., Berland and Reiser 2009; Ford and Wargo 2012; McNeill et al. 2006; Ruiz-Primo et al. 2010; Songer and Gotwals 2012; Yang and Wang 2014), the explanation serves to support the relationship between evidence and a certain claim, assuming that science explains natural phenomena by gathering evidence and making arguments based on the evidence (Brigandt 2016). Others look into the act of explaining, i.e., to communicate an explanation to others) for exploring students' science communication competence (e.g., Kulgemeyer and Schecker 2013). In addition, few studies focus on explanation as a causal account that describes what happens, based on theoretical ideas of science of how and why it happens. Considering this, more work is still needed to characterize students' scientific explanation in order to be able to support students' learning.

This is the goal of this paper—to present a system of analysis of students' scientific explanations. For that, we will first describe the process of construction and how we used it to categorize students' answers, and second, we will present a categorization of students' answers and their distribution within a sample of 189 eighth grade students. This paper will start with a definition of scientific explanation in order to identify its key characteristics. From the many competing theories and models, we adopted the causal model (Salmon 1984; Strevens 2008; Woodward 2003) and the unification model (Friedman 1974; Kitcher 1989). The first model is useful for its inputs on the underlying causes of phenomena, and the second one provides us with a broad account concerning *big science ideas* used for making sense of natural phenomenon. Based on the two models, we will present our framework of what represents a good scientific explanation, which was the starting point for developing our system of analysis. We will illustrate the system of analysis using examples from the students' answers Then, we will use the system of analysis for categorizing students' answers and for describing the distribution of different categories of explanations among the student samples. Lastly, based on the qualitative and quantitative analysis, we will discuss students' difficulties concerning the construction of a scientific explanation and the adequacy of the system of analysis for characterizing students' scientific explanations and for tracing their progression.

Defining Scientific Explanation for Science Education

Explanations vary according to the nature of the questions that they intend to answer, to the different purposes they serve, and to the context in which they are provided (Gilbert et al. 1998a, b; Norris et al. 2005; Yeo and Gilbert 2014). Notwithstanding, they do have different usages across different contexts such as everyday life and science, and they serve different purposes, namely, providing requested information or a description, clarifying a point of view or a particular idea, justifying an action or belief, supporting claims, or providing a sequence of causes for an event (Gilbert et al. 1998a, b; Norris et al. 2005).

In science, explanations present with some particular characteristics. First, they tend to be more systematic, deeper, and more accurate than common sense explanations (Woodward 2014). And second, they aim to make sense of a phenomenon taking into consideration other scientific facts or formulating new theories to account for the behavior of a new phenomenon (Osborne and Patterson 2011). Successful scientific explanations increase our understanding of the natural world (Strevens 2008), making sense of why a natural phenomenon occurs, how it comes about, and why it persists (McCain 2015). These characteristics make science explanations central within science practice and, consequently, in science education (Braaten and Windschitl 2011).

Despite the enormous contributions that were made regarding a model of scientific explanations, the concept is still not clear or unproblematic (Woodward 2014). This is not surprising considering the many activities involved in the construction of explanations and the differences that exist in it. When facing these difficulties, many authors pose that rather than looking for one singular theory of explanation, efforts should be conducted to illuminate the virtues of various theories across the different areas of scientific inquiry (Salmon 1984, 1989; Strevens 2008; Woodward 2014).

Philosophers of science have been developing theories and models of scientific explanation, and important contributions were made adding to the discussion about its structure, as well as the strengths and weaknesses of its propositions (Salmon 1989; Woodward 2014). Hempel and Oppenheim (1948) made an earlier attempt to define scientific explanations by presenting a *deductive–nomological* model. According to the authors, this explanation is successful when the argument is logically deduced from the antecedent facts and laws; that is why, it is considered a deductive model. For instance, we can explain the length of the shadow cast by a flagpole by deducing it from a set of facts (i.e., length of the flagpole and the angle of the sun) together with the relevant laws of optics. However, not only arguments logically deduced from other facts and laws account as explanations, and, in fact, the *deductive–nomological* model fails to solve some of the problems, namely, it does not respect the asymmetrical relationship of the explanation. Actually, this model implies that the explanation should be a symmetrical relationship, because, in fact, we cannot explain the length of the flagpole by the length of its shadow but only deductively infer its height. Also, there are some other problems that this model does not account for, which challenges the logical and empirical emphasis of the Hempel and Oppenheimer model and require other models; for instance, models that pay attention to the consequences, functions, and purposes of phenomena (Kitcher 1989).

Over the last decades, new perspectives have arisen, namely, constructivist perspectives, which started challenging the logical and empirical emphasis of the Hempel and Oppenheimer model. It is not our goal to explore that discussion here but rather to highlight some aspects that we consider relevant for our framework. More recent models of explanations tend to fall into one of two broad models: the causal explanation model and the unification model. The causal explanation model focuses on the nature of explanations stressing the importance of identifying the underlying causes beyond the phenomenon in order to understand how and why a particular phenomenon behaves like it does (Salmon 1984; Strevens 2008; Woodward 2003). The unification model relies on the *big ideas* of science to provide a unified framework to understand a wide range of related phenomena (Friedman 1974; Kitcher 1989).

Consistent with the causal explanation model (Salmon 1984; Strevens 2008; Woodward 2003), events can only be explained by tracing the story of their causes. Although deductive arguments may also be involved, the causal accounts rely on the relevant causes that produce the phenomenon and on the relationship between them (Strevens 2008). Referring back to the example of the flagpole, the length of the shadow is not a relevant cause that explains the height of the flagpole. One critical issue in a causal model is that an explanation does not intend to show that the phenomenon being explained is correct, but rather to trace its causal story (Brigandt 2016). For example, we explain how a chemical reaction occurs by specifying the nature and the properties of all the entities involved and by describing the events in which they participate (Thagard 2007). Although this may seem to be an unproblematic idea, deciding on which causal factors and the type of causal relations account as propositions, it is not entirely straightforward. Much of the discussion around the notion of causality gave rise to several different theories/models of causation (Salmon 1984; Strevens 2008; Thagard 2007; Woodward 2003). Despite this discussion, the truth is that many of the scientific explanations are causal (Salmon 1984; Strevens 2008) and for decades, the causal explanation models have enjoyed great popularity in the science and philosophy of science communities under the argument that causal facts are a critical part of the natural phenomena (Salmon 1984; Woodward 2003).

The unification model has its roots in the work of Friedman (1974) who maintained that a model of explanations must tell how explanations promote understanding. Also, in such a model, the understanding increases as several distinct natural phenomena are linked by big ideas. This model emerges from the idea that science seeks to explain natural phenomena through building comprehensive ideas that connect various aspects of the universe. According to Kitcher (1989), who later developed this model, the explanatory force of an account lies in the potential of its theoretical framework to unify seemingly unrelated phenomena and to organize knowledge within a comprehensive, coherent explanatory framework (for instance, kinetic molecular theory for understanding why the water in a puddle evaporates and why a ball will deflate at low temperatures). In other words, the same assumption is used again and again to derive different facts, reducing the arbitrariness of the phenomenon (Woodward 2003).

Neither of these models is mutually exclusive. They can be used together: the unification model provides the theoretical groundwork for the explanation and the causal explanation model provides the sequence of the information that tells the causal story of the phenomenon through a coherent and progressive way. Both models are of particular importance for science education. First, the unification model seeks to explain natural phenomena with as few scientific ideas as possible. One of the goals of science education is to provide students with the big ideas of science that can be used to grasp the essentials of diverse phenomena that apply globally to phenomena, not just locally (Braaten and Windschitl 2011; Brewer et al. 1998). This perspective, widely accepted and welcomed in science education reforms (Harlen 2015; NCR 2012; Osborne and Dillon 2008), recognizes that big ideas have "explanatory power in relation to a large number of objects, events, and phenomena that are encountered by students in their lives during and after their school years" (Harlen 2015, p. 14) and that they can be used to construct new scientific explanations.

Second, while involved in identifying a causal explanation for a phenomenon, students are prompted to infer about the underlying causes and to discover the structural connections of phenomena in the world. In doing so, students develop a deeper understanding of natural phenomena rather than a superficial generalization from direct observations (Grotzer 2003; Windschitl et al. 2008). Furthermore, constructing explanations that require causal reasoning positively contributes to the understanding of the nature of explanations and to the idea that explanations in science are tentative accounts for making sense of natural phenomena (Braaten and Windschitl 2011; Grotzer 2003; Perkins and Grotzer 2005; Ohlsson 2002).

Therefore, both models not only provide a good understanding of the logical structure of scientific explanations, but they also positively align with important aims of science education. Indeed, a number of frameworks about students' scientific explanations were informed by these models (e.g., Braaten and Windschitl 2011; Brewer et al. 1998; Tang 2016). In fact, our idea of scientific explanation has much in common with Braaten and Windschitl's (2011) framework that states an explanation involves the construction of causal stories that makes sense of phenomena by describing what happens and using the big ideas of science to theorize about how and why it happens. As expected, students' explanations will be simpler than scientific explanations. Despite this, if students can learn the logical structure of scientific explanations, they can engage in scientific practices of constructing better explanations; consequently, these models are of particular importance for science education (Braaten and Windschitl 2011). However, we feel that there is also a need for a system of analysis that covers in greater detail the features of students' explanations—identifying their needs and introducing the representational levels—and is fundamental to explaining natural phenomena related to the particulate nature of matter and areas where students experience difficulties (Taber 2013). In the next section, we will present the development of our framework for conceptualizing the quality of scientific explanations that builds from both the causal models and the unification models.

Key Elements of a Good Explanation

In the previous section, we defined scientific explanation and conceptualized its logical structure according to two models from the Philosophy of Science. In this section, we will conceptualize a good scientific explanation, based on the framework of Braaten and Windschitl (2011).

The construction of scientific explanations requires that students provide a conceptual framework for the observed phenomenon, to identify the relevant information, to infer on the unobservable world, to grasp underlying causes, and to establish a logical connection between these causes. In addition, it requires students to explore and use the big ideas of science for understanding how and why a particular phenomenon occurs. In order to be considered a good scientific explanation, an account has to present four dimensions: relevance, conceptual framework, causality, and the appropriate level of representation. Students often face difficulties with each one of these dimensions (Faria et al. 2014; Grotzer 2003; Kang et al. 2014; Zangori et al. 2015). Thus, these dimensions are critical issues that must be taken into account in assessing students' explanations and their evolution in the construction of better explanations. Below, we will describe the four dimensions, their role in the construction of a good scientific explanation, and the difficulties faced by the students.

First, the information presented in good scientific explanations must be relevant to the phenomenon. Relevance is an essential feature of scientific explanations in the causal model of explanation (e.g., Salmon 1984, 1989; Strevens 2008). According to these authors, only the relevant information must be considered. Other authors, such as Brewer et al. (1998), Grotzer's (2003), and Keil's (2006) state that from an early age, children are able to provide very complete accounts to explain particular events. Nevertheless, student's explanations are frequently not appropriate or are provided at a poor level of detail (Keil 2006) because students are unable to recognize which key aspects of the phenomenon are relevant and which ones must be isolated and highlighted (Faria et al. 2014; Russ et al. 2008). Since it is not straightforward for students to identify relevant information, yet relevance is a central issue of a well-succeeded explanation, we consider that a good explanation presents relevant information.

Second, an explanation must provide a conceptual framework based on the theoretical ideas of science. According to the unification model, an essential feature of scientific explanations is promoting a global understanding of the natural phenomena rather than a locally restricted understanding (Friedman 1974; Kitcher 1989). However, several studies (e.g., Ehrlén 2009; Faria et al. 2014; Taber and García-Franco 2010; Zangori et al. 2015) show that students frequently focus their attention on the details, have difficulty reducing apparently disconnected events into one global idea and determining "the intelligibility of the phenomena" (Brewer et al. 1998, p. 134). In fact, learning the science concepts does not necessarily imply that one can use them for understanding and explaining the natural phenomena. Rather, this requires conceptual understanding: the ability to use the ideas of science in building an explanation (McCain 2015; EC 2007). As such, looking at the ability of students to provide a conceptual explanatory framework was considered an important criterion for the analysis of the nature of students' constructed explanations.

Third, an explanation must trace the causal story of the phenomenon. We consider good explanation accounts those that present logical and coherent causal stories, in which the phenomenon is attributed to a set of underlying processes. As we previously discussed, a central idea in causal models is that an explanation is not a list of events preceding the phenomenon, rather in order to have explanatory force, the phenomenon has to be attributed to these events (Salmon 1984, 1989; Strevens 2008; Woodward 2003). Moreover, as Woodward (2003) argues, the virtues of a causal explanatory account lie in its depth as the more in-depth explanations are good causal stories about the ways in which the phenomenon happened. Depending on the phenomenon under explanation, and the context in which it is produced, a causal story can consist of simple linear relation between contiguous events or more complex relations, combining various causal factors interacting with each other (Grotzer 2003). Whereas almost all explanations of natural phenomena, even everyday explanations, consist of a complex chains of relations (Keil 2006; Ohlsson 2002), which requires one to infer intermediate causes, these complex chains of relations might be non-obvious (Grotzer 2003; Perkins and Grotzer 2005). Therefore, helping students uncover the causal relations behind an observed phenomenon is critical for making sense of and scientifically understanding it. Nevertheless, students frequently struggle when presenting a causal story in which events result from interactions among multiple components (Grotzer 2003; Perkins and Grotzer 2005). Studies (e.g., Faria et al. 2014; Kang et al. 2014; Parnafes 2012; Zangori et al. 2015) show that students' explanations often lack logic and consistency. In the presence of unfamiliar contexts, students tend to reduce the complexity of the information, focusing their attention on a restricted set of causes and ignoring other relevant ones. It is common that students complete their causal schemes with common sense ideas that they perceive form a compelling consistent sequence (Taber and García-Franco 2010). Finally, students tend to simplify their reasoning, forming simple and linear causal sequences where each cause is a consequence of another contiguous one, and where effects are felt in one direction only (Grotzer 2003; Perkins and Grotzer 2005). As a result, another key element to a good explanation is telling a causal story of the phenomena.

Fourth, a good causal story requires an appropriate level of representation (Strevens 2008). Most of the time, grasping the causal stories of natural phenomena involves moving beyond the surface and making inferences about abstract entities and processes (Grotzer 2003; Taber and García-Franco 2010; Yeo and Gilbert 2014; Windschitl et al. 2008). For instance, explaining how and why a breeze on a hot day makes us cooler (Strevens 2008) involves specifying the nature and the properties of the entities involved and describing its behavior and the events in which they participate at two distant but related levels of representation: the macroscopic—the level of the observable and tangible events—and the submicroscopic—the level of the unobservable and theoretical entities (Taber 2013; Talanquer 2011). Studies have shown that students have great difficulty conceptualizing phenomena in terms of each level and considering the connections between them. For example, Prain et al. (2009) reported students' difficulties in transferring macroscopic properties, such as expansion of heating, to the submicroscopic domain, such as discrete particles with empty space between them, moving faster or slower. The difficulties with these levels hinder students' ability to make sense of the observable phenomenon (Cheng and Brown 2015; Prain et al. 2009; Taber and García-Franco 2010; Yeo and Gilbert 2014) and to explore the underlying causes, resulting in fragmented explanations (Grotzer 2003). Therefore, using an adequate level of representation for explaining phenomena is considered one more key element of a good explanation.

Context and Data Collection

This particular study is part of a broader research project, whose goals are to know how students construct scientific explanations about chemical phenomena and to understand how they can be supported to improve their explanations. In the initial stage of this project, we applied a questionnaire to the participating students where they were required to construct explanations of natural phenomena. The purpose of the questionnaire was to characterize the quality of students' explanations before they were involved in a learning sequence based on inquiry activities in which they were explicitly engaged in the construction of scientific explanations about observed phenomena (the second stage) and in order to know whether the quality of their explanations improved.

The questionnaire consisted of four open-ended questions, which required that students constructed an explanation concerning a natural phenomenon that they observe in their everyday life or that they had previously explored in science lessons. Before the application of the questionnaire, we were assured that all students had already been taught the contents required, so that all had a fair chance to construct a good scientific explanation based on what they already learned in their physics and chemistry classes. Phenomena under explanation were the mixture of liquids with different densities (question 1), the dissolution of sugar in water (question 2), the condensation of water on the surface of a cold can (question 3), and the thermal expansion of a gas (question 4).

The questionnaire was undertaken by 189 students (97 female and 89 male) in eighth grade physics and chemistry classes. Students were studying in two different Portuguese public schools following the elementary physics and chemistry curriculum, which in Portugal consists of the last 3 years of the third cycle of basic education, from seventh to ninth grade (12—15 years). Two teachers were involved in the project: one of them has a Ph.D. in science education and 14 years of teaching practice; the other is a Ph.D. student in the same field, with 18 years of teaching practice.

The questionnaire was applied by the teachers in the presence of the first author, during a regular 45-min lesson. Both teachers followed the same procedure: first, they discussed with the students what *to explain* means, as in science classrooms, terms such as *to describe*, *to explain*, *to justify*, etc. are often used interchangeably (Braaten and Windschitl 2011; Horwood 1988), and then they defined what they considered a good explanation. Afterwards, teachers constructed, together with the whole class, a scientific explanation for the phenomenon: the diffusion of floral oil scent around a room. In this joint activity, students were explicitly prompted to describe what they observe/sense during the phenomenon; include what they think may have happened, but that they could not observe/sense; and identify the scientific ideas that they think would apply to the phenomenon; identify how the things that they cannot observe/sense are important to produce what they observed/sensed. After constructing the explanation for the phenomenon jointly, the students answered the questionnaire individually. Teachers provided occasional feedback and only for clarifying the meaning of some words or sentences. The first author observed all of the classes in which the questionnaire was applied, assuming a role of non-interventionist observer (Cohen et al. 2007).

Data Analysis

The main goals of this paper are as follows: first, to describe the process of construction of the system analysis and to illustrate how we used it to categorize students' answers; second, to discuss the adequacy and usefulness of the system in analyzing students' scientific explanations. For that, we used both qualitative and quantitative analyses. Qualitative analysis for categorizing students' answers and quantitative analysis to explore the consistency of the distribution of students' answers with the literature.

Qualitative Analysis

For the purpose of this study, we selected questions 2, 3, and 4. Question 1 was excluded from analysis, as most students presented an explanation not aligned with what had been required of them. In order to construct the questionnaire, we first reviewed the learning goals of the Portuguese elementary science curriculum of physics and chemistry (MEC 2013) to determine what target scientific concepts related to the phenomena should be considered in students' explanations. We then outlined a hypothetical good scientific explanation, considering students' curricular level and the framework of scientific explanation previously developed. Figure 1 illustrates for each one of the three questions the target scientific concepts, causal links, and representational levels that were considered.

Second, we constructed a system of analysis for coding students' answers. Initially, the first author closely read all of the students' answers. This initial analysis followed a constant comparison method (Strauss and Corbin 1998) in order to determine whether there were apparent patterns in students' constructed explanations. Each one of the collected answers was carefully read, compared, and tentatively assigned into groups of explanations based on its similar characteristics. The answers that were difficult to classify following the first reading were placed in a separate group and discussed with the other two authors. After a consensus was reached, these answers were assigned to one of the previous groups. The initial emergent categories were *non-explanation*, *pseudo-explanation*, and *explanation*. In order to distinguish *non-explanations* from potential explanations (at this phase, either *pseudo-explanation* or *explanation*), we asked three questions:

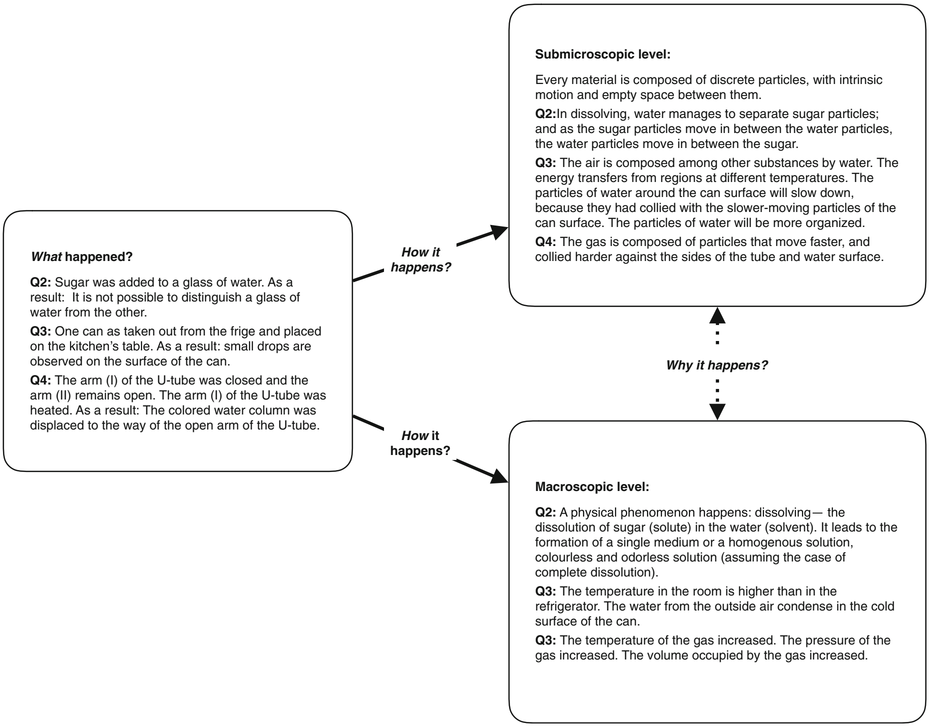

Fig. 1 The scheme of the scientific explanations for the three phenomena under analysis

1. Is the information presented in the students' explanation relevant to the phenomenon?
2. Do students use a conceptual framework to guide their explanations?
3. Are the students' accounts more than reformulations or restatements of what was previously exposed and provide additional insights, enabling a possible understanding of the phenomenon?

Every account that did not positively answer any one of the above questions was classified as non-explanations. With all *non-explanations* assigned to one of the groups, we then turned our attention to the accounts evidencing explanatory potential. At that point, we asked whether students' answers described what happens (i.e., *pseudo-explanation*) or, otherwise, account for how and why the phenomenon occurs (i.e., *explanations*). *Pseudo-explanation* was considered accounts that described the observed events yet paid little attention to the specific entities and the underlying processes that produced the phenomenon and that presented a poor causal scheme. *Explanations* were considered accounts that presented logical and coherent causal stories that relied on a conceptual framework, in which observed events are attributed to the underlying processes.

When all of the students' answers were classified into one of the three previous categories, a new closer re-reading of all of the answers was conducted. This process led us to a deeper analysis, in which we recognized particular characteristics within each one of the previous categories. This closer analysis, informed by the framework of a good explanation previously presented, allowed us to distinguish these particular characteristics within the students' explanations. Based on this, a second analysis was done with respect to the nature of causal relations and the representational level of explanation.

Regarding the nature of causal relations, four characteristics for distinguishing the nature of causal relations presented by the students were considered:

1. Students describe events in terms of patterns and surface features and do not make any suggestions of the processes involved; these descriptions are considered sufficient for explaining the phenomenon.
2. Students make regular associations of events or properties, with no close connection; the phenomenon is seen as a result of a single and determinant cause.
3. Students tell a simple causal story; this story is presented as a sequence of immediate causes and effects following only one direction; the phenomenon is seen as a result of many causes that are directly related to each other, without considering possible interconnections.
4. Students tell a complex causal story, coordinating multiple relations and considering possible mutual causes, conditions, or constraints.

In addition, we also considered the representational level of the explanations: (1) students' answers present a conceptualization at the macroscopic level, i.e., answers describe the observed events considering its macroscopic properties, namely, temperature, volume, homogeneity, etc. and (2) students' answers present a conceptualization at the submicroscopic level, inferring theoretical entities and underlying processes that are too small to be seen by the naked eye.

Based on both dimensions, we refined the previous categories *pseudo-explanation* and *explanation.* The category *pseudo-explanation* was further divided in two categories: the *descriptive explanations* (which includes two subcategories: *macro* and *mix descriptions*) and the *associative explanations*. The category *explanation* was split into the subcategories *simple* and *complex explanations*. Based on these categories, a system of analysis was constructed (see Fig. 2).

After constructing the system of analysis, the first author used it to code again all of the students' answers. In order to ensure the agreement among the three authors on which answer would be code in which categories, we considered the degree of agreement in the coding answers by calculating the ratio between the number of actual agreements and the number of possible agreements (Cohen et al. 2007). The second and third author used the system of analysis for classifying 10% of the students' answers. The answers were randomly and independently assigned to each one of the authors. A summary of the inter-rater agreement scores between the first and the second and between the first and the third author is given in Table 1.

After the second and third authors had classified the answers independently, the three authors met to compare and discuss their individual analyses and to refine minor aspects of the system of analysis (e.g., some terms and language usage). The inter-rater differences were mainly encountered when answers were difficult to understand due to language or grammar usage. In these circumstances, differences were resolved through a discussion between the three authors that led to mutual agreement among them.

Quantitative Analysis

In order to have a global image concerning the students' answers in all eight of the classes, we did a descriptive analysis of the answers. Despite collecting 189 student questionnaires, each one of the questions had a diverging number of valid answers (question 2—88,4% of the students' answers were considered valid and were analyzed; questions 3—81.4% of valid answers and question 4—74.6% of valid answers); non-valid answers were answers left blank

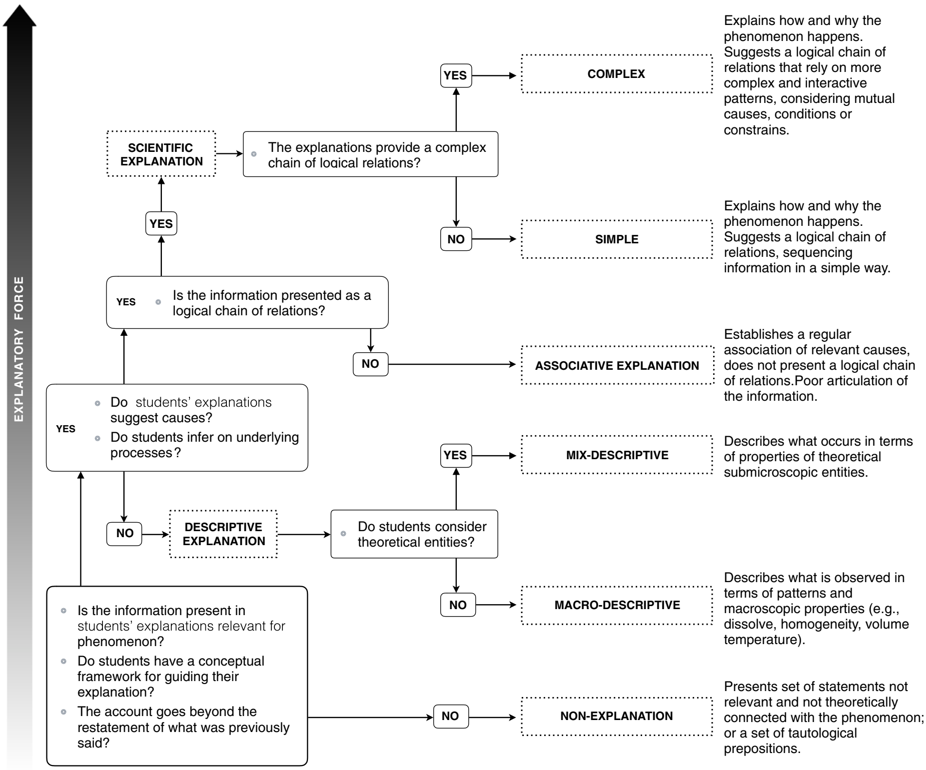

Fig. 2 The system of analysis for categorizing students' answers

and non-sense answers. In addition, we calculated the correlation of students' answers using Spearman's rank correlation coefficient and we compared the distribution of the categories of analysis in each question using Friedman non-parametric test for related samples.

Results

Qualitative Analysis of Students' Explanations

Non-explanations

For an account to be considered a potential explanation, it has to use relevant information, i.e., the events, entities, and its properties have to be relevant in producing the observed phenomenon. In addition, it has to present a conceptual framework based on major theories of science, instead of

Table 1 Inter-rater agreement for the system of analysis

	Inter-rater agreement		
Coders	Coding		
	Question 2	Question 3	Question 4
First and second authors	0.83	0.84	0.81
First and third authors	0.87	0.86	0.85

one framework that can only be applied locally to the observed events. Finally, the account has to go beyond the posed information proposing new insights, i.e., an account that goes beyond tautological ideas. Students' answers that do not positively respond to one of these claims were considered non-explanations. The following are examples of non-explanations:

> *As sugar melts in water and as water is denser than the sugar, we cannot see it by the naked eye* (*Student ACA20—Question 2*).
> *As he took the can from the fridge, the can still had some ice in it. Now, as the can was in an environment with a higher temperature, the ice melted* (*Student ACA08—Question 3*).
> *The air column moved to the end* (*II*), *because after heating up* [*the U-shaped tube*], *the portion of the air contained a lot of carbon dioxide* (*Student ACB12—Question 4*).

In each of the above accounts, students describe events such as "the portion of the air contained a lot of carbon dioxide," "sugar melts in water (…) water is denser," or "the can still had some ice in it (…) the ice melted." These events are not relevant to the phenomenon under explanation. Moreover, each of the above accounts also failed to present a conceptual framework based on canonical scientific ideas, namely, "a gas expands when it is heated," "the dissolution of sugar in water," or "the water from outside air condenses when it comes in contact with a cold surface." Since a conceptual core is absent, the framework's coherence is limited.

Accounts that indicate tautological ideas were also classified as non-explanations, such as the following:

> *As the hot air is at the extremity* (*I*) *the colored liquid goes into the extremity* (*II*). (*Student AIB02—Question 4*)
> *As both are equal. Despite one having sugar, it is impossible to distinguish one from another.* (*Student ACE14—Question 2*).

Each of the above examples evidence just a reformulation of what was previously stated, without providing any new insight. All of the information provided in each of the two instances had been presented in the legend of the texts or photos illustrating the question under analysis. Students drew upon this information to present an account, but they have not identified causes for the observed results. Accounts like these reflect tautological reasoning, relying on superficial ideas that have no explanatory force and were classified as non-explanations.

Descriptive Explanations

Descriptive explanations are those accounts that simply describe events preceding the phenomenon and do not discuss how these events are related to each other in bringing out the phenomenon. These descriptive explanations were classified as macro or mix descriptive, considering its level of representation.

Macro-Descriptive

Macro-descriptive explanations include answers based on common observations and description of patterns that merely picture the macroscopic properties or functions of the entities. The following are some instances of these types of explanations:

> *[The colored water column moves to the open side* (*II*)*] because the portion of the air at the end* (*I*) *increased its pressure and pushed the liquid to the "free" part of the tube* (*Student ACA06—Question 4*).
> *Mary cannot distinguish, as when one mixes water and sugar, it results in a homogeneous mixture. Homogeneous means that one cannot see the solution* (*Student ACE13—Question 2*).
> *As sugar is dissolved in water, there is no evidence that the glass containing the water in which sugar is dissolved is the glass containing sugar* (*Student ACA06—Question 2*).
> *As the can was cold, when it contacted the air, the air condensed.* (*Student AIB12—Question 3*).

In each of the above instances, relevant properties were identified for the phenomenon under explanation, namely, "the pressure increased," "the formation of homogeneous solution," "sugar dissolves in water," or "the condensation of the air," which were perceived as sufficient to explain the observed events. However, the identified properties remain at the macroscopic level of representation; these examples do not recognize that every material is composed of submicroscopic particles, with intrinsic motion. Each of the above samples focuses on what happened without grasping the causes for how and why it happened. For instance, students explained the displacement of the water column as a direct result of the increase in pressure, or that condensation occurs as a result of the contact with a "cooler surface," without disclosing the process by which these events came about. In the other examples, students recognized that sugar dissolves in water, forming a single medium, although no further information was presented about why the dissolving occurs. Therefore, these accounts were classified as macro-descriptive.

Mix-Descriptive

The *mix-descriptive explanations* include those answers that identify relevant entities that participate in the phenomenon and its properties even though the students do not use these ideas for inferring on the underlying processes, as well as on the causes and effects. Therefore, the accounts included in this category essentially remain descriptive. The following are some examples of such explanations:

> *Mary cannot distinguish, without tasting, which glass contains only water from the one that contains water and sugar, as the sugar dissolved in the water. So, she cannot distinguish between the two, since we cannot see it with the naked eye. However, we know that the water and sugar particles are there* (*Student ACC22—Question 2*).
> *Because the air particles dispersed, i.e., because they occupied more space* (*Student AIB15—Question 4*).
> *As air particles were attracted to the can, as the can was cold* (*Student ACA17—Question 3*).

Each of these accounts addresses relevant properties of the nature of entities involved, for instance, "every material is composed of discrete particles," "that we cannot see," "when heating up something," "particles (…) occupied more space," or "come together" if "something is cooler." Nevertheless, students did not use these ideas to disclose how the invoked entities took part in the underlying processes in order to produce the observed phenomenon. Each of the above instances focuses on predetermined theoretical ideas that the students merely asserted as facts. The phenomenon was approached from the point of view of a result, and these ideas are seen as sufficient enough to explain the phenomenon, which compromises the explanatory force of the students' accounts.

Additionally although the students recognized, in the first two examples, the submicroscopic level, they conceptualized it in terms of macroscopic ideas, for example, "they cannot be seen with the naked eye" or "they occupied more space." This was also a criterion of *mix-descriptive explanations*.

Associative Explanations

Associative explanations are those accounts that associate pieces of information yet fail to establish how the information is related, as can be appreciated in the following examples:

> *Because sugar particles have spread inside the water particles, occupying their empty spaces. So, there is no sugar on the bottom of the glass* (*Student ACB20—Question 2*).
> *Around the can, there were water particles. The temperature of the fridge and the air outside the fridge was different. While Sara was talking with her friend Marta, those water particles around the can become water drops due to the difference in temperature* (*Student AIB03—Question 3*).
> *By increasing the temperature, the pressure of particles also increases. By heating up the air, this exerts a greater pressure on the water particles, causing it to move more towards the end* (*II*) *of the tube* (*Student AIC23—Question 4*).

In the first example, the event "sugar particles occupied the empty spaces between the water particles" was seen as an isolated cause for dissolving, without disclosing other aspects of the nature of entities that led to this event, for instance, "particles have intrinsic motion." Similarly, in the last example, the pressure was seen as a direct result from an increase in temperature; the student actually repeats this idea twice. Apparently, the student does not recognize the intermediate events in which the entities participate, namely, that as temperature increases, particles' motion increases and collide more with each other, causing the pressure to increase. Although associations between the nature of the entities and its behavior were established, and insights about how the events came about were given, the causal story of the phenomenon remained fragmented. The second example goes further in explaining the condensation process that occurs on the surface of a cold can. The student did infer relevant underlying causes; for instance, differences in temperature can cause changes in the physical states of matter. Nevertheless, many gaps remain among the events in which the entities participate and the consequences of these events. For example, how does the difference in temperature cause "a change in the physical state of the water around the can." In general, these answers show evidence of an association of relevant properties, yet the phenomenon is still attributed to single causal isolated relation. In these accounts, students tend to over-generalize the causes involved constraining its explanatory force.

Explanations

As asserted before, for an account to be considered an explanation, it has to present relevant information and a conceptual framework, and it must trace the full causal story for how and why the phenomenon happens at the appropriate level of representation. Most of the time tracing such a story requires establishing complex causal chains and identifying interactive relationships among mutual events, constraints, or conditions. These explanations were classified as simple or complex explanations depending on if a sequence chain of contiguous cause-effect was presented or if a complex chain of interactions between several dynamic events interacted with each other was presented.

Simple Explanations

The following answers are instances of the linear-causal explanations:

> *Mary cannot distinguish, as after a period of time the sugar dissolved in the water. As sugar particles are always in motion and as there are empty spaces, sugar particles end up dissolving in the water. As a result, we cannot see the sugar in the water. That is the reason why Mary cannot distinguish one glass from the other glass* (*Student ACB16—Question 2*).
> *Because when the end* (*I*) *was being heated, the particles of the air became more agitated when they felt that the temperature was rising; the particles of air were pressed and so they started coming down causing it to go towards the end* (*II*) (*Student ACB18—Question 4*).

Each one of the above accounts was presented at the submicroscopic level, invoking relevant entities and its properties, and inferring on processes in which they are involved. In the first example, for instance, "water particles with intrinsic motion and empty spaces dissolves sugar particles" or, in the second instance, "temperature was rising," "particles became more agitated," causing "more pressure." Moreover, in the above accounts, the observed phenomenon was attributed to a sequence of immediate relations, following a linear path with no interactive relations between more than one event. For instance, in the first example, the sequence of events that takes place in the process of dissolving is due to one single entity "water" and the events in which it participates. Similarly, in the second example, to fully trace the causal story of this particular phenomenon, some conditions that interplay with the sequence of events must be considered, for instance: the tube is closed at the end I and open at the end II. Since each of the above answers lacked this feature, they were considered simple explanations.

Finally, some of the accounts included here suggest informal language. In the second example, for instance, the student refers to: "the particles of the air (…) *felt* that the temperature was rising." This account shows evidence of relevant information about the underlying processes and presents causal relations between the many events; however, considering that our aim is to characterize the nature of the students' explanation, this type of account was also considered a simple explanation.

Complex Explanations

The following answers are instances of interaction-causal explanations.

> *The column of air was displaced, because by closing and heating the end (I), the particles' agitation progressively increased and by hitting at each other and the walls of the tube, they created pressure, making the water move* (*Student ACA21*).

> *Maria cannot distinguish one glass from the other as sugar dissolve in water. As all particles are in constant motion, both corpuscles mixture with each other and occupy the empty spaces. As a result is impossible to see which glass contains sugar* (*Student ACE04*).

Each of the above answers represents instances of explanations that enable one to trace the full causal story of the observed phenomenon. To be a complex explanation, and despite the many features further considered, an account should reflect a logical causal chain that relies on complex interactive patterns, considering the several events and its conditions or constraints. Indeed, each of the above accounts reflects the interplay between events, for example, the first answer states, "because by closing and heating the end (I)," and similarly, the second example points out, "This will displace the water, because the other end is uncovered." The second example reflects the mutual processes of dissolving: the solvent particles move in between the solute particles and the solute particles move in between the solvent particles.

Each of the above accounts presents many features of an explanation: only relevant information is invoked, a conceptual framework that goes beyond the situational context is presented, the observed events at the macroscopic level are conceptualized regarding its properties and related in a causal manner, and the interconnected relation with the inferred processes at the submicroscopic level is highlighted. These accounts are close to our target explanation. They describe what happened and provide causal stories theorizing about how and why the phenomenon happened in that way, and in doing so, they reflect a process of making sense about the nature of the observed phenomenon, exhausting the many possible "whys."

Quantitative Analysis of Students' Explanations

Quantitative analysis of the explanations reveals that the quality of students' answers differed depending on the question asked and that this difference was statistically significant for a confidence level of 95% (Friedman test; $\chi^2(2) = 58{,}601$; $p = 0.000$). In addition, answers for each questions are not correlated (Rs $_{Q2\text{-}Q3} = 0{,}237$; Rs $_{Q2\text{-}Q4} = 0{,}350$; Rs $_{Q3\text{-}Q4} = 0{,}356$).

Figure 3 represents the distributions of students' scientific explanations for the three questions under analysis across levels of explanation. Concerning question 3, in particular, most of the answers were non-explanations (55,2% of all the answers for this question). This contrasts with the percentage of non-explanations for questions 2 and 4 (respectively, 15 and 22%). Furthermore, for question 3, students did not provide any explanation (either simple or complex). This contrasts with answers to questions 2 and 4 (simple explanation, respectively 2.4 and 4.3%; and complex explanation, respectively 1.2 and 1.4%).

For all three questions, students tended to present descriptive accounts (68.3% descriptive explanations for question 2, 36.2% for question 3, and 49.6% for question 4). However, concerning questions 2 and 3, the descriptions mostly represented the phenomenon at the macroscopic level (respectively, 60.5 and 88.1% of descriptive explanations), while in question 4, most answers are mix-descriptions (65.7% of descriptive explanations).

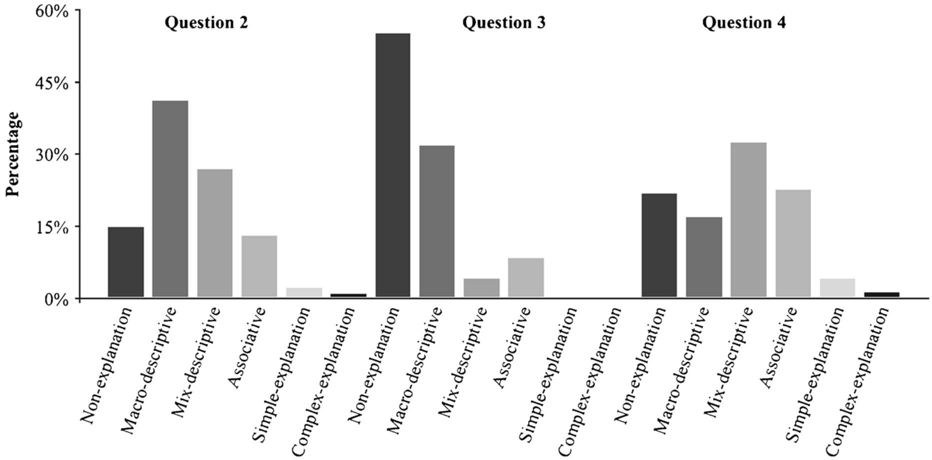

Fig. 3 Distribution of students' scientific explanations across levels of explanation

Discussion and Conclusions

Although scientific explanations play a central role in science education literature, research in this area has been endorsed by different conceptual frameworks considering different ideas of what constitutes a good scientific explanation, and within this, many different instruments of analysis have been proposed. Among the many proposals in the literature, explanations tend to be treated within two perspectives: (1) to assess students' conceptual ideas and students' reasoning regarding a particular scientific topic; in these cases, the quality of the explanation is assessed by considering scientific correctness of exposed ideas; the focus is on scientific content; (2) as a process of constructing and defending arguments; in these cases, the explanation is assessed by considering the use of appropriate and sufficient evidence and the strength of the arguments on why the evidence justifies the claim. Therefore, we find a gap in the literature related to the analysis of students' scientific explanations, specifically focused on conceptual framework, relevance, nature of causal relations, and level of representation. Considering that the construction of scientific explanations requires students to use "big ideas" of science for understanding how and why a particular phenomenon occurs, to infer on the unobservable world and to establish logical causal relations presented at an appropriate level of representation, we developed a system of analysis that takes into consideration all these elements.

This paper describes this system of analysis and how it was used to categorize students' explanations. Results show that very few students presented a scientific explanation with a higher level of explanatory force, i.e., one that tells the causal story of how and why one specific phenomenon occurs, using the big ideas of science and establishing complex systems of causal relations. Indeed, the majority of the students' answers were accounts that described what happened without proposing underlying causes or they just presented associations of information. These accounts reveal that students can propose a valid framework and identify relevant information. However, they face difficulty in organizing their ideas and structuring a progressive sequence of events; this difficulty constrains the construction of a causal and coherent story (Faria et al. 2014; Kang et al. 2014; Zangori et al. 2015). Aligned with other results (e.g., Grotzer 2003; Perkins and Grotzer 2005; Russ et al. 2008; Taber and García-Franco 2010), our results show that students tend to reduce the complexity of the information, focusing their attention on a restricted set of causes or filling in their explanations with fragmented information or common sense ideas; in other cases, students tended to simplify the causal story of the phenomena, by solely reporting single occurrences of events without attributing the causes. In fact, our results show that a great number of explanations were statements about a general explicit law, e.g., particles are more agitated, water condenses, water dissolves the sugar. These general laws are considered sufficient, by the students, for explaining observed phenomena. These results add strength to the idea that students often understand the theoretical concepts and can use them, i.e., they understand *what* without understanding the phenomenon itself, i.e., without understanding *how* and *why* (McCain 2015; Strevens 2013).

In addition, the quantitative analysis of the students' answers reveals that the quality of the students' explanations differed depending on the phenomenon under analysis. Regarding Q2 and Q3, most of the students' answers are macroscopic descriptions, while for Q4, the accounts mostly represent the phenomenon at the submicroscopic level. Additionally, concerning Q3, most of the students' answers are non-explanations, contrary to Q2 and Q4 where no student presented an explanation having the maximum level of explanatory power. These findings are in line with the evidence showing that students' thinking varies with the context, and that their conceptual knowledge is difficult to characterize (Russ et al. 2008, Taber and García-Franco 2010). Every student arrives to the science classroom with productive knowledge, and they may vary in how they apply that knowledge, so it is difficult to perceive what takes priority in particular cases (Siegler 1996). As a result, students may apply some knowledge in one context and a different knowledge in what seems like a similar context. With regard to our results, we have some suggestions for the in-subject discrepancies observed in the quality of students' accounts.

In Portuguese science curriculum (MEC 2013), during the seventh grade, the phenomena of dissolution (Q2) and of physical transformations and energy transfer (Q3) are first presented under a macroscopic conceptualization. Later, in the eighth grade, the particulate nature of matter is introduced and the same phenomena are revisited under a submicroscopic conceptualization. Physical transformations are now interpreted based on freedom of movement and on the proximity of the particles, and the freedom of movement is related to variations in temperature. The dissolution of substances is now related to the constant motion of particles and the empty space between them. However, the phenomenon of thermal expansion of a gas (Q4) is only introduced in the eighth grade, with the introduction of particulate nature of matter. In their attempt to make sense of observed phenomena (Q2 and Q3), students may be using macroscopic concepts which, in their perception, is relevant and sufficient enough to explain the phenomenon; however, they are unable to recognize the non-observable submicroscopic entities that lay beyond the observable. Apart from this, thermal expansion of a gas was never approached in school from a macroscopic perspective, which may account for the results—most of the answers at the submicroscopic level.

Students constantly test the viability of their ideas, and if they *fit* the observed phenomenon, they are perceived as sufficient to explain the phenomenon (Taber,, and García-Franco 2010; Parnafes 2012). For example, a study by Taber and García-Franco (2010) with secondary school students showed that a single student can explain apparently similar phenomena, such as the mixing of two substances, using different frameworks. For some phenomena, e.g., salt dissolving in water, students recognize causes and seek causal agents, yet for other phenomena, e.g., diffusion of vegetable dye in water, students do not identify the causes, and they will attribute events to the inherent nature of the materials, i.e., substances naturally react, because it is just how it happens.

For students to develop an integrated view of the phenomena, they have to shift between macroscopic and submicroscopic levels. Such explanations do not occur spontaneously, rather they have to be carefully supported and guided by the teacher for long enough periods of time (Taber 2013). Without this support, students can hardly relate their previous conceptions to each of these levels (macroscopic and submicroscopic), so "naturally," students will continue to reason according to a macroscopic conceptualization. Regarding Q3, in particular, the presented phenomenon is counter-intuitive (the idea that an ice cube melts outside the fridge is more intuitive than the idea that air condenses on the surface of a can). This particular characteristic poses increased difficulties for choosing a conceptual framework that students can use for telling a causal story. Research has shown that identifying ideas of science that can be used to make sense of a natural phenomenon is difficult for students (Tang 2016; Russ et al. 2008), even more when they are required to conciliate apparently disconnected phenomenon in one global idea. In these situations, students tend to use restricted and situational conceptual frameworks (Faria et al. 2014; Zangori et al. 2015).

Finally, the results presented here give strength to the system of analysis. The distribution of students' answers is consistent with the literature, illustrating the difficulties they face when involved in constructing their own scientific explanations. Additionally, the system of analysis proved useful for assessing the quality of the students' explanations, as well as for identifying their difficulties with basic dimensions when they are required to construct a good scientific explanation. Therefore, our results are aligned with other studies illustrating students' difficulties when involved in the construction of their own scientific explanations (e.g., Cheng and Brown 2015; Faria et al. 2014; Kang et al. 2014; Tang 2016; Yeo and Gilbert 2014; Zangori et al. 2015). Educational studies also suggest that students have to have real opportunities at being involved in the construction of their own explanations throughout their science classes in order to improve (NRC 2012; Tang 2016; Zangori et al. 2015). Many studies point out that science teaching practices are based on compartmentalized, not contextualized learning, experiences (Faria et al. 2014) providing the students with few opportunities for getting involved with authentic scientific practices. As a result, these teaching practices hinder the development of more abstract reasoning about complex processes (Perkins and Grotzer 2005; Zangori and Forbes 2015). Studies in this domain (e.g., Kang et al. 2014; NRC 2012; Parnafes 2012; Russ et al. 2008; Tang 2016; Zangori and Forbes 2015) show the importance of breaking down the process of learning to construct explanations at various levels of progressive difficulty. With the present system of analysis, we hope to contribute to support the systematic analysis of students' explanations, throughout the level of explanatory force, and to help teachers and educators in supporting students to improve their constructed explanations.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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