An empirical method for the study of scientists' explanations to students

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Abstract

Students in interdisciplinary science educations are faced with the challenge of combining knowledge and standards from different disciplines. To help them overcome this challenge it would be helpful to reflect more explicitly on what differences in epistemic aims there may be between the different disciplines. To aid further studies that will strengthen such discussions this paper outlines an empirical method that can be used to expose possible qualitative differences in explanations from different disciplines. The method is based on the use of science textbooks as sources of explanations. I will argue that it is important to be very clear about how explanations are identified in the sources if the aim of the study is to make a strong empirical claim about the nature of explanations. Following a discussion of similar studies (Z. Dagher, 1991; A. I. Woody, 2004a) I will present an alternative procedure for identifying explanations in written sources that suits the purposes of this study better. A pilot study is then presented to illustrate the method and its limitations.

> *The aim of physics at its most fundamental level is not just to describe the world but to explain why it is the way it is.*
>
> Steven Weinberg

1 Introduction

Within philosophy of science there has been considerable interest in scientific explanations for several decades. There is a general agreement in this literature that constructing and evaluating explanations is a very important part of what practicing scientist do, but there is less agreement on *how* and *why* they do it. Many of the classical studies of scientific explanations aim to answer the question of how scientists explain by giving a general account of the essential characteristics of every scientific explanation (Friedman, 1974; Hempel, 1965; Salmon, 1998). Against this overall project Van Fraassen argued that there are no interesting common features in explanations across all the sciences (Van Fraassen, 1980). Others have argued that although explanations are important in all the sciences, the standards for what counts as a *good* explanation can change as disciplines change over time (McMullin, 1993) and it is widely recognized that disciplines coexisting at one period of time have different standards for what counts as a good explanation (Godfrey-Smith, 2003, ch 13; Woodward, 2011; A. I. Woody, 2003).

Given that explanations play a key role in scientific practice, learning to construct and evaluate explanations should be an important part of any science education. This has also been recognized within the science education literature (Braaten & Windschitl, 2011) and researchers in this field have therefore taken an interest not only in scientific explanations given by scientists to their peers and how these differ from every day explanations but especially in explanations intended for students. One conclusion from this research is that there is a need for more explicit teaching in making high quality explanations (see for instance (Solomon, 1995) & (Peker & Wallace, 2011)).

Many studies in the science education literature refer to studies from other disciplines such as philosophy, linguistics or discourse analysis (Edgington & Barufaldi, 1995; Rowan, 1988; Unsworth, 2001) as a general framework for the development of a more detailed analysis of explanations from textbooks or teaching situations. It is interesting to note that the discussions about the potential paradigm dependence of the criteria for high quality explanations have been somewhat overlooked in the science education literature.

In this paper I will outline a methodology that can be used to study and compare explanations in different disciplines. In so doing I hope to provide a different philosophical input to the science education debates than the classical philosophy of science studies that focus on the general nature of scientific explanations.

The main aim of this paper is to formulate an empirical method based on gathering and analyzing practicing scientists' actual use of explanations in education that can be used to expose possible *qualitative differences in explanations from different scientific disciplines*. This method will provide a descriptive account of practicing scientists' use of explanations in educational settings that is sensitive both to differences in practices between different disciplines and to differences in practices between different educational levels.

Knowledge gained from such a study can for instance serve as a starting point for further studies aimed at addressing some of the difficulties that students in interdisciplinary university educations face when transferring knowledge from one subject to another (Christiansen & Rump, 2008).

2 Andrea Woody's account of explanations in chemistry

Empirical studies of explanations are rare in the philosophy of science literature. An important exception is the empirically based account of explanation in chemistry that has been developed by Andrea Woody (A. I. Woody, 2004a; A. Woody, 2004b). Although the aim of Woody's study of explanations is quite different from mine, it is interesting to discuss her general argument for choosing an empirical method.

2.1 Why choose an empirical method

Woody has chosen an empirical method for two reasons[1]. One is her wish to give a highly descriptive account of explanations in chemistry (A. I. Woody, 2004a, p. 17-18). The other reason is that she sees a flaw in the argumentation in earlier case based studies that she wants to avoid.

According to Woody the typical way to analyze explanations in philosophy of science has been through inductive arguments starting from a small set of paradigmatically successful explanations (2004a, p. 36). The structure of these inductive arguments can roughly be represented by what we might call the classical pattern of argument or just CP (*ibid.*):

1.1. *a* is a successful explanation of *b*
1.2. The basic, or most noteworthy, characteristics of *a* are {j,k,l,…}.
1.3. Members of the set {j,k,l,…} are (quasi)tokens of corresponding types {J,K,L, …}

Infer by generalization

C_{CP}: The requirements for successful explanation are {J,K,L, …}

We can now go on to test C_{cp} by analyzing other paradigmatically successful explanations.

Friedman (1974) seems to be using a version of this pattern when he argues that the kinetic theory of gasses, which is a "typical scientific theory" (p. 14), effects a significant unification of our view of nature. He then concludes that "this is the crucial property of scientific theories we are looking for; this is the essence of scientific explanation" (p. 15). Friedman deviates from the CP by omitting the last part, where you test your conclusion on a different case.

The easiest way to argue against conclusions drawn from CP is to find a paradigmatically successful explanation *c* whose characteristics are not (quasi)tokens of {J,K,L, …}. An example of this strategy can be found in (Weatherall, 2011) where an explanation of why inertial and gravitational mass are equal in Newtonian mechanics is discussed. Weatherall argues that the essential features of this explanation (and others like it) are not captured by any causal theory of explanations, neither by Kitcher's unificationist account nor by the Deductive-Nomological account of explanation. Thus it represents a counter example to the inductive foundations of these theories.

Woody's critique of this way of analyzing scientific explanations is that the justification for the choice of paradigmatically successful explanations is deficient. This would not be a problem if it was possible to identify a relatively large set of candidates that everyone (or at least all philosophers of science) would intuitively accept as successful explanations. But unfortunately we do not have such a set. This has led to what Woody sees as a rather pointless debate:

[1] Woody actually calls her method "semi-empirical"(A. I. Woody, 2004a). This seems reasonable given that her empirical material is limited to just one textbook. However there is nothing semi-empirical about the methodology employed in the study.

> **[Philosophers] quarrel famously over a set of reputed, but still disputed, "counter-examples": the flagpole and the shadow, the ink spill on the carpet, leukemia and radiation exposure, John Jones' recovery from pneumonia. This dispute cannot possibly be settled in this manner.** (A. I. Woody, 2004a, p. 15)

It seems then that claiming that a certain case is a good example of a successful explanation is far from trivial. This means that the choice of cases needs additional justification. According to Woody (2004a, p. 39), the only *theoretical* justification that can be offered for the choice of the examples is an appeal to pre-analytic intuitions about the general nature of (successful) explanations. However, Woody argues that that kind of justification would make the account viciously circular:

> **It is precisely the general nature of explanation […] we are attempting to determine via this argument. Thus either we are involved in a vicious form of circular reasoning or we need some independent means of justifying [this premise].** (A. I. Woody, 2004a, p. 39)

Hence Woody's second argument for choosing an empirical method is to avoid this kind of vicious circular reasoning (hereafter referred to as Woody's circularity objection). Here an empirical method means identifying sources of explanations that practicing scientists deem successful and extract the explanations from these. This way, according to Woody, it is possible to avoid the kind of vicious circular reasoning involved in the earlier studies.

The question is of course a) what sources to choose, and b) how to identify the explanations in the sources? Woody's answer to a) is that science textbooks are highly useful sources if used correctly (see (A. I. Woody, 2004a, pp. 18-19) for details). I agree with her on this, and in section 2.3 I will spell out the details of how they can be used for the purposes of this article.

With respect to b), Woody fails to give an explicit answer to how we can identify explanations in textbooks. In section 2.3 I will argue that this weakens her general argument. I will present my own answer in section 6.

Assuming (for now) that there is a good answer to these two questions at hand, will the empirical method developed here avoid Woody's circularity objection? To the extent that Woody's circularity objection is valid I believe the method outlined below will address the objection.

The methodology developed in this paper can be used to identify explanations from a given discipline with a certain *quality*, namely explanations that are accepted by practicing scientists from this discipline as good explanations to give to students. If the identification of these explanations was based on pre-analytic intuitions about the nature of explanations with this quality the study would certainly be viciously circular. But this is not what I propose. What I suggest is that the focus should be on explanations in sources that we have independent reason to believe contain *only* explanations with the desired quality. Thus I avoid the vicious *normative circle* where a normative claim about the nature of *good* explanations to give to students is based on intuitions about what constitutes a *good* explanation to give to students. However the argument is still based on a *descriptive* circle since I need to assume something about the nature of explanations in order to identify them in the sources. Thus the description of the explanations in the sources relies on an explicit or intuition based pre-analytic description of explanations that enables us to recognize explanations in the sources, so clearly my method involves circular reasoning. But this kind of circularity, which is present in any empirical investigation, is not vicious (Nersessian, 1995)

So if Woody's objection is interpreted as a reference to only the vicious *normative* circularity involved in earlier studies, the method developed here will not be targeted by the objection. This of course will only be the case if satisfactory answers to questions a) and b) can be provided along with independent reasons for why the chosen sources contain only the desired kind of explanations.

2.2 Identifying good sources

What would be a good source of explanations given to students by practicing scientists from a given discipline? Since my primary interest here is in explanations that are *widely accepted* within the discipline as being of high quality it seems reasonable to look mainly to written sources that have been through some kind of critical review. These kinds of written sources fall into two general categories: 1) peer reviewed journal articles and other documents that aim to convey novel results to practicing scientists, and 2) textbooks and other documents that aim to convey established knowledge from the discipline to students (among others).

Since widely accepted explanations used in teaching[2] are of interest the study should focus primarily on the widely used textbooks from the disciplines under investigation. Furthermore in order to gain knowledge about how practicing scientists' explanations to students develop as these students progress through their education, it will be important to make sure that the selection of textbooks include both introductory and advanced texts.

2.3 How to identify explanations in the sources selected?

Once a set of sources is identified, the next step is to identify the explanations in them. The problem here is the subtle distinction between explanation, description and prediction.

In the philosophy of science literature there is general agreement that the concepts explanation, description and prediction are closely related, but different (Cushing, 1991; Friedman, 1974; Salmon, 1998; see also A. I. Woody, 2003, p. 23). Some descriptions and predictions are clearly not explanations. It is possible, for example, to predict a storm by looking at a barometer, but that does not mean that it is also possible to explain why the storm occurred. Furthermore, it is not necessary to be able to predict a phenomenon in order to have an explanation of it. For instance, the movements of a chaotic pendulum may be explained even if it is not possible to predict its movements precisely.

[2] Textbooks are not only particularly suited for studies of explanations to students, they are also more generally good sources of explanations. Indeed, anyone interested in widely accepted explanations should be interested in textbooks, since the explanations found in scientific papers are not necessarily uncontroversial. Furthermore textbooks are useful for a study (like Woody's) that aims to answer *why* explanations are so important in scientific practice, because textbook explanations can provide clues as to why and how explanations are valuable to practitioners since one of the aims of a textbook is to show future practitioners how to use the tools of the discipline. (A. I. Woody, 2004a p. 18)

Thus, when studying the sources the investigator should expect them to contain explanations, but not necessarily *just* explanations. A textbook might for instance contain various descriptions of phenomena, regularities, experiments or episodes in the history of the particular science as well as examples of how to use specific theories to predict the value of a certain variable at some point in time, even though this prediction is not recognized as an explanation by practitioners. It is important to be able to distinguish between these types of discourse. This is not merely a quarrel over what words to use. It is also a question of epistemic status. Explanations express the understanding of the explainer and are a means for this understanding to be transferred to other parties. This is not the case with mere descriptions or predictions. Thus, until a prediction or a description in a textbook is accepted to be an explanation as well, it is not accepted as providing understanding to the student. A student might *feel* that he gains understanding from a description, but unless the description is accepted as an explanation as well, this feeling will not be seen as genuine (Trout, 2002), and the task still remains for the teacher to help the student gain a genuine understanding of the subject matter.[3] What the methodology developed in this article might help to show is that what is considered to provide genuine understanding might differ between disciplines. And thus a description or prediction in one discipline might constitute an explanation in another. This can be challenging for the student in an interdisciplinary university education, for instance when she is attempting to convince herself and others that she has understood some specific subject matter.

What is needed then is some form of criteria that can be used to identify the explanations that are contained in the sources. Once these criteria have been specified, they can be used to identify explanations in the chosen sources.

The search for such criteria takes us back to Woody's writings. In (A. I. Woody, 2004a) Woody presents some examples of *explanatory structures*, that is theories, parts of theories, pictures, diagrams and other structures that play important roles in explanations. Woody has identified these in a general chemistry textbook (Mahan & Myers, 1987).

In order to be able to establish that something is an explanatory structure it needs to be established that the structure plays an important role in explanations. Thus, one needs to be able to identify explanations in order to identify explanatory structures. Unfortunately, Woody does not tell us how she identified the explanatory structures in the textbook. This is unfortunate since the failure to specify how the explanatory structures are identified in the textbook weakens Woody's argument.

According to Woody (2004a, p. 40) the important difference between hers and earlier studies of explanations is that her study rests on the empirical claim that the explanatory structures she presents can be found in textbooks, rather than on pre-analytic intuitions about the nature of explanations. Of course simply making an empirical claim is not valuable in itself. If the claim is based on a biased dataset gathered using a spurious method it should not be considered any better than an invalid theoretical argument. Since Woody does not explicate how the explanatory structures that she presents were identified, *the quality of the empirical claim*

[3]Of course this need not be a *full* understanding. A textbook explanation might very well be accepted because it provides the student with a *partial* but genuine understanding of a certain subject matter.

that Woody makes cannot be judged, and thus it cannot be judged whether the turn to an empirical method has actually been beneficial. The results might simply be ill-founded in a different way.

Before judging the quality of the empirical claim it is essential to know whether the explanations were identified via some general intuitions about explanations, or through explicit criteria for - perhaps even a definition of – when a passage in a textbook can be considered an explanation. If explicit criteria were used then it is important that these are made known, only then is it possible to discuss whether there could be biases in the data gathered.

In section 6 I will present a more detailed discussion on the challenges facing a study based on general criteria. For now I will briefly discuss some problems with basing a study of explanations on the intuitions of the investigator(s).

3 Studying science teachers' explanations

Zoubeida Dagher and George Cossman have categorized explanations given by science teachers in junior high schools, based on extensive empirical material (Z. Dagher & Cossman, 1992). In an earlier paper (Z. Dagher, 1991) Dagher provides insight into how these different categories were identified. Dagher notes, however, that identifying explanations in sources (in her case recordings of classroom discourse) can be problematic:

> **While the purpose of the analysis was perfectly clear, the question about what constituted an explanation, particularly a teacher explanation, became more obscure. […] The literature that was reviewed presented serious dilemmas. In the case of educational theory, the adoption of any particular definition appeared to fail to discriminate between 'explanations' and other categories of verbal behavior. In the case of philosophy of science, definitions tended to restrict the sense of explanation so as to eliminate instances that seemed to be legitimate teacher explanations.** (Z. Dagher, 1991, p. 68-69)

So instead of combing the transcripts with a definition Dagher chose to search the transcripts for passages that intuitively "looked like" explanations believing that it was possible to justify the selection later on (p. 69). When personal intuitions were unclear Dagher resorted to the "conscious and tacit entertainment of various literature based 'attributes' of explanations" (p. 70).

For a researcher who is philosophically minded and who knows the field under study very well this approach is likely to be productive. However, for the purposes of this study two concerns can be raised.

First of all this approach explicitly identifies what the investigator deems explanatory, and unless the investigator is highly familiar with the field under study this may differ from what practicing scientists in that field deem explanatory. This could be tested by asking practicing scientists if they agree with what the investigator has identified. But if this step is needed in order to get a useful result, why not go all the way and simply leave it to the scientists to identify the explanations in the sources? (see section 5 below).

Secondly, Dagher admits that the results of her investigation would probably look different if the analysis was performed by someone else (Z. Dagher, 1991, p. 76). This is of course often the case with such interpretive studies, and it is not necessarily a problem. However, the study outlined in this text aims to provide a methodology that can be used by science educators trying to improve interdisciplinary university educations. To this end it would be advantageous if any changes in practice that may result from this study are not strongly influenced by the intuitions of one investigator.

For these reasons it will be preferable to base the study on explicit criteria that can be judged by others, or alternatively to base it on the intuitions of the practicing scientists themselves.

4 Conclusions on Woody and Dagher

From the above discussion it was seen that one way to expose possible qualitative differences in explanations given by practicing scientists from different disciplines to students, is to use a varied selection of textbooks as sources of explanations. When explanations in these sources have been identified the explanations from the different disciplines can be characterized and compared. While these later stages present their own challenges, my main focus so far has been on how to identify explanations in the selected textbooks.

I have argued that it is essential to explicate how this is done in order to construct a strong empirical argument. Furthermore I have argued that basing the identification largely on the investigator's intuitions will lead to results that are investigator dependent to an extent that is undesirable for given the purposes of this study.

I will therefore proceed to discuss two different (but not mutually exclusive) ways to identify explanations in textbooks:

1. Ask practicing scientists from the discipline under investigation to go through the texts and identify explanations.
2. Make explicit assumptions about sufficient (but non-necessary) conditions for identifying explanations in textbooks, use these to identify the explanations in the textbooks and learn more about the detailed structure of explanations within the given discipline.

I will argue (in the following section) that the first option could provide some very interesting insights if combined with follow up interviews, but that it is more suited for providing a detailed account of explanations within one specific discipline than for mapping differences in explanations from different disciplines.

In section 6 I will discuss the theoretical advantages and limitations of the second option and provide some insight into the practical challenges as I discuss the results of a pilot study based on textbooks from chemistry and physics.

5 Ask practitioners to identify explanations

One way to investigate what practicing scientists deem to be explanations in a selection of textbook material could be to ask practicing scientists themselves to identify explanations in the material. This approach certainly has advantages. First of all, it ensures that the explanations found are indeed deemed to be explanations by practicing scientists, not just by philosophers or other outsiders. As I have argued, this satisfaction is not trivial to obtain through other means. Secondly, the investigator can avoid making assumptions about the nature of explanations, which might be desirable for investigators that are worried about Woody's circularity objection.

The downside to this approach is that it is likely to be very resource consuming and thus difficult to carry out in practice.

Furthermore, since disagreements between the scientists about which passages in the texts are explanations are to be expected, it will be necessary to develop a way to decide when enough participants have marked a passage as an explanation to qualify it as a *widely accepted* explanation to give to students. If the requirement is that *everyone* approached has to have marked a specific passage as an explanation before it can be allowed into the pool of data then there is likely to be little data unless the number of sources that the science practitioners have to study is very high. Relying on a simple majority will on the other hand be too permissible since the minority might contain a significant number of the most experienced teachers or specialized researchers from the area of the discipline from which the candidate explanation originates.

One way to overcome these difficulties would be to gain more knowledge about the researchers (and about their position in their field) and also about why they chose the different passages for example by interviewing the practitioners afterwards or inviting them to "think aloud" while identifying explanations in textbook samples. Adding this extra layer to the investigation could yield a more detailed picture of explanations in the disciplines under investigation but is also likely to be highly time- and resource consuming.

However, the more detailed picture of explanations in the disciplines to be compared that this approach may yield is not strictly necessary. Differences that could pose problems to students in interdisciplinary educations are likely to be rather substantial. If substantial differences exist, they should be detectable through a comparison of a less detailed picture of explanations from the disciplines compared.

I will therefore go on to discuss the possibility of identifying explanations using a set of sufficient conditions in order to assess whether the theoretical and practical limitations of this approach are more suited to the purposes of the current study.

6 A series of sufficient conditions

As previously argued a descriptive study of explanations does not necessarily result in a vicious circle by assuming a definition of what constitutes an explanation before identifying explanations in the textbooks. What I have not yet considered is whether it is useful to proceed in this way.

Actually, I have already made assumptions about an essential *function* of explanations, namely that successful explanations provide understanding. So why not start from this assumption and then investigate how understanding is gained in the discipline in question?[4] The problem with these kinds of assumptions is (as Salmon has also noted (1998, p. 126)) that they do not help further investigations if they are kept too general. The nature of understanding and intelligibility is not better mapped than the nature of explanation, so simply assuming that one provides the other does not help the study. A more detailed description of what is meant by understanding and how an explanation can provide this understanding is required for this approach to prove useful. If this is done on the basis of theoretical arguments, one could end up identifying what ought to provide understanding from a theoretical perspective rather than identifying what practicing scientists deem to be good explanations to give to students[5]. This is exactly what this study aims to avoid.

Alternatively, one might assume something about the linguistic indicators of explanations[6]. For instance, it may be possible to search for specific language structures, or even certain key words.

However, Stephen Draper has argued that there are no linguistic traits common to *all* explanations (Draper, 1988). Some, but not all, will be answers to why- or how-questions. Many will contain the word 'because', but some will not. More generally, Draper argues that there are no words or sentence structures that can be called *necessary* for explanations. Thus "[…] a search of a transcript for their occurrence will not pick out anything like the complete set of the explanations present" (Draper, 1988, p. 20).

Draper does admit that the presence of a word like 'because' can be seen as a *sufficient* condition for the presence of an explanation (p. 19). So there is nothing in the theoretical arguments that prevents us from saying that a search for keywords in a textbook could yield a good *sample* of the explanations found in the text. And this is really all we need! The question now is whether the sample will be big enough to be practically useful, and whether we have reason to think that the sample will not reflect the diversity in the explanations in the textbooks because the keyword search leaves out certain important types of explanations?

I will discuss the former question of sample size in detail when I present my pilot study in section 6.2.

To see whether we will miss any important types of explanations in a keyword search I have to elaborate a bit more on which keywords should be used.

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[4]See (Chambliss, 2001) for an example of a study of explanations based on assumptions about understanding.

[5] A different kind of objection to this approach might also be raised: Even if it can be safely assumed that any good explanation will increase the reader's understanding of the explanandum, this does not mean that a good explanation is *necessary* for an increase in understanding. Thus we will be making the fallacy of affirming the consequent if we claim to have found explanations by identifying passages that increases the readers understanding. Lipton (2009) has explored other sources of understanding (for instance thought experiments), and this potential objection could be overcome by simply assuming that Lipton's list of sources of understanding is exhaustive. If a textbook passage increases the readers understanding *and* does not belong to one of the other sources of understanding on Lipton's list, it can safely be assumed that an explanation has been found.

[6] Rowan (1988) has also discussed the advantages and challenges related to the study of explanations through assumptions about either their *function* or their *structure*. She argues that if the purpose of the study is to improve teaching, then assumptions about the function of explanations is preferable, but unfortunately she does not give us any hints as to how the practical problems associated with this approach might be overcome.

6.1 Introducing the keywords

It should be possible to find those explanations to which the textbook authors draw attention and actually use the word "explain" or "explanation". So perhaps these are the most obvious candidates for a list of sufficient conditions for the presence of an explanation. Authors might for instance write "the explanation for this is that …" or "this explains …".

Furthermore there is a broad consensus both in philosophy and in science education that the primary function of explanations (especially those in textbooks) is to provide understanding (Regt, Leonelli, & Eigner, 2009; Rowan, 1988). So although one cannot search for passages that will provide understanding to the reader, one can search for those passages that the author(s) of a textbook has explicitly stated *should* provide understanding[7], passages like "To understand this …" or "this helps us understand …". Thus, versions of the word 'to understand' and 'understanding' could be added to the list of keywords to be searched.

As mentioned earlier, Draper (1988) (among others) acknowledges that "because" is a (non-necessary) indicator for the presence of an explanation, and therefore can also be added to the list of keywords.

Finally, one can search for explanation seeking questions, at least if it is possible to specify more concretely the nature of such a question. When philosophers discuss explanations they often focus on answers to why-questions (Goodwin, 2003; Salmon, 1998; Van Fraassen, 1980), but it is also widely recognized that being an answer to a why-question is not a necessary condition for being an explanation. The molecular biologist attempts to explain *how* the cell works, and the geologist might try to explain *what* went on in the Cambrian explosion. In general there is no reason to believe that answers to questions involving certain interrogatives can be excluded as being explanations. (Draper, 1988; Faye, 1999).

The reason why answers to these other kinds of questions are not discussed as much as answers to why-questions may be that it becomes less clear when answers to these kinds of questions are explanations. Whereas we can treat relevant answers to why questions as explanations we cannot automatically do the same with answers to questions involving other interrogatives.

Thus a reasonable way to proceed would be to start out by searching for answers to why-questions, the word "because", and all versions of the words "explanation", "to explain", "to understand" and "understanding", and use the data gained in this search to paint a more detailed picture of explanations. This could then be used to analyze answers to other kinds of questions yielding an even more detailed picture, and so on until a sufficiently detailed account that enables one to make comparisons to other disciplines is at hand.

Having identified some useful keywords for seeking explanations in texts, I will return to the question of whether one might miss important types of explanations by relying on these keywords. Since the list of keywords contains no necessary conditions for the presence of an explanation, it is difficult to argue decisively that every type of explanation will be found. However one can argue that the keyword search will detect at least as many types of explanations as other methods. Take for instance the ten categories that Dagher and

[7] Bearing in mind the possible objection raised in note 5 about the possibility of other sources of understanding.

Cossman present (Z. Dagher & Cossman, 1992, pp. 364-366), one can argue that a keyword search would identify all of these categories.

Dagher and Cossman present an example of each of the ten types of explanations taken from their transcripts after describing the characteristics of each of the categories. Half of these examples contain either a why-question or the word 'because'. One further category (tautological explanations) is partly defined as answers to how/why questions. So in these cases a search for key words like, 'why' and 'because' in the transcripts would not only identify explanations of the same type, but it would even identify the examples presented by Dagher and Cossman.

Is there reason to believe, that explanations of the remaining four types could not be found through a keyword search? Two of the remaining categories will be familiar to most readers: teleological explanations and explanations that explain through analogy. Such explanations can be and are given as answers to why-questions. Practical explanations which instruct "how to perform physical or mental operations" (Z. Dagher & Cossman, 1992, p. 365) are not the focus of this discussion, but to the extent that they are explanations of why it is important to perform the task in one way rather than another some will be detectable when searching for "because".[8]

Last but certainly not least an important type of explanation in textbooks appears as descriptions of *what* happens, rather than *how* things work, or *why* they happen (as Woody has also pointed out (A. I. Woody, 2003, p. 23)). Dagher calls these genetic explanations, and they present quite a challenge for anyone interested in explanations who wants to distinguish between descriptions that are not explanations and those that are also explanations. Descriptions that are also explanations are considered to provide (genuine) understanding, and therefore should be identifiable through a search for the term 'understanding' or 'to understand', given that these terms are in fact used regularly in the textbooks. As we shall see in the following section this is in fact the case, at least in introductory textbooks.

All in all, this shows that the sample of explanations that be may found through a keyword search as outlined above will be at least as diverse as a sample gained through an intuition based search.

Let me finally illustrate how the approach outlined so far could be used in practice.

6.2 Some results from a pilot study

To test the practical limitations of the first steps in this approach I performed a small pilot study. I chose to focus on thermodynamics. This topic is central to both physics and chemistry, and there is an abundance of textbooks on the market aimed at audiences ranging from novices to experts. I chose a textbook from each end of this spectrum to see whether the usefulness of my approach depended on the intended audience of the textbooks. More precisely the sample studied consisted of chapters 17-20 (both included, 126 pages in total) from *University Physics* (Young & Freedman, 2010) which is a very widely used introductory textbook in physics

[8] Otherwise, such explanations are often very clearly visually marked in textbooks since students have to return to some of them frequently. So they will not be hard to find, if needed.

and chapters 2-8 (107 pages) from an older textbook called *Chemical Thermodynamics* (Kirkwood & Oppenheim, 1961) which is "intended to serve as the basis of a senior or graduate course" for chemists[9].

I searched for each of the keywords ('because, answers to why questions plus versions of 'explanation', 'to explain', 'to understand' and 'understanding') in turn and will comment briefly on the results in the following sections.

Versions of "explanation" and "to explain"

I first searched the sample for versions of the keywords "explanation" and "to explain". The final count of instances of either of these words in the body text of both samples was only *five*. Of the five instances two appeared in *Chemical Thermodynamics*, one in a general introduction to a chapter pointing to specific discussions later on and the other in this later discussion (Kirkwood & Oppenheim, 1961, sec. 5.2). In *University Physics* the search yielded three instances in total. Like in *Chemical Thermodynamics* one instance was in the introduction to a chapter pointing to a discussion later on (Young & Freedman, 2010, ch 20).

Another instance was partly stated in a caption to a picture[10]. We are told that "[e]vaporative cooling explains why you feel cold when you first step out of a swimming pool" (Young & Freedman, 2010, p. 568) and then pointed to a picture of three children in a swimming pool. The caption elaborates a bit on the claim made in the main text:

> **[…] it may be a hot day, but these children will be cold when they step out of the swimming pool. That's because as water evaporates from their skin, it removes the heat of vaporization from their bodies** (Young & Freedman, 2010, p. 568)

A striking feature of all the discussions linked to this word search is that they are not based on mathematical calculations, but rather on qualitative arguments. To the extent that they do appeal to any general laws these are postulated rather than derived. This is particularly striking for *Chemical Thermodynamics*, since it aims to "present a rigorous and logical discussion of the fundamentals of thermodynamics […]" (p. v).

Why-questions

The word "why" appears 992 times in the whole of *University Physics*[11], so even though Woody might be right that there is lots of explanatory content that is not phrased as answers to specific questions (A. I. Woody, 2003, p. 23) it might turn out that there is simply so much explanatory content is these books that the small fraction of it that *is* phrased as direct answers to why questions will be more than enough for purposes of this method. In the sample chapters from *University Physics* the word "why" appears between five and seven times per chapter.

[9] The book was recommended to me by a lecturer in physical chemistry as the most rigorous presentation of chemical thermodynamics that he knew of.

[10] The final instance also appears in the caption to a picture (Young & Freedman, 2010, p. 564)

[11] This makes it more abundant than the words "explain" and "understand" which appear 821 and 500 times respectively, but less abundant that the word "because" which appears 1009 times.

The chapters from *Chemical Thermodynamics* truly live up to Woody's characterization of a textbook. Lots of theory is described and discussed but there are very few questions asked in the text. In fact, the word "why" does not appear *at all* in the sample! This is interesting since it challenges the coexistence of the common approximation used in philosophy that all explanations are answers to why-questions and the assumption that explanations are important to scientific practice. If further studies can establish that why-questions do not play a key role in advanced textbooks perhaps the approximation or the importance ascribed to explanations, as outlined above, should be re-evaluated. Since it is possible to argue independently for the importance of explanations it seems likely that the approximation would be the focus of such a re-evaluation.

Because

The word "because" is the most abundant of the keywords in the texts. A prominent feature of the explanations involving "because" in both samples is their qualitative nature and brevity. Often the explanandum and the explanans are contained within a single or just a few sentences. Take for example the following passage:

> **The thermal conductivity of "dead" (that is non-moving) air is very small. A wool sweater keeps you warm because it traps air between the fibers. In fact, many insulating materials, such as Styrofoam and fiberglass are mostly dead air.** (Young & Freedman, 2010, p. 571)

In this respect they resemble the explanations found in the search for "explanation" and "to explain".

Understanding

The search for the versions of "understanding" and "to understand" in *Chemical Thermodynamics* yielded only two occurrences. One coincided with an instance of because and one pointed to the lack of understanding of the expressions for the entropy of a gas (real or ideal) until the advent of quantum mechanics.

University Physics yielded 55 hits. Versions of the words regularly show up in the introduction to chapters or sections to debut the theory that will be explained later or to stress the importance of certain explanations. For instance the following statement occurs after a passage describing the temperature dependence of the internal energy, *U,* of an ideal gas (*T* denotes the temperature):

> **Make sure you understand that *U* depends only on *T* for an ideal gas, we will make frequent use of this fact** (Young & Freedman, 2010, p. 636)

Thus the preceding argument is meant to provide understanding to the student, and should be considered an explanation. Understanding is commonly used in *University Physics* to point to other passages that for the purposes of this study can be treated as explanations. It is not always clear, however, how the promised understanding will be provided. For instance the following is found in the introduction to chapter 17:

The concepts in this chapter will help you understand the basic physics of keeping warm and cool (Young & Freedman, 2010, p. 551)

In this instance further indicators are needed about *where* in the chapter this understanding is provided and *how* it is provided. A partial answer to this question is that the concepts help us to answers to certain why-questions like the one concerning children in a swimming pool mentioned above (This manuscript, p. 13).

Most instances of the word "understanding" however appear in the titles of the 'Test your understanding' questions that are generously distributed throughout the whole text[12]. These explanation requesting questions allow the student to test whether she has gained sufficient understanding of the subject matter discussed in the preceding section to proceed to the next sections. The authors' answers to these questions are given at the end of each chapter. These answers could be relevant for the current study since they explicitly serve as guides to what an appropriate answer to an explanation seeking question looks like in the current discipline at the current level.

This leads me to the more general question of how one can use the exercises in textbooks as sources of explanations.

6.2.1 Including the exercises

Learning to construct high quality explanations requires practice. In science educations an important part of this practice comes through solving textbook exercises and evaluating the answers. Explanations are among the kinds of answers the textbook question writer is hoping to elicit.

I will refer to an exercise that is formulated as an explicit request for an explanation or as a why-question, as an 'Explanation Requesting Exercise' or just an ERE. Could one extend the material searched to include the exercises in order to identify the EREs and perhaps use the solution manuals containing elaborated solutions to exercises that are available for many textbooks as a source of explanations?

I believe that this approach could be useful, but it is important to be sensitive to its limitations. Introductory textbooks usually contain an abundance of exercises. *University Physics* for instance contains well over a hundred exercises after each chapter, and though the majority of the exercises are not EREs the sheer number of exercises means that it will be possible to get some data. The more advanced textbooks generally contain much fewer exercises than introductory textbooks and the density of EREs is also much lower.

University physics

The EREs in *University Physics* fall into two general groups. The first group a) is formulated as a description of a phenomenon or a result of a calculation combined with a request for an explanation. For instance (Young & Freedman, 2010, p. 622):

[12] This type of questions is common in more recent introductory textbooks.

Explain why in a gas of N molecules, the number of molecules having speeds in the finite interval $v + \Delta v$ is $\Delta N = N \int_{v}^{v+\Delta v} f(v) dv$.

Answers to this type of exercise can be taken as explanations without question.

The second group b) contains EREs where students are asked to explain their reasoning behind a certain answer. This kind of ERE is completely absent from the more advanced textbook passages that I have looked at (see next section). In the type b) exercises the main function of the word explain is to force the students to make an elaborate answer. Take for instance the following discussion question (Young & Freedman, 2010, p. 579):

Q18.23: If the root-mean-square speed of the atoms in an ideal gas is to be doubled, by what factor must the Kelvin temperature of the gas be increased? Explain

The question posed can be answered by stating a single number ("4"). Thus if "explain" was omitted it could easily be thought that a satisfactory answer to this question is simply "4". However the addition of the word explain indicates that the student has to come up with a more elaborate answer such as "4, because the root-mean-square speed of the atoms in an ideal gas is proportional to the *square root* of the Kelvin temperature of the gas".

"Why/Why not" or simply "Why?" is also often added after questions that can be answered very briefly. Thus the addition of "Why?" or "Explain" after other kinds of questions than why-questions can be seen as a clarification from the authors that the question just posed is indeed an explanation seeking question as well, not just what might called fact seeking question.

Type b) EREs are particularly interesting for two reasons. First they pose explanation seeking questions that are not why- questions. As mentioned there is some consensus that answers to this type of question should be treated as explanations, but little attention has been given to them so far. Secondly one will need knowledge about this kind of explanation seeking questions if data is to be gathered from the exercises in the more advanced textbooks[13], since EREs are so rare in these, as I will illustrate below.

More advanced textbooks

Chemical Thermodynamics contains no exercises at all. I therefore made a brief search in two other textbooks, *Introduction to Electrodynamics* (Griffiths, 1999) and *Statistical Physics* (Mandl, 1988), both aimed at slightly more advanced physics students than *University Physics.* Searching the exercises of two random chapters in each book[14] gave a total of 65 exercises none of which contained versions of the word "explanation" or "to

[13] Assuming that there is data to be found. It may be that the reason why explanation seeking questions are so hard to find in more advanced textbooks is because they are not posed, but given the commonness of explanation seeking questions in everyday discourse and the consensus among philosophers and scientists that explanations are important in science I find that highly unlikely.

[14] Chapter 3-4 in (Mandl, 1988) and chapter 8-9 in (Griffiths, 1999)

explain". The search for why-questions yielded only one result: In problem 9.19 in *Introduction to Electrodynamics* the author asks "Why are metals opaque?". This indicates that even if an elaborated solution manual can be found to these more advanced textbooks, it may still be difficult to use them to get information.

As mentioned earlier it is important to gather data from introductory and advanced textbooks if one is to say anything about how practicing scientists change their explanations according to the level of the students. As I have argued the keyword search in both the body text and (especially) the exercises in the more advanced textbooks gave far less data than the search in the introductory textbooks. It will therefore be important to pay special attention to the more advanced textbooks when going through the sources with the new search criteria that will be derived from the results of the first keyword search. The knowledge gained from type b) EREs in introductory textbooks will be important here. However it is beyond the scope of this paper to explore details.

A further complication related to the more advanced textbooks is that it is usually only the introductory textbooks that have solution manuals that elaborate on how the exercises should be solved. Most solution guides just give the result, and even the most elaborate solution manuals do not always contain solutions to the EREs, especially if the solution requires the construction of a qualitative argument. Thus the inclusion of the exercises from the more advanced textbooks might not be of much use in practice if due to time limitations it is not possible to make large scale studies of how practitioners would solve these explanation requesting exercises, or unless the investigator herself is capable of producing the solutions, which would require something close to contributory expertise (as opposed to interactional expertise (Collins, 2004)) for the most advanced textbooks.

All in all I find that the exercises from the introductory textbooks and their solutions are a valuable source of explanations from the different disciplines. However it is not yet clear whether the exercises from more advanced textbooks can become as valuable, since the tools discussed in this paper are of limited use when trying to analyze these exercises. However the results gained through the analysis of the introductory textbook exercises could provide the necessary tools for studying the more advanced exercises.

7 Conclusions

Philosophers' studies of scientific explanations have served as background and inspiration for studies in science education on many occasions. Although it is widely recognized that explanatory practices differ between scientific disciplines philosophers have almost exclusively focused on what similarities there may be. The aim of this paper was to develop an empirical method for exposing possible differences in explanations given by practicing scientists to students. Empirical studies of explanations are rare in both philosophy of science and science education. The ones that exist share the assumption that the nature of explanations is best studied through the identification of a set of concrete explanations that can be used as the basis of an inductive argument. I have followed this assumption in this paper, and thus I have not considered other possible approaches to an empirical study of explanations[15].

When presenting an empirical study of explanations based on a set of concrete explanations it is important that the data collection procedure is made transparent. Otherwise the strength of the empirical claim is difficult to judge. In this paper I have argued that the data collection procedure is not transparent in Woody's empirical account of explanations in chemistry. I further argued that given that the method developed in this paper is meant to serve as an empirical basis for changes in educational practice it would be undesirable if data collection was based on the intuitions of the investigator. I therefore went on to discuss the possibility of using explicit criteria for identifying explanations. Since it is not essential to identify every explanation in a textbook in order to have a useful data set, and since there is no consensus on a definition of an explanation, I chose to use a list of sufficient but non-necessary conditions for the presence of an explanation as the basis for data gathering. The list consisted of a number of keywords that should be fairly uncontroversial to use as identifiers of explanations. I then showed that the use of these keywords could yield a dataset that was as varied as the dataset gathered by Dagher, and the pilot study showed that the introductory textbooks gave plenty of data whereas the more advanced textbooks produced less data. This highlighted the need to reevaluate the search criteria after the first search, and go through the sources more than once using increasingly sophisticated criteria.

The method developed here was designed to fit a very specific purpose, and parts of the argumentation rest heavily on this specific purpose, especially the arguments for limiting the study to just. However, the usefulness of an empirical approach based on relevant sources of explanations is not dependent on the specific purposes considered here. As mentioned one could gain a very detailed picture of explanations in any scientific discipline if a combination of textbook studies and interviews was conducted. Such studies could provide an important supplement to the many case studies of explanations from different disciplines that are in current philosophical literature.

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[15] An alternative approach would be to interview practicing scientists and ask them what characterizes good explanations for students or what they think are the main differences between the explanations given to students in their discipline and explanations given to students in other disciplines. How useful such an approach would be is an empirical question, and I am not aware that it has ever been attempted.

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