

Yao, Jian-Xin; Guo, Yu-Ying; Neumann, Knut

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Deutsches Institut für Internationale Pädagogische Forschung (DIPF)
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E-Mail: pedocs@dipf.de
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Towards a hypothetical learning progression of scientific explanation

Jian-Xin Yao^{1,2,3}, Yu-Ying Guo^{1*} and Knut Neumann²

* Correspondence:

yyguo@bnu.edu.cn

¹Department of Physics, Beijing Normal University, Beijing 100875, China

Full list of author information is available at the end of the article

Abstract

The construction of scientific explanations, as a key scientific practice, has been highlighted in policy documents. However, research suggests that students lack competence in constructing scientific explanations and this is due to a lack of appropriate scaffolding in science instruction. To address this problem, researchers have developed the Claim-Evidence-Reasoning framework, as scaffolding for constructing scientific explanations. Derived from that framework, a learning progression of scientific explanations has been proposed for the entry point of K-12 science education. However, a clarification on the theoretical foundation of the Claim-Evidence-Reasoning framework and a further extending of the learning progression of scientific explanation has been called for. Therefore, in this paper we aim to add to this research area by first refining its theoretical foundations. More specifically, through linking perspectives on scientific explanations in philosophy of science and in science education, we develop the Phenomena-Theory-Data-Reasoning framework. Then we design a hypothetical learning progression of scientific explanation, based on the Phenomena-Theory-Data-Reasoning framework. The paper ends with a discussion of implications for future research and instruction on scientific explanation in science education.

Keywords: Science Education, Scientific Explanation, Learning Progression

Introduction

Constructing scientific explanations for natural phenomena is a main aim of scientific enterprise. Equipping students with the competence to construct explanations scientifically is also a fundamental target of science education (Kultusministerkonferenz 2004; Ministry of Education, P. R. China 2011; NGSS Leading States 2013). In the context of K-12 science education, scientific explanation is understood as explicit applications of theory, which go beyond descriptions of natural pattern, to reveal the causal relationship or model the mechanism for a specific situation or phenomenon (Braaten and Windschitl 2011; National Research Council 2012). While explanations are frequently included in teacher-student discourses in science classroom, students, even after several years of science instruction, still have difficulty in constructing a proper scientific explanation (e.g., McCubbin 1984; McNeill et al. 2006). Part of this difficulty is due to a lack of sufficient knowledge base (e.g., the understanding of core scientific concepts and principles), but the knowledge base itself cannot guarantee for making a proper scientific explanation. Therefore, scholars suggested that complex scientific practice like scientific explanation should

be consciously and explicitly taught in classroom (McNeill et al. 2006; Solomon 1986). According to this explicit way of teaching scientific explanation, a framework is needed for scaffolding students' progression towards the competence of scientific explanations.

This study, through revealing the linkage between the theories of scientific explanation in philosophy of science and explanation instruction in science education, aims at refining existing framework by unpacking how a potential progression of scientific explanation might happen. The method used in this paper is a systematic review of literature (Bennett et al. 2005; Evans and Benefield 2001). The first step of this review method is identifying review research question. Transferring from above purpose of this study, the review research question of this study is that what and how research about scientific explanation can help conceptualize scientific explanation in K-12 science education and develop a hypothetical learning progression of scientific explanation. The second step is characterizing the literature that establishes the foundation of the review. Two groups of literature were characterized: research in science education and research in philosophy of science. Then (the third step) we set the inclusion criteria: Educational articles should be closely relevant to research topics and published in a Social Science Citation Index (SSCI) journal; Philosophical articles or books should be cited by the two most authoritative review work of this area by Salmon (1989) and Woodward (2014). In step 4 we conduct an overview of each articles and synthesize the literature. Finally, we develop our result and disseminate it in the following sections.

Explanations in traditional science classroom

The famous childhood anecdote of the physicist Richard Feynman indicates that, children have an instinct to ask “why” questions:

... when I pulled the wagon, I noticed something about the way the ball moved. I went to my father and said, “Say, Pop, I noticed something. When I pull the wagon, the ball rolls to the back of the wagon... Why is that?” “That, nobody knows,” he said, “The general principle is that... this tendency is called ‘inertia’, but nobody knows why it’s true.” (Feynman 2010, 1 min 8 s – 1 min 50s)

Developing this instinct to into competency of scientific explanation is a major task of every science educator across the world (e.g., Kultusministerkonferenz 2004; Ministry of Education, P. R. China 2011; NGSS Leading States 2013). Explanations are frequently occurring in science classroom (Dagher and Cossman 1992; Tang and Chiu 2010) and received particular emphasis from competency evaluations like PISA (OECD 2013). However, research on students' explanations found that there are a considerable number of students, from primary school to college, who cannot properly construct a scientific explanation (e.g., McCubbin 1984; McNeill et al. 2006; Songer and Gotwals 2012). It is not uncommon to see that junior students equip an imperfect explanation model when beginning their science journey. Even after years of instruction, pre-causal explanations like reaffirmation, tautology, teleology, or simple juxtaposition are still used when students confronting explanation tasks (Solomon 1986; McNeill 2011). The students are not the only group who has difficulties in constructing scientific explanation. Some teachers, even several learning materials also use incorrect explanations or confuse explanation with description (Horwood 1988; Tang and Chiu 2010). For

example, through video analyses, Dagher and Cossman (1992) summarized ten kinds of explanations including analogical, anthropomorphic, functional, genetic, mechanical, metaphysical, practical, rational, tautological, and teleological explanations. Many of these explanations do not count as scientific, based on the definition of scientific explanation in K-12 education (Braaten and Windschitl 2011; National Research Council 2012).

Above research showed that considerable amount of explainers still did not know the basic logical structure of explanation, even after years of education. Also they did not understand the necessary of uncovering the causal relationship or in-depth mechanism when constructing a scientific explanation (McNeill et al. 2006; Sadler 2004). In addition, constructing a scientific explanation is difficult as it is not merely a skill of language but also involving conceptual understanding in science (Solomon 1986), like Thagard (1992) suggested the development of explanation is an evolution of schemata and as such is part of a conceptual revolution in mind. Therefore, a lack of basic understanding on relevant scientific content will also most likely lead to a failure in constructing a scientific explanation.

Facing this muddled circumstance on explanations in science classroom, Treagust and Harrison (2000) made the first clarification by attributing the explanations in science classroom into three categories: folk explanation, instructional explanation, and scientific explanation (Fig. 1). The folk explanation is the start point when students entering science classroom. Student and teacher work together towards the learning goal—competency of scientific explanation. Teachers' instructional explanations are meant to facilitate above transition.

With this classification, an initial account for students' incompetency of scientific explanation after years' instruction can be proposed. It is that, at the same time, too many functions were loaded on teachers' instructional explanation. The first function of instructional explanations is promoting students' scientific understanding, which has already been a challenge to some teachers. Because to construct an effective instructional explanation for conceptual learning, teacher needs an "explanatory framework", which should take multiple factors into consideration including student factors, content characteristic, and learning environment etc. (Treagust and Harrison 1999, 2000; Wittwer and Renkl 2008). If asking teachers' explanation to fulfill a second function: providing typical example for students to imitate appropriate method of explaining, this overload might be the source of frustrated results:

It might be hard to teach explicitly about the different forms of explanation. Meta-knowledge about the procedures of a subject is not easy to understand at any age.

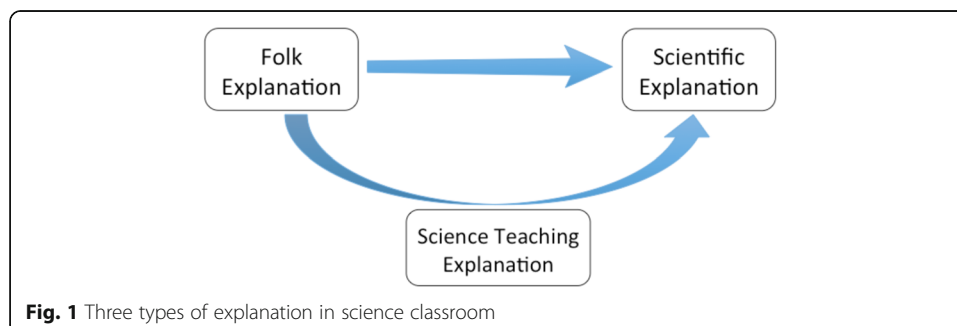


Fig. 1 Three types of explanation in science classroom

For whatever reason, or none at all, instruction is not given: it is left to the students to pick up appropriate ways of explaining by the ostensive example of the teacher. There are always some who fail. (Solomon 1986, p.43)

Initial framework for explicit explanation instruction

From above situation, developing students' competence in constructing scientific explanation calls for explicit guidance (Solomon 1986; McNeill et al. 2006; Braaten and Windschitl 2011). Departed from Toulmin's argumentation pattern and abridged it to suit young students' cognition ability, the Claim-Evidence-Reasoning (CER) framework was developed to modeling scientific explanation and adopted for guiding students' explanation (e.g., Sandoval and Reiser 2004; McNeill et al. 2006; Songer et al. 2009). Using this framework, students were expected to construct an argumentation, which is composed of a claim, appropriate and sufficient evidences, and reasoning backing the connection between evidences and claim, to explain phenomena:

"... Students construct scientific explanations about phenomena in which they justify their claims using appropriate evidence and scientific principles. ... The claim is an assertion or conclusion that answers the original question. The evidence is scientific data that supports the claim. ... The reasoning is a justification that shows why the data count as evidence to support the claim. (McNeill et al. 2006, pp. 155–158)"

Based on the CER framework, Songer and her colleagues further developed and validated a learning progression for scientific explanation in the context of elementary biology (Gotwals and Songer 2013; Songer et al. 2009; Songer and Gotwals 2012). In their learning progression, students cyclically progress from the scaffolded minimal levels (e.g., student makes a claim and backs it with sufficient and appropriate evidence with scaffolding) to un-scaffolded complex levels (e.g., student makes a claim, backs it up with evidence, and provides reasoning to tie the two together).

The CER framework and the learning progression based on it are the first systematic endeavor for developing students' competency in scientific explanation, which made this research topic available in science education. In addition, evidence has proved its effectiveness in guiding explanation construction by children at the entry points: students gain significantly in conceptual understanding and explanation ability when they immersed in a well-scaffolded inquiry environment (e.g., McNeill et al. 2006; Songer et al. 2009). But similar to the history of "Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light", there are also several clouds casted on the horizon of educational research on scientific explanation. The first "cloud" is the insufficient linkage between the educational framework of scientific explanation and its own philosophical foundations. Some scholars argued that the educational framework of scientific explanation and educational framework of scientific argumentation should not share the Toulmin's argumentation model as their philosophical base (Osborne and Patterson 2011, 2012). That is to say, a stronger conceptualization of scientific explanation in science education needs to be made (Braaten and Windschitl 2011). Therefore, the abundant effort on scientific explanation in philosophy of science should be used when developing an educational framework for scientific explanation.

Another “cloud” on this research field is about the further extending and elaboration for learning progressions of scientific explanation (Braaten and Windschitl 2011; Tang and Chiu 2010). Existing efforts on developing a learning progression of scientific explanation need to be continued and extended in order to expand and deepen our understanding of how to help students develop competence in constructing scientific explanations. For students with more complex and integrated knowledge base, the development of competency in scientific explanation will go beyond the increasing of components and the decreasing of scaffolding. This means a more extended learning progression of scientific explanation should not only clarify the existing of key components, but also delineate the levels for each component-exiting learning progression of scientific argumentation (e.g., Berland and McNeill 2010) and scientific modeling (e.g., Schwarz et al. 2009). With these two “clouds” in mind here we go one step back to classical research in philosophy of science, then back to the discussion on above issues.

Building on theories of scientific explanations in philosophy of science

Explanation, as defined by *The Cambridge Dictionary of Philosophy*, is “an act of making something intelligible or understandable, as when we explain an event by showing why or how it occurred” (Audi 1999, p. 298). In the *Stanford Encyclopedia of Philosophy*, Woodward (2014) points out that scientific explanation are a subset of explanations and a subset of scientific language, which means only a specific kind of discourse can be counted as scientific explanation while others cannot: “In fact, the notion of *scientific explanation* suggests at least two contrasts—first, a contrast between those explanations that are characteristic of *science* and those explanations that are not, and, second, a contrast between *explanation* and something else.” More than 60 years’ philosophical discussion accumulated abundant perspectives for delineating the two contrasts and defining the concept of scientific explanation (for a systematical review, see Salmon 1989; Woodward 2014). In the following we briefly summarized four important models/theories, which were used in developing an educational framework for scientific explanation.

Hempel and the covering-law model

The Deductive-Nomological model (D-N model) proposed by Hempel and Oppenheim (1948) is one of the earliest and most fundamental models for scientific explanation in philosophy of science. According to this model, an explanation can be divided into two constituents: the explanandum—sentences describing the phenomenon to be explained, and the explanans—the class of those sentences adduced to account for the phenomenon. The explanans contains two subclasses: “one of these contains certain sentences C_1, C_2, \dots, C_k which state specific antecedent conditions; the other is a set of sentences L_1, L_2, \dots, L_r which represent general laws” (Hempel and Oppenheim 1948, p. 137). An explanans appropriately explaining an explanandum need to meet four requirements:

“(R1) The explanandum must be a logical consequence of the explanans. (R2) The explanans must contain general laws, and these must actually be required for the derivation of the explanandum. (R3) The explanans must have empirical content; i.e., it must be capable, at least in principle, of test by experiment or observation. (R4) The sentences constituting the explanans must be true. (Hempel and Oppenheim 1948, p.137)”

The first requirement relates to the deductive essence of scientific explanation and the second is indicating the nomological essence. Stemming from the logical empiricism tradition, Hempel viewed science as a discipline illuminating the law of nature and believed that the pattern of world can be described by a set of “general laws”. Therefore, general law locates in the core position of D-N model. In this model, scientific explanation is considered as a sense-making process based on the general law covering the phenomenon. For instance, explanations like using the law “light travels in straight lines” to explain the shadow or using Boyle’s law to explain the expansion of a heated balloon, are typical explanations meeting the D-N model.

In 20th century, research in atomic physics, genetics and quantum mechanics etc. constructed a series of scientific models to explain patterns in the nature world, in which probability and statistics play a centric role. Within this background, philosophers began to expand scientific explanation model. First, Hempel included statistical law into the general law and then developed the Deductive-Statistical model (D-S model) to explain the probability for a particular event (Hempel 1962, 1965). Then he proposed another scientific explanation model—the Inductive-Statistical model (I-S model), based on the same statistical foundation but different reasoning—inductive reasoning. Facing the inadequacy of inductive reasoning, Hempel (1965) added the fifth requirement - requirement of maximal specificity (RMS) for I-S model. According to the D-S model and the I-S model, when the premise-meeting explanans guarantee the explanandum a high probability of occurrence, it can be accounted as a scientific explanation. As a result of above expansions, models of scientific explanation started to adopt statistical law as an important premise, and the reasoning strategy were also enriched (Salmon 1989; Zhang 2002).

As Hempel put the general law (deterministic law or statistical law) at the centre position of explanations, researchers call his models “the covering-law model”. The covering-law model is one of the most important foundations in this research area. However, some counterexamples challenged the completeness of the covering-law model. Difficulty like “explanatory asymmetries” and “explanatory irrelevancies”¹ revealed the basic problem within this theory: focusing on the syntax of scientific explanation but omitted the role of semantics and pragmatics (Zhang 2002). The following paragraphs show how other scholars challenged “the covering-law model” in alternative perspectives.

Salmon and the causal-mechanical model

One of the earliest alternatives to Hempel’s model is the Statistical-Relevance model (S-R model) proposed by Salmon (Salmon 1971, 1989). Compared to Hempel’s models, the S-R model has several distinctive features. The most significant one amongst these features is the core premise of relevance. Salmon (1971) defined relevance as follows: For one class A , an attribute B and another attribute C , iff $P(B | A, C) \neq P(B | A)$, the attribute B will be statistically relevant to the attribute C . Here we adapt Hempel’s “strep infection example” (Hempel 1965) to illustrate the employing of S-R model: $S = x$ who has an infection, $Q =$ quickly recover, T or $-T$ refers to whether x is treated with a specific medicine y or not, R or $-R$ refers to whether the infection is resistant to one medicine or not. If it happened that the resistant medicine is just the medicine y , then: $P(Q | S, T, R) \neq P(Q | S, T, -R)$. On the other case, if the infection is resistant to another medicine, which we name it z and has nothing to do with y , then: $P(Q | S, T, R) = P(Q | S, T, -R)$.

S. T. -R), because this medicine resistance is an irrelevant factor. Not only can successfully exclude irrelevant ingredients, the *S-R* model also can avoid the high probability requirement in *I-S* model, that's why it doesn't need to mention a recover rate in the above example.

Comparing Hempel's statistical model with Salmon's *S-R* model, a transition from a syntax framework to an ontic perspective had begun (Kitcher and Salmon 1989; Zhang 2002). Salmon went one step further on the ontic perspective by proposing the Causal-Mechanical model (*C-M* model). Salmon claimed that a scientific explanation should illuminate an event's natural structure and how it fits into the causal nexus. From this perspective, a scientific explanation should be aiming at uncovering the causal interaction and the intrinsic mechanism. To define the causal interaction, Salmon differentiate between genuine causal processes and pseudo-processes. The genuine causal process is a physical process that transmitting "nonzero amount of an invariant quantity" (Salmon 1994, p. 308). For example, "a billiard ball hit another and made it move" is a genuine causal process, while the intersection between their shadows is a pseudo-process. Departed from uncovering the ontic connection, the *C-M* model solved several difficulties in Hempel's model and exhibited a higher self-consistency. Today, the *C-M* model is regarded as one of the most competitive model in scientific explanation (Newton-Smith 2000; Woodward 2014).

Unificationist account of explanation

From the history of science, milestone developments like Newton's unification of terrestrial and celestial mechanics or Maxwell's equations manifested the important role of the unificatory perspective in science. Using a unified theory (for example the law of universal gravitation) to connect and account for various phenomena (the gravity on the Earth and the motion pattern of celestial bodies) is an ideal explanation meeting the unificatory perspective. When discussing the relation between explanation and scientific understanding, Friedman (1974) first put forward the unificationist idea for scientific explanation. By emphasizing the global view of scientific understanding, Friedman suggested that scientific explanation should degenerate various phenomena into a more comprehensive one. Then Kitcher (1981) further elaborate this perspective into the explanatory unification theory. Kitcher proposed the concept of explanatory store and then argued:

"... the fundamental task of a theory of explanation is to specify the conditions on the explanatory store ... associated with science at a particular time contains those derivations which collectively provide the best systematization of our beliefs. Science supplies us with explanations whose worth cannot be appreciated by considering them one-by-one but only by seeing how they form part of a systematic picture of the order of nature. (Kitcher and Salmon 1989, p. 430)"

Pragmatic² theories of explanation

Asides from above epistemological or ontic perspectives in scientific explanation, scholars like van Fraassen advocated the pragmatic approach for explanation. They emphasis the pragmatic foundation of explanations and claim that whether an explanation is accepted or not depends on the context like the background knowledge of the

audience (van Fraassen 1980). For example, when discussing refraction in a middle school physics class, illuminating can be better achieved through utilizing the Snell's Law rather than introducing the Fresnel equations, as the Fresnel equations might be unintelligible for students at that age. Simply said, the pragmatic theories of explanation deny the possibility of a universal logical structure can solve the whole issue of explanation (Woodward 2014). In any explanation activities, the explainer first has to, logically connect the explanans to an explanandum based on his or her advanced understanding; the explainee also judge and accept (or deny) the explanation using their prior knowledge about the phenomenon. In sum, the pragmatic theory suggests the success and appropriateness of explanation needs not only a valid logical structure, but also, at least in some extent, a psychological concern (Kitcher and Salmon 1989; Woodward 2014).

A brief summary of above philosophical models/theories

Hempel suggested that scientific explanation should be a logically deduction from general laws to answer a "why" question. Therefore, a syntax framework needed to be developed to generalize the core requirement and basic structure of this kind logical deduction (Hempel 1965). Extending his theory to include statistical explanations, Hempel's models of scientific explanation became "the first landmark" and "epoch-making" in research on scientific explanation (Kitcher and Salmon 1989; Woodward 2014), although they were challenged by competitive theories developed in other perspective. Amongst these theories, Salmon developed one of the most competitive models—the C-M model. The C-M model grounded explanation on an ontic connection-causal relationship. He argued that a scientific explanation is a series of sentences revealing the cause or mechanism behind phenomena. Although we cannot assert that all explanations are based on causal interaction, seldom will doubt the central position of causal relationship in scientific explanation. Therefore, Newton-Smith (2000) commented in *A Companion to the Philosophy of Science*, the C-M model "fits our actual explanatory practices in science and ordinary life much better than the D-N model (p. 129)". Other competitive theories like the unificationist view and pragmatic perspective uncovered the key position of cognitive subject in explanation, although these two models didn't provide a stereotype structure for scientific explanation. Pursuing on unification and conciseness in science, the unificationist theory offered a criterion for valuing scientific explanation. Taking pragmatics into consideration, judging an explanation based on its acceptability to cognitive subject becomes one of the main trends in philosophy after logical positivism.

Mapping philosophical theories into educational practice: the PTDR framework

Based on philosophical theories of scientific explanation presented in previous section, this section discusses how we propose a hypothesis for the learning progression of scientific explanation. Ideally, a learning progression should reconstruct a coherence framework, which indicating a lower anchor, intermediate levels and an upper anchor, for the multiple facets of science education (Gotwals and Alonzo 2012; National Research Council 2007). It is an iterative process between the theoretical development/

adjustment and the empirical testing/validation for diminishing the gap between adults' instructional schema and children's real learning (Duschl et al. 2011; Krajcik et al. 2012; Yao and Guo 2014), like a dual searching within theory and data. This suggests that when developing the hypothesis for a learning progression of scientific explanation, the acceptability and adequacy of students need to be given the same, if not more, weight than the correctness or completeness in the philosophy (Berland and McNeill 2012; Braaten and Windschitl 2011). Departed from this assumption, following paragraphs discuss how we propose our hypothesis through fusing theories in philosophy of science and data in science education.

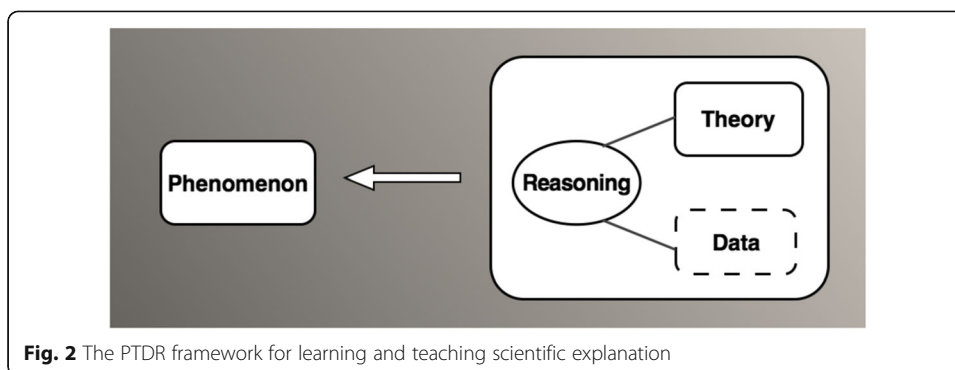
Overview of the PTDR framework

Considering both the appropriateness to students and the epistemological development required in K-12 science education, the educational framework of scientific explanation should be built upon relatively basic or simplified philosophical theories (e.g., Sandoval 2003; McNeill et al. 2006). Similar to the educational framework of argumentation established on Toulmin's model of argumentation (e.g., Erduran et al. 2004; Zohar and Nemet 2002; for a review, see Osborne et al. 2012), Hempel's covering law model, which has both basic philosophical accuracy and educational acceptability, offered a syntax structure that an educational framework of scientific explanation can be located on. Therefore, the three elements in the covering law model (explanandum, general laws, antecedent conditions) should become the first three key components when introducing students the idea of scientific explanation. Other philosophical theories informed us that a well-defined framework of scientific explanation should not neglect things underneath a syntax structure. For instance, the causal-mechanical model emphasized the importance of causal interaction or mechanism revealed in a scientific explanation (Salmon 1984, 1994; Woodward 1989). This notices us, besides the components that composing a syntax structure, the semantic linking plays an important role when deciding whether a discourse is explanatory or not. In response to this concern, we added reasoning as the fourth component in our educational framework for scientific explanation.

On balance, when students in K-12 education construct a scientific explanation, we expect them to identify the *phenomenon* that will be explained, then find *theories* and *data* that could be used to explain, last but not least, make sense of the association between the materials used to explain and the phenomenon needing explanation through *reasoning* (Fig. 2). Above discussion made an initial linkage between the educational framework of scientific explanation and its own philosophical foundations. Using the initials of the four elements (phenomenon, theories, data, reasoning), we name this framework "the PTDR framework for teaching and learning scientific explanation". In the following we further justify our selection of the four elements and define each component.

The phenomenon component

Comparing to the CER framework, which starts with the component of claim, the PTDR framework starts with the phenomenon component. The phenomenon component in the PTDR framework comes from the explanandum in the covering law model



(Hempel and Oppenheim 1948). But considering students' familiarity and acceptances, we used the term phenomenon instead of the term explanandum, which is seldom used in everyday communication. The claim component in CER framework, which came from the Toulmin's argument pattern, has some extent the nature of debatable and uncertainty. In contrast to the claim component in the CER framework, the phenomenon component in the PTDR framework—a description of the phenomenon to be explained—is more objective and certain, which befits the common implication of scientific explanation and also suits to helping students beginning their explanation practice with specific observation. The phenomenon component settles a goal for the whole explanation activity.

The theory component

Although both having the reasoning component, the PTDR framework adjusted the intention of this component by separating the theory component from it. Policy document like NGSS endorse the significant role of scientific principles in explanation (NGSS Leading States 2013). The CER framework emphasized the role of scientific theories as well, but included it into the reasoning part. "Reasoning is the logic for why the evidence supports the claim, which can often include scientific principles (McNeill et al. 2006, p.156)". The theory component is also not neglected in the learning progression derived from the CER framework. Songer et al. (2009) integrated content learning progression with the learning progression of scientific explanation (see also, Gotwals and Songer 2013). The nature of Songer et al.'s emphasis on the necessities of combing content understanding with explanation construction together is an emphasis on the center role of scientific principles to scientific explanation. For example, in their learning progression of explanation, one of the important variables is the scaffolding about disciplinary core idea, which is contained by four levels from seven levels in total (Gotwals and Songer 2013). Scientific theories are also valued in the philosophical concern. For example, in the covering law model, the theory component (law sentences) is the core of an explanans (Hempel and Oppenheim 1948; Hempel 1965). Another example in the unificationist account, some theories like the Newton's law of universal gravity generated more coherent understand for the world so that a better explanation can be constructed based on it (Kitcher and Salmon 1989). This means the universal explanatory of an explanation strongly depend on the scientific theory adopted.

Existing research using the CER framework indicates that students have the most problem in the reasoning component when constructing explanation (e.g., McNeill

et al. 2006; Songer et al. 2009). But due to the reasoning component in the CER framework is twofold, using that framework is not easy to diagnose whether the problem located in their invoking and understanding of scientific theory, or located in their reasoning ability. On balance, the imperative role of the scientific theory and the aim for a more discernible diagnosing suggest that the theory component better not be incorporated into the reasoning component but as a separated component.

The reasoning component

In the research in scientific reasoning, there are two different research traditions: domain-general approach in cognitive psychology and domain-specific approach in science education (Schauble 1996; Zimmerman 2000). After separating the theory part, the reasoning component in the PTDR framework is more close to the domain-general intention to scientific reasoning. A basic definition of scientific reasoning includes: isolation and control of variables, combinatorial reasoning, correlational reasoning, probabilistic reasoning, proportional reasoning, etc. (e.g., Lawson 1978, 1985; Lawson et al. 2000). Above definition of scientific reasoning is a relatively traditional one (Holyoak and Morrison 2012). Other scholars like Klahr and Dunbar from the information processing perspective, Kuhn et al. from the epistemology perspective, and Osborne from the argumentation perspective proposed different interpreting on scientific reasoning (Klahr and Dunbar 1988; D. Kuhn et al. 2008; Osborne 2013). However, as the Lawson's definition of scientific reasoning has been widely used by researchers around the world, their interpretation is adopted in our framework.

The data component

In the CER framework, the evidence component "is scientific data that supports the claim" (McNeill et al. 2006, p.158). However, if referring to its exact definition, evidence ought to be neutral information, which "is generally taken to be all the information a person has, positive or negative, relevant to a proposition" (Audi 1999, p. 293). By emphasizing the function of supporting, the evidence component in the CER framework might achieve a simplification that is necessary for students in lower ages. But too much highlighting the supporting function may hinder students' data-driven critical thinking in the future. From the nature of science, the development of science stands on the persistent and critical progression of organizing and interpreting data (T. Kuhn 1970). In addition, the term data is closely associated with another practice—analyzing and interpreting data (NGSS Leading States 2013). Therefore, the PTDR framework substituted the evidence component with the data component to convey the neutral character of the information we observed from the nature world and help students consciousness of data driven elaborating, examining, even reconstructing scientific explanation.

A hypothetical learning progression of scientific explanation for K-12 science education

Based on the PTDR framework, we continue to focus on the second "cloud" –further extending and elaboration for learning progressions of scientific explanation. Besides the increasing of components and the decreasing of scaffolding suggested by Songer

et al. (Songer et al. 2009; Songer and Gotwals 2012), this essay makes one step further by delineating potential progression levels for each component (Table 1). The delineating of levels was based on existing learning progression research on scientific explanation (e.g., Songer et al. 2009; Songer and Gotwals 2012; Gotwals and Songer 2013), influential policy documents like the NGSS and the PISA framework (NGSS Leading States 2013; OECD 2013), and other related research (e.g., Perkins and Grotzer 2005; Berland and McNeill 2012).

The hypothetical learning progression of scientific explanation based on the PTDR Framework can be used in assessment developing, instructional design and learning scaffolding. Here we take a specific instance to initially illustrate how to use the learning progression of scientific explanation based on the PTDR framework to analyze a task. For example, a typical task in middle school can ask students to explain why it is harder to knock over the pins when bowling with volleyball instead of a bowling ball at the same speed (Fortus et al. 2013). The phenomenon here is clear and involves only one variable—mass of the ball. Students can use this key variable as the clue to the scientific theory that the kinetic energy depends on the object’s mass/speed ($E = 1/2 mv^2$). The data set for this task is appropriate and small (mass of bowling ball vs. mass of volleyball). Through simple deduction reasoning, student can explain that: The volleyball with bigger mass has more kinetic energy comparing to the bowling ball at the same speed. Therefore, it’s more difficult to knock over the pins with the volleyball than using a bowling ball.

Table 1 The Hypothesis of Learning Progression of Scientific Explanation based on the PTDR Framework

| Components | Lower Level | Upper Level |
|------------|---|---|
| Phenomenon | Affirming and describing the phenomenon. [The phenomenon is clear; it has single variable or has a few variables but their relationship is simple; the changing pattern is conform to everyday experience.] | Abstracting and representing the phenomenon. [The phenomenon needs processing from real context. It has several variables and their relationship is complex; the changing pattern may not conform to everyday experience.] |
| Theory | Applying scientific ideas, law-like sentences, etc. under the scaffold from teacher or instructional materials. | Using the key variable as the clue for independently selecting scientific concepts, laws, theories and principles. |
| Data | Searching data in a small data set. Data set is limited to appropriate data Data set is ready for directly processing | Searching data in a big data set. Data set includes both appropriate/inappropriate data/non-related data set Data is collected by directly observation, measurement, etc. |
| Reasoning | Making basic logical connection between idea, data, and phenomenon, though generalization, induction, or simple causal reasoning. | Designing a unification model that connecting phenomenon, evidence, and theory, though scientific reasoning including but not limited to isolation and control of variables, combinatorial reasoning, probabilistic reasoning, hypothetical-deductive reasoning, etc. |

In assessment, resolving students' performance on explanation tasks with the PTDR framework and the hypothetical learning progression can provide detail knowledge about students' developmental outcome in scientific explanation (e.g., Gotwals and Songer 2013; Yao, Guo and Yang 2016). For example, research found that some lower level students' explanations just had a claim about the phenomenon, lacking of sufficient data and scientific reasoning supporting their claims (Songer et al. 2009; Yao, Guo and Yang 2016), and that only some higher level students' explanations can have a complete language structure (Gotwals and Songer 2013; Yao, Guo and Yang 2016) and can reveal the in-depth mechanism of the phenomenon (Yao, Guo and Yang 2016). Above information about students' progression in scientific explanation is also useful for instruction organization. Other research and our study both found that fading scaffolding which is based on the learning progression of scientific explanation can facilitate students' development of this competence (e.g., McNeill et al. 2006; Yao, Guo, et al. 2016).

Reflection and implication

Three decades have passed, since Solomon's call for an explicitly instructional intervention on developing students' ability in construction of scientific explanation (Solomon 1986). During the last decade, science educator developed the first framework, the CER framework, which can serve as a foundation for effectively and systematically cultivating students' competence in constructing scientific explanations (e.g., McNeill et al. 2006; Songer et al. 2009). Starting from clouds casted on the CER framework, this paper first attempts to establish an educational framework on the ground of philosophical theories of scientific explanation. Subsequently we elaborate and extend the learning progression of scientific explanation based on the PTDR framework.

Although the PTDR framework shares some similar features of the CER framework, the philosophical foundations are distinct from each other. The most significant implication is that the PTDR framework emphasizes the core position of scientific theories. Because the theory or general law offers an explanatory framework, which is essential to how a scientific explanation satisfy people:

“... When you ask why something happens, how does a person answer why something happens? ... And when you explain a why, you have to be in some framework that you allow something to be true. Otherwise, you're perpetually asking why. (Feynman 2015, 48 s – 1 min 50s)”

However, the inclusion of a theory component in the PTDR framework raises two issues that require further discussion: (1) Should the general law or scientific theory be strictly defined during K-12 science education? (2) Should the selection and usage of theory be adopted as criterion for judging students' competence in scientific explanation construction? With respect to the first issue, suggested by the pragmatic view students' reconstruction of scientific ideas should be evolving during K-12 study. Therefore, at entry point of science education, some simple principles like “light travels in straight”, or “sound transmitted faster in water than in air” can be adopted as a general law on which a preliminary explanation can be constructed. When their knowledge base is ready, students can be taught about what can be regarded as a scientific law and

how to construct an explanatory and unificatory explanation from it. Regarding the second issue, we refer to philosophical accounts that understanding and explanation are closely connected in nature (von Wright 1971). Therefore, we suggest the competency of constructing scientific explanations, at least to a certain extent, depends on scientific content and students' understanding of these content. As a consequence, the understanding, selection, and application of theory cannot be taken apart when assessing students' ability to explain. This view is shared by Songer et al. (2009) and also in accordance with standard documents (e.g., NGSS Leading States 2013): the content knowledge and practice are intrinsically entangled and cannot be separated from each other.

As the CER framework and the learning progression derived from it have undergone extensive testing thereafter proved they are more effective comparing to traditional intervention (e.g., McNeill and Krajcik 2008, 2009; McNeill et al. 2006; Songer et al. 2009; Songer and Gotwals 2012), the hypothetical learning progression we propose also needs further empirical testing. Fusing the coding and analyzing method developed in previous research (Gotwals et al. 2012; McNeill and Krajcik 2009) with the PTDR framework, cross-age or longitudinal assessment study would have the promising to detect how the theory component interacts with other components and how these components together affect the whole explanation (Yao, Guo and Yang 2016). In addition, an integrated instruction can be designed by fusing the learning progression of scientific explanation with other learning progressions like the concept of energy or matter (e.g., Yao et al. 2015; Hadenfeldt et al. 2014). Teaching experiments on this instructional design can not only provide a chance for closing observation on how students enhancing their scientific explanation ability around one core ideas, but also help to answer the question that in what learning outcome and at what extent students after learning integrated science unit will differ from students under traditional intervention. For example, our recent research fused the learning progressions of energy understanding and scientific explanation into an integrated learning-teaching sequence. Rest on that we carried on a quasi-experiment study found: students in treatment group got a synergetic improvement of energy understanding and explanation ability, which the students in control group didn't (Yao, Guo, et al. 2016).

Endnotes

¹Detailed counterexamples and analysis see a review made by Salmon (1989).

²The term "pragmatic", "pragmatics" and "pragmatism" are referring to their meaning in the philosophy of language. Pragmatism is "a philosophy that stresses the relation of theory to praxis and takes the continuity of experience and nature as revealed through the outcome of directed action as the starting point for reflection" (Audi 1999).

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Authors' contribution

All authors contribute to the idea and writing of the manuscript. All authors read and approved the final manuscript.

Competing interest

The authors declare that they have no competing interest. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere.

Author details

¹Department of Physics, Beijing Normal University, Beijing 100875, China. ²Department of Physics Education, Leibniz Institute for Science and Mathematics Education at Kiel University, Kiel 24118, Germany. ³National Center for School Curriculum and Textbook Development, Ministry of Education, Beijing 100029, China.

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