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Kok-Sing Tang

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Kok-Sing Tang

National Institute of Education, Nanyang Technological University, Singapore, Singapore

ABSTRACT

This paper reports on the design and enactment of an instructional strategy aimed to support students in constructing scientific explanations. Informed by the philosophy of science and linguistic studies of science, a new instructional framework called premise–reasoning–outcome (PRO) was conceptualized, developed, and tested over two years in four upper secondary (9th–10th grade) physics and chemistry classrooms. This strategy was conceptualized based on the understanding of the structure of a scientific explanation, which comprises three primary components: (a) premise – accepted knowledge that provides the basis of the explanation, (b) reasoning – logical sequences that follow from the premise, and (c) outcome – the phenomenon to be explained. A study was carried out to examine how the PRO strategy influenced students' written explanations using multiple data sources (e.g. students' writing, lesson observations, focus group discussions). Analysis of students' writing indicates that explanations with a PRO structure were graded better by the teachers. In addition, students reported that the PRO strategy provided a useful organizational structure for writing scientific explanations, although they had some difficulties in identifying and using the structure. With the PRO as a new instructional tool, comparison with other explanation frameworks as well as implications for educational research and practice are discussed.

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Introduction

In recent years, curriculum reforms and standards around the world are putting more emphasis on the construction of scientific explanations. In the Next Generation Science Standards (NGSS) from the U.S.A., a central focus is the construction of logically coherent explanations, which are defined as 'explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study' (National Research Council, 2012, p. 52). The Common Core Standards for Literacy in Science and Technical Subjects – another influential curriculum document in the U.S.A. – focuses on the literacy aspect of explanation by outlining it as a key text-type that K-12 students need to learn in science (Council of Chief State School Officers,

CONTACT Kok-Sing Tang koksing.tang@nie.edu.sg National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore

2010). In Singapore where this study was conducted, one of the assessment objectives in the science syllabus specifies that 'students should be able to – in words or by using symbolic, graphical, and numerical forms of presentation – present reasoned explanations for phenomena, patterns and relationships' (e.g. Ministry of Education, 2013, p. 4).

Constructing explanations in the science classroom is a complex endeavor involving various cognitive, epistemic, linguistic, and semiotic competencies (Gilbert, Boulter, & Rutherford, 2000; Sandoval, 2003; Yeo & Gilbert, 2014). As such, there have been numerous studies conducted to enable students in overcoming various difficulties in scientific explanations. Notably, an instructional support based on Toulmin's (1958) claim, evidence, and reasoning (CER) framework is widely used to help students structure written explanations (e.g. Forbes et al., 2014; McNeill, Lizotte, & Marx, 2006; Ruiz-Primo, Li, Tsai, & Schneider, 2010; Sandoval, 2005; Wang, 2014). However, recent debate on the nature of explanation and argument has raised questions on whether the CER framework is more suited for argumentation arising from empirical inquiry, rather than theoretical-driven explanations that aim to provide causal accounts of natural phenomena (Berland & Mcneill, 2012; Osborne & Patterson, 2011). This distinction is crucial because what is defined as explanation in many national curriculum standards, such as NGSS, posits explanations as the '*explicit applications of theory* to a specific situation or phenomenon' (National Research Council, 2012, p. 52, emphasis added). In this theoretical-driven aspect of explanation, there have not been many instructional supports from the literature that explicitly support students to use accepted scientific knowledge (e.g. theories, laws, models) to provide a causal account of why or how natural phenomena happen.

In this study, I present a new instructional framework that was developed to help students construct scientific explanations. Called the PRO (premise–reasoning–outcome) strategy, this heuristic framework was conceptualized based on studies in the philosophy of science and systemic functional linguistics (SFL). The PRO strategy was enacted and tested in four 9th-10th grade physics and chemistry classrooms in Singapore over two years. As this was the first time the strategy was tested in the classrooms, the purpose of this exploratory study was to examine the enactment of the PRO strategy and how it related to students' written explanations, rather than evaluate its effectiveness through a quasi-experimental design. As such, the broad research question for this study was: How was the use of the PRO strategy manifested in the students' written explanations?

Research on explanations

Delineation of explanation

The word *explanation* is often used with multiple meanings in science education. Yet, what constitutes an explanation is not straightforward and requires further unpacking. First, an important distinction needs to be made between pedagogical versus scientific explanation (Horwood, 1988). Pedagogical explanation is, strictly speaking, more an explication that involves expanding the meaning of a scientific term or elaborating a scientific theory or concept (Braaten & Windschitl, 2011). Such pedagogical explanation is commonly found during science instruction when a teacher 'explains' a scientific idea to promote students' understanding. Such explanation often involves various discursive strategies such as repetition, paraphrase, metaphor, analogy, and vignette (Braaten & Windschitl, 2011). This loose usage of explanation is also found in curriculum and assessment documents, such as this question found in the Cambridge O-Level Physics Examinations: 'Explain what is meant by the term *specific heat capacity*'. The Cambridge syllabus (Cambridge International Examinations, 2013, p. 36) further provides a glossary that defines the phrase 'explain what is meant by … ' as:

> Normally implies that a definition should be given, together with some relevant comment on the significance or context of the term(s) concerned, especially where two or more terms are included in the question. The amount of supplementary comment intended should be interpreted in the light of the indicated mark value.

Scientific explanation, on the other hand, goes beyond descriptions of observable natural phenomena or supplementary comment on scientific terms and definitions. Instead, it is a theoretical or mechanistic account of why or how phenomena happen the way they do (Achinstein, 1983). Thus, to 'explain what is meant by specific heat capacity' would not be considered a scientific explanation as it only involves a definition and perhaps some elaboration of the context in which the term is used. There is no specific phenomenon to account for in this question. However, if the question was: 'explain why water has a high specific heat capacity' or 'explain why water is often used as a coolant', then this would be a scientific explanation as there is a specific phenomenon that can be explained using accepted scientific theories or knowledge. For the first question, a theoretical model and microscopic account involving intermolecular hydrogen bonds between hydrogen-containing polar molecules is used to explain the phenomenon of water having a high specific heat capacity. For the second question, the established knowledge of water having a relatively high specific heat capacity as well as the physics concept of heat capacity are now used to explain why water is used as a coolant. Both are explanations involving accepted theories or knowledge to account for the natural phenomena.

Besides pedagogical explanation, another important distinction is between scientific explanation and scientific argument (Osborne & Patterson, 2011). Although explanation and argument are closely related, they differ largely in their epistemic functions. An explanation seeks to either make sense of an observed phenomenon based on prior scientific knowledge or formulate new theories to account for the underlying causes or genesis of a new phenomenon. An argument, on the other hand, seeks to persuade others by justifying a claim or position in light of supporting or contradictory evidences. According to Osborne and Patterson (2011), a defining criterion that distinguishes explanation and argument is the tentativeness of the account to be explained or argued. In an explanation, the phenomenon to be explained is not in doubt or has already occurred. Thus, questions such as 'how does an airplane fly?' or 'why did dinosaurs become extinct?' are explanation questions because the phenomena (i.e. an airplane flying, dinosaurs are extinct) are not in dispute.

In an argument, however, there is always a degree of uncertainty over the claim to be argued, without which there would be no argument. As such, an argument involves the justification of a claim through the use of supporting evidences (Braaten & Windschitl, 2011). For instance, although 'dinosaurs are extinct' is not in dispute, the statement 'a catastrophic asteroid impact wiped out the dinosaurs' is a claim that is not universally accepted among geologists and paleontologists as there are other competing claims in contention (e.g. volcanic eruption, climate change). In order to justify the asteroid claim and convince the scientific community to accept it, an argument needs to be built from supporting empirical evidences; for example, the time and formation of the Chicxulub crater or the high concentration of iridium found in clay boundary layer around the world. The argument of an asteroid impact also needs to be evaluated in the light of other competing claims and their supporting evidences. Only when the scientific community no longer disputes a claim, then the claim will be accepted as scientific knowledge or 'fact' (Latour & Woolgar, 1979).

Explanation and argument are often conflated because the validity of an explanation often requires argumentation, and conversely, the process of argumentation often involves multiple explanations. It is easy to see this confusion from the above example on dinosaur extinction. For example, to explain how an asteroid impact *can theoretically* wipe out the dinosaurs would require a causal explanation. The logic of the explanation will be judged according to the extent the account is coherent (Thagard, 2008), both internally within the explanation as well as externally to accepted scientific knowledge (e.g. laws, theories, facts). However, the explanation cannot be judged by whether the asteroid impact actually wiped out the dinosaurs. To address the later question will require an argumentation involving supporting empirical evidences as well as alternative explanations in contention. Thus, the validity of an explanation as well as the focus of an argument centers on whether an explanation is better than another alternative explanation, and not within the explanation itself (Osborne & Patterson, 2011).

Instructional supports for writing explanations/arguments

In the last decade, there have been numerous intervention studies designed to promote explanation and argumentation. While these interventions are notable in their drive toward inquiry-based instruction, they tend to either treat explanation as synonymous to argumentation or prioritize argumentation over explanation (Braaten & Windschitl, 2011). A common intervention is the use of a three-part instructional structure consisting of claim, evidence, and reasoning, or CER (e.g. McNeill et al., 2006; Moje et al., 2004; Ruiz-Primo et al., 2010; Wang, 2014). For example, in a middle school chemistry lesson developed by McNeill et al. (2006), the students in the study were prompted to write a claim statement on whether they thought a nail and a wrench were made of the same substance or not. They were then provided with data (to be used as evidences) and prompted to write a reasoning of how the evidences justify their claims. Although such an intervention is useful in providing support for students to justify claims by using evidences, what is involved in the reasoning is not explanatory for two reasons (Braaten & Windschitl, 2011; Osborne & Patterson, 2011). First, the structure of CER corresponds to an argument (Toulmin, 1958) rather than an explanation. Second, the intervention tends to emphasize empirical investigations and justification through observations, and focus little on the underlying causal or theoretical accounts of the phenomenon concerned. According to Osborne and Patterson (2011), it is important to distinguish between the pedagogical practices of explanation and argumentation because the cognitive, linguistic, and epistemic demands for each of these practices are different. Therefore, while much research has been done to scaffold students' argumentation practices, there are few similar interventions designed to support explanation construction.

Nevertheless, there are two useful lessons we can learn from past intervention studies on argumentation. First, providing a rhetorical structure such as the CER framework is a useful instructional strategy as students who were provided with the CER structure performed better in their argumentative writing in terms of quality and coherence (McNeill et al., 2006; Wang, 2014). The use of the CER structure also supports the theoretical idea of providing a scaffold to support the students' cognitive and linguistic development until they are able to write arguments without the scaffold (Bruner, 1966). These studies suggest that a similar rhetorical structure more suited for constructing explanations could be useful in enabling students to write scientific explanations. The second lesson we can learn is that any rhetorical structure needs to be explicitly taught to the students at the beginning of the intervention and continually reinforced throughout the curriculum unit. For instance, in McNeill et al.'s (2006) study, the intervention began with a focal lesson where the teacher introduced the CER framework and modeled how to use it to write arguments before the students used it subsequently. The use of the CER framework in the writing tasks was then repeated throughout the 8-week curriculum unit for various topics.

Separately, in literacy research, scientific writing has been an area of interest among many literacy researchers (e.g. Fulwiler, 2007; Halliday & Martin, 1993; Wellington & Osborne, 2001). As the genre of scientific explanation is not a familiar form of writing for many people, most students often find it challenging to write explanations simply because they do not know where to begin. As such, several instructional scaffolds have been developed within literacy research to support students in recognizing the structure of the genre and the style of writing required. One such structure is the use of a 'writing frame' to guide students in recognizing the key features of the genre they are writing (Wray & Lewis, 1997). In particular, Wellington and Osborne (2001) suggest a writing frame suitable for writing scientific explanations. Such a writing frame consists of a number of successive prompts such as 'I want to explain why … ', 'An important reason for why this happens is that … ', 'The next reason is that … ', and so on. These repetitive prompts are designed to help students write the causal sequence of reasoning until they are satisfied with the explanation. Although writing frame provides a useful pedagogical structure for students to write explanations in a sequential manner, they lack the epistemic specificity of helping students recognize and understand the functions and relations of the components within an explanation; much like what the CER structure does in terms of unpacking how the components of claim, evidence and reasoning function together to constitute a scientific argument.

Theoretical underpinnings of PRO

To develop an instructional framework suitable for the construction of scientific explanations (i.e. PRO strategy), I draw on several theoretical ideas from the philosophy of science and SFL.

The logic of explanation from philosophy of science

In the philosophy of science, the nature of scientific explanations has been studied and debated for debates. The broad consensus among philosophers is that a scientific explanation is a theoretical account of why or how a natural phenomenon occurs (Achinstein, 1983). Such theoretical account typically provides some mechanistic or probabilistic reasons as the underlying causes of the phenomenon. At the same time, explanations also invoke generalizable laws, theories, or rules in addition to unseen entities and constructs (e.g. atoms, photons, energy, mole, gene). This is what makes explanations different from descriptions, which are unrelated and isolated bits of information (Horwood, 1988).

Applying a philosophical lens in science education, Braaten and Windschitl (2011) conceptualize five models of scientific explanations that are relevant for science educators. The five models are Covering Law, causal, statistical-probabilistic, pragmatic, and unification. In the present study involving physics and chemistry education at the upper secondary level, I consider the Covering Law, causal, and unification models most relevant to the conceptualization of the PRO strategy. As such, these models will be further elaborated.

The Covering Law model, also called the deductive–nomological (D–N) model, was the first model of scientific explanation proposed by philosophers of science (Hempel & Oppenheim, 1948). In this model, scientific explanations are constructed based on regular patterns that are derived from and validated through empirical observations. As these patterns get expressed into generalizable statements, and subsequently become well established and accepted in the scientific community, they become known as 'natural laws'. Well-known laws that are learned by most secondary science students include Newton's Laws of Motion, Laws of Thermodynamics, Avogadro's Law, and Mendelian's Law of Inheritance. Once a law is established – and until it is invalidated by the scientific community, scientists seek to use laws as the basis, or premise, to account for an observable phenomenon through deductive and logical reasoning. Laws are also frequently used to predict the outcomes of an anticipated phenomenon or experiment. Thus, the Covering Law model works by appealing to natural laws or regularities as the basis for logical deductions to explain a phenomenon.

Philosophers of science recognize that there are limitations with the Covering Law model because not all explanations are governed by natural laws, especially outside the discipline of physics. They have also debated over the precise meaning of a natural law, and how a law is distinct from a principle, rule, model, or theory. However, for the purpose of designing instructional supports, we do not need to be dogmatic over the nature of a law in order to use the Covering Law model to help K-12 students construct scientific explanations. Rather than relying on laws in the strict sense, many scientific explanations in school science use 'law-like' rules or generalizations as the premises of the explanation. For instance, in explaining why a raw egg sinks in tap water but rises in salt water, an acceptable explanation will invoke a general rule that the buoyancy of an object is determined by its density relative to its surrounding fluid. With this general rule as a premise, one can explain the raw egg sinks because its density is higher than water (at 1000 kg/m^3) and floats on sea water because its density is lower than salt water (at around 1050 kg/m^3). In this example, it is important to note that the rule where buoyancy is determined by relative density can itself be explained by a more fundamental rule such as Archimedes' principle. Thus, what can be accepted as a relevant premise to an explanation must also be considered based on the learners' prior knowledge and the curriculum standard at various grade levels.

The second relevant model of scientific explanation is the unification model. This model is conceptualized based on the argument that the power of an explanation rests on its utility to unify seemingly disconnected phenomena with an overarching and coherent framework or theory (Friedman, 1974). A good example is the kinetic model of matter which provides a unifying framework to understand a wide range of phenomena involving air pressure, temperature, thermal energy, latent heat, and diffusion. Similarly, Darwin's theory of evolution provides the overarching framework to account for speciation, genetic diversity, and adaptation in biology (Scheiner, 2010). Thus, the unification model of explanations seeks to explain the natural world with as little general theories or big ideas as possible. In fact, one of the longstanding goals in physics has been to develop a 'theory of everything' or a single explanatory framework that is able to link all the physical aspects of the universe together. In a way, the unification model functions very similar to the Covering Law model in that both models work by relying on generalizable statements or big ideas (known or assumed to be true) as the basis for explaining many specific and disparate phenomena. As such, these two models can be used complementarily for the teaching of science.

Besides the Covering Law and the unification models, another commonly used model in science education is the causal model (Braaten & Windschitl, 2011). Osborne and Patterson (2011) argue that this is probably the most prevalent form of scientific explanation in the classrooms as the main focus of classroom discourse is often the construction of causal accounts of natural phenomena. Many philosophers have also identified that the key attribute of an explanation that differentiates it from a description is causation (Horwood, 1988; Salmon, 1989). In particular, the value of an explanation is enhanced when it identifies some underlying causes or mechanisms that cannot be readily observed empirically. The causal model differs from the Covering Law model in that a law or rule may not be necessary for the explanation. Instead, the emphasis of the causal model lies on firstly, identifying a known or plausible factor as an underlying cause and secondly, establishing a logical connection to the subsequent effects. In science, this is commonly the case for explaining a phenomenon via a microscopic mechanism at an atomic, molecular, or cellular level. For instance, to explain why aluminum is malleable and ductile, the cause of the explanation is often attributed to its metallic structure (specifically a polycrystalline lattice structure). With this structure as the cause, the consequential effect is that layers of aluminum atoms are able to slide over one another easily. The causal model is not mutually exclusive with the Covering Law and unification models. They can be used together where the Covering Law and unification models provide the 'first cause' or basis of an explanation, while the causal model provides the subsequent cause-and-effect deductions that follow from the first cause.

The genre of explanation from SFL

The philosophical models of explanation provide science educators with a good understanding of the logical structure of a scientific explanation (Braaten & Windschitl, 2011). However, as these models were conceptualized within an idealized and philosophical context, they do not account for how scientific explanations are actually constructed through oral and written language within a social setting. This is where I draw on the research from SFL (Halliday, 1978) to further examine how a scientific explanation is constructed. In particular, the notion of genre from SFL is relevant in unpacking the linguistic structure of an explanation.

According to Martin (1992), a genre is a staged, goal-oriented, and social activity, which is reflected in the way texts are structured in order to fulfill the activity. For example, a science experiment is a social activity and the language surrounding this activity evolves historically over the years to suit the communication needs of scientists. As the tasks required to perform an experiment involve multiple steps, therefore the genre of an experimental report has correspondingly developed various sequential stages (e.g. aim, procedures, results, conclusion), with each stage having a unique and recognizable linguistic feature. From past research in scientific written texts, functional linguists have identified four major genres in science (Halliday & Martin, 1993). These genres and their functions are: (a) experimental report – to present the procedures and results of an experiment, (b) information report – to organize information about things or events in the world, notably through classification, decomposition, description, or comparison, (c) argument – to state a claim or position and present supporting evidences in favor of the claim or position, and (d) explanation – to account for the underlying causes or processes of a phenomenon.

In written texts, a genre has distinct functional stages or schematic structures which can be identified on the basis of lexical and grammatical shifts in the text (Martin, 1992). In an explanation text, the schematic structure comprises three functional stages called phenomenon identification (what is being explained), implication sequences (series of logical clauses), and closure (Unsworth, 2001; Veel, 1997). The phenomenon identification typically comprises a general statement that introduces the topic or context of the explanation. As such, it tends to appear grammatically as simple clause(s) with timeless present tense verb; for example, 'Matter exists as either as a solid, liquid, or gas'. By contrast, the implication sequences stage of an explanation is grammatically more elaborated. According to functional linguists, the linguistic features of the implication sequences stage are the defining characteristic of a scientific explanation.

Two linguistic features are prominent in the implication sequences of an explanation (Martin, 1993). First, the implication sequences contain a high percentage of action verbs (e.g. water *evaporates*, molecules *escape*). By contrast, another genre such as an information report usually contains a larger proportion of relational verbs (e.g. water *is* a liquid, an atom *consists of* nucleus and electrons). Second, the implication sequences are connected together in a logical sequence. This is achieved grammatically through the use of conjunctions that join successive clauses or sentences coherently within the explanation text. Conjunctions construct various logical relations across clauses and sentences. Common logical relations in an explanation genre in science include: consequential (e.g. because, therefore, so, hence), temporal (e.g. when, first, then, next), comparative (e.g. but, however, while, although), and conditional (e.g. if, unless, provided). The functions of these conjunctions cannot be underestimated as these are the words that construct the 'logic' of an explanation (Wellington & Osborne, 2001). Unsworth (2001) also calls the distinctive patterns of logical relations formed by conjunctions the 'language of reasoning' within an explanation.

Instructional design of PRO

Comparing the work from both the philosophical and linguistic studies of science, there are many similarities we can draw to develop an instructional support for constructing explanations. First, it is clear that scientific explanations have a unique rhetorical structure with different functional stages. Second, this structure is distinct from that of argument in terms of both the logic and genre. Third, the structure of explanation should be made explicit to teachers and students so that they are clear about what counts as a scientific explanation, both epistemologically and linguistically (Braaten & Windschitl, 2011; Unsworth, 2001).

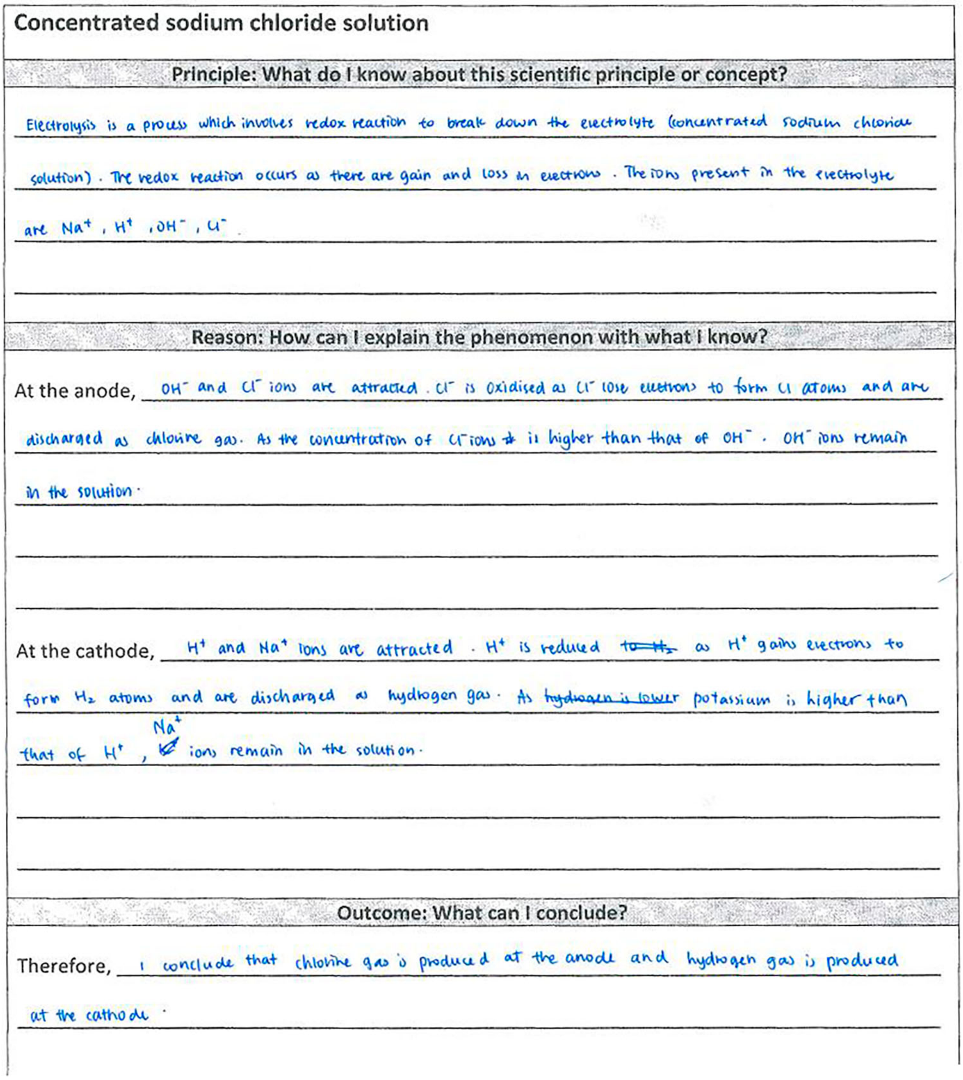
PRO framework

Synthesizing the work from both research perspectives, I developed the PRO instructional strategy to help students construct explanations by identifying three components of a scientific explanation: premise (P), reasoning (R), and outcome (O). The *premise* of an explanation provides the basis of the account in the explanation. This is informed by the Covering Law model, where the premise is a 'law-like' statement that is well established and accepted in the scientific community, as well as the unification model, where the premise is a general theory or big idea that connects multiple phenomena with an overarching framework. As the basis or 'first cause' of an explanation, the premise does not require further elaboration or justification in the context of the explanation. (However, this does not mean that students should not question the source of their knowledge for the premise.) Once a premise is established, the next part of the explanation is the *reasoning*. Informed by SFL, the reasoning is the implication sequences which comprise a series of successive clauses that build up the 'causation' of the explanation. Grammatically, this causation is achieved by the use of consequential, temporal, comparative, or conditional conjunctions (e.g. because, subsequently, although, if). Finally, the series of implication sequences leads to the *outcome*, which according to SFL genre of explanation, is the phenomenon identification stage of the explanation (what is being explained).

As a heuristic tool, the PRO strategy was presented as a linear and sequential model (from P to R to O) because this sequence is deductive and easy to remember for instructional purpose. However, this does not imply that the construction of scientific explanation must conform to such a linear manner. The students in the study were taught that they did not need to follow this linear sequence in their writing. Furthermore, as will be shown later, the teachers in the study often used the PRO strategy to teach the students how to construct an explanation in a non-sequential way by first identifying the outcome and relevant premises and then retrospectively construct the reasoning process. The use of the PRO strategy as a non-linear reasoning tool will be further discussed in the implication section.

Design of scaffolds

The PRO structure was explicitly taught as a meta-language for the students and teachers to identify and discuss the functions and relationships among the various components (premise, reasoning, and outcome) of the explanation. Besides this explicit instruction and discussion during classroom discourse, another instructional aspect of the PRO strategy was the provision of scaffolds to help students write scientific explanations. Figure 1 shows an example of a written scaffold provided for the following question: 'A concentrated sodium chloride solution was used for an electrolysis experiment with inert graphite


Concentrated sodium chloride solution

Principle: What do I know about this scientific principle or concept?

Electrolysis is a process which involves redox reaction to break down the electrolyte (concentrated sodium chloride solution). The redox reaction occurs as there are gain and loss in electrons. The ions present in the electrolyte are Na^+, H^+, OH^-, Cl^-.

Reason: How can I explain the phenomenon with what I know?

At the anode, OH^- and Cl^- ions are attracted. Cl^- is oxidised as Cl^- lose electrons to form Cl atoms and are discharged as chlorine gas. As the concentration of Cl^- ions is higher than that of OH^-. OH^- ions remain in the solution.

At the cathode, H^+ and Na^+ ions are attracted. H^+ is reduced ~~to H_2~~ as H^+ gains electrons to form H_2 atoms and are discharged as hydrogen gas. As ~~hydrogen is lower~~ potassium is higher than that of H^+, Na^+ ions remain in the solution.

Outcome: What can I conclude?

Therefore, I conclude that chlorine gas is produced at the anode and hydrogen gas is produced at the cathode.

Figure 1. Example of a PRO scaffold in a student's worksheet.

electrodes. Explain how the products are formed at the anode and cathode.' In general, the PRO written scaffold consists of prompts and guiding questions for each of the premise, reasoning, and outcome component. For instance, a typical guiding question for the premise is: 'What do I know about this scientific principle or concept?'. Sentence starters such as 'At the anode' and 'At the cathode' were also occasionally provided as hints for the kind of content-specific information required in the explanation.

The PRO written scaffold is quite similar to the use of a writing frame (Wray & Lewis, 1997) that was reviewed earlier. However, the key difference is the organization of the writing according to the epistemic and logical functions of the explanation, in terms of its premise, reasoning, and outcome. These PRO written scaffolds were used throughout the intervention research whenever students needed to write an explanation in any topic.

At the beginning of a new topic, more prompts, guiding questions, and sentence starters were provided as the students were still learning the content of the topic. Subsequently, the written scaffolds were gradually removed as the students construct new explanations within the same topic (e.g. electrolysis). The fading of written scaffolds was also practiced across the academic years. At the beginning of the year when the students were new to the PRO structure, there were more written scaffolds provided. As the students became more familiar with the use of PRO, progressively fewer scaffolds were provided.

Methodology

Research and instructional context

The study of the PRO strategy was situated within a larger three-year research project in Singapore that utilized a design research methodology (Collins, Joseph, & Bielaczyc, 2004). The purpose of the design research was to develop literacy strategies (e.g. reading, writing) that are specific to the learning of science as well as appropriate to the local context of science teaching in Singapore. The first phase of the design research was a naturalistic baseline observation of how the participating teachers taught science in their respective classroom environment (see Tang, in press). Consistent with the methodology of design research, the second phase of the research involved a collaboration with the participating teachers to co-develop teaching strategies and materials to be used during the intervention. It is within this research and instructional context that the conceptualization and development of the PRO strategy emerged. Among several other literacy strategies that were developed and trialed throughout the research project, the PRO strategy stood out as most popular and widely used by the teachers and students. The reason was twofold. First, national science examinations in Singapore place a high emphasis on written explanations. Second, all the teachers reported that many of their students struggled in writing scientific explanations.

The design research took place in two secondary schools. Two physics and two chemistry teachers were invited and subsequently participated in the research. They were recommended by the school leaders on the basis that they were experienced teachers and were keen to improve their teaching repertoire. The teachers in each school attended three professional development workshops conducted by the researchers at various junctures of the design research. During the workshops, they learned about science literacy in general and various literacy strategies, such as PRO in particular. They also reviewed their lessons with the researchers and discussed lesson ideas and implementation issues during the workshops.

In the joint development of the lessons with the participating teachers, it was decided that every lesson unit should be designed based on an inquiry model of teaching where students explored real-world phenomena and subsequently constructed explanations to account for their observations. Using the 5E Inquiry Model (Bybee et al., 2006) as a pedagogical approach, every lesson unit usually began with a hands-on experiment or demonstration to illustrate a puzzling phenomenon. At times, the predict–observe–explain strategy (White & Gunstone, 1992) was used to help students predict the outcome of the demonstration before writing their observations and explanations. After this *Engage* stage, students in groups conducted some investigations and discussed their initial ideas during the *Explore* stage. This was followed by the *Explain* stage where relevant scientific ideas and concepts were introduced by the teachers and discussed as a class. During this stage, the PRO strategy was used to help the students construct the explanations. In the subsequent *Elaborate* stage, students were given new questions in a different context from the first phenomenon, and asked to write the explanations using the PRO strategy. During the Elaborate stage, the written scaffolds were gradually removed until the students wrote an explanation for the last question without any scaffold. Finally, with the help of the teachers, students reviewed their peers' explanations and evaluated their own learning at the end of the lesson unit.

This inquiry model of teaching, together with the PRO strategy, was carried out for selected topics over two years. For physics, the topics covered were Newton's Laws, forces and moment, density, kinetic model of matter, wave, and sound. For chemistry, the topics were chemical bonding, atmosphere, qualitative analysis, redox, and electrolysis. On average, a lesson unit took about a total of 5 hours to complete, ranging from 3 hours for a small topic like waves to 9 hours for a major topic like electrolysis.

During classroom implementation, the term 'premise' in the PRO was changed to 'principle' because it was felt that students might have difficulty in understanding the meaning of the word premise. However, on hindsight, it may be better not to change the term. This is because the meaning of premise is broader and includes statements that are technically not a scientific principle (e.g. definition, formula, facts).

Research design, data sources, and analytical methods

While the design research involved four teachers in the development of the lessons and teaching materials, the present study reported in this paper involved only two of the teachers – a physics teacher from one school and a chemistry teacher from the other school. Due to manpower constraints, only one class from each of these teachers was selected for data collection, which included classroom observations, collection of students' writing, and focus group discussions (FGDs). The observed physics class from the first school had 31 students, while the chemistry class from the second school had 28 students. Both classes were at 9th grade at the start of the research. These students were generally motivated and their academic ability ranged from average to above average, according to results from the Primary School Leaving Examination (PSLE; a national examination at 6th grade). About half of these students indicated that they grew up speaking English at home. This proportion is typical in Singapore where English is the first language and the main medium of instruction for all content subjects.

As the primary goal of the design research project was to develop and understand the use of literacy strategies that emerged from the classroom context, the present study did not utilize a quasi-experimental research design to evaluate the effectiveness of the strategy. The nature of the research with a small group of teachers and students also precluded the choice of a large-scale experimental design. Instead, the focus of the study was more exploratory in nature to examine how the use of the PRO strategy was manifested in the students' written explanations. With this purpose in mind, the specific research questions for this study were:

(1) What are the differences in the students' written explanations between those that had a PRO structure and those that did not?
(2) How did the students perceive the use of the PRO strategy?

Quantitative data for the first research question were generated from term tests that were administered to every student as part of the school assessment. The test questions were set and graded by the teachers. Consistent with the assessment requirement from Cambridge GCE 'O' Level Examinations, which students in Singapore need to take at the end of 10th grade, the format of these tests consisted of multiple-choice questions, numerical calculations, short definition or descriptive-type questions, and open-ended explanation questions. Within the period of the intervention study, the research team collected three term tests from each school. From these test papers, we analyzed the students' written explanations for selected test questions based on two criteria. One, the test question was asking for a scientific explanation, and two, the topic of the question was among one of the topics taught during the design research interventions (e.g. Newton's Laws, forces and moment, kinetic model of matter, sound, chemical bonding, qualitative analysis, and electrolysis). Four questions for each subject (physics and chemistry) were identified and selected for analysis. A list of these questions can be found in Appendix A.

For the analysis, two sets of scores were obtained for every written explanation. The first set of scores was the marks from the teachers' grading. Following the assessment requirement set by Cambridge Examinations, the teachers awarded the marks based on content coverage and accuracy as well as understanding of concepts, rather than the language or structure of the explanation. The marks given for every question ranged from 2 to 4, depending on the level of difficulty and the length of the explanation required. To facilitate comparison across topics, the research team normalized the marks from 0 to 1 and calculated the mean normalized test score for every question. In this study, these test scores are used as proxy to the quality of the explanations as assessed by the classroom teachers.

Independently, the research team coded the structure of the students' explanations to generate the second set of scores. This was based on the PRO structure and the identification of the premise (P), reasoning (R), and outcome (O) in a student's written explanation. For every component, say P, a score of 1 was given if a premise statement was identified. In determining the presence of P, R, or O, the correctness or accuracy of the statement was not evaluated. For example, if the question was: 'Explain why iron is a good conductor of electricity', then the premise should be a general statement about the particle model or lattice structure of iron or metal while the reasoning is about the causal mechanism of electrons moving freely within the metal. Thus, when a student wrote: 'The atoms of the iron are tightly packed', it would be counted as a premise because it is a fact-like general statement about the iron, even though the statement would be insufficient in terms of content coverage. Two analysts were involved in the coding of the PRO structure and the inter-rater reliability between them, measured by Cohen's kappa coefficient, was 0.757.

The teachers did not know beforehand that the research team would be separately analyzing the students' test answers for a PRO structure. Because the two scoring processes were done independently, this allowed a valid comparison between the presence of PRO and the teachers' grading. In particular, we did an independent samples *t*-test to compare the mean normalized test scores between two groups: those with a PRO structure (with all P, R, and O identified) and those without (any of the P, R, or O was missing). For each subject, the mean normalized test score was calculated by averaging the normalized test scores from all the students for all four questions. The sample size for physic and chemistry test answers was 118 and 91, respectively. The comparison could not be carried out for individual questions because the sample size was too small (e.g. in some questions, there were less than five students who did not have a PRO structure).

For the second research question, qualitative data were generated from student FGDs, which were carried out at the end of every intervention topic. Four FGDs were conducted with each class, and each FGD consisted of four students. The focus of the FGD was to find out what the students thought about the inquiry model of teaching in general and the PRO strategy in particular. Each FGD was conducted by a research assistant and lasted about 30 minutes on average. All FGDs were video recorded and subsequently transcribed. For the analysis, I used open coding to examine and interpret the students' perception of the PRO strategy. In particular, Glaser and Strauss's (1967) constant comparative method was used to systematically and inductively generate emerging patterns from the data. This coding method involved noting and labeling provisional codes from similar incidents and constantly comparing one incident with others within and across codes to find consistencies and differences among them. From the emerging patterns and categories, preliminary assertions were then generated and triangulated with other data sources, such as classroom observations and students' writings. In particular, the qualitative findings were used to corroborate or provide more nuances to the quantitative results from the first research question.

Results

What are the differences in the students' written explanations between those that had a PRO structure and those that did not?

The means (M) and standard deviations (SD) of the normalized test scores for written explanations with and without a PRO structure are shown in Table 1. The independent sample t-test showed that the test scores for physics explanations with the PRO structure ($M = 0.68$, SD $= 0.28$) were significantly higher than those without the PRO structure ($M = 0.27$, SD $= 0.28$) with very strong effect size, $t(116) = -7.278$, $p < .001$, $d = 1.456$. Similarly, the test scores for chemistry explanations with the PRO structure ($M = 0.66$, SD $= 0.44$) were also significantly higher than those without the PRO structure ($M = 0.39$, SD $= 0.43$) with moderate effect size, $t(89) = -2.589$, $p = .011$, $d = .63$.

The above results show that written explanations that exhibit a PRO structure are graded better by the teachers. This could suggest that students who wrote with a PRO structure were able to produce conceptually better explanations. At the same time, it could also suggest that in a logical and conceptually sound explanation, a PRO structure

Table 1. Statistics of normalized test scores for groups with and without the PRO structure.

	With PRO		Without PRO		*t*-Test	
	n	*M* (SD)	*n*	*M* (SD)	*t*	*P*
Physics	82	0.68 (0.28)	36	0.27 (0.28)	7.278	<.001
Chemistry	68	0.66 (0.44)	23	0.39 (0.43)	2.589	.011

will be observed, even when the students were not conscious about using the PRO structure in their writing. Although it cannot be concluded that there was any kind of causality in terms of the effects that the PRO instruction had on the students' written explanations, the results nevertheless suggest there is a relationship between the presence of PRO and the quality of an explanation.

To further explore how the students wrote scientific explanations with the PRO structure, I broke down the performance for various components of P, R, and O, and examined how they related with the quality as assessed by the teachers. The bar graphs in Figures 2 and 3 show the proportion of the PRO structure as well as the individual P, R, and O found in the students' explanations across different topics for physics and chemistry respectively. For comparison, the line graph plotted on the same chart shows the mean normalized test score across the topics.

The proportion of PRO in Figures 2 and 3 is obtained by counting the number of explanations with all the P, R, and O components identified. As such, this proportion is naturally lower than each of the individual proportion of P, R, and O. From the bar chart distribution in Figures 2 and 3, we can see what was the main problem that accounted for the lack of PRO structure in the students' explanations for every topic. For instance, the low proportion of PRO was due to an overwhelmingly lower proportion of R in Moments, a lower proportion of P in Electrolysis, and lower proportions of both P and O in Qualitative Analysis. In addition, we can also see a general match between the normalized test score (plotted as line graph) and the proportion of PRO. When the proportion of PRO is low, the normalized test score tends to be low as well (e.g. moments, qualitative analysis), and vice versa (e.g. sound, chemical bonding 2).

From Figures 2 and 3, the distribution of the PRO structure and its components across topics shows no consistent pattern and trend. There are two possible explanations for this result. First, although every scientific explanation has a PRO structure, what is considered a valid premise and reasoning in an explanation is context specific, depending on the topic and question. Consequently, the students' performance in identifying P, R, and O varied across topics and this could explain why there is no consistent pattern in the bar graphs

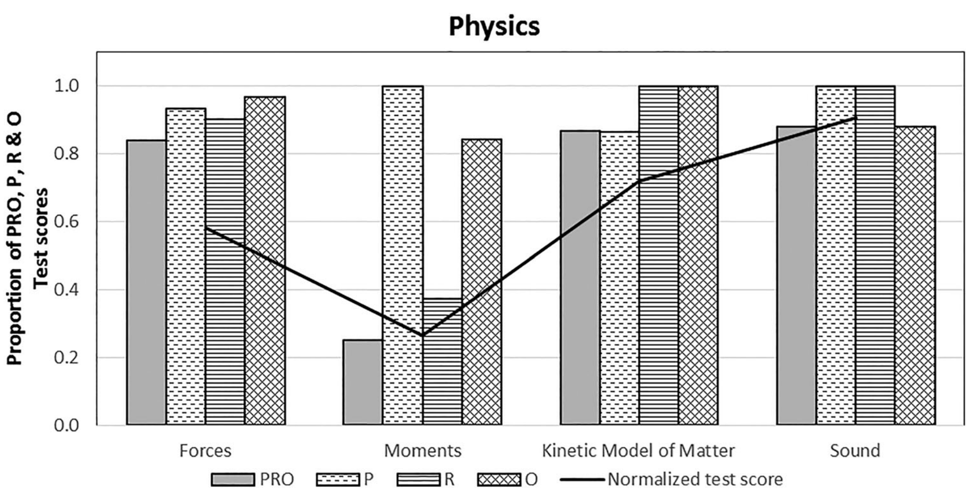


Figure 2. Students' performance in PRO and test scores across physics topics.

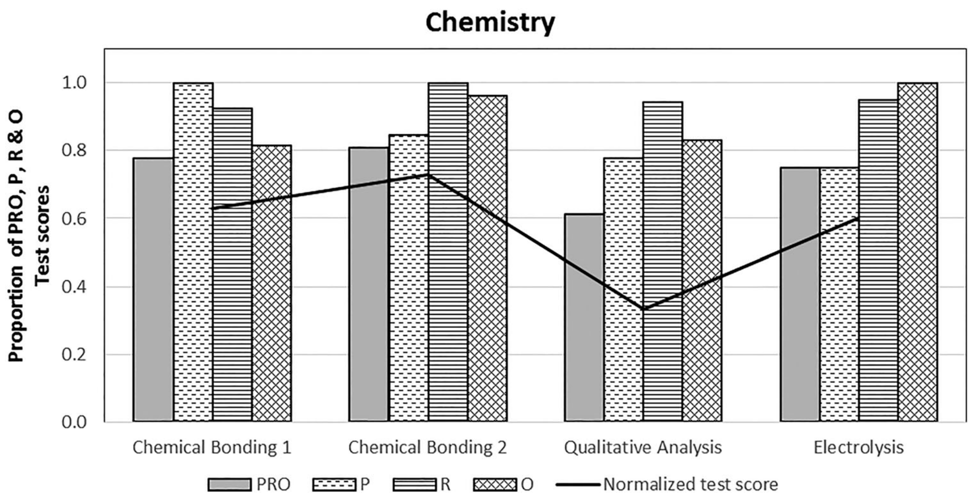


Figure 3. Students' performance in PRO and test scores across chemistry topics.

shown in Figures 2 and 3. In addition, due to the context specificity of a PRO explanation, it is difficult to track the students' development of explanation construction across time. As such, we do not see an overall trend or improvement in the proportion of PRO as well as the normalized test scores across the years.

How did the students perceive the use of the PRO strategy?

From the analysis of the FGD data, three themes emerged concerning how the students perceived the PRO strategy: (a) usefulness in providing a structure, (b) initial challenges in differentiating PRO components, and (c) opinions about the rigidity of a structure. These will be further elaborated in the following sub-sections. In the excerpts shown below, all names are pseudonyms in order to protect the students' identity.

Useful structure

Most students felt that the PRO strategy was useful in providing an organizational structure for writing scientific explanations. The following excerpt illustrates a typical response from the students when asked about their opinions of the PRO strategy:

Interviewer:	So what do you think about this PRO?
Boon Chin:	Ever since he's [teacher] introduced that answering method to us, it's been *easier to answer those like structured essay questions*. Like usually I won't know how to phrase answers, like, I understand the logic in questions but *I seriously don't know how to phrase the answers*
Jenny:	How to go with the flow
Boon Chin:	But when I use PRO, I can solve like more of the questions … For me *I think I need the method and how to phrase it*, like that, like the PRO, like I used to not know how to phrase, but then I saw PRO, and I started getting correct for my essay questions

Many students like Boon Chin related they usually did not know how to answer the so-called structured essay questions or open-ended explanation questions in contrast to multiple-choice or calculation questions typically found in science tests and examinations. Thus, when the teachers began introducing the PRO strategy during the research, the students noticed the difference and could identify its value in helping them 'phrase' their answers. When probed about how the PRO strategy specifically helped them in writing explanations, students generally mentioned that the PRO provided a structure to help them organized their ideas. For example, in the same FGD, a student Rachel elaborated how the PRO helped her to organize her ideas, which were previously 'all over the place', in a more logical and sequential manner:

Interviewer: How, how does it like, um, help you to craft a better explanation?
Rachel: *PRO like, organizes our ideas better,* like last time when we were given a question, like maybe have the right answer, but we don't know how to phrase it, *the ideas are all over the place*. But with PRO, like *we know which one to put first, which of our ideas to write down first, so it's like that, it organizes our ideas*

This was further echoed by another FGD where the students elaborated how the PRO helped them write an explanation. In particular, two students below explained the thought processes in using the PRO structure; Damini teased out the different functions of the P and R while Yasmin explained how the PRO helped her identify and synthesize the different thought processes:

Interviewer: How does it make it easier for you?
Damini: Because, *principle is basically, you are stating like a fact,* or what is going on, and *reasoning is you, further more explain* in the, you know
Yasmin: Like we have many different thoughts, and *we know how to like, separate the thoughts, and then arrange them* to answer the question.

The responses from these students corroborate with the quantitative findings which suggest that students who wrote with a PRO structure were able to produce better written explanations.

Besides providing a structure for writing explanation, another thread that emerged under this theme is how the students described their teachers breaking down the thought process of an explanation using the PRO strategy. For example, a student Aung described how he was able to 'understand more' because of the way his physics teacher used PRO to unpack the explanation:

Aung: Use PRO, like *understand more*, because he goes step by step, and then, *he teaches us to put the P and O first*, and after that, we are to *plan into the reason*, because, um, this, we can link back to what, what, um, the P, the principle, and we know, um, we need to use the principle to, um, find the answers

In the above excerpt, Aung's description is telling as he understood that the thought process in using the PRO strategy is not necessarily linear. Instead, according to what he was taught, he saw the importance of first identifying the starting principle (P) and the final outcome (O), and then retrospectively 'plan' the reasoning steps in order to link back to the starting principle.

Challenges

Another common theme from the FGDs was the difficulties that many students faced in differentiating the 3 components of PRO in an explanation. This was particularly prominent at the beginning when the students heard about the PRO structure for the first time from their teachers. In particular, several students could not differentiate between either P and R, or R and O. However, most students also felt that this was probably due to the initial unfamiliarity and they would get more familiar if they used the strategy more often. The following excerpt from one of the first FGDs illustrates this theme:

Interviewer:	And how useful do you think is the PRO?
Jia Min:	I think it's quite useful, but I *can't differentiate* the observation
Vanessa:	Like the R and the O
Serene:	Like sometimes it makes me even more confused
Vanessa:	The *R and the O, reason and observation, I cannot differentiate*
Sesha:	I *cannot differentiate the principle and reason*
Serene:	Yeah
Jia Min:	But it's effective, but it's *our first time using it, if we do it more, then it should be okay*

In the later FGDs, there were fewer comments in general about the challenges in differentiating the PRO components. However, what emerged as a common theme was the change in opinion of using PRO for different topics, as illustrated in this extended conversation:

Interviewer:	Okay so you know PRO, actually quite a lot … quite a large proportion of students in your class indicated that PRO is useful too. Do you share the same thought? Like … *this time round*?
Rui En:	I think *this year is better*
Interviewer:	Okay
Rui En:	Last year I didn't use it at all
Interviewer:	How so? How do you think it's better this year?
Rui En:	I think *this year* [for electrolysis] *there's like actual observation that you can see*. And you can link it backwards. You gotta link it back.
Interviewer:	Okay
Winnie:	I think cause this year uh for … what's the topic we're learning now?
Rui En:	Electrolysis
Winnie:	Uh yeah for electrolysis, it's like's *new topic, so the way that we have to phrase it is also kind of new*. So um … firstly Mrs Tan taught us through the PRO format. That's why most of us learn to use it that way. So it like sticks with us, cause we learnt it for the first time
Interviewer:	Okay
Winnie:	For last year we learn like [for the first time] … um … from lower sec, like different kind of styles … so that's why we don't follow the PRO
Interviewer:	Mmhmm. Okay
Elena:	I think for me it's the exact opposite. *Last year I used PRO, now I don't use PRO anymore.*
Interviewer:	How so?
Elena:	Because I don't find … I *don't understand the difference between the principle and the reason*
Interviewer:	Okay
Christine:	Uh … for mine is *I like PRO for electrolysis* only because it's like very structured. It's just what attracted to what, then the next one the reason, then just observe. Like, can really follow lah

Winnie: Yah

In the above excerpt, the students expressed different thoughts and preferences for the topic of electrolysis which was taught 'this year', as compared to chemical bonding and qualitative analysis from 'last year'. Rui En, Winnie, and Christine found that it was easier to use PRO for electrolysis. For Rui En, this was because the outcome for electrolysis phenomena tends to be something they could observe (e.g. copper is produced at the anode, electrolyte turns green). By contrast, the outcomes for chemical bonding and qualitative analysis questions tend to be unobservable (e.g. copper has high melting point, solution contains Ca^{2+}). This was further elaborated by Winnie when she explicitly mentioned that the way to phrase an explanation using the PRO format for a 'new topic' (i.e. electrolysis) was 'also kind of new'. Christine also echoed this sentiment and she further explained that she liked the PRO approach for electrolysis because it was 'very structured'. However for Elena, it was 'the exact opposite' as she could not understand the 'difference between the principle and the reason' for the topic of electrolysis. Thus, she did not use PRO for electrolysis as compared to last year where she used PRO for the topics of chemical bonding and qualitative analysis.

The differences in the way students used or preferred the PRO strategy across topics highlight the context specificity of a scientific explanation despite the general structure of PRO. This corroborates with the earlier quantitative findings (i.e. Figures 2 and 3) that show the variation in the students' performance in identifying P, R, and O across different topics. The distribution of O in the chemistry tests (Figure 3) also corroborates with what the students said about the nature of outcomes in the topics of chemical bonding, qualitative analysis, and electrolysis. In electrolysis, as Rui En related that the outcome tends to be an 'actual observation that you can see', this could explain why the proportion of O is highest for electrolysis (at 1.0) as compared to other topics (0.81 for chemical bonding 1, 0.83 for qualitative analysis). In addition, as what is considered a valid premise or reasoning in an explanation is context dependent on the topic and the question, this also explains why the students had difficulties differentiating P, R, and O for different topics.

Tension between structure and creativity

Lastly, an interesting theme that emerged from the FGD is the mixed opinions concerning whether the PRO structure imposed a restrictive pattern that stifled creativity in the writing of explanations. This was captured aptly in the following conversation where the students debated over this issue with one another:

Nicholas: Actually I don't really like using it [PRO], because like, when we're fixed to a certain draft, like, it has to be first this way, it kind of like *blocks my creativity*, it kind of blocks the way I want to phrase it, like, must be P, R, O, normally I don't use it.
Interviewer: So after you use it, do you think it helps in your structuring of your explanation?
Nicholas: It *helps, but then*
Jenny: It *feels restrictive*
Nicholas: It feels too strict, it's *like a pattern*
Jenny:

	It's *not too strict* lah, it's more like, you know, if you need help in answering a question, use a structure, you just have to *fit in the ingredients, it's like, a mould* and you fit in whatever stuff to make it, you know
Boon Chin:	Yeah, but I also don't like using the PRO actually, actually, when they give me a question, I try using PRO, I *actually got full marks* for that question, *so it actually works even though I don't like using it*

The above excerpt illustrates the tension between the utility and restriction of using a structure such as PRO. While the students said that the PRO 'helps' and 'actually works', they also 'don't like using it' because it was 'restrictive', 'fixed to a draft', and 'blocks their creativity'. What the students meant here was that they felt restricted when they had to follow a structure to write an explanation instead of having a free hand in writing. This ulitity versus restrictive dilemma was best expressed by Boon Chin who 'got full marks' when he used PRO despite not liking it. In addition, there was a difference in opinion among the students over to what extent they felt the PRO pattern was restrictive. When Nicholas commented that the PRO was too strict, Jenny rebuked that 'it's not too strict *lah* (a pragmatic particle used in Singapore Colloquial English to express strong negation in this context)'. Jenny further explained that they can choose to use the structure if they needed help. She also gave an analogy that the PRO was only a 'mould', which would still require them to 'fit in the ingredients' to construct the explanation, rather than following a strict pattern.

The issue on the rigidity of the PRO structure was also discussed in the classrooms when the teachers explained to their students the purpose of the PRO as a scaffold, as seen from this conversation:

Interviewer:	Okay, maybe can you all interpret what Mr Lim is trying to tell you all here?
Wee Kang:	He just say that PRO is just a structure, a draft or structure for us to follow so that we can better form an answer. But then, *when we actually become better at it, we don't actually have to follow it* because we can just like craft
Charmaine:	*Craft our answer on our own*
Benjamin:	Yah
Huimin:	Like I said, PRO is just like organiser for our ideas. But *if you can already organise on your own, then you don't really need to use it.* If you confident that you can organise it without PRO

Limitations and future research

Although it was found in this study that students' written explanations with a PRO structure were graded better by the teachers, we cannot conclusively claim that there was an improvement due to the PRO strategy from the intervention research. While the results from both the quantitative *t*-tests and qualitative FGDs suggest that students who used a PRO structure were able to produce better explanations, it is also possible that they might already be producing good explanations without being consciously aware of an underlying PRO structure. To show there was an improvement would require a pre- and post-test, and to further associate the improvement to the use of the PRO strategy would require a control group. As the purpose of this exploratory study was to develop an explanation strategy, test its feasibility, and understand its manifestation and challenges in practice, a quasi-experimental study was not planned for.

In addition, an issue encountered in this study was the small sample size from the physics (31 students) and chemistry class (28 students). To conduct an independent samples *t*-test between students who wrote with a PRO structure and those who did not, this would divide the sample from each class further and make the *t*-test unsuitable for each test question. For this reason, I aggregated the four test questions from each student to obtain 118 answers for physics and 91 for chemistry (with some missing data as some students missed the term tests), and performed the tests according to the number of answers rather than the number of students. However, as each student had more than one answer, the samples were not totally independent. This may potentially affect the statistical results. Thus, to evaluate the effectiveness and impact of the PRO strategy, future research will need to involve a larger sample size in addition to the use of a quasi-experimental design.

Another limitation is that this study only considers the structure of a scientific explanation and brackets other factors that are also important in shaping the quality of an explanation. The distribution of the students' performance in identifying the components of P, R, and O across topics (see Figures 2 and 3) strongly suggests the importance of context-specific factors, such as the content matter, students' conceptual knowledge and language ability, teachers' knowledge and experiences, and instructional methods used in class. Given that explanation construction is a highly complex task (Gilbert et al., 2000), investigating these factors is clearly beyond the scope of this study. Nevertheless, considering that many researchers (e.g. Sampson & Clark, 2008; Wellington & Osborne, 2001) have argued for the importance of structure in the quality of a scientific explanation, this study has proposed and tested a new framework (i.e. PRO) that could help students better structure their written explanations. Future research can build on this work and investigate other factors in conjunction with the use of the PRO explanation structure.

One potential area to investigate is the relationship between students' ability and the use of the PRO structure. In particular, to what extent is the PRO strategy useful for students with various abilities? From past research (e.g. Hyland, 2007; Lemke, 1990; Schleppegrell, 2004), it has been postulated that two groups of students may benefit most from a genre-based structure like the PRO: (a) students who are weak in science and (b) students who are not native speakers of the language of instruction, such as English language learners (ELLs). This is because these students are most likely not familiar with the genres of academic science.

In a related note, the FGDs revealed that there was a mixed opinion and tension on whether the PRO strategy was more useful or restrictive. The students' feedback on the restrictive structure of PRO draws parallel to criticisms of genre pedagogy in the research literature. In particular, some researchers found a genre-based instructional approach to be too prescriptive (Hyland, 2007). However, many scholars have also argued that as the specialized nature of scientific writing is vastly different from narrative writing which is more expressive in nature (Fang, 2005; Lemke, 1990), more instructional support needs to be given to scaffold students' language development in science without dictating how they should write (e.g. Martin, 1993; Unsworth, 2001). This is especially so for students who are not proficient in both the academic content and language. Thus, the question in this debate should be reframed as: To whom does a genre-based instruction most beneficial among students with different abilities? Using the PRO strategy as an example of a genre-based instruction, more research on students from different ability groups can be carried out to add insights to this ongoing debate.

Implications and conclusion

Constructing explanations based on scientific theories and models is an important practice in science. In the emphasis of teaching the content of science, this process skill is often not explicitly taught in most classrooms (Braaten & Windschitl, 2011). Part of this reason is also because teachers do not have an instructional tool to teach the process of constructing scientific explanations. Hence, the PRO strategy presented in this paper was conceptualized and developed to fill this void. The findings from this study suggest that the PRO was a viable strategy that could improve students' competency in constructing written explanations. As such, science teachers can use the strategy to teach science content as well as address students' weakness in writing scientific explanations.

Besides supporting students' language development in writing explanations, the PRO strategy can also be used as a cognitive support to develop students' thinking and reasoning process. This was alluded to during the FGDs where some students spoke about how the PRO helped them organize their ideas and structure their thought processes in constructing explanations. They also spoke of how their teachers used the PRO structure to explicitly unpack the underlying logic and causal sequences of an explanation. For example, one of the physics teachers often broke down the reasoning structure of an explanation by asking the students to first identify the premise and outcome, and then reason retrospectively to link the outcome back to the starting premise (see Tang, 2015). Current analysis is examining how the teachers used the PRO strategy during classroom talk to foster logical thinking. These analyses will help to identify pedagogical ways of using the PRO strategy to support cognitive development. With more research in this area, teachers can emulate these approaches to help their students think about the logical reasoning and sequences of an explanation, instead of focusing on the accumulation and dissemination of isolated facts and information.

The PRO strategy can also be used as a form of diagnostic assessment to examine the difficulties students have in constructing scientific explanations. This follows a similar approach of breaking down the individual components of P, R, and O as I had done in this study (see Figures 2 and 3). As a form of formative assessment, teachers could ask their students to indicate P, R, or O for every statement in their written explanation. By examining which component is incorrect or missing, teachers could then diagnose what is the main problem faced by the students. For instance, if the P is incorrect or missing, this suggests that the student does not have the prior knowledge or is not able to identify the relevant premises for the explanation. If the R is incorrect or missing, then it is likely that the student is not able to make connection between the premise and outcome or further elaborate the causal processes. If the O is wrong, it may imply that the student simply does not understand the question, especially if the outcome is already stated somewhere in the question.

Lastly, the PRO structure can provide a language for teachers to discuss the nature of science and epistemic processes of constructing scientific explanations. Very often, students learn many canonical explanations as the 'right' answers without an in-depth understanding of what exactly is a scientific explanation. With the use of a PRO framework, teachers can explain how an explanation works in terms of the generalization and

Table 2. Comparison between the PRO and CER instructional framework.

	PRO (premise–reasoning–outcome)	CER (claim–evidence– reasoning)
Derived from	Philosophy of Science SFL Genre Theory	Toulmin's Argument Model
Instructional emphasis	Making sense of phenomena from accepted theories or models	Making claims from observations or data
Suitable for	Theoretical-driven account	Empirical inquiry

explanatory power of a few premises. Teachers can highlight why certain statements (e.g. laws, theories, models) within an explanation cannot be explained. These statements are simply accepted premises within the scientific community. Although these statements cannot be explained, it does not mean that we should not question their validity and how they were accepted as premises through the process of scientific argumentation. For instructional purpose, teachers can help students understand the epistemic nature of some premises (e.g. Newton's Laws, kinetic model of matter), such as the empirical evidences and argumentation process that led to the formulation and acceptance of these premises. Teachers can also mention that these premises are not universal truths, but are tentative claims that can be replaced by better theories and models in the future (Kuhn, 1962). Thus, the PRO strategy can be used to help teachers and students distinguish between phenomena (i.e. outcome) that can be explained and premises that cannot be explained, but are developed and accepted through argumentation.

For science education research, the PRO strategy can provide a starting point to resolve current entanglement between explanation and argumentation. While many researchers tend to treat explanation and argumentation rhetorically as a single practice, there are others (e.g. Braaten & Windschitl, 2011; Osborne & Patterson, 2011) who argue that the field will benefit by teasing apart aspects of scientific explanation from argumentation. Furthermore, science teachers will benefit from clear instructional supports that are designed to develop explanation and argumentation as separate practices. In the teaching of argumentation, the claim–evidence–reasoning (CER) framework is widely used among science educators. However, as there is currently no comparable framework suited to support the teaching of explanation, the CER framework has been misleadingly adopted by many science educators to construct explanations even when there is little argument construction going on in the instructional tasks. With the PRO as another instructional framework, a clearer distinction between argumentation and explanation can be made when both the CER and PRO frameworks are juxtaposed and compared. To this end, Table 2 provides a comparison between the CER and PRO frameworks.

Finally, the PRO strategy can be used to complement the CER framework where one is used to make sense of specific phenomena through theories and models, while the other is used to conduct investigations and make claims through evidence-based argument. Both practices are distinct and equally necessary for scientific inquiry. Therefore, the PRO strategy introduced in this study could bring about greater clarify in how to achieve the goals of science education reform; in particular towards seeing 'science as argument and explanation' in the National Science Education Standards (National Research Council, 1996), as well as fostering the scientific practices of 'constructing explanations' and 'engaging in argument from evidence' in the more recent NGSS (National Research Council, 2012).

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Notes on Contributor

Kok-Sing Tang is an Assistant Professor of Science Education at the National Institute of Education, Nanyang Technological University of Singapore. He holds a BA and an MSc in Physics from the University of Cambridge and an MA and a PhD in Education from the University of Michigan. Kok-Sing will be moving to Curtin University as a senior lecturer in the second half of 2016.

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Appendix A – List of questions from the schools' term tests used for the analysis

Physics:

1. Forces – Mr Sim is sitting on a rolling chair as shown. He kicks against the wall. Explain why Mr Sim moves backward after kicking against the wall.
2. Moments – Explain, with reference to the diagrams above, why the cup will always return to its upright position.
3. Kinetic Model of Matter – Ice is placed inside the can and the can is sealed again. The can becomes partially crushed. Explain, in terms of molecules of air inside and outside the can, why this happens.
4. Sound – With an aid of a diagram, describe how the sound is transmitted from the whistle to the microphone.

Chemistry:

1. Chemical Bonding 1 – Explain why copper has a high melting point of 1036^{0}C.
2. Chemical Bonding 2 – Explain why iron is a good conductor of electricity.
3. Qualitative Analysis – The experiment was repeated the same way, except that silver was used in place of electrode E. Explain why, after a short while, a cloud of white precipitate was observed around electrode E.
4. Electrolysis – The electrolyte was tested with a few drops of Universal Indicator after ten minutes. Suggest the change in colour of the indicator around electrode E. Explain.