SCIENTIFIC ARGUMENTATION AS A FOUNDATION FOR THE DESIGN OF INQUIRY-BASED SCIENCE INSTRUCTION

A. FALK and L. BRODSKY
Lawrence Hall of Science, University of California, Berkeley
Berkeley, CA 94720
andrewhfalk@berkeley.edu

Abstract

Despite the attention that inquiry has received in science education research and policy, a coherent means for implementing inquiry in the classroom has been missing [1]. In recent research, scientific argumentation has received increasing attention for its role in science and in science education [2]. In this article, we propose that organizing a unit of instruction around building a scientific argument can bring inquiry practices together in the classroom in a coherent way. We outline a framework for argumentation, focusing on arguments that are central to science—arguments for the best explanation. We then use this framework as the basis for a set of design principles for developing a sequence of inquiry-based learning activities that support students in the construction of a scientific argument. We show that careful analysis of the argument that students are expected to build provides designers with a foundation for selecting resources and designing supports for scientific inquiry. Furthermore, we show that creating multiple opportunities for students to critique and refine their explanations through evidence-based argumentation fosters opportunities for critical thinking, while building science knowledge and knowledge of the nature of science.

Introduction

Science education plays a critical role in preparing students for multiple aspects of their future lives: thinking logically and critically, making decisions involving scientific information both personally and as active citizens and, for some, making science a vocation [3, 4]. In order to educate students with these goals in mind, a special emphasis has been placed on students' learning through scientific inquiry. Learning through inquiry involves the skills needed to ask questions, generate data, interpret evidence from first-hand investigations and from text, and make evidence-based explanations [5]. Enacted well, inquiry demands critical thinking to identify assumptions and to weigh alternative explanations, which requires an understanding of the nature of science [5, 6].

The ongoing challenge for educators lies in designing instruction that accomplishes what are sometimes competing goals. Science instruction must authentically engage students in the multiple components of science inquiry in a coherent way [7]. At the same time, it must support students' developing understanding of accepted science content and scientific ways of knowing

The Journal of Mathematics and Science: Collaborative Explorations Volume 13 (2013) 27 - 55

[8]. In recent years, there has been increasing attention paid to the role that argumentation plays in science and the role it could play in science education [2, 9-11]. We argue that instruction should be designed to support students in building a scientific argument for an explanation of a carefully selected phenomenon. Working toward better explanations through argumentation creates coherent opportunities for students to engage in multiple aspects of scientific inquiry while building science knowledge. Science knowledge has been described as a social construction that is the result of the inquiry process and communication with the scientific community, that is, through the process of argumentation [12]. By participating in argumentation, students are provided with a context and a rationale for the process skills of inquiry. In addition, due to the nature of argumentation, students necessarily practice the critical thinking skills that are vital to inquiry, as they need to evaluate evidence and critique alternative explanations. As students engage in the process of critique, reasoning based on evidence and communicating and justifying explanations play a central role, emphasizing key aspects of the nature of science.

In this article, we propose a set of design principles for using scientific argumentation as a focus for the backward design of inquiry-based science learning activities, grounded in the theoretical and empirical literature on argumentation and science education [13]. In the first part of this article, we will outline a conceptual framework for thinking about important aspects of argumentation across disciplines, and then narrow the focus to argumentation in science. We will concentrate on a type of argumentation that is central to science, argumentation for the best explanation, and outline the general structure of an argument for a particular explanation. In the second part of the article, we will map this structure to a set of principles for designing a sequence of inquiry-based learning activities that build toward students constructing a scientific argument.

The Nature of Argumentation across Disciplines—Argumentation Is a Dialogue about Alternative Positions within a Particular Community

Argumentation and argumentation in science have been studied in multiple ways from a variety of theoretical perspectives [14, 15]. As the subject of ongoing study and development, there is not a consensus definition of argumentation across scholarly communities. In this article, we draw from several theoretical perspectives to construct a definition of argumentation that is consistent with arguments in science research, and affords opportunities for argumentation to serve as a tool for students to engage in joint knowledge construction and critical thinking as they conduct science inquiry activities.

We define argumentation in general as the process of communal dialogue that determines the merits of alternative positions in relation to the available information marshaled in support of each position. There are two important aspects of argumentation to be examined. The first is the structure of argumentation that allows a particular position to be supported, examined, and critiqued. The second is the social nature of argumentation, which pertains to the characteristics of argumentation that arise from its taking place through interaction between people.

The Structure of Argumentation

Defining argumentation as a dialogic process presents an immediate challenge—where can it be said that an argument starts, and where does it end? Whether for the purposes of study or instruction, we need to identify a bounded unit that can be constructed and examined on its own. We propose a unit that has utility for thinking about argumentation: a line of argument.

A line of argument consists of several interrelated components: a *claim*, the position taken in relation to a particular topic, question, or issue; the *grounds*, the information submitted as support for the claim; and, the *justification,*[1] the rationale for how or why the grounds provide support for the claim [16]. A line of argument can also, but does not need to, include a *rebuttal*, an acknowledgment of possible exceptions to the claim. A *counterargument* is a line of argument that establishes a competing claim to one previously established, with corresponding grounds and justification. In the interest of a manageable level of complexity, we will limit our focus to claims, grounds, and justification. Figure 1 is a diagrammatic representation of the basic components of a line of argument and their relations to each other. The grounds lead to the claim, and their relation is supported by the justification.

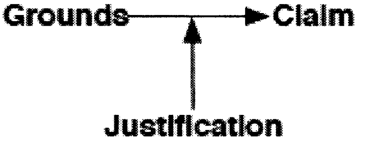

Figure 1. Diagrammatic representation of a line of argument.

[1] While Toulmin generally refers to this component of argument as "warrant," he describes its function as one of justification. Given that *justification* is likely to be a more widely understood term, we have employed it here.

A simple example of a line of argument might be as follows: I *claim* that smoking should be made illegal on the *grounds* that smokers are more likely to die of cancer than non-smokers, death by cancer has multiple negative impacts, and laws should prevent negative outcomes. My *justification* for the grounds supporting my claim is that my claim is consistent with the grounds that I offer: a law banning smoking would prevent negative outcomes—death and its repercussions. I also offer a *rebuttal* to acknowledge a possible exception. If denying people their freedom of choice in deciding whether or not to smoke is determined to be a greater negative outcome, then smoking should not be made illegal.

The Social Nature of Argumentation

The second aspect of argumentation that we submit as important to consider for the purposes of design is the social nature of argumentation; i.e., the fact that argumentation occurs through interaction between people. Without at least one person to take a position, and at least one other to evaluate and/or contest it, there can be no argumentation. This does not suggest that an individual cannot engage in argumentation alone. However, the focus for and criteria applied in evaluating a given line of argument do not exist a priori, but are derived from the standards of particular communities, and thus are social in origin. In developing a line of argument, a scientist does so with a specific audience in mind. This social nature has multiple important implications for how argumentation is conducted.

Argumentation Depends on Socially Established Criteria

To be productive, it is not enough for argumentation simply to take place between people. It must take place between members of a particular community—a community that has implicit or explicit collective criteria for what is worth arguing about, and how a case intended to support a particular position is established and evaluated [15]. Without these collective criteria, participants could be left arguing about apples and oranges, and proposing positions that are not comparable, based on support that is not considered mutually acceptable.

The criteria for argumentation within a community can be subdivided based on their application to the various structural components of a line of argument: claim, grounds, and justification. First, criteria are required for what constitutes an appropriate claim to argue about within the community, as well as what makes one claim superior to another (given equivalent support). For example, in the scientific community it is appropriate to make a claim about the best way to explain how a particular natural phenomenon occurs (e.g., the lengthy process that creates fragile cave formations), but not a claim about how people should be required to behave in relation to that phenomenon (e.g., human access to the caves should be restricted). Argumentation regarding claims about whether to restrict human access might take place within a political policy community.

Second, criteria are required to determine what counts as legitimate grounds (the information submitted to support a position), as some kinds of information may not be admissible at all. For example, personal beliefs or decrees by persons in positions of political or religious authority are never admissible as grounds in argumentation in natural science. Another set of criteria is used to evaluate what counts as more or less credible information to support a position. In other words, once information is determined to be admissible, its quality still must be evaluated. For example, in science, recorded measurements that were collected through imprecise or unreliable methods might be admissible in form, but considered of low quality and unlikely to be credible.

Finally, if an appropriate claim is made, and the grounds are determined to be legitimate and acceptably credible, another set of criteria is used to evaluate the justification of the relative merits of the claim in relation to the following: 1) the grounds that are offered, and 2) any other information that is available and determined to be relevant. This set includes both criteria used to evaluate a line of argument by itself (e.g., whether its grounds reasonably support its claim), and criteria used to evaluate two lines of argument in relation to each other in order to determine which is superior. For example, if a line of argument proposes and supports a particular explanation with data, that explanation may reasonably account for all of the data submitted as grounds for that line of argument. However, it may ultimately be judged inferior to a counterargument proposing another explanation that accounts for the same data, as well as additional data for which the first explanation cannot account.

The Nature of Argumentation in Science—Scientific Argumentation Is Used to Develop Increasingly Better Explanations for the Workings of the Natural World

As previously stated, the goals of argumentation depend on the goals of the community that is engaging in it, and it can focus on any of an array of contested or contestable outcomes. These outcomes could include an individual's guilt or innocence, the policy that would most benefit a society, or the best decision or course of action [16, 17]. In science and science education, the primary focus of argumentation is to develop, consider, and determine the best of a proposed set of alternative explanations that account for observable phenomena in the natural world [2, 3, 18]. An *explanation* in science is a causal story that describes how or why a particular phenomenon comes to be or behave as it does. What makes an explanation distinct from a line of argument is that by itself, an explanation does not require support or justification. It is through argumentation that an explanation's quality, its ability to account for the phenomenon in a satisfactory manner, is determined [2]. In this section, we will outline and describe the components of an argument for an explanation in science, drawing on the elements of the conceptual framework established in the previous section. Wherever possible, we will illustrate these components by drawing from a single example of a seminal argument in science: Watson and Crick's postulation of the molecular structure of DNA [19, 20].

The Anatomy of an Argument for an Explanation in Science

The Question about the *Explanandum* — Implicitly or explicitly, any argument begins with a question about which of multiple possible positions (which themselves may not yet have been articulated) is the best one. In science, the central arguments are motivated by a question about some aspect of the natural world, and the best explanation for it [2]. For example, in their research, Watson and Crick were immediately arguing for a particular answer to the question, "How are the molecules that make up DNA arranged?" This was part of a larger ongoing line of inquiry into the question, "Why do successive generations of organisms have similar characteristics?" This initial question is the clearest link between scientific argumentation and inquiry. If inquiry is the process of asking and investigating a question [6], then a line of argument is the end product of those investigations, a tentative but supported explanation that seeks to answer that question.

The focus of the question is the *explanandum*, the phenomenon that is to be explained. The most important characteristic of the *explanandum* in scientific argumentation is that it is not in doubt within the community engaging in argument [2]. At the time of Watson and Crick's publications, the scientific community did not disagree that DNA existed, or that characteristics reappeared in successive generations. The explanation for the phenomenon, the account of how or why it happens the way it does, is what is uncertain and therefore is subject to argumentation. The question that is to be answered through argumentation is therefore slightly different than the question about the mechanism underlying the phenomenon itself. For Watson and Crick, that question would be, "What is the best explanation for how the molecules that make up DNA are arranged?"

<u>The Claim: The Superiority of a Particular Explanation</u> — A line of argument includes a claim, a tentative position that is taken and supported. In argumentation around a scientific explanation, the claim consists of two components: the explanation itself, which must be explicitly stated, and the position that the explanation provided is the best account available for the *explanandum*. Watson and Crick explicitly suggested their structure was a better alternative to others already proposed by colleagues, which consisted of three strands, or situated the bases on the outside of the strand, and which they described as "unsatisfactory" [20].

All explanations for phenomena are efforts to develop a more coherent causal story describing the mechanisms that result in the phenomenon as it is observed. Telling this story requires the creation or use of a cast of protagonists, entities with particular characteristics that interact with one another to bring about the *explanandum* as it exists [21]. These protagonists range from the observably material, such as a rolling ball, to the purely conceptual, such as the kinetic energy of the ball as it rolls. What science requires of these entities, regardless of whether they are ever observed, is that they have the same characteristics and behavior across the explanations in which they play a role [21]. While energy is never directly observable, it can be quantified across the contexts between which it is transferred, and that quantity remains ever the same [22].

Crick and Watson use van der Waals forces (weak intermolecular forces) as protagonists in multiple parts of their explanation of the structure of DNA [19]. The van der Waals forces account for why a particular configuration is or is not possible, depending on whether or not it violates the distance that the weak repelling forces between molecules would permit. While these forces and the molecules that give rise to them are not directly observable, they are important conceptual actors in the explanation, and the explanation depends on their consistent behavior in permitting only limited proximity. In their discussion, Crick and Watson foreshadowed the use of DNA with the structure they suggest as a protagonist in future explanations of the replication of genetic material, explanations that depend on the complementary strands that they proposed.

Science is replete with these conceptual actors—gravity, electrons, energy, tectonic plate boundaries, charge, fields, spherical planetoids—which may not have directly observable material existence, but which play critical and consistent roles in explanations of what we can observe. Moreover, while many explanatory protagonists have maintained their utility and presence in scientific explanations, others have come and gone. Phlogiston, once thought by many scientists to play a critical role in combustion, has since vanished from their explanations. Moreover, Michelson and Morley showed that the luminiferous ether was an unnecessary protagonist in explaining the propagation of light [23].

The way that Watson and Crick's explanation suggests a causal mechanism for the reproduction of genetic material illustrates another important aspect of explanations: progress toward causality. Braaten and Windschitl provided a useful analysis of the forms of explanation in science based on scholarship in the philosophy of science, and offer a framework for working toward increasingly causal explanations in a science education setting that provides initial criteria for evaluating the quality of claims [24]. In general, scientific explanations should work toward an increasingly complete causal story for the mechanisms that lead to the *explanandum* as it is observed. To do so, they should use unobservable or theoretical protagonists and powerful science ideas (e.g., kinetic molecular theory) to account for the observable event. In progressing toward this level of causality, explanations may describe patterns in observable variables, or propose relations between variables without addressing underlying mechanisms or incorporating unseen protagonists. The authors acknowledge that there is a range of forms and standards for explanation across the scientific disciplines and the scholarship that has examined them. However, based on their work with students and pre-service teachers, they advocate and report initial success with a framework for explanation that presses for a progression from description of observable patterns toward the explication of increasingly unified underlying causes for observable phenomena.

The Grounds: Data and Existing Science Ideas — A line of argument also includes grounds, the information used to support the claim. Where scientific arguments are concerned, we will refer to grounds as *evidence*. In scientific argumentation, evidence includes some combination of new data, previously existing data, and existing science ideas. Data are systematic and recorded observations or measurements of some aspect of the natural world [3]. A line of argument may include new data that was gathered for the purpose of constructing the proposed explanation, and/or existing data; i.e., data that is not being used as part of an argument for the *explanandum* for the first time. Evidence also includes existing science ideas, which are themselves condensed representations of previously gathered data.

Research on both the nature of science and in science education support this perspective of ideas as evidence originally derived from data. In his analysis of the elements that distinguish the modern scientific culture, Latour advocates a shift in focus away from changes in ways of thinking or economic infrastructure [25]. Instead, he emphasizes the developments in the means by which symbolic inscriptions are produced based on empirical study, reproduced, compared, discarded or compiled, and synthesized. He follows the process of "the transformation of rats and chemicals into paper," and the process by which the resulting inscriptions are taken up and reproduced by scientific colleagues. His description provides a clear picture of how the representation of a science idea is the end product of this process of inscriptional distillation that began with the recording of empirical data. Similarly, in their development of the Evidence-Based Reasoning framework for science education, Brown, Furtak, Timms, Nagashima, and Wilson draw on Duschl to show how students analyze and interpret specific data to develop rules, more general statements that can be applied to other relevant circumstances though argument [26, 27]. In the next section, we draw on their framework for developing and applying rules in defining reasoning in scientific argumentation.

In their argument for the double-helical structure of DNA, Crick and Watson employ two kinds of evidence [19]. They use existing data, such as the x-ray images of DNA produced by their colleagues and the ratios of the four bases in samples of DNA from different organisms [28]. They also use existing ideas, such as the 3-dimensional structure of adenine, as inferred by Broomhead through calculations using measurements of x-ray reflection through crystalline samples of adenine hydrochloride [29]. They coordinate this evidence to strategically build a line of argument for the structure they propose as the best in relation to alternatives that have been or might be proposed.

As we stated previously, information provided as grounds is subject to evaluation by the audience to determine whether it is legitimate and credible, and therefore acceptable as grounds to support a position. In order for the audience to evaluate data, the presenter must provide sufficient information about the methods by which it was gathered (e.g., what specifically was observed or measured, what methods were used to achieve validity and reliability, and how any records depict or represent what was observed). In order for the audience to evaluate science ideas, they need information about the source of the ideas and how they were developed. If the ideas are drawn from sources outside the immediate experience of the audience and are subject to question, the audience will require more information about the source of the ideas. This could include either a description of the process of inference from more direct observation by which they were constructed, or some assurance that the people who developed them used methods that would be considered acceptable by the audience (e.g., in science, the audience of a peer-reviewed journal relies on these assurances). For example, Crick and Watson do not describe the methods Broomhead used to infer the molecular structure of adenine, but provide sufficient reference information that a skeptical reader could obtain a description of those methods from the original work [19]. Some ideas, however, are so well established within a given community that they are used as a taken-as-given fact. Crick and Watson repeatedly use density as an idea to support their arguments about the structure of DNA, but never define it [19]. They reasonably assume that their audience likewise accepts and understands density as an established fact.

<u>Reasoning: Connecting Data, Ideas, and Explanation</u> — Establishing the connections between the data, the ideas, and the explanation (or some component of it) requires one of several kinds of reasoning, which is the presumption of particular conclusions based on the relevant grounds. Reasoning can be further subdivided into generalization and application: generalization is the construction of a general rule based on analysis and interpretation of a set of specific instances (data), while application uses that general rule to draw a conclusion about a specific circumstance determined to be relevant [26]. Each form of reasoning can involve one of several kinds of general rules: patterns, the consistent occurrence or variation of some observable characteristic; causal relationships, the identification of a causal link between two variable factors; or, causal mechanisms, a description of the means by which one factor affects another.

As a simple example, Crick and Watson reason that because a) tests for the presence of adenine in DNA have been positive and b) that adenine in samples of adenine hydrochloride has been inferred to have a particular structure, then the adenine found in DNA must also have that structure [19]. Their argument for the structure of DNA involving the pairing of specific bases (i.e., adenine and thymine) is in part dependent on this reasoning being valid. Table 1 summarizes these different forms of reasoning, and provides a brief example in a single context (the relationship between latitude and average temperature) to illustrate each.

Table 1
Types of Reasoning with Examples

	Pattern	Causal Relationship	Causal Mechanism
Generalizing	Inferring that a pattern more generally holds true, based on a specific set of instances. *E.g., Average temperatures are high in Mexico City, medium in Kansas City, and low in Winnepeg; therefore, temperatures are lower further north from the equator.*	Inferring that factors are causally related, based on a correlation or a single aspect of disagreement (a controlled comparison). *E.g., Average temperatures are lower in locations where the Earth is more steeply curved; therefore, temperature is causally related to the Earth's curve.*	Inferring an underlying mechanism for an identified causal relationship. *E.g., Average temperatures are lower in locations where the Earth is more steeply curved; the greater distribution of direct sunlight in steeper areas results in less energy input and lower average temperatures.*
Applying	Inferring that a general pattern extends to a specific relevant instance or context. *E.g., Vancouver is further north than San Francisco, and temperatures are lower further north from the equator; therefore Vancouver has lower average temperatures than San Francisco.*	Inferring the presence of a known associated causal factor, based on the presence of the other. *E.g., Reykjavic has low average temperatures, and temperature is causally related to the Earth's curve; therefore, Reykjavic is at a steeply curved location on the Earth.*	Inferring initial conditions, processes, or results, based on the implications of a particular mechanism. *E.g., Minneapolis is in a location that is more steeply curved during February compared with July, and more steeply curved areas receive less direct sunlight; therefore, Minneapolis is colder in February.*

Like the other components of a scientific argument, the reasoning that is presented is subject to critique by the audience. Generalization and application are each critiqued by different criteria. Generalization is examined for whether the rule that was inferred from specific data is plausible, based on the following: a) the number of specific instances examined (i.e., the sample size); b) the similarity between the specific instances and the categories included in the rule (e.g., generalizing a rule about all mammals based on the study of rats); and, c) the existence of plausible alternative rules that might be generalized from the same instances. Application is examined for whether the rule that was used can be described in the following ways: a) relevant to the specific instance to which it was applied; b) was applied in a way that draws valid conclusions based on the rule; and, c) is accurate, in that it is consistent with accepted science ideas.

Justification: Making a Case for the Superiority of the Explanation Based on the Grounds — Finally, a line of argument in science must provide justification for its claim that the explanation it provides is superior to any alternatives, based on the socially established criteria specific to the scientific community. These criteria can be usefully represented as critical questions that can be asked about a given argument for an explanation, and asked about the following: a) the argument in relation to other information that could be included as evidence for or against the explanation, b) alternative explanations that could be proposed, or c) counterarguments that have been made to support an alternative explanation [30]. Explicit justification included in the argument would take the form of responses to these questions.

While there are no doubt a variety of criteria that might be considered, we will focus on three that we suggest are central to science, and useful for science instruction. The first criterion is refutation, an aspect of science emphasized by philosopher of science Karl Popper, and represented as the critical question, "Is there evidence (data or ideas) that conflicts with the explanation?" [31] The second is coherence, which is similar to the emphasis placed by philosophers of science on unification—the capacity of a scientific explanation to unify a range of related observations or ideas [32]. It is represented by the critical question, "How consistent is the explanation with available relevant data and accepted science ideas?" Coherence includes validity, whether the reasoning employed generalizes or applies rules in appropriate ways, and completeness, the degree to which the explanation accounts for all data or ideas that could be considered relevant. The third is causal depth: "How does the explanation further develop the causal storyline by adding elements to or relationships between the factors that underlie the phenomenon?" [24] Providing examples of all three criteria, Watson and Crick justify their claim that their explanation is superior to their colleagues' for the following reasons: 1a) it has greater causal depth—it provides a clear mechanism that holds the structure together, while their colleagues' does not; 1b) it is more nearly complete—it is consistent with existing ideas about the repelling forces of negative charges; and, 2) it is not refutable—it does not conflict with ideas about the limits of van der Waals distances [20].[2]

It is difficult to visualize the multiple components and interrelations we've described. The diagram below (see Figure 2) is a representation of a portion of Watson and Crick's argument, in order to illustrate the specific components and their relations to each other in this

---

[2] The numbering scheme reflects the numbers included by the authors, but we sub-divide their first point as reflective of two criteria.

example. Given the complexity of the argument the authors presented, we had to simplify our descriptions of some of the evidence and relevant ideas, but we believe the essence of the argument is intact. Their reasoning is represented by the arrows connecting the evidence and the sub-components of the explanation.

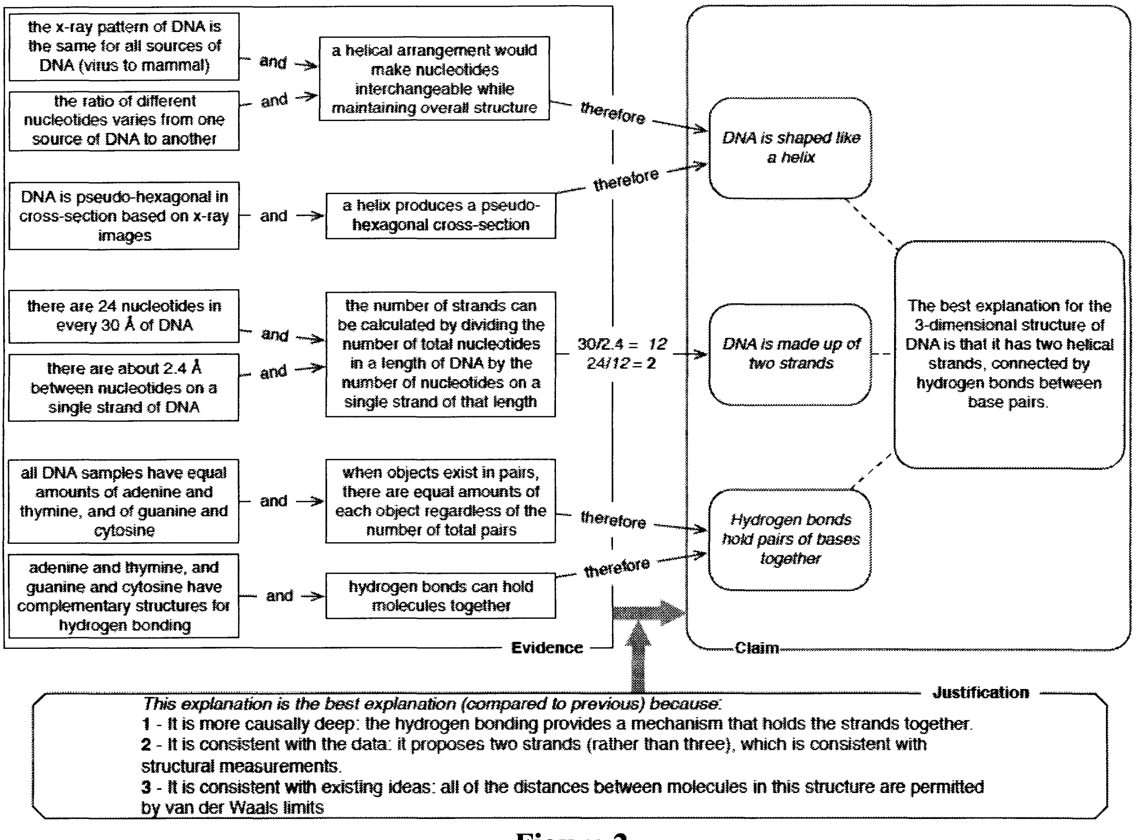

Figure 2.
Diagrammatic representation of a portion of Watson and Crick's argument.

The Implications of Science Argumentation for the Design of Inquiry Activities

If constructing better explanations for phenomena is the primary goal of scientific inquiry, and argumentation around alternative explanations is the means by which scientists work toward better explanations, then supporting students in arriving at better explanations through argumentation should be a high-priority goal of inquiry-based science education. Using the features of argumentation described thus far, we propose a set of design principles to guide curriculum developers and teachers in their creation of inquiry-based science learning activities that will strategically engage students in argumentation toward causal explanations. We will illustrate these principles by developing a single example drawn from our grade 6 earth science unit focused on the major factors that influence regional climate. A preview of the principles and their alignment with the features we've described is outlined in Table 2.

Designers Should Organize Science Inquiry Learning Activities around Developing Increasingly Better Explanations of an Intentionally Selected Focal Phenomenon

First, to align with the primary work of science, a significant portion of *students' science learning and activity should be organized around developing better explanations of a launching focal and puzzling phenomenon and/or class of phenomena.* This approach provides a specific *explanandum* that can serve as the focus of students' investigative activities and learning [33]. For example, in our curriculum, we use photographs and narrative to introduce students to the Atacama Desert, a region in South America, as presenting a puzzle. It is literally the driest place on Earth, receiving no annual rainfall, but is not far from the Amazon jungle, one of the world's wettest places. How is it that the two regions can be so close to one another, yet have such drastically different climates?

While scientists can spend entire careers focused on constructing knowledge of a relatively narrow set of phenomena, science education aims to develop students' integrated understanding of the more general, broadly applicable ideas in science [3]. In learning to explain the Atacama Desert, it is our goal that students develop more broadly applicable ideas about ocean currents, prevailing winds, differential heating, evaporation and condensation, local topography, and their relations to regional climate. If the puzzling phenomenon provides a focus for students' learning, the guiding question provides the broader outer bounds.

Table 2

Alignment of the Core Features of Science Argumentation and Corresponding Design Principles for Science Inquiry Activities

Feature of Science Argumentation	Design Principles
Argumentation in science is in response to a question about an *explanandum*	Students' science learning and activity should be organized around their developing increasingly better explanations of a launching focal and puzzling phenomenon and/or class of phenomena.
A line of argument makes a claim for a particular explanation of the *explanandum*	Designers should construct and analyze a target explanation for the *explanandum* that is appropriate to what is expected of students at that grade level. The guiding question / *explanandum* / target explanation should require core science ideas, align with grade-level content standards, and connect with students' experience.
A line of argument uses data and ideas as evidence in support of the explanation	Designers should determine the data related to the *explanandum* that students will need in order to construct the target explanation, and provide them as students can identify them as necessary. For each of the rules and the protagonists that were identified in analyzing the explanation, designers should identify the sources of evidence—both first-hand experiences and texts—that will provide a basis for students to infer the relevant rules, and understand the characteristics of the protagonists.
A line of argument requires reasoning that connect the evidence to the explanation	Designers should identify the kinds of reasoning students will need to use in constructing rules and the target explanation, and create scaffolds to support their developing thinking.
A line of argument provides justification for the claim of the superiority of the explanation, based on: • Absence of refuting evidence	Students should be provided with opportunities during the unit to consider and critique multiple explanations (of the focal phenomenon, or as part of sub-investigations) for their relative merits in relation to each other. Learning activities should be sequenced in order to help students develop explanations with increasing causal depth.

• Coherence of explanation with available data and ideas • Causal depth of explanation	
Argumentation is a dialogic process	Designers should provide students with periodic opportunities to engage in more and less formally structured argumentation over the course of the unit in order to work toward increasingly better explanations.
Argumentation uses socially defined criteria to evaluate the merits of evidence, explanations, and lines of argument	Designers should provide students with opportunities and support for evaluating the quality of information that might be used as evidence. Designers should provide students with opportunities during the unit to consider and critique multiple explanations for their relative merits in relation to each other, either of the focal phenomenon, or as part of sub-investigations.

The guiding question is a question posed in student-accessible language that guides their inquiry into the mechanisms underlying the larger class of phenomena represented by the focal puzzling phenomenon. In the case of the Atacama Desert, an appropriate guiding question is "Why do different places have different weather patterns?"

It can be easy for someone, teacher or curriculum designer, who is familiar with the ideas underlying a phenomenon to move quickly to incorporating those ideas into questions or discussion. We advocate introducing and incorporating those ideas slowly and cautiously, in a kind of "slow reveal" of the explanation and its protagonists. If students do not already have a command of the relevant underlying ideas (e.g., the role of currents in climate), the initial focus should be on what is observable and most familiar (e.g., precipitation, experienced humidity). Just as scientists begin only with their pre-existing ideas and the observable characteristics and patterns relevant to a phenomenon, so should students. This ensures that students are not being expected to take up ideas that are unfamiliar to them before they have the opportunity to construct those ideas using appropriate resources. When students are incorporating these ideas into their explanations, they have sources and shared knowledge to draw on as they do so.

Selecting an appropriate puzzling phenomenon and associated guiding question requires careful thought. *The guiding question, explanandum, and corresponding explanation should* *require core science ideas, align with grade-level content standards, and connect with students' experience.* The phenomenon should be something that requires the use of powerful science ideas to adequately explain, ideas that provide a foundation for future learning, or can be applied to a variety of contexts. The science content required in the explanation should also be aligned with local and/or national science content standards so that students learn required content in the process of developing explanations through argument.

The phenomenon should also be selected to serve as a source of motivation to learn. It should connect to authentic experiences or questions in students' everyday lives, such that they can reasonably be expected to already have some ideas about and investment in it. Alternately, it should be presentable in a classroom setting using first-hand experience or secondary documentation, and be sufficiently potentially puzzling, creating cognitive dissonance for students [34]. The Atacama Desert by itself (or deserts more generally) is not particularly familiar to students, but photographs of it and the Amazon rainforest can provide some sense of their striking contrast, and students can help to "populate" the class of phenomena by providing their own examples of and questions about places with different weather patterns. In selecting and developing a puzzling phenomenon, designers should ask themselves the following question: "How can the phenomenon be directly or indirectly presented to provide students with sufficient information to support their understanding of the context and motivation to seek an explanation for it?"

The focal phenomenon not only provides a focus for instruction, it affords an initial opportunity for assessment. After students are introduced to the phenomenon for the first time, they should be invited to explain it as best they are able based on their incoming ideas, creating representations of their explanations. These representations generate records of the prior knowledge that students see as relevant to the focal phenomenon, and can also provide impetus and material for subsequent investigation and argumentation. For example, in their initial explanations of the Atacama, students might variously attribute the difference in precipitation as due to differences in local winds, or differences in temperature. These initial ideas could be the impetus for seeking data that would support one position or the other, and create an opportunity for students to engage in argument around their respective positions.

Organizing instruction and learning around questions about a focal phenomenon and a related class of phenomena aligns it with authentic science inquiry. Inquiry is initiated by asking questions, and in science it is asking questions about the workings of the natural world. The focal phenomenon grounds the inquiry process in the natural world, while inviting students to pose their own questions in relation to it or a similar phenomenon. Choosing a phenomenon of scientific significance and of interest to students creates opportunities for them to learn core content and incorporate their own ideas and life experiences. Eliciting students' initial explanations supports a focus on explaining the mechanisms underlying the natural world, and makes their ideas a substantive part of the inquiry process from the beginning.

Designers Should Analyze and Identify the Components of the Target Explanation

A scientific argument supports an explanation: *designers should construct and analyze a target explanation for the explanandum that is appropriate to the knowledge and understanding expected of students at that grade level.* It therefore will incorporate some, but not all, of the potentially relevant science ideas, at an appropriate depth and level of sophistication. A given phenomenon could serve as the *explanandum* at multiple grade levels; what would vary is the sophistication and depth of the explanation that is set as a goal. We expect students to be able to explain that the Atacama Desert is as dry as it is for two primary reasons. First, **prevailing winds** blow air that contains a lot of **water vapor** that **evaporated** from the waters of the **warm currents** off the eastern coast of South America, most of which falls as **rain** as the **wind** carries it over the Amazon rainforest. The remainder falls on the **windward side** of the **mountains** before the air reaches Atacama (the **rain shadow effect**). Second, the waters of the **cold currents** on the western coast **evaporate** very little **water vapor** into the air above them. The **water vapor** that does **evaporate** is carried away by **prevailing winds**, or does not reach the Atacama due to a similar **rain shadow effect**. If we expected greater detail or causal depth, however, we might also ask students to explain the role of energy and molecular movement in the differing rates of evaporation or the rain shadow effect.

A scientific explanation is not monolithic; it includes a variety of protagonists, and a series of events or interactions that involve them. For example, an early component of the Atacama Desert explanation is liquid water evaporating at a relatively high rate from the water of a warm Atlantic current, to become water vapor suspended in the air. This component idea is only a fragment of the full explanation, but by itself represents a complex process. Students will have to come to understand the protagonists and their characteristics (e.g., currents, temperature, water vapor, evaporation) and what rules describe their interactions (e.g., at the higher temperatures of warm currents, more water becomes water vapor through evaporation). To design learning activities that will lead to students successfully constructing and supporting the target explanation, designers should deconstruct the explanation into its component ideas in order to analyze them.

For each of the component ideas that make up the target explanation, designers should determine what protagonists and rules are involved, and what resources students will use to build an understanding of them. First, the designer should identify the protagonists, the actors involved in the target explanation. Referring back to our summary of the Atacama target explanation, the primary protagonists are highlighted in bold. Next, the designer should identify any rules that students will need to infer by reasoning from the data provided related to the focal phenomenon. For example, although they do not do so during the unit, students need to recognize that annual precipitation in South American cities decreases from east to west toward the Atacama, and infer that this means the amount of water vapor in the air is moving as the prevailing wind is decreasing. Finally, the designer should identify the rules that students will need to apply in constructing the explanation because they are relevant to the circumstances, such as the relationship between temperature and evaporation rate. These rules will be the foci of instructional activities (the intermediate learning goals) as students work toward a complete explanation.

Designers Should Identify Sources of Evidence for the Explanation and Relevant Rules

A scientific argument typically uses specific data to support the explanation offered as being the best available. *Designers should determine the data related to the explanandum that students will need in order to construct the target explanation, and provide them as students can identify them as necessary.* For example, for students to explain the primary factors affecting the climate of the Atacama Desert, they would need data representations for South America's precipitation, temperature, topography, prevailing winds, and local ocean surface current movement and temperature. Just as science ideas should not be introduced or incorporated until students have need of them as they construct the explanation, the different types of data should not be introduced until students are in a position to identify them as relevant. For example, until students are familiar with the idea that a given region has prevailing winds that reliably blow in a particular direction, they will have difficulty interpreting a map representing them, or understand its significance.

Another important possibility to consider is providing students with more data than is necessary or immediately relevant to explaining the focal phenomenon, either by including superfluous data points in the representations of relevant data (e.g., the annual precipitation of a city far from the Atacama, and not aligned with the prevailing winds), or representations of data that might be seductive but is irrelevant to constructing the explanation (e.g., the population density of South America). Providing these kinds of data will likely increase the cognitive demand on students in constructing their arguments, but it also creates opportunities for them to develop and demonstrate important science practices in identifying relevant data to use as evidence [18]. Grounding any final explanation of the focal phenomenon in data emphasizes important aspects of science inquiry; it gives priority to evidence as students construct their explanations, and provides a culminating opportunity for them to analyze and interpret data relevant to the unit focus.

For each of the rules and the protagonists identified in analyzing the explanation, designers should identify the sources of evidence—both first-hand experiences and texts—that will provide a basis for students to infer the relevant rules, and understand the characteristics of the protagonists. Some rules can reasonably be generalized based on hands-on investigations in the classroom setting. Of these, some can be constructed using data gathered through direct investigation in the classroom setting; these activities afford students the opportunity to design and conduct first-hand investigations themselves, an important aspect of science inquiry. For example, to generalize a rule about the relationship between water temperature and evaporation rate, students could measure the surface level in containers of water kept at different temperatures, observing that the level decreased more in containers kept at higher temperatures. An important consideration for these activities will be the tools and techniques that students will require to gather data. If sophisticated methods are required, designers should build in opportunities for students to become familiar with them. Some methods, whether procedural or analytical, can be introduced through model texts, which describe scientists using the methods for authentic purposes [34].

Other rules will be generalizable based on physical models that function similarly to corresponding real-world phenomena. Students can infer rules from hands-on investigation of these models, but will need support in analyzing how the model is similar and different in comparison to what it is modeling. Any rules they infer should only be based on aspects that are similar. For example, when students learn about the factors that influence the movement of surface ocean currents, they model the currents in a small tank of water, creating "wind" by blowing through straws and observing the water movement in and around foil "continents." Students can conclude that wind and continent shape influence surface currents, but also need support in recognizing that the winds do not blow in arbitrary directions—there are prevailing patterns in winds that in turn create patterns in surface currents.

Not all questions are directly investigable in a classroom setting, and students can learn important content and practices by analyzing and critiquing secondary data [35]. Designers should identify rules that are best inferred though second-hand investigation using texts that provide data and describe the methods used to gather it [34]. This includes rules that are derived from contexts that are inaccessible or use methods that are not feasible. For example, when students learn about evaporation and ocean currents, they analyze maps that show evaporation rates and the movement of surface currents of different temperatures. They identify patterns across the maps, and infer a general rule about the relationship between current temperature and evaporation rate. The maps summarize authentic data that would never be feasible for students to collect themselves, and allow them to engage in an analysis of the data and derive an accurate general earth science principle in context.

A common misinterpretation of constructivist learning theory is that students must discover all science knowledge for themselves, essentially inferring all of the rules and protagonists that make up currently accepted science knowledge [36]. It is hardly pragmatic for students to do so, and such an approach would not prepare them to make sense of science texts presenting abstract ideas, which will be common in their future experiences as learners and citizens. Designers should determine which protagonists or rules need to be introduced to students through expository text or other representations, because they are not directly observable and will be difficult to infer. They can then select texts and design activities to support students in making sense of the text, integrating the protagonists into the rules and explanations, and applying the rules to specific scenarios. For example, we decided that molecular interactions in evaporation and condensation are too much for students to infer on their own, and introduce them through a set of texts and animations. Students are then prompted to incorporate these new protagonists into predictions and explanations that involve phase changes of water, drawing on the information sources as appropriate. Drawing from a variety of sources of data, generated through first-hand investigation and interpreted from text, reflects the view of inquiry as a diverse set of practices [5].

Designers Should Identify Reasoning and Design Scaffolds to Support It

Finally, having analyzed the explanation, the data supporting it, and the means by which students will construct the rules they need to understand to explain the focal phenomenon, *designers should identify the kinds of reasoning students will need to use in constructing rules and the target explanation, and create scaffolds to support their developing thinking.* Reasoning in the construction of evidence-based explanations is a vital part of inquiry that can be particularly challenging for students [37]. Designers should identify the reasoning that students will need to use in generalizing the rules that they will ultimately use in their explanation. For example, students observe and record the behavior of balloons filled with water of different temperatures and salinities when placed in a tank of room temperature fresh water. From this data, they need to infer the general patterns that colder water sinks in warmer water, and saltier water sinks in fresher water. They are then introduced to the protagonist density and the relative densities of the different types of water, and must incorporate density with the patterns to construct a causal relationship. Designers should also identify the kinds of reasoning students will need to use in applying rules to construct the target explanation. For example, students need to apply the rain shadow effect to explain the lack of precipitation in the Atacama Desert, attending to the mountain range bordering the Desert, and the prevailing winds that blow perpendicularly to it.

Having identified the reasoning that will be required, designers should create scaffolds that will be provided and faded to support students in reasoning in the ways identified and in articulating their reasoning clearly. For example, once students have learned about the rain shadow effect, they examine several hypothetical situations, determining whether or not the effect is likely to be responsible for a particular dry region. In doing so, they are practicing identifying situations in which the rule is applicable. When writing arguments, they are provided with sentence stems that structure explicit articulation of reasoning: "We know that the rain shadow effect occurs when . . . We can see from the data that . . . Therefore . . ." In addition, when first using a reasoning in a particular way, the teacher explicitly names that kind of thinking, and encourages students to name it thereafter. "We are looking at each situation to decide whether or not the rain shadow effect can help us explain why the area is so dry. In science, we call using an idea to conclude something about a relevant situation *application* of that idea."

Designers Should Provide Students with Opportunities to Learn about and Practice Evaluating Lines of Argument in Science Using Explicit Criteria

Because the quality of a line of argument ultimately rests on the quality of its grounds, *designers should provide students with opportunities and support for evaluating the quality of information that might be used as evidence.* These opportunities can take multiple forms as students develop understanding and facility. Students should first be provided with models of the thinking involved in evaluating sources, including the teacher explicitly modeling the process with a source used by the class, and/or model texts that show scientists engaged in evaluating information—procedures, data, or informational text—for legitimacy and credibility. Students can then be provided with opportunities to evaluate and choose between sources of evidence to use to answer an explanatory question, where the sources differ in quality. Furthermore, students should have opportunities to critique provided arguments based on the credibility of information that is used as evidence, or the transparency regarding the source (or lack thereof) that allows for critique.

Designers should also provide students with opportunities during the unit to consider and critique multiple explanations for their relative merits in relation to each other, either of the focal phenomenon, or as part of sub-investigations. The teacher should have access to multiple explanations that could be introduced to and evaluated by students, but also be in a position to capitalize on different explanations generated by students. We mentioned previously that having students represent their initial explanations of the focal phenomenon can provide multiple explanations for comparison. Any provided explanations should vary in ways that allow one to be identified as superior, based on the criteria for justification. They could differ in causal depth, with one explanation extending further than the other. They could differ in refutability, where one explanation conflicts with some available evidence. They could differ in coherence, with one explanation accounting for more of the available evidence than the other. Also, they could differ in the credibility of the evidence, with one explanation drawing on evidence that is more credible in some way (this is similar to students' critique of arguments we described in the previous paragraph).

Comparing multiple explanations presents an opportunity to specifically confront alternative conceptions held by students that can be resolved through argumentation; these explanations could be developed based on alternative conceptions reported in the literature or from common ideas that have been generated by students in other classes [38]. It is important, however, that these explanations be refutable based on evidence that the class has or could obtain. If students don't already have access to the information necessary to refute it, deciding between multiple explanations might require a return to investigation to gather relevant data. For example, one explanation students might offer for the sinking of a saltwater balloon is because it is denser than a freshwater balloon. Another explanation could be because the saltwater balloon weighs more. If students have read an expository text about density and sinking and floating, they could critique the second explanation based on consistency with available information. If they have yet to read such a text, they could return to investigation, comparing a smaller saltwater balloon that weighs less to a freshwater balloon that weighs more—which could then motivate the reading of the expository text to introduce density as a protagonist.

Designers Should Create Iterative Opportunities for Students to Engage in Argumentation to Develop and Refine Their Explanations of the Focal Phenomenon

Learning to critique sources of evidence and explanations prepares students to construct and critique lines of argument in more holistic and iterative ways. To emphasize the dialogic nature of argumentation, *designers should provide students with periodic opportunities to engage in more and less formally structured argumentation over the course of the unit in order to work toward increasingly better explanations.* These opportunities can include the following: casual discussions about how newly constructed rules or newly acquired data support or suggest revisions to current explanations; structured discussions for which students have time to prepare a particular explanation and marshal evidence for it before talking with their peers in small or whole-group settings; or, a scaffolded process in which students create and critique written arguments with their peers. Supporting these kinds of interaction require cultivating a classroom community that treats each argument as a collaborative effort to work toward the best explanation by testing multiple possibilities against evidence and criteria. This perspective on argumentation differs from many students' everyday perspectives on argumentation, which often view it as an emotionally loaded situation in which individuals feel hesitant to risk being attacked or being wrong [15].

To support students' re-conceptualization of argumentation, designers should include regular opportunities for students to revisit and revise their arguments about the focal phenomenon. Students may revise their arguments in multiple ways, and should have support for all that might be relevant at a particular point in the unit. They may revise their explanation to be consistent with any relevant rules that they have developed since their previous explanation. New rules may also prompt students to identify data that they require that is relevant to the explanation; designers should anticipate when students might do so, and ensure that the data is available in resources already available to them, or can be provided by the teacher. Moreover, students should justify explicitly how and why a new explanation is better than previous and/or alternative explanations. The process of revisiting and revising their arguments provides students (and teachers) with evidence of their developing understanding of the focal phenomenon, as well as experience using an explicit set of criteria to assess and improve that understanding.

Designers should determine a sequence of learning activities that will afford opportunities for students to improve and refine their explanations of the focal phenomenon through a connected series of investigations. While there are no doubt multiple ways to achieve this, we suggest that *learning activities should be sequenced in order to help students develop explanations with increasing causal depth*. This means beginning with the focal phenomenon and moving "backward," using the answer to one question to generate the next, extending the causal story, or identifying new relationships between protagonists. For example, presenting the contrast between the Atacama and the Amazon prompts the question "Why is one area drier than the other?" A brief analysis of precipitation data might then prompt the question "Where does the rain come from?" which in turn leads to "Where does water vapor come from?" Mapping back through the causal story in this way corresponds to the way in which findings often generate new questions in science [7].

An approach that organizes instruction around opportunities for students to work toward better explanations of a focal phenomenon through guided inquiry and argumentation offers dual benefits. It not only creates opportunities for students to develop an understanding of core science ideas, but it does so by their engaging in and developing facility with the fundamental practices of inquiry science. Students ask and pursue answers to questions about the workings of the natural world. Students conduct investigations and analyze texts in order to generate new data and identify relevant credible information. They analyze the data and ideas to use as evidence in supporting or revising their explanations based on a critique using common criteria and, in doing so, develop new science knowledge which in turn leads to new questions. We recognize that there are other practices that can and should be incorporated into students' learning, such as engineering and design, but we propose that explanation and argumentation should be a dominant focus, as multiple practices fundamental to inquiry (questioning, investigating, gathering and analyzing data, modeling, critiquing and interpreting texts) can all be incorporated as authentic tools in arguing toward better explanations [18].

Conclusion

If inquiry is important for the critical thinking skills it teaches, the training of citizens in a democracy for making evidence-based decisions, and for preparing some students to make science a vocation, then finding a way to coherently embed inquiry in school science is essential. Designing units around a scientific argument connects the practices of inquiry to the content and to each other in a meaningful way. By focusing on the construction of a scientific argument, students will not be learning just procedures or discrete facts, but will be practicing critical thinking skills as they address a question, and seek and evaluate evidence to construct increasingly complex explanations. It is this type of critical thinking that is needed to make choices outside of the classroom as well. Throughout a unit of argumentation, the role of the student will be to question assumptions and to think not just about finding a right answer, but about finding the best answer that relies on the best available evidence. Learning to critique and to weigh alternatives are invaluable skills that are applicable well beyond the science class. Finally, by participating in the co-construction of these classroom explanations, students will have a better appreciation for the nature of scientific knowledge. Understanding the process of communal knowledge construction practiced by scientists will provide students with real preparation for pursuing a career in science, and will better equip them to evaluate the science they encounter as they make decisions in their lives.

While these design principles are grounded in a coherent conception of scientific argumentation and provide initial guidance in constructing learning activities, continued empirical testing with students is a critical next step. As students attempt to explain focal phenomena using the data they gather and ideas they have derived from interpretation of text, new opportunities and challenges will become evident. Analysis of how students work to take up the practices and values of science in their efforts to explain the natural world will reveal areas of unexpected promise and difficulty.

References

[1] R.D. Anderson, "Reforming Science Teaching: What Research Says About Inquiry," *Journal of Science Teacher Education*, **13**(1) (2002) 1-12.

[2] J.F. Osborne and A. Patterson, "Scientific Argument and Explanation: A Necessary Distinction?" *Science Education*, **95**(4) (2011) 627-638.

[3] *Taking Science to School: Learning and Teaching Science in Grades K-8*, National Research Council, Washington, DC, 2007.

[4] *Benchmarks for Science Literacy*, American Association for the Advancement of Science: Project 2061, Oxford University Press, New York, NY, 1993.

[5] *National Science Education Standards*, National Research Council, Washington, DC, 1996.

[6] W.A. Sandoval and B.J. Reiser, "Explanation-Driven Inquiry: Integrating Conceptual and Epistemic Scaffolds for Scientific Inquiry," *Science Education*, **88**(3) (2004) 345-372.

[7] J. Krajcik, P. Blumenfeld, R. Marx, and E. Soloway, "Instructional, Curricular, and Technological Supports for Inquiry in Science Classrooms," in J. Minstrell and E.H. van Zee (eds.), *Inquiring into Inquiry Learning and Teaching in Science*, American Association for the Advancement of Science, Washington, DC, 2000.

[8] B.A. Crawford, "Learning to Teach Science as Inquiry in the Rough and Tumble of Practice," *Journal of Research in Science Teaching*, **44**(4) (2007) 613-642.

[9] K.L. McNeill, D.J. Lizotte, J. Krajcik, and R.W. Marx, "Supporting Students' Construction of Scientific Explanations by Fading Scaffolds in Instructional Materials," *Journal of the Learning Sciences*, **15**(2) (2006) 153-191.

[10] R. Driver, P. Newton, and J. Osborne, "Establishing the Norms of Scientific Argumentation in Classrooms," *Science Education*, **84**(3) (2000) 287-312.

[11] M.P. Jiménez-Aleixandre, A. Bugallo Rodríguez, and R.A. Duschl, "'Doing the Lesson' or 'Doing Science': Argument in High School Genetics," *Science Education*, **84**(6) (2000) 757-792.

[12] M. Garcia-Mila and C. Andersen, "Cognitive Foundations of Learning Argumentation," in S. Erduran and M.P. Jiménez-Aleixandre (eds.), *Argumentation in Science Education*, **35** (2007) 29-45.

[13] G. Wiggins and J. McTighe, *Understanding by Design*, Association for Supervision and Curriculum Development, Alexandria, VA, 1998.

[14] M.P. Jiménez-Aleixandre and S. Erduran, "Argumentation in Science Education: An Overview," in S. Erduran and M.P. Jiménez-Aleixandre (eds.), *Argumentation in Science Education*, **35** (2007) 3-27.

[15] L.A. Bricker and P. Bell, "Conceptualizations of Argumentation from Science Studies and the Learning Sciences and Their Implications for the Practices of Science Education," *Science Education*, **92** (2008) 25.

[16] S. Toulmin, *The Uses of Argument*, Cambridge University Press, Cambridge, MA, 1958.

[17] S. Toulmin, R. Rieke, and A. Janik, *An Introduction to Reasoning*, Macmillan, New York, NY, 1984.

[18] *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, National Research Council, Washington, DC, 2011.

[19] F.H.C. Crick and J.D. Watson, "The Complementary Structure of Deoxyribonucleic Acid," *Proceedings A of the Royal Society*, **223** (1954) 80-96.

[20] J.D. Watson and F.H.C. Crick, "Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid," *Nature*, **171**(4356) (1953) 737-738.

[21] J. Ogborn, G. Kress, I. Martins, and K. McGillicuddy, *Explaining Science in the Classroom*, Open University Press, Buckingham, England, 1996.

[22] R.P. Feynman, *The Character of Physical Law*, MIT Press, Cambridge, MA, 1967.

[23] D. Trafimow and S. Rice, "What If Social Scientists Had Reviewed Great Scientific Works of the Past?" *Perspectives on Psychological Science*, **4**(1) (2009) 65-78.

[24] M. Braaten and M. Windschitl, "Working toward a Stronger Conceptualization of Scientific Explanation for Science Education," *Science Education*, **95**(4) (2011) 639-669.

[25] B. Latour, "Drawing Things Together," in M. Dodge, R. Kitchin, and C. Perkins (eds.), *The Map Reader*, John Wiley & Sons, Ltd, 2011.

[26] N.J.S. Brown, E.M. Furtak, M. Timms, S.O. Nagashima, and M. Wilson, "The Evidence-Based Reasoning Framework: Assessing Scientific Reasoning," *Educational Assessment*, **15**(3-4) (2010) 123-141.

[27] R. Duschl, "Assessment of Inquiry," in J.M. Atkin and J.E. Coffey (eds.), *Everyday Assessment in the Science Classroom*, NSTA Press, Arlington, VA, 2003.

[28] M.H.F. Wilkins, W.E. Seeds, A.R. Stokes, and H.R. Wilson, "Helical Structure of Crystalline Deoxypentose Nucleic Acid," *Nature*, **172**(4382) (1953) 759-762.

[29] J.M. Broomhead, "The Structure of Pyrimidines and Purines. II. A Determination of the Structure of Adenine Hydrochloride by X-Ray Methods," *Acta Crystallographica*, **1**(6) (1948) 324-329.

[30] D.N. Walton, "Abductive, Presumptive, and Plausible Arguments," *Informal Logic*, **21**(2) (2001)141-169.

[31] K.R. Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, Routledge, New York, NY, 2002.

[32] P. Kitcher, "Explanatory Unification," *Philosophy of Science*, **48**(4) (1981) 507-531.

[33] M. Windschitl, J. Thompson, and M. Braaten, "The Beginner's Repertoire: Proposing a Core Set of Instructional Practices for Teacher Preparation," Paper presented at the Discovery Research K-12 Meeting, National Science Foundation, Washington, DC, 2009.

[34] G.N. Cervetti and J. Barber, "Text in Hands-on Science," in E.H. Hiebert and M. Sailors (eds.), *Finding the Right Texts*, The Guilford Press, New York, NY, 2009.

[35] S.J. Magnusson and A.S. Palincsar, "Teaching to Promote the Development of Scientific Knowledge and Reasoning about Light at the Elementary School Level," in M.S. Donovan and J.D. Bransford (eds.), *How Students Learn: Science in the Classroom*, The National Research Council, Washington, DC, 2005.

[36] *How Students Learn: Science in the Classroom*, National Research Council, Washington, DC, 2005.

[37] K.L. McNeill and J. Krajcik, "Inquiry and Scientific Explanations: Helping Students Use Evidence and Reasoning," in J. Luft, R.L. Bell and J. Gess-Newsome (eds.), *Science as Inquiry in the Secondary Setting*, NSTA Press, Arlington, VA, 2008.

[38] R. Driver, A. Squires, P. Rushworth, and V. Wood-Robinson, *Making Sense of Secondary Science*, Routledge, London, 1994.