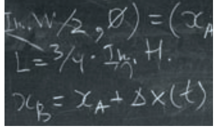
Science AAAS

Arguing to Learn in Science: The Role of Collaborative, Critical Discourse

Jonathan Osborne

Science **328**, 463 (2010);
DOI: 10.1126/science.1183944



of these initiatives, we might be able to help teachers situate literacy and science each in the service of the other as students gain tools and proficiency in both. The agenda is surely daunting, but the costs of avoiding it are high and the rewards for pursuing it are substantial.

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10.1126/science.1182595

REVIEW

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Jonathan Osborne

Argument and debate are common in science, yet they are virtually absent from science education. Recent research shows, however, that opportunities for students to engage in collaborative discourse and argumentation offer a means of enhancing student conceptual understanding and students' skills and capabilities with scientific reasoning. As one of the hallmarks of the scientist is critical, rational skepticism, the lack of opportunities to develop the ability to reason and argue scientifically would appear to be a significant weakness in contemporary educational practice. In short, knowing what is wrong matters as much as knowing what is right. This paper presents a summary of the main features of this body of research and discusses its implications for the teaching and learning of science.

The goal of science is to produce new knowledge of the natural world. Two practices essential to achieving this objective are argument and critique. Whether it is new theories, novel ways of collecting data, or fresh interpretations of old data, argumentation is the means that scientists use to make their case for new ideas. In response, other scientists attempt to identify weaknesses and limitations; this process happens informally in laboratory meetings and symposia and formally in peer review (*1*, *2*). Over time, ideas that survive critical examination attain consensual acceptance within the community, and by discourse and argument, science maintains its objectivity (*3*). Critique is not, therefore, some peripheral feature of science, but rather it is core to its practice, and without argument and evaluation, the construction of reliable knowledge would be impossible. Whether it is the theoretician who is developing new models of phenomena or the experimentalist who is proposing new ways of collecting data, all scientists must subject their ideas to the scrutiny of their peers. But what of science education?

Science Education and the Absence of Argument

Science education, in contrast, is notable for the absence of argument (*4*, *5*). Although instructors and teachers may offer many explanations, these are not arguments. To offer an explanation of a fact is to presume it is true. An argument, in contrast, is an attempt to establish truth and commonly consists of a claim that may be supported by either data, warrants (that relate the data to the claim), backings (the premises of the warrant), or qualifiers (the limits of the claim) (Fig. 1). Some or all of these elements may be the subject of rebuttals or counter-arguments (*6*). Arguments containing rebuttals are thought to be of the highest quality, as they require the ability to compare, contrast and distinguish different lines of reasoning. Within science, arguments may be verbal or written and are commonly reliant on supporting visualizations in the form of graphs or symbolic models.

Typically, in the rush to present the major features of the scientific landscape, most of the arguments required to achieve such knowledge are excised. Consequently, science can appear to its students as a monolith of facts, an authoritative discourse where the discursive exploration of ideas, their implications, and their importance is absent (*7*). Students then emerge with naïve ideas or misconceptions about the nature of science itself—a state of affairs that exists even though the National Research Council; the American Association for the Advancement of Science; and a large body of research, major aspects of which are presented here, all emphasize the value of argumentation for learning science (*8*–*10*).

The common explanation of the absence of argument is that it is a product of an overemphasis by teachers, curricula, and textbooks on what we know at the expense of how we know (*11*). Deep within our cultural fabric, education is still seen simplistically as a process of transmission where knowledge is presented as a set of unequivocal and uncontested facts and transferred from expert to novice. In this world-view, failure of communication is the exception and success the norm. However, in reality, education is a highly complex act where failure is the norm and success the exception (*12*). For instance, a meta-analysis of 14 classes taught using traditional methods shows that students achieved an average gain of only 25% between their pre- and posttest scores. In contrast, when lecturers paused and asked students to discuss the concept presented in pairs or small groups (three or four students), students achieved an average gain of 48% (*13*).

Argumentation and Learning Science

Over the past two decades, in an attempt to address the problem posed by the failure of traditional methods, educational research has explored the contribution of collaborative discourse and argumentation to learning. Drawing on theoretical perspectives that see language as core to learning and thought and language as inseparable, the implications of these ideas for education have been developed by a number of theorists (*14*–*17*). A critical feature of this work is a view that learning is often the product of the difference between the intuitive or old models we hold and new ideas we encounter (*18*). Through a cognitive process of comparison and contrast, supported by dialogue, the individual then develops new understanding. Consequently, learning requires opportunities for students to advance claims, to justify the ideas they hold, and to be challenged. Although this may happen within the individual, it is debate and discussion with others that are most likely to enable new meanings to be tested by rebuttals or counter-arguments.

In this sense, learning to argue is seen as a core process both in learning to think and to construct new understandings (*19*, *20*). Comprehending why ideas are wrong matters as much as understanding why other ideas might be right. For example, students who read texts that explained why common misconceptions were flawed (as well as explaining why the right idea was right) had a more secure knowledge than those who had only read texts that explained the correct idea (*21*). Likewise, researchers have found that groups holding differing ideas learn more than those who hold similar preconceptions, many of whom made no progress whatsoever (*22*, *23*). Indeed, one study found that even if the difference between individuals was based on incorrect premises, significant learning gains can occur—a case of two wrongs making a right—and with learning effects that were still significant on delayed posttests (*24*).

These findings are also supported by a number of classroom-based studies, all of which show improvements in conceptual learning when students engage in argumentation (*25*–*28*) (Fig. 2). For instance, students who were asked to engage in small-group discussions significantly outperformed a group of control students in their use of extended utterances and verbal reasoning (*25*), features that are rare in formal science education (*29*). Significant improvements were also produced in their nonverbal reasoning and understanding of science concepts. Another study with two classes of 16- to 17-year-old students studying genetics required students to engage in argumentative discourse about the appropriate answer to specific problems. Compared with a control group, the students who engaged in discussion used biological knowledge appropriately (53.2 versus 8.9%) significantly more often (*26*).

A recent meta-analysis of 18 studies grouped learning activities into three major categories: those that are interactive and require collaborative discourse and argumentation (either with a peer or an expert tutor); those that are constructive and require individuals to produce a product

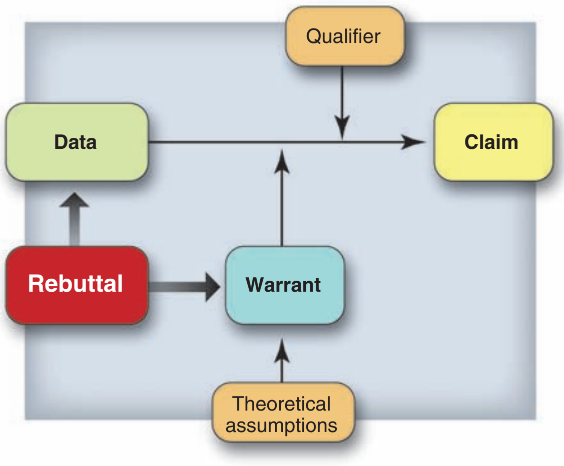

Fig. 1. Toulmin's argument diagram offers a generic representation of all arguments that are claims to knowledge (*6*). For instance, the claim that climate change is happening is supported by data, e.g., rising CO_2 levels, melting glaciers. A warrant is the justification that explains the relation of the data to the claim. Often, warrants rest on theoretical assumptions that are only tacitly acknowledged. Finally, qualifiers express the limits of the validity of the claim. Arguments arise when attempts are made to rebut or refute the claim either by attacking the validity of the data or the validity of the warrant. In science, arguments arise over the predictions and validity of theories, the methods of collecting data, and the interpretation of data sets.

School of Education, Stanford University, 485 Lasuen Mall, Stanford, CA 94305, USA. E-mail: osbornej@stanford.edu

such as an essay or lab report; or those that are active, such as conducting an experiment (*30*). Comparing the learning gains achieved when using each of these three approaches, the work shows conclusively that a hierarchical schema of learning activities exists from interactive (the most effective), to constructive, to active (the least effective). Studies show, however, that group discourse that contributes to learning effectively is dependent on a number of factors. Most important, students need to be taught the norms of social interaction and to understand that the function of their discussion is to persuade others of the validity of their arguments. Exemplary arguments need to be modeled, and instructors need to define a clear and specific outcome. Student groups need materials to support them in asking the appropriate questions and to help in identifying relevant and irrelevant evidence; also, consideration needs to be given to the relative ability of group members (*31–34*).

Fig. 2. Scientists routinely debate their theories, their data, and the implications. Research shows that argumentation in the classroom can improve conceptual learning.

Scientific Reasoning and Argumentation

Argumentation in science education requires students to construct and evaluate scientific arguments and to reason scientifically. The picture that research presents of students' ability to undertake scientific reasoning is complex (*35*). Students' ability to argue would appear to depend on the nature of the possible outcome, with students tending to adopt reasoning strategies with a confirmatory bias rather than using logical criteria. It is also dependent on their domain-specific knowledge. For instance, individual's ability to identify covariation is significantly enhanced by knowledge of a plausible theoretical mechanism (*36*), for example, that levels of carbon dioxide in the atmosphere could be a cause of climate change. The situation is somewhat confounded, however, by a recent study where Chinese physics undergraduates outperformed comparable American undergraduates on tests of content knowledge, in some cases by three effect sizes, yet there was no difference in their performance on a domain-general test of scientific reasoning (*37*). Moreover, there is disagreement about how and when students capabilities with reasoning develops between those who argue that it develops through adolescence versus those who argue that even preadolescent children are capable of making evidence-based inferences (*38*)—essentially that the limits on student's capability is attributable to their lack of knowledge rather than their reasoning capability.

In addition, notions of what constitutes scientific reasoning differ somewhat. Much of the research on individual's capability with scientific reasoning is a product of laboratory-based, psychological research examining individuals skills with specific competencies. Early Piagetian studies defined scientific reasoning as the capability to undertake a set of logico-mathematical operations such as seriation, logical reasoning, probabilistic thinking, and manipulating abstract variables—for instance, whether students could conserve volume when water was transferred from a thin, tall cylinder to a wide, short, one (*39*). More recent research has focused on a wider set of skills such as students' ability to develop testable hypotheses, to generate experimental designs, to control variables, to coordinate theory and evidence, and to respond to anomalous evidence (*35*).

"Critique is not, therefore, some peripheral feature of science, but rather it is core to its practice, and without [it], the construction of reliable knowledge would be impossible."

Sociologists, however, offer a different, empirically based vision of scientists marshalling resources to mount persuasive arguments for the validity of their cases. Philosophers, in contrast, offer a normative, idealized description of how science functions. A synthesis of the work from these three domains would suggest that the reasoning skills that science education might seek to develop are these abilities:

- to identify patterns in data, such as covariation, and to make inferences;
- to coordinate theory with evidence and to discriminate between evidence that supports (inclusive) or does not support (exclusive) or that is simply indeterminate;
- to construct evidence-based, explanatory hypotheses or models of scientific phenomena and persuasive arguments that justify their validity; and
- to resolve uncertainty, which requires a body of knowledge about concepts of evidence such as the role of statistical techniques, the measurement of error, and the appropriate use of experimental designs, such as randomized double-blind trials.

The study of reasoning also offers an opportunity to explore the types of arguments used in science, which may be abductive (inferences to the best possible explanation), such as Darwin's arguments for the theory of evolution; hypothetico-deductive, such as Pasteur's predictions about the outcome of the first test of his anthrax vaccine; or simply inductive generalizations archetypal represented by "laws."

Enhancing Student Argumentation and Reasoning Skills?

Do students become better at scientific reasoning if it is an overt feature of their education? Many studies have shown that explicit teaching of specific strategies does improve students' scientific reasoning. For instance, a laboratory-based study found that the performance of students explicitly taught about the control of variables through a structured intervention improved significantly compared with a group who were given no such instruction (*40*). Similar findings emerge from a recent classroom-based study that showed significant developments in students' strategic and meta-strategic thinking (*41*). The strongest evidence comes from a U.K. classroom-based study using 30 lessons dedicated to the teaching of reasoning over 2 years in 11 schools with children from grades 7 and 8. Students' scores on test of conceptual knowledge in the intervention schools were significantly better than those of the control sample (*42*). Additionally, 2 years later, these students significantly outperformed a control sample not only in science, but also in language arts and mathematics, which led the authors to argue that their program had accelerated students' general intellectual processing abilities. This finding has been replicated many times by the same authors, who have collected data from new cohorts in the schools that use this program. The form of reasoning measured here, however, was restricted to the students' ability to perform logical operations based on Piaget's studies. In a 1-year classroom intervention aimed at improving students' ability to construct arguments, they showed improvements, but these were not significant (*43*).

Future Challenges

Research on the development of students' skills in argumentation is still in its infancy and lacking valid or reliable instruments with which students' competency can readily be assessed. In addition, we still need to understand in greater detail how argumentation produces learning and what features of learning environments produce the best arguments among students (*44*). Much is understood about how to organize groups for learning and how the norms of social interaction can be supported and taught, but how such groups can be supported to produce elaborated, critical discourse is less evident (*45*). Where studies are unequivocal, however, is that if student skills are to develop not only must there be explicit teaching of how to reason but also students need a knowledge of the meta-linguistic features of argumentation (claims, reasons, evidence, and counterargument) to identify the essential elements of their own and others' arguments (*46*). Younger students, particularly, need to be desensitized to the negative connotation of conflict surrounding these words and to see argument as a fundamental process in constructing knowledge.

What is in little doubt is that employers, policymakers, and educators believe that individuals' ability to undertake critical, collaborative argumentation is an essential skill required by future societies (*47*). Of its own, the evidence from research to date is that mere contact with science does not develop such attributes. Indeed, the cultivation of critical skepticism, a feature that is one of the hallmarks of the scientist, would appear to have only minimal value within science education. Yet, research has demonstrated that teaching students to reason, argue, and think critically will enhance students' conceptual learning. This will only happen, however, if students are provided structured opportunities to engage in deliberative exploration of ideas, evidence, and argument—in short, how we know what we know, why it matters, and how it came to be. Evidence would also suggest that such approaches are more engaging for students (*48*). Collaborative discourse where students engage constructively with each other's ideas therefore offers a means for improving the quality of the student experience, the depth of student thinking, and their learning of science itself.

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Post date 11 June 2010

Review: "Arguing to learn in science: The role of collaborative, critical discourse" by J. Osborne (23 April, p. 463). The credit for Fig. 2 did not appear in print; it is RYAN MCVAY/PHOTODISC/GETTY IMAGES.