The Epistemology of Science and the Epistemology of Science Teaching

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Abstract: Paul Kirschner has criticized constructivist science educators for confusing epistemology with pedagogy. He has also criticized them for a retrograde conception of science. This paper starts by agreeing with his second point and elaborates it into a fuller critique of naïve scientific epistemology, arriving at the conclusion that a better epistemology points to a better pedagogy. The key is a programmatic view of science, which sees the scientific enterprise as working continually toward stronger explanations of natural phenomena. This is a program that can be joined by people at all levels of sophistication, including young children, the goal always being to make today's ideas superior in some demonstrable way to yesterday's. Engaging students in explanation improvement has numerous advantages over atheoretical inquiry and project-based activities. Knowledge Building is highlighted as an approach that gives idea improvement a central place in its pedagogy.

Keywords: epistemology, nature of science, scientific method, Knowledge Building

Introduction

In a series of papers Paul A. Kirschner (1992, 2009; Kirschner, Sweller, & Clark, 2006) has argued that the epistemology of disciplines is a poor basis for the design of education in those disciplines. Although presented as a general criticism of constructivist, inquiry, and discovery educational approaches, Kirschner's argument is a direct challenge to approaches that take disciplinary practice as a model for education in the disciplines. Kirschner's position most obviously challenges Jerome Bruner's proposal (1960) that the "structure of the disciplines" should shape instruction—the pedagogical implication of which was that the way to learn a discipline is to practice it: "The schoolboy learning physics *is* a physicist, and it is easier for him to learn physics behaving like a physicist than doing something else" (Bruner, 1960, p. 14). A number of curriculum innovations in the 1960s, mostly but not exclusively in science, followed this line of thought. Perhaps the most extreme version of bringing disciplinary practice into the heart of educational practice, however, is Knowledge Building (Scardamalia & Bereiter, 2006, 2014; Scardamalia, Bereiter, & Lamon, 1994) where "knowledge creation," as practiced in research laboratories and innovative companies, becomes the principal means of education in the disciplines (Bereiter & Scardamalia, 2014). Thus Knowledge Building, at least in Scardamalia's and my formulation of it, takes a diametrically opposite position to Kirschner's. Despite this, I agree with almost everything Kirschner says in advancing his argument. How, then, do I arrive at an opposite conclusion?

In accord with many contemporary cognitive scientists and philosophers, Kirschner uses the term epistemology broadly to refer not only to how knowledge claims are justified but also to how they are produced. He draws the following distinction between epistemology and pedagogy:

> Modern curriculum developers and instructional designers confuse the epistemological nature of a domain with the psychological bases of learning and the pedagogic bases for teaching. Epistemology refers to how knowledge is acquired and the accepted validation procedures of that knowledge; pedagogy refers to how something is taught. (Kirschner, 2009, p.151)

Kirschner criticizes constructivists not only for failing to honor this distinction but also for promoting an inductivist epistemology that he calls "basically flawed" (1992, p. 275), citing a number of authorities who make this point: e.g., "Gardner (1975) calls the notion that 'scientists patiently gather piles of evidence which they can put together inductively to form a law is absurd . . . inductive reasoning may be involved in the checking stage of a law, but not at the formulation stage' (p. 17)." In his 2009 paper, Kirschner makes the same point more briefly, but calls it a digression from his main point about the difference between epistemology and pedagogy. This is where we part company. I see the "flawed epistemology" on which much of constructivist pedagogy is based as a critical factor in what is wrong with it, and this leaves open the possibility that pedagogy based on a better epistemology could perform better and might be preferable to an "instuctivist" pedagogy. The purpose of the present paper is to explore this possibility and what it entails for educational design.

Can students carry out disciplinary knowledge production?

Kirschner does not object in principle to education based on the epistemology of disciplines. His objection is a practical one: It's too hard; students aren't equipped for it. Although he draws on theoretical backing from Piaget and Vygotsky in his 2009 paper and on cognitive load theory in Kirschner, Sweller, and Clark (2006), the question of whether young students can actually practice disciplinary knowledge creation is an empirical, not a theoretical question. Claims that they cannot do so stand to be refuted by empirical demonstration. I believe the accumulated research on Knowledge Building provides such refutation (Bereiter & Scardamalia, 2010; Scardamalia & Bereiter, 2014; Scardamalia, Bereiter, & Lamon, 1994). Some of the research involves experimental comparisons, usually of a before-and-after nature, but for the present purpose even anecdotal data can carry weight. It is beyond the scope of this paper to present evidence supporting this claim; the following example may, however, at least serve to clarify what is being claimed. The example comes from a grade one (age approximately six years) class reported in Scardamalia (2002) and based on a teacher's report:

> After a fall outing, the children came up with the question: Why do leaves change color in the fall? The students contributed notes proposing explanations. The teacher or an aide provided help with spelling as needed. Some examples of student contributions:
> "Because the sap cant get to the leaf because of a plug. Then the chlorophyll dies and the leaf changes colour." (Illustrated with drawing of sap running through the branches.)
> "fall – i think the chlorophyll goes into the tree to keep warm for the winter."
> "i think leaves change colour because when the leaf falls down I think that the chlorophyll goes to the outside of the leaf so it leaks off the leaf."
> "Because it's too cold for the chlorophyll to make food for the tree."

Notice that although the theories are faulty they do hypothesize physical processes and they are potentially testable. To test whether cold alone was sufficient to explain leaves changing color, the first-graders put green leaves into a freezer. More remarkable is something that occurred months later during a field trip to a maple-tree farm to see how maple syrup is made. One child, watching the sap flow from the tree, remarked that her theory regarding chlorophyll must be wrong, because the sap she saw was not green. Others raised many other issues about what they saw, and how the flow of sap gave them new ideas about the internal structure of a tree, and the relation of its internal structure to their theories. A new theory emerged to the effect that there are two paths for sap to flow, one near the outside of the tree trunk for colorless sap and one deeper inside for the chlorophyll-bearing sap. In rudimentary form, all the essential elements of scientific theory-building are evident among these six-year-olds.

Some common limitations of children's scientific thinking are evident in this example: a lack of system (Vygotsky, 1934/1962, p. 116), a penchant for single-cause explanations, and a susceptibility to animism (the chlorophyll trying to keep warm). Except for the animism, these limitations may be found in abundance in the comments by adults on internet news sites. But on the positive side, the children demonstrated the fundamentals of authentic scientific thinking: the creation of explanatory hypotheses and the testing and revision of these on the basis of evidence. It has seemed, on the basis of numerous examples of young children's explanation-building, that their implicit epistemology is more advanced than the "scientific method" they will be taught in later years. It seems these six-year-olds intuitively understood that the job of theories is to explain facts, not to achieve the status of facts. I have seen evidence of this in even younger children. They display a level of scientific thinking that apparently gets dragged down by later instruction.

Kirschner agrees that students need a better epistemology—a better understanding of disciplinary practice—but says they should not be left to discover this for themselves or to develop it intuitively through the usual constructivist diet of "guided discovery" exercises and hands-on projects. Teaching scientific epistemology to school students is not a walk in the park, however. Carey and Smith (1993) identified three levels of student understanding of the nature of science and scientific knowledge. At the lowest level, as noted previously, students see science as the unproblematic accumulation of facts. At level 2 the uncertainties of knowledge claims and the importance of evidence are recognized. At level 3 the role of theories in both the formulation and interpretation of scientific research is recognized. Through Carey and Smith's own research and through much subsequent research, it has been found that moving students from level 1 to level 2 is achievable, but that movement to level 3 is rare (Chuy, Scardamalia, Bereiter, et al., 2010). The bulk of research on student epistemologies, starting with that of Robert Perry and continuing through a steady flow of descriptive and occasionally experimental studies, has for the most part not recognized level 3 at all but has instead concerned itself with level 1 and variations within level 2—generally variations between solipsistic relativism and recognizing that some beliefs can be better justified than others. According to Chinn and Malhotra (2002), theory plays virtually no role in forms of inquiry common in school science education. Level 3 is evidently rare among teachers as well. Windschitl (2004) found that teachers' own beliefs about the nature of science overlooked its creative, theory-focused character.

The reduction of science to atheoretical fact gathering and hypothesis testing coupled with an emphasis on the uncertainties of scientific knowledge make for a pedagogical brew that provides students little motivation to seek scientific careers and leaves "it's just a theory" as a reason to reject climate change, the descent of *homo sapiens* from earlier life forms, or any other unwelcome truth. Students may still find things of interest in science, sometimes because of inherent interestingness of topics such as dinosaurs and space travel, sometimes because the hands-on activities are intriguing. But this is a far cry from the central motivation of science, which is to understand how the world works.

The importance of understanding the nature of science ("NOS") is by now well recognized in curriculum planning. However, failure to understand the nature and role of theory is failure to understand NOS—and on that basis failure can be said to be endemic. Failure to understand the nature of theory does not only affect those who might pursue careers in science but has social, political, and personal consequences. Political controversies often involve theories and theoretical models, current examples being controversies about climate change and economic policy. Public support of basic research requires some appreciation of the value of theory, of the theoretical value of research on organisms and phenomena of little obvious practical significance, and the often crucial importance of understanding a problem before plunging ahead with possible solutions. All of these real-life functions of scientific knowledge require understanding science as an effort to construct a coherent and testable understanding of the world—in short, as theory building. This implies an epistemology that goes well beyond the shallow constructivism of contemporary school science.

The crucial importance of progressivity in knowledge

If it is agreed that students should be gaining a better understanding of the nature of science, then the next question is what *is* the nature of science? Any perusal of contemporary philosophy of science will make it clear that this is by no means a settled issue. There are a number of opinions, which may be roughly categorized as no-difference, methodological, and programmatic. Arguments for these positions are all plausible enough that I do not see any virtue in educationists trying to decide which is right. A pragmatic approach holds more promise (cf. Resnik, 2000)—in this case an approach based on consideration of what position is best for the design of school science education.

The no-difference position does not hold that there is no discernible difference between scientific and other practices, only that there is no clear line of demarcation. Whatever is singled out as distinctive in scientific practice can also be found in some form in everyday thought or in pseudo-sciences such as astrology and dianetics. As applied in school, however, the no-difference position would seem to legitimate low-level relativism: whatever belief feels right to you is okay. Methodological views of the nature of science hold that there are certain practices for arriving at conclusions that are different from other ways and that these practices are what make conclusions "scientific." From a pedagogical pragmatic viewpoint, the question is not whether methodological criteria for what constitutes science are correct or adequate but whether they represent a good basis for educational design. I have already signaled my main objection: Education based on a conception of science as method represents it as a joyless, pedestrian occupation with its whole bold, creative, frontier-advancing character bled out of it.

The programmatic view of the nature of science is probably the least recognized in education, although it has strong philosophical backing. It requires viewing science over time spans and at a systemic level, which goes against the educational tradition of treating science as first and foremost a matter of individual knowledge and the testing of isolated hypotheses. Although beginnings of a programmatic view may be found among logical positivists, it was Imre Lakatos (1970) who explicitly argued that the proper object of scientific evaluation is not particular theories or knowledge claims but rather research programs. At the root of Lakatos's argument was the observation that scientists rarely abandon a theory because of disconfirming evidence (as schooling in the "scientific method" would have us believe). Instead they try to improve the theory or modify the knowledge claim in order to accommodate the troublesome evidence. What he called "progressive" research programs deal with anomalous data in ways that lead to stronger and stronger theories, whereas non-progressive programs deal with it in a variety of other ways, as documented by Chinn and Brewer (1998). Evolutionary theory has had to deal with numerous discoveries that challenge existing theory and has grown progressively stronger as a result, so that inexplicable findings become increasingly rare. By contrast, Intelligent Design, as a research program, keeps getting weaker as its knowledge claims in the form "Evolution cannot explain…" succumb to evidence that evolutionary theory can in fact account for the phenomenon at issue. Intelligent Design researchers have to keep looking for new things they believe evolutionary theory cannot explain, and in recent times have shifted their ground from the evolution of species and structures to the origin of the life and the universe—which are matters that evolutionary theory does not claim to deal with.

As a basis for educational design this programmatic conception of science has significant advantages over both no-difference and methodological conceptions:

- It allows the curriculum to start with whatever students currently (rightly or wrongly) understand and move on from there in a progressive fashion.
- It solves the teacher's problem of how to respond to students' inventive but wrong ideas. By actively promoting the working assumption that all ideas are improvable, the teacher is free to respond with "That's a wonderful idea. How could we make it even better?"
- It allows ample room for the creative aspect of science, which tends to be suppressed in methodological conceptions (i.e., the traditional "scientific method"), but also avoids the "anything goes" implication of no-difference conceptions.
- It sets out a realizable goal for students—idea improvement—rather than a discouragingly lofty one.
- It invites students to work collaboratively at idea improvement and to take mutual responsibility for it.
- It allows students to work progressively within their developmental and information processing capacity limits. Students can do productive work with ideas even though they lack "conservation of substance," "control of variables," and other elements of mature scientific thinking.
- It supports a progression from self-centered to idea-centered. Alice's idea and Jaime's idea (which may or may not be the same idea and which may be so vague that it is impossible to tell) are eventually absorbed into a collectively produced theory or solution that becomes community rather than individual property.
- Efforts to improve ideas so that they explain more facts or solve more problems tend to move beyond singular ideas and combinations of ideas to integrated structures of ideas—that is, toward theories.
- Although Lakatos was mainly concerned with theoretical programs, the idea of progressive programs applies equally to ones that address practical problems or social issues—and to some educators these are the most important objectives of science education for the masses.
- It provides a basis for students' seeing their work as part of a larger project of knowledge creation and becoming enculturated into a society of knowledge creators, with its long history and high prospects.

Students as practitioners of progressive science

The programmatic view of science has clear advantages for developing student understanding of the nature of science, but is it applicable to students' own scientific inquiry, as carried out under normal school and laboratory course conditions? Its applicability is severely limited if inquiry is confined to brief and unconnected episodes. Continuity and progressive development of explanations are essential according to the programmatic view. This means that, in order to be practitioners rather than only assimilators of progressive science, students need to be engaged not only in explaining but in building stronger explanations. Drawing mainly on Thagard's theory of explanatory coherence (2000), but with echoes of work by others such as Karl Popper and David Deutsch, we can stipulate that an explanation is getting stronger to the extent that

1. it explains more facts
2. it excludes more false statements
3. it connects to more other explanations
4. it explains things in more detail
5. parts of the explanation interlock so that it becomes increasingly difficult to modify parts without altering the whole
6. it is able more clearly to identify what it fails to explain
7. it generates better predictions
8. it explains *how* identified causal factors work, rather than only identifying and quantifying their effects.

An explanation that satisfies all these criteria is not something student explanation building is likely to achieve very often. However, the criteria themselves are not difficult to understand and thus represent something students can work toward collaboratively. In doing so, they will be engaged in theory building (Bereiter, 2012). Theory development, theory testing, and theory improvement are what basic research in science is all about. This is not a high-flown notion beyond the grasp of young students. It is perfectly comprehensible to them. They take naturally to producing theoretical explanations of natural phenomena and judging and modifying them in the light of evidence (Chuy, et al., 2010). It is schooling in the so-called "scientific method," with its often pointless testing of predictions, that may be responsible for students later losing their grip on this understanding. However, if Newton's laws are taken as an exemplar, theory building is apt to seem forbiddingly difficult and definitely not for everyone. Newton's laws and most physical theory building in the physical sciences represent what Bruner (1986) defined as the "paradigmatic mode," grounded in mathematics and logic and typically universal in scope. Young students can function in paradigmatic mode, as indicated by their ability to work out rules accounting for numerical or geometric progressions (Moss & Beatty, 2006). But most of their theorizing about natural and social phenomena is going to take place in what Bruner called the "narrative mode." In this mode, a process or phenomenon is explained by a series of events, with one causing the next. Building on children's narrative competence affords a way of getting students into scientific explanation without running up against the cognitive demands of paradigmatic explanation.

Of particular interest for science education at the school level is the "how-it-works" narrative. The progress of a plant from seed to fruition lends itself to an event sequence narrative, but often the narrative is complicated by the fact that things happen concurrently. A story about how an electric bell works must recognize that the same movement of the striker that sounds the bell also breaks the circuit that drew it to the bell, thus resulting in its springing back from the bell in readiness for a new cycle. Nutrition, respiration, and circulation are all processes that can be given explanations in narrative form, with the stories gaining complexity and undergoing correction as students' knowledge advances. Evolutionary explanations of the emergence of wings, legs, sexual reproduction, and so on, all have a story-like structure that students can grasp, elaborate, and criticize.

Oeijord (2003, p. 145) has set out criteria that a causal narrative must meet in order to be of scientific value. These are similar to the criteria of strong explanations set out above. Causal narratives that fall short on these criteria are often called "just so" narratives. I would argue that "just so" stories have value in education as improvable ideas—ideas that acquire more explanatory strength as they encompass more facts and as problems with them are solved. Constructing causal narratives is something children and novices can do that engages them with important scientific concepts and problems and that gives them realistic practice in a mode of thinking (abduction) that is a vital mechanism of creative work with ideas (Paavola & Hakkarainen, 2005b). The point most relevant to the issue of epistemology's relation to pedagogy is that, while the epistemology of science projects a landscape that contains heights beyond normal student capabilities, it also contains relatively gentle slopes that ordinary students can negotiate.

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The knowledge creation/ knowledge building alternative

Project-based science is aimed at engaging learners more directly in the kinds of practices that characterize "doing science" in the real world (Marx, Blumenfeld, Krajcik, & Soloway, 1997). However, project-based learning covers a wide range of approaches. At one extreme we have the traditional school project, in which students produce documents on selected topics that resemble encyclopedia articles in content and often in structure as well. Despite use of Web resources and computer-based representation tools, the basic pedagogy has not changed significantly in a hundred years. Then there are projects organized around some fictitious or real-life theme (e.g., planning a trip to Mars or analyzing pollution in a nearby stream). Although these can have genuine merit, they fall short of engaging students in the core enterprise of theory building—working to make systematic sense of the physical, biological, and social world. There is an alternative that engages students directly in this core sense-making enterprise. It is Knowledge Building (Scardamalia & Bereiter, 2003, 2006, 2014), defined as the production and continual improvement of ideas of value to a community. (I capitalize the term when referring to the cited program but use lower case when discussing concepts and processes.) Paavola and Hakkarainen (2005a) have shown that there is a close affinity between knowledge building as carried out in schools and knowledge creation as carried out in research laboratories and innovative companies. Scardamalia and I have argued (Bereiter & Scardamalia, 2014) that they are indeed the same concept, with differences in application due to context. One of these differences, of course, is that in an education context knowledge building/knowledge creation is expected to produce learning—and its success is ultimately judged by learning outcomes rather than by the quality of the ideas collectively produced.

Knowledge Building is not limited to any particular subject. It may include artistic and engineering types of knowledge creation. The creation of literary works, invention of mechanical and electrical things that work, and various sorts of creative computer program development may all constitute knowledge creation in so far as something new is added to the cognitive resources available to the knowledge-building community. However, the most distinctive and challenging kind of knowledge building in educational contexts is the creation and improvement of explanatory theories or theory-like "conceptual artifacts" (Bereiter, 2002). New education standards are calling for teaching "big ideas," and most modern programs honor this call in some fashion; but Knowledge Building makes the ideas themselves objects of inquiry.

The driver of students' idea-centered work is knowledge-building dialogue, which may involve argumentation but only as part of a collaborative effort to solve problems of explanation (Scardamalia & Bereiter, 2006). Students do experiments and other kinds of empirical work, often self-initiated, but always with the purpose of advancing the knowledge-building dialogue. The vast information resources of the Worldwide Web become an integral part of the process, which makes Knowledge Building a distinctly 21st-century approach. It is not expected that students will invent or discover through experiments big ideas like universal gravitation, natural selection, and photosynthesis, but neither is it left to the teacher to convey these ideas through didactic instruction. Instead, it is expected that students will encounter and assimilate them through their use of Web resources in efforts to improve their own explanations of natural phenomena. Whereas guided discovery, argumentation, and project-based learning may engage students in some of the elements of scientific practice, Knowledge Building incorporates all of these into the fundamental scientific effort to build coherent theoretical explanations of the phenomenal world.

Conclusion

Separating pedagogy from the epistemology of disciplines makes sense in many practical respects, but only up to a point. Creative instructional designers will do more than schedule topics according to logical or empirical dependencies. They will try to identify learnable concepts that are legitimate simplifications or reduced versions of target concepts (White, 1993). But doing this requires getting deeply into the structure and essence of the concepts, a sort of thing philosophers of science do. Kid-level concepts need to lead in the right direction, toward eventual grasp of the target concepts and not toward roadblocks and misconceptions.

In this paper I have elaborated on other ways in which the epistemologies of the sciences and science education intersect. With regard to students understanding the nature of science, Kirschner and I and many science educators agree that the conventional version of "the scientific method" is fundamentally flawed. But its basic flaw is epistemological, with its pedagogical drawbacks following as a consequence. I reviewed several competing conceptions of what distinguishes science from non-science, an epistemological issue that I would not presume to judge. But from a pedagogical point of view I think there is no doubt that a programmatic conception is preferable to a no-difference or a methodological conception, no matter how well-reasoned these may be. This is not epistemology directing pedagogy, but it is a pedagogical choice that could not have been formulated without the work of Lakatos and other philosophers of science.

Understanding what constitutes real science is one thing, but doing real science is another, and one that arguably deserves priority. Naïve empiricism provides a simple answer to engaging students in real science: Get them practicing "the scientific method" by generating hypotheses (guesses), turning them into predictions, and testing the predictions. (For an indication of how ubiquitous this practice is, do an image search on "science fair.") But if students are to do the kind of science that significantly advances understanding of how the world works, they need to build coherent explanations and work to make them better. Their theorizing should lead them to experimentation, whereas hands-on experimentation leading to theorizing, although it does happen in real science, is more a pipe-dream of learning-by-doing enthusiasts than something that can be expected to motivate inquiry in the classroom. Building and improving explanations means working *within* a discipline, not just carrying out some of the visible practices of researchers and applying received ideas to what one observes. Providing support for knowledge creation—what in educational contexts we call Knowledge Building (Bereiter & Scardamalia, 2014)—requires attending seriously to and supporting the knowledge processes through which research programs advance knowledge frontiers. In designing this kind of education, pedagogy cannot be separated from epistemology, as Kirschner would seem to advocate. Instead, the epistemology of the disciplines needs to be extended to encompass the peculiar conditions of disciplinary knowledge production in educational settings.

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