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Readers' Forum

The Scientific Method: Critical yet Misunderstood

It looks as though there is indeed a single, scientific method, not in the sense of a method that scientists necessarily use exclusively in their day-to-day work, but in the sense of a method, or general plan, that is at the core of most science and that guides, or should guide, the work of scientists and the way science progresses. In this piece I will overview the scientific method, provide evidence that many science educators and curriculum materials appear to lack a knowledge and/or understanding of it, and consider how a more explicit use of the scientific method would improve both science education research and learning in science classrooms.

The scientific method. To ask whether or not there is a scientific method is confusing, because the answer can be yes or no, depending on how the term *method* is defined. Harwood (2004) interviewed over 50 research scientists, representing a broad range of fields, to find that, as they went about their work, they engaged mainly in as many of the following 10 activities, and in whatever order (including using a particular activity more than once), as was needed: Asking questions, observing, defining the problem, forming the question, investigating the known, articulating the expectation, carrying out the study, examining the results, reflecting on the findings, and communicating with others. This multiplicity of approaches taken by scientists is echoed by Bell, Blair, Crawford, and Lederman (2003): "There is no single prescribed set of procedures that all scientists follow when conducting investigations. Rather, scientists use a variety of methods and approaches when conducting research" (p. 497).

However, upon analyzing the work of scientists more closely, it appears that their efforts do, at the same time and in the main, either follow a more general plan or contribute to this plan, even if the scientists themselves might not realize it. In this more general sense, then, there does appear to be a scientific method, a method that is also referred to as the hypothetico-deductive (HD) approach (Lawson, 2000, 2005, 2010a, 2010b). The steps in the HD approach are as follows:

1. A **puzzling observation** is made. An observation is particularly puzzling if it contradicts the predictions of current understanding.

2. A **causal question** about the observation is asked (i.e., why does this happen?). A causal question may even be the result of a descriptive study (i.e., a study void of hypothesis generation). Rather than following from a puzzling observation, a causal question may also be derived from a theory.

3. A **hypothesis** (i.e., a proposed explanation) is advanced to answer the causal question. The making of such an inference is called abduction, because one's store of declarative knowledge, which includes analogies with already-explained observations, is being used (i.e., being abducted, stolen, or transferred). Alternatively, rather than originating from a puzzling observation, a hypothesis in the HD process may stem from one or more existing theories. A second type of inference being used here, and one that happens

subconsciously, is that of retroduction, whereby one checks that the proposed explanation explains what is already known (i.e., the puzzling observation).

4. A **prediction** is generated from this hypothesis, based on the assumption that the hypothesis is correct (this represents the inference of deduction), and a **test** is designed and conducted to check on the prediction.

5. The results of the test are compared with the prediction from the hypothesis and a **conclusion** is made as to whether the results of the test support or contradict the hypothesis. If the latter is the case, and the deduction and test appear to be sound, there is the need to return to Step 3 and propose a modified, or new, hypothesis. This drawing of a conclusion represents the inference of induction, but not induction in the sense of enumerative induction that some have claimed generates general conclusions from limited cases (i.e., reasoning from observed particulars to general statements, or "laws," or hypotheses), a reasoning process that probably doesn't exist (Lawson, 2005; Popper, 1965). At best, enumerative induction might suggest a descriptive claim that is in need of deductive testing (Lawson, 2010a).

It might be noted that support for a hypothesis from such a test does not prove the hypothesis correct, because a different hypothesis may make the same prediction. However, the HD process is cyclic in the sense that a hypothesis can be subjected to further and further testing in this same way, and the more a hypothesis, or explanation, stands up to continued testing the more confidence we gain in it.

The heart of the HD approach, then, is the generation and testing of hypotheses, a process that is also really quite intuitive and common sense, even though we may often use it implicitly without being conscious of the fact. It follows an "If...and…then…And/but…Therefore…" (or, for brevity, "If/then/therefore") pattern of reasoning; that is, in trying to answer a causal question, we reason along the lines of "if this hypothesis (i.e., explanation) is correct, and we do this planned test, then we should get this result (i.e., the prediction). And/but when we do the test we get these results (results that may be circumstantial, correlational, or experimental [Lawson, 2000]). Therefore, we can reach this conclusion about the hypothesis."

Misunderstanding and misuse. Curriculum materials, teachers, and science education researchers often confuse the term hypothesis (or hypothesized) with the term prediction (or predicted), inappropriately using the former to mean the latter, as exemplified by the following:

- A hypothesis is "a sentence describing what you think your experiment should demonstrate" (Hsu, 2005, p. 9).
- "A hypothesis is a statement about data expectations" (DeSantis, 2009, p. 20).
- A hypothesis is an "educated guess or prediction that can be tested about how a scientific investigation or experiment will turn out" (Center for Gifted Education, cited in Kim, Bland, & Chandler, 2009, pp. 41-42).
- "A hypothesis is a prediction of the effect that changes in the independent variable will have on the dependent variable" (Cothron, Giese, Rezba, 2006, p. 45).
- "A hypothesis is a prediction with an explanation" (Davis & Coskie, 2009, p. 58).
- "Hypothesis: There is a negative relationship between the incidence of cosmic rays and the thickness of the ozone layer" (Brouwer et al., 2009, p. 495).
- "We hypothesized that open inquiry students . . . will outperform students who experienced guided inquiry" (Sadeh & Zion, 2009, p. 1137).

- "Our hypotheses are: (a) that explicit teaching of MSK (meta-strategic knowledge) in an authentic setting will have a positive effect on students' performance regarding both DRQ (define research questions) and FRH (formulate research hypotheses) thinking strategies; (b) that this effect will be preserved in delayed transfer tasks; and (c) that LA (low achieving) students will benefit from treatment more than HA (high achieving) students (Ben-David & Zohar, 2009, p. 1662).

Indeed, even scientists get it wrong. For example, virtually all contemporary biological research incorrectly claims to test hypotheses, when in fact the research describes patterns rather than testing mechanisms underlying the patterns (McPherson, 2001). Science revolves around the answering of causal questions, and by misrepresenting the scientific (HD) method in such ways, we lose the logic of generating and testing hypotheses that is central to this scientific task.

Improving science education research. Carey and Smith (1993) posit that there are three levels of science epistemologies:

1. Descriptive (i.e., does not involve the generation of hypotheses).
2. Hypothesis generation and test (where knowledge comprises well-supported hypotheses).
3. Theory driven (i.e., theories are generated and their postulates tested, and theories are used to generate specific hypotheses that are tested).

Applying this to, and for the betterment of, the field of science education, science education researchers have a way to go in desirably progressing the field towards Level 3 (Lawson, 2010b). While much research in science education is at the descriptive level, it is common for researchers working at a higher level and who do understand the scientific method to generate and test hypotheses in a largely implicit way. The more conscious and explicit use of the scientific (HD) method by science education researchers would result in vastly improved research efforts and reports (Lawson, 2010a). Where applicable, research reports should be structured so as to make hypothesis (or hypotheses), prediction, test (outcome), and conclusion clear.

To provide an example of improving science education research, consider a descriptive study that uses interviews and surveys, for example, to determine students' reasons for leaving a course of study. Often, such a study will summarize the reasons provided by subjects, present this summary in the form of conclusions, and end with a consideration of implications of the study, but Anton Lawson (personal communication, February 10, 2010) views this as being insufficient. Rather, he suggests the data collected from subjects in the form of reasons for leaving the course are better viewed as hypotheses for testing, in the HD way, using appropriate interventions. However, perhaps it is here that we run into an obstacle with science education research that may at least help explain why progress towards a Level 3 epistemology in the field has been somewhat slow; it can be very much more difficult to implement interventions with real people and/or in real classrooms, and especially if the testing requires a longitudinal component, than to simply manipulate variables on command in a science proper investigation.

Improving classroom learning. Since the scientific (HD) method is at the core of how science progresses, a more explicit and more often use of it in science classrooms would impact positively on the development of scientific literacy. Let's consider how this might be accomplished.

Learning science in a school is a very different context from practicing science research proper, and one difference is that student investigations in school subjects are often conceived rather artificially. Considering the possibilities, I cannot imagine a worse way to introduce students to a scientific investigation than to have them turn the page of their textbook to find an investigation title--and a rather non-informative one at that, such as “Let’s Make a Splash”--for a stand-alone activity (i.e., one that is not integrated into a learning sequence in the text) that is accompanied by a series of steps to be followed “blindly” by students, and was very surprised to find just this structure in a relatively recently-published textbook for lower high school students. The students are expected to follow the “cookbook” without even knowing what they are trying to cook, which hardly appears motivating.

Improving on this, one might provide students with a title, aim, and procedure, which now provides students with some sense of purpose. Better still, though, the activity can be made more authentic by providing a question instead of an aim. Now, here comes a crucial moment. Questions can be causal or non-causal, and a non-causal question, such as “is there a relationship between the incidence of cosmic rays on the surface of the Earth and the thickness of the ozone layer?” does not require a hypothesis to be generated, because there is nothing to explain. Non-causal questions like this one, “what types of structures does a flower have,” and “does eating spicy food cause your body temperature to rise” have a place in science education, but answering them does not require the scientific (HD) approach.

To provide students with experience in using the scientific (HD) method, then, we need causal questions (either supplied to students or generated by the students themselves) for them to investigate, and these might arise naturally during a course or be “engineered” by the teacher. For example, following from everyday experience students might be asked: “Why does a basketball go flat when used outdoors in winter?” Indeed, a teacher can even engineer a situation so as to change a non-causal question into a causal one. For example, instead of asking “what local climate changes are associated with El Niño,” students might investigate the question “why does our local climate change?” by testing, possibly among others, the hypothesis that local climate changes are caused by El Niño. Or, instead of asking “is there a relationship between the incidence of cosmic rays on the surface of the Earth and the thickness of the ozone layer?” students might be asked to investigate: “What causes the incidence of cosmic rays on the surface of the Earth to vary?” In this case, students would be invited to generate hypotheses (with even the teacher suggesting one or more if it helps to achieve the goals of the learning experience), one of which might be that a thicker ozone layer prevents more cosmic rays from reaching the Earth’s surface. Students would devise a way to collect appropriate data and find that a decrease in the thickness of the ozone layer is indeed associated with an increase in the incidence of cosmic rays, concluding that their results support the hypothesis. The student lab reports, featuring hypothesis, prediction, test (outcome), and conclusion, would then reflect one complete hypothetico-deductive cycle or argument. Of course, the alternative hypothesis that an increase in cosmic ray incidence degrades the ozone layer and thereby allows more cosmic rays to reach the surface would also be supported by the evidence (illustrating how support for a hypothesis does not prove it correct), and the need for further research to distinguish between these two explanations could also appear in the reports.

Comparing the different ways in which a non-causal question and a causal question need to be investigated, it is now perhaps easy to understand why so many curriculum materials incorrectly label the prediction of, or guess about, the answer to a non-causal question a hypothesis. As David Rudel wrote: “There is a push today to get students to use the scientific method as much as possible. If a textbook says a hypothesis is merely a guess as to what will occur in a given experiment, the procedure can be applied [albeit incorrectly] to almost anything the student is asked to study” (personal communication, May 25, 2010). Perhaps only after establishing such confusion does a statement such as “the first thing scientists do to conduct an experiment is to form a hypothesis" (Kim, Bland, & Chandler, 2009) make sense! Finally, perhaps another mechanism for providing students with experience with the scientific method is to structure even lectures on it.

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