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Until science teachers are able to view scientific inquiry as part of the content of science—and until teachers become well grounded in the history and philosophy of science—they cannot be educated to teach science as inquiry. So says the author of this thoughtful article.

The Role of Inquiry in Science Teaching

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Inquiry and Content

When it comes to the teaching of science it is perfectly clear where we, as science teachers, science educators, or scientists, stand: we are unalterably opposed to the rote memorization of the mere facts and minutiae of science. By contrast, we stand foursquare for the teaching of the scientific method, critical thinking, the scientific attitude, the problem-solving approach, the discovery method, and, of special interest here, the inquiry method. In brief, we appear to agree upon the need to teach science as process or method rather than as content.

Judging, however, by what we can see taking place in many, if not most, classrooms and by the kinds of tests that teachers use, we might reasonably conclude that there is a large gap between our practices and our convictions. This may well be the result of many factors—the natural conservatism of science teachers, a failure of those who call for change and innovation to provide teachers with effective models and materials, and others. *One* of the contributing factors, it seems clear, has been a failure to recognize and take fully into account the close organic connection between process and content in science. It is here suggested that the effective teaching of the physical sciences as inquiry becomes possible in a particular and important sense once we understand that the conclusions of science are closely linked with the inquiry which produced them, and, conversely, that the nature of a given inquiry depends upon the topic under investigation. The choice is *neither* facts and laws *nor* inquiry and process; it is *both* facts and laws *and* inquiry and process.

Inquiry as Content

First, the designation "teaching science as inquiry" needs some clarification. It is currently being used in at least two general ways. Sometimes it is employed in a way which emphasizes that inquiry is really part of the science content itself. It acknowledges that there is a pattern of inquiry characteristic of a given science, or of a given field within a science, and that such patterns form an integral part of what science "is." At other times, the phrase "teaching science as inquiry" is used to refer to a particular technique or strategy for bringing about learning of some particular science content. This is the meaning associated with the term "inquiry *method*." The distinction here is between "inquiry as it appears in the scientific enterprise," on the one hand, and "using the method of scientific inquiry to learn some science," on the other. For purposes of brevity, I shall refer to the former as *inquiry as content* and to the latter as *inquiry as technique*.

One other matter of semantics needs attention: whether speaking of inquiry as content or inquiry as pedagogic technique, the modifier "scientific" is implied. It is *scientific* inquiry we are concerned with, not inquiry in general. Otherwise, if all that is intended by the inquiry method is that we should encourage a student to be inquisitive, curious, to ask questions, and to try to find answers for himself, then we are advocating no more than what good teachers have long believed in and practiced. Thus we must keep in mind that it is scientific inquiry that is being offered by some people as a paradigm on which to base a teaching strategy.

As a basis for discussion, two topics which might seem to lend themselves to the teaching of science as inquiry have been selected from the subject matter of physics. An examination of these two quite different cases gives substance to the following conclusions:

(*1*) It is possible to gain a worthwhile understanding of science as inquiry once we recognize the necessity for considering inquiry as content, and operate on the premise that the concepts of science are properly understood *only* in the context of how they were arrived at and of what further inquiry they initiated.

(*2*) As a corollary, it follows that it is possible to learn something of science as inquiry without the learning process itself having to follow precisely any one of the methods of inquiry used in science. That is, inquiry as technique is not absolutely necessary to an understanding of inquiry as content.

(*3*) While the laboratory can be used to provide the student experience with and knowledge of some aspects or components of the investigative techniques employed in a given science, it can effectively do so only after the *content* of the experiments have been carefully analyzed for their usefulness in this regard.

Universal Gravitation as an Example Emphasizing Content

The two examples to be used are those of universal gravitation and the law of reflection of light from surfaces. These topics are covered in all physics courses and in most physical science or general science courses. Let us turn first to the law of universal gravitation.

Science teachers surely wish to help each of their students acquire an "understanding" of universal gravitation. But when can they be satisfied that a student does in fact understand that concept? One cannot, of course, draw an absolute boundary between complete understanding and no understanding. Nevertheless, with a concept of the magnitude of universal gravitation, it seems reasonable that at least two conditions should be fulfilled before we could assume a student has acquired an acceptable understanding. The first is that the student become aware of the *range* of applicability of the theory. The second is that he have some knowledge of the network of inquiry, the sequence of investigations and thought, which led to the final formulation by Newton. Certainly we would all agree that the student does not understand universal gravitation just because he can recite the equation $F = G\ m_1m_2/r^2$ and work simple problems using it.

As far as the range of the law of universal gravitation is concerned, the first step is to bring the student to an awareness of its magnificent successes. The brilliant way in which the Newtonian principle of universal gravitation explains so many diverse terrestrial and celestial phenomena—comets, tides, procession of the equinoxes, and geographical variations of g—and in which it was able to predict other phenomena—the existence of undiscovered planets being, of course, the most spectacular instance—are really part of the content of the concept itself. So in fact are the additional investigations which it instigated. In examining a wide array of phenomena to find out just how *universal* universal gravitation is and in studying the relationship between that formulation and the new inquiries stemming from it, the student will come to see that Newtonian mechanics does indeed have limitations. The interesting point for our purposes is not so much that relativistic and quantum mechanics were ultimately needed, but that the long series of investigations stimulated in great part by Newton's formulation of universal gravitation itself led to the kind of knowledge which would expose its own limitations. Thus in studying universal gravitation in the context just described, the student may gain the insight that an important attribute of scientific theory is that it generates new investigations even if in doing so its own conceptual weaknesses are mercilessly exposed. A good theory stems from successful inquiry and generates additional ones.

Turning to the other condition for "understanding," it has been claimed here that an acceptable understanding of the concept of universal gravitation implies a knowledge of the network of inquiry which led to it. The discovery, or the "invention," to use the terminology of Atkin and Karplus,[1] of universal gravitation was the outcome of inquiry on the grand scale, involving, as it did, the investigations and insights of many people in many places over a substantial span of time. The giants upon whose shoulders Newton admitted standing were practitioners of the art of inquiry into the nature of the physical world. Each practiced his art in his own characteristic way. No one of them can serve as the perfect model of how a contemporary investigator should proceed, but their work taken as a whole illuminates beautifully many facets of the scientific enterprise. If one wishes to study science as process, it is surely wiser to look at the work of several scientists in the context of a significant scientific problem than to concentrate upon the work of a single scientist or to settle for some abstract formulation of inquiry divorced from science content. By noting the contributions and modes of operation of the men whose work led to the law of universal gravitation, the student learns his science as both content and inquiry.

If one looks upon the concept of universal gravitation as the culmination of a long series of investigations and the beginning of still another series, then a variety of insights on the complex nature of scientific inquiry may accrue. For purposes of illustration, only a few of these are cited:

(*1*) The power of indirect experimentation is dramatically demonstrated by Galileo's work with the pendulum and the inclined plane. Incidentally, the approach recognizes that these instruments have their main interest as experimental equipment rather than as objects to be understood for their own sake.

(*2*) The importance of being able to formulate experiments and ideas in the language of mathematics is shown in the work of Galileo, Kepler, and Newton himself.

(*3*) Both the necessity for and the limitation of accurate data in scientific inquiry are brought out by the use made of Tycho Brahe's magnificently precise planetary observations. In the hands of Kepler they played a key role in the overthrow of the two thousand year old conceptual reliance upon uniform circular motion. But these same facts were unable to lead Tycho himself to a correct interpretation, and indeed we know now that facts alone are never enough to provide us with understanding of nature.

(*4*) Kepler's speculations, fanciful and sometimes even bizarre, but always in the end put to the test of measured fact, present another facet of inquiry. Furthermore, the use of Kepler's laws made by Newton allows one to emphasize the difference between empirical laws and explanatory laws or principles, and the importance of one to the other.

(*5*) The significance of physical and metaphysical preconceptions in shaping a scientific investigation is illustrated by the reluctance of Copernicus, no less than Ptolemy, to abandon uniform circular motion.

One could add many more items to this list. But perhaps the point has been made: to understand the concept of universal gravitation, it is important that the student be made familiar with the key experimental and theoretical inquiries (and their interactions) which ultimately were synthesized by Newton so succinctly in a single equation.[2]

Now surely no one would advocate that

the student be brought to this kind of an understanding by conducting his own investigations, that is, by the application of inquiry as technique. Anyone tempted to do so should reconsider the strong arguments put forward by Gagné.[3] But this is not to discourage the teaching of physics as inquiry; instead it is to suggest that if the nature of scientific inquiry is taken to be an integral part of the subject matter itself, then neither the conclusions of science (the facts, laws, principles, theories, conceptual schemes, etc.) nor the process of discovery and investigation which lead to those conclusions will be neglected. Content and inquiry will appear as the warp and woof of a single fabric, which is, after all, the way science really is.

Light Reflection as an Example Emphasizing Procedure

Let us turn now to the second example, that of the law of reflection. Here is a relatively small topic upon which the student might be expected to conduct an investigation, that is, to learn about scientific inquiry at first hand rather than vicariously. At least that would seem so judging by the number of classrooms in high school and elementary school in which students "discover" the law of reflection. Typically, the student is given a plane mirror, some pins, a protractor, a straight edge, and instructions on how to locate the path of incoming and reflected light rays. He is then asked to find the relationship between the angle of incidence and the angle of reflection (after, of course, these have been defined for him). A little thought, however, suggests that whatever other value such an "experiment" may have, it has little merit as an honest exercise in scientific inquiry, even assuming that the student is not told the answer ahead of time. The following few points are offered merely to add substance to this claim. Any effort to devise a laboratory procedure which will enlarge the student's investigative skills while discovering the law of reflection must, surely, take these and similar criticisms into account:

(*1*) The concept of "light ray" is a fairly abstract one. In fact, as used in such experiments, a light ray is fictitious: its virtue is that it provides a useful way to talk about certain optical phenomena, in this case the regularity of image reflection. It is the invention of the light-ray as the physical analogue of the Euclidian straight line, and the related acceptance of the correspondence between plane geometry and optical phenomena (rather than the discovery of the rule of equal angles), that was the key step here.[4] This suggests, at the very least, a prior need for the student to consider evidence for the rectilinear propagation of light, and for working out an operational definition of "light ray."

(*2*) But if we admit that the student cannot uncover such an abstract notion by his own inquiry, that is not to say all is lost. We might claim, with Atkin and Karplus, that after the teacher has supplied the invention, the student can then investigate, *i.e.*, discover, some of its consequences. That is, fortified with the idea of "light ray" the student might be asked to find out how it could be used to explain reflection from mirrors. Perhaps so, but not, certainly, if the student is provided all of the apparatus right at the beginning, as is the usual case. To do so reduces the "experiment" to a mere puzzle, for it excludes the student from participation in the development of the experimental strategy to be employed in the investigation. For instance, just the fact that the student is provided only with a plane mirror limits severely the scope of the inquiry. Reflection takes place, after all, from spherical and parabolic surfaces, not to say irregular ones. One of the important techniques used in scientific inquiry is to seek out the simplest useable instance of a phenomenon for preliminary investigation. As the reflection experiment is commonly done students are bound to miss this point. A better strategy, better in the sense of having a more meaningful connection with the substantive content, would be to provide students an opportunity to observe reflection from an array of mirrors of different shapes, and then to require them to participate in working out some of the details of the experiment, including which kind of a mirror to use.

(3) The angles of incidence and reflection are defined for the student, and in a way that would not seem natural to him. The measurement of those angles with reference to the normal to the surface rather than to the surface itself is not self-evident. It is a matter of convention, the usefulness of which has to do primarily with Snell's law of refraction, and not with reflection from plane surfaces at all. The way this experiment is usually handled, however, deprives the student of an opportunity to learn that while definitions of physical quantities are arbitrary, consideration must be made of their likely usefulness in carrying out further investigations.

These few remarks concerning the laboratory investigation of the reflection of light are intended to indicate that even when one examines a relatively simple topic, it is not immediately and unequivocally clear just how it should be presented to the student so that it will contribute to the goal of teaching science as inquiry. Certainly this and other topics *can* so contribute, but not until each has been carefully analyzed from the standpoint of its relationship to the body of physical knowledge from which it is extracted. Only after such an analysis has been made can we possibly know which facts, definitions, presumptions, principles, and relationships are involved. At that point some investigation must be made as to which of these aspects of the topic particularly lend themselves to teaching by the method of inquiry. Thus there are two interrelated tasks to be accomplished. First, an analytical study needs to be made (from the standpoint of science as inquiry) of each of the usual topics encountered in introductory courses in the physical sciences. Second, some number of laboratory oriented experiences need to be devised which can contribute to the understanding of the nature of scientific inquiry *as it actually happens.*

Conclusion

In all of this discussion, whether dealing with the monumental concept of universal gravitation or the more modest one of light reflection, the emphasis has been on viewing scientific inquiry as part of the content of science itself. To separate conceptually scientific content from scientific inquiry is to make it highly probable that the student will properly understand neither. From this there follows an inescapable conclusion regarding the feasibility of teaching science as inquiry: science teachers must come to understand just how inquiry is in fact conducted in the sciences. Until science teachers have acquired a rather thorough grounding in the history and philosophy of the sciences they teach, this kind of understanding will elude them, in which event not much progress toward the teaching of science as inquiry can be expected.

References

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