The Nature of Science in Science Education

Rationales and Strategies

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10. A HISTORY OF SCIENCE APPROACH TO THE NATURE OF SCIENCE: LEARNING SCIENCE BY REDISCOVERING IT

My interest in teaching the nature of science came from attempts to integrate history into physics courses for teachers at the Bakken Library and Museum beginning in 1985. My background in the history of science and in teaching physics appeared ideal for helping teachers transform the science of facts and equations they typically teach into science as a human activity. Michael Matthews labels this a distinction between "technical" and "liberal" science. The trouble was that many course participants had degrees in biology or chemistry, and were unfamiliar even with "technical physics." Having no foundation to build on, I choose to teach both, and the question was how to do it.

By that time, I had already been convinced that physics could be taught to all students by shifting the emphasis from the memorization of facts to developing skills of thinking, reasoning, and systematic purposeful work by students. I decided to try investigative laboratory experiments as one of the main vehicles for achieving this purpose. Teachers conducted experiments in groups and individually. When they brought the new labs to their schools, they appealed to the majority of students and raised their interest in learning science. The peculiar feature of these laboratory activities was that many of them recreated historical experiments.

The idea of reproducing historical experiments in the classroom came from Devons and Hartmann (1970). I could have achieved my goal with other experiments as well, but I wanted to use history as much as possible, and the historical experiments did have an advantage over the "real-life investigations" practiced by some teachers, such as finding the cause of the clogged classroom sink or determining which paper towel is most absorbent. First, with the historical approach, the result is always known to the instructor, which is not the case with the sink and towels. Second, a historical experiment can be chosen so as to help teach a narrow scientific topic, while most real-life phenomena are too complex and complicated for students' study. Third, for the first two reasons, the students' chances to succeed are higher with the historical experiments than with the other ones. Finally, a success in repeating a historical scientific discovery may boost students' self-confidence much more than in fixing the plumbing. It is not that technological problems are unusable; if carefully chosen, they are. However, it is easier to learn the necessary investigative skills in historical scientific experiments and then use them to tackle the frequently more complicated problems in technology.

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Soon, it became clear that with all its advantages, the historical approach brings to the forefront very difficult questions of science usually suppressed in textbooks, such as the changeability of theories, the meaning of experimental support and its application in selecting one of several competing theories, and others. Some teachers came up with such questions on their own, while others recalled similar challenges from their brighter students, who having found out from popular science books and television programs that theories come and go concluded that scientific knowledge is of no real value. Teachers realized a necessity in answering those questions, but they did not know how to do so.

Thus, I realized that in the environment that emphasizes thinking and usage of history, teachers had no choice but to address basic issues of the nature of science, and they must be taught how to do it. Teachers certainly could have benefitted from proper philosophy of science courses (Matthews, 1990; McComas, 1995), but I expected them to obtain such training elsewhere. On my part, I tried a more practical approach that could be complementary to theoretical courses: to bring up the issues of the nature of science from within the science, in particular when engaging teachers into "doing science." This chapter will give an example of such an activity and the way it addressed the questions related to the scientific method[1].

THE NATURE OF SCIENCE: A HISTORICAL APPROACH

The historical approach in science teaching has had several periods of popularity. In the late 1950s, James Conant suggested that all necessary knowledge of the nature of science could be gained from studying a few historical cases. The cases must come from the "old" science (usually, this means scientific ideas from the 17-19th centuries), for only the old science can allow a nonspecialist a sufficiently good grasp of the subject matter (Conant, 1959).

While Conant's cases were written for universities, several authors incorporated his idea into the secondary school curriculum, some explicitly and others implicitly. At one extreme, the nature of science was advocated as a separate instructional element, the understanding of which is emphasized more strongly than that of the science content involved (Klopfer, 1961, 1992). In Klopfer's scheme, student booklets, prepared for each case, contain excerpts from primary sources alternated with the author's narrative, and also questions directing students' attention to various aspects of science as described in the text. Blank spaces are provided for student to write answers to these questions. Some of the questions refer to various aspects of the nature of science (Klopfer, 1964). The idea of using original historical materials

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[1] The term "scientific method" used here means the *common* features of research strategies applied by scientists in modern times that we want students to learn.

together with questions to answer was appealing, however, I found its practical realization unsatisfactory. While some historical experiments were included, their purpose was largely illustrative. Most important, I did not believe that "nature of science" can survive in the secondary school as a separate subject.

At the other extreme, history was used solely to aid in learning scientific concepts, and if students were expected to draw conclusions about science and scientists, they had to do this on their own, using historical examples incorporated in the text (Rutherford et al., 1964). There were also attempts to provide a middle ground between these two extremes by balancing the study of nature of science with that of scientific concepts, or using inquiry as a vehicle for learning science (Schwab, 1964). The general approach is appealing, but the role of a historical element in it is rather limited. In general, Schwab's approach appears sound, but the historical element in it plays only a casual role, if any. For instance, although Galileo's name is mentioned, students' experiments with pendulums have nothing to do with the historical ones.

After a period of neglect, historical approaches reappeared in the 1980s, with the emphasis on evaluating case studies, role playing and doing historical reading. Some issues of the nature of science come up when students discuss historical accounts in the class (Lochhead & Dufresne, 1989). Unfortunately, while the role-playing activities will be of some interest to all students, only those few who are actively involved as panelists or actors will get the full intellectual benefit from these activities, because only they had done all the reading. For the majority of students, a better way to integrate the historical element would be to recreate history in action rather than on stage. Some historical experiments have already found their way into teachers' education (Devons & Hartmann, 1970; Teichmann, 1986). My intention was to do it on a more comprehensive basis and to make history an organic component of science.

Learning the Nature of Science While Learning Science

Although teachers report that they like learning about the history of science, they fell that it is unlikely that they will pass much of that knowledge on their students, because they have no time for any "extra" units, such as those devoted specifically to the history and nature of science. For this reason, I subordinated the discussion of historical and philosophical issues of science to learning scientific concepts superimposing them so as to make them inseparable. The topics of units are the same as in regular science courses, such as "electrical conductors and nonconductors," and the goal is the same: to formulate the laws of phenomena. The difference is in the ways the unit is taught.

History and the nature of science are involved in three areas. The first concerns the way a new scientific concept is introduced. I have found that understanding of a concept improves if it is "rediscovered" with active participation on the part of the learner. Usually, it begins with the instructor's demonstration of a relevant historical experiment, for instance, the first experiment of Stephen Gray[2]. After a short discussion, students begin repeating and modifying this experiment following a certain plan (see Table I). The instructor stops students every 10-15 minutes to discuss the intermediate results. If some groups differ in their results, this particular experiment is repeated until a consensus is established. After the final conclusion is formed, the instructor informs students of Gray's subsequent procedures and results, and the participants can compare how closely they came to the scientist. Although technically the experiments are simple, it is not easy to draw a conclusion from them, because it involves introducing a new concept of conductivity (Kipnis, 1996). Thus, students get a lesson about a possibility of various interpretations of experimental results (including the erroneous ones) and a difficulty of making the best general conclusion (it was not Gray who introduced the general concept of "conductors and "nonconductors").

If pedagogically advisable, the chain of "rediscoveries" follows historical events. This is the case with static electricity, for instance, which led some teachers to replace their whole static electricity unit with the one developed at The Bakken (Bakken, 1995). However, occasionally, history defies what we call "common sense," as with the case of interference of water waves being discovered after interference of light. In such cases, I prefer to sequence instruction in ways that students will find easier to grasp. Later, we discuss that scientific developments are not always "logical" and may be very convoluted.

The second area concerns the type of experiment used. I emphasize investigative experiments which require students to imitate scientists rather than use artificial or contrived experiments. In another lesson from history we see that since much of physics remained a qualitative science up to the middle of the nineteenth century, an obsession with measurements in high-school physics appears unjustified. Thus, I began to emphasize qualitative experiments where students study a certain phenomenon to find a qualitative empirical law to describe it (Kipnis, 1995). The result is considered "true" if obtained by all groups. These experiments are preceded and followed with theoretical discussions in such a way as to "recreate" an introduction into science of a new physical concept (potential, for instance) or a law (such as the relationship between potential and capacitance) (Kipnis, 1992, 1996). The investigation is, to a certain extent, guided by the teacher. However, since students have some freedom of action, we can consider this imitation of the work of

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[2] In 1731, the English physicist Stephen Gray observed, while rubbing a glass tube corked at the ends, that not only glass attracted a feather, but so did the cork. Gray supposed that electricity produced in glass by rubbing somehow moved to the cork. When he inserted a nail in the cork, electricity reached the nail too. Through his work with long "communicating lines," Gray discovered the concept of "conductors" and "non-conductors."

scientists sufficient to give students a taste of the problems scientists face. By making students "discoverers" we achieve two objectives. First, we remove some of the "mystery" from science by showing it to be a professional activity that requires certain skills, and that everyone with necessary skills and motivation can discover something new and useful. Involving history has additional advantages. Seeing that they are capable of repeating on their own certain important steps of famous scientists or deciding who was right in a scientific dispute (Lawrenz & Kipnis, 1990) gives students a tremendous boost to their self-confidence. Second, they will see how easy it is to choose an incorrect direction of research, how difficult it is to invent a good procedure, and how easy it is to reach a false conclusion. Students will realize that while not everyone can become Newton or Volta, everyone can discover something. This will teach them a proper appreciation of great discoveries of the past, on the one hand, and a habit of critically analyzing information about modern discoveries, on the other.

The third area deals with the strategy of experimenting. The one discussed here is distilled from scientific treatises of the past (Table I). The strategy consists of two stages: Preliminary and Main Parts. The Preliminary Part is the one with which teachers are least familiar. It comprises the origin of the problem and initial experiments, which do not follow any plan but aim at discovering a few plausible variables and a reliable experimental procedure. The problem with the widely spread method of doing open- ended experiments is that usually a teacher solicits students' suggestions about the variables to study after they observe a single demonstration. Having received a considerable number of ideas, the teacher asks each group to investigate a different variable, with the idea that all these partial results can be combined at the end into a general one. One problem with this approach is that bringing variables "out of the blue" is inefficient. In our case, students do a sufficient number of modifications of the original experiments until they can say which changes appear to affect the result, and select the corresponding parameters as variables. Also, only the most obvious two or three variables are selected for the further examination in the Main Part, which allows all groups to study all variables eliminating a possibility of false results due to poor statistics.

The Main Part is the planned stage of an investigation (Table I). Each variable is examined while keeping the rest constant, and this examination follows a certain plan identical for all variables. We start with preliminary experiments which result in a certain hypothesis about the way this variable affects the phenomenon. Although students may have some idea of this hypothesis from the Preliminary Part, this knowledge is not definite, for in some initial experiments several variables are changed at a time. Unlike those, the preliminary experiments are "clean," for everything but one variable remains constant. To advance a hypothesis even two experiments may be enough. But to test it more experiments are needed, and they must be different from the preliminary ones. If the test shows that the hypothesis is false, we do additional experiments and suggest another hypothesis. Finally, we summarize all conclusions about separate variables and formulate a law or a rule. While studying each subsequent variable we use the results about the variables previously examined. Thus, it makes sense to insist that all groups investigate the variables in the same order, at least, during the period when students learn how to investigate and need more assistance.

It must be noted that teachers cannot have too many full-scale investigations with 2-3 variables, similar to the one in the example, because they take from one to three hours and require a careful preparation on the teachers' part. For this reason, teachers supplement them with a greater number of shorter experiments (10-20 minutes each), which deal only with a single variable.

TABLE I

A strategy for investigation

I. PRELIMINARY PART

1. Background (origin of the problem)
2. Initial observations and experiments
3. Formulating a problem
4. Selecting variables
5. Selecting a procedure

II. MAIN PART

Variable 1
  a. Preliminary experiments
  b. Hypothesis
  c. Test
  d. Conclusion

Variable 2
  a. Preliminary experiments
  b. Hypothesis
  c. Test
  d. Conclusion

Additional Variables

General Conclusion Formation

An Example of the Strategy in Action: Does Light Travel Along a Straight Line?

Some features of this technique are illustrated in the following example. In this context, "student" can refer to any learner, while "teacher" can be either a university instructor or a secondary school teacher who knows this strategy. The description of the experiment is a hypothetical student report which follows the plan illustrated in Table I, in which several possible answers imitate results from different groups. In an actual experimental report, a student can use the same format writing in the the blank space under relevant headings.

The law of rectilinear propagation of light is one of many that may be "rediscovered" during a unit on optics and vision. This example is based on the book for teachers *Rediscovering Optics* (Kipnis, 1992), and the following discussion includes excerpts from it. This study is recommended for secondary students (12-18 years of age), although its modified version is quite applicable for those in upper primary grades (9-12 years of age). If students have not had geometry, the teacher should familiarize them with the concept of similar figures using models and drawings.

The teacher begins the unit on light with the question: "what conditions are necessary to see a certain object?" Students provide a variety of answers, including: "a healthy eye," "a sufficient amount of light," "the requirement that the line of vision should not be blocked," etc. Subsequently these answers serve to introduce a variety of topics to study, beginning with the eye and the meaning of "vision." During this first lesson the teacher describes some early theories of vision using a combination of lecture and discussion. In particular, in the "extromission" theory, the eye sends out a "fire" which touches an object and receives information of its shape, size, and color (something similar to a radar). According to the "intromission" theory, something (a "mask" or an "image" of the object) detaches itself from its surface and moves toward the eye. When students start smiling at such "naive" ideas, it is useful to challenge them to refute any of these notions. Students will quickly realize that the matter is not as obvious as it may have appeared at first, and the teacher may use this case as an example of an important maxim of science that "obvious is something you have never thought about."

The teacher summarizes that ancient philosophers finally realized they could not resolve the problem of vision in full, and began focusing on some part of it that could be resolved. That was done by Euclid (ca. 300 BC) who ignored what agent is moving between the eye and the object, which direction, and how it interacts with the eye, and paying attention only to the trajectory of the agent's motion. That is how the concept of a *ray* was born. While Euclid was thinking of a *visual ray* coming from the eye, to Ibn al-Haytham (ca. 965-1039 AD) it was a *light ray* coming from the object. Whatever the case, they agreed that the trajectory must be a straight line. The teacher challenges students to prove this experimentally. As illustrated by the following interaction, students will probably come up with the following idea that many teachers use to study reflection and refraction.

> Mary. I would use three pins and a ruler. First, draw a straight line on paper using a ruler and place two pins at its ends. Second, move a third pin between the two until all three appear to coincide. Finally, check whether the third pin is on the same straight line with the others.
>
> Teacher. This sounds like an easy experiment. Let us do it following Mary's instructions. . . . we'll repeat the experiment three times. What are the results?
>
> John. It's true, and all the pins make the same straight line.
>
> Teacher. Incidentally, do you take it for granted that a ruler's edge is straight?
>
> John. No, I can prove it. For instance, if I look along the edge of a ruler and see all its points on a straight line, the edge is straight.
>
> David. Wait a second! We've just proved experimentally that light moves rectilinearly on the basis of the coincidence of the line of vision with the line drawn with a ruler. Now, you are saying that the ruler's edge is straight because it coincides with the line of vision. This is circular reasoning!

Indeed, it appears that the proof is impossible. For this reason, Euclid simply *postulated* that a ray is a straight line. However, to al-Haytham that was not good enough, and he tried to find a physical demonstration.

To test whether the light of a flame spreads rectilinearly, Ibn al-Haytham employed a tube with a pinhole. To extend his proof to the light scattered in the atmosphere, he let light into a room through a one-foot hole into the outer wall and two identical holes in the inner wall. He found that a luminous spot C (Figure 1) on the floor appeared only when this spot and the holes B and A on both walls were on the same straight line as verified by a stretched thread.

Students may say that because the holes are big, points A and B have a large range of movement within each hole, which implies many different lines connecting them and producing different projections C on the floor. Then the teacher suggests another test based on comparing the shape of an object and of its shadow. The idea came from Aristotle (384-322 BC), who claimed to deduce from it that light rays cannot be straight lines. Students may look surprised at this conclusion, and the teacher suggests to investigate whether Aristotle was right. The following excerpt from *Rediscovering Optics* (Kipnis, 1992) describes a hypothetical student's investigation. The discussion is dramatized to present different possible views or results achieved by different groups.

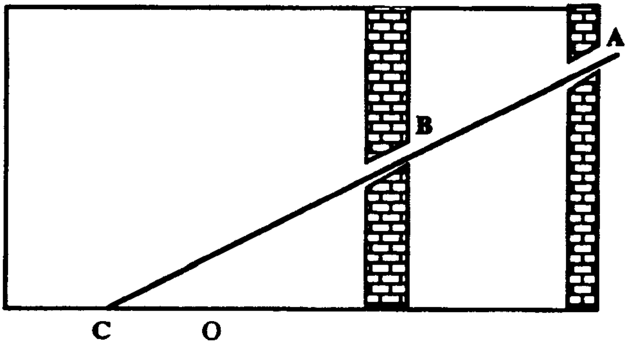

Figure 1. Alhazen's demonstration of the rectilinear propagation of light

As discussed with reference to Table I, the actual investigation consists of two elements, the preliminary part and the main part. Each of these elements has subsections. The lesson begins with a short overview of the previous lesson on vision and a short demonstration by which the teacher introduces the subject for an investigation connecting it with Aristotle's problem -- what should the shadow resemble: the object or the sun?

Teacher. Here I have two holes cut in an index card, one circular and the other rectangular. I will shine light on them from a desk lamp, and you watch their images on a white screen. What do you see?

John: Both images are round. But this is impossible!

Teacher: What would you expect?

John: A circle and a rectangle.

Teacher: That was what Aristotle thought too. He asked:

Why is it that when the sun passes through quadrilaterals [a rectangular grid], as for instance in wickerwork, it does not produce a rectangularly-shaped figure, but one that is circular? Is it because the sun's rays fall in the form of a cone and the base of a cone is a circle, so that no matter what object they fall upon, the rays of the sun must appear circular? For if the rays were straight the figure formed by the sun would necessarily be bounded by straight lines. For when the rays fall straight onto a straight line they do produce a rectilinear figure (Aristotle, *Problems*, 334-5).

Here Aristotle is referring to the geometrical theorem that if the straight lines originating from a single point touch the extremities of a figure, its projection on a parallel plane must be similar to the original (Figure 2).

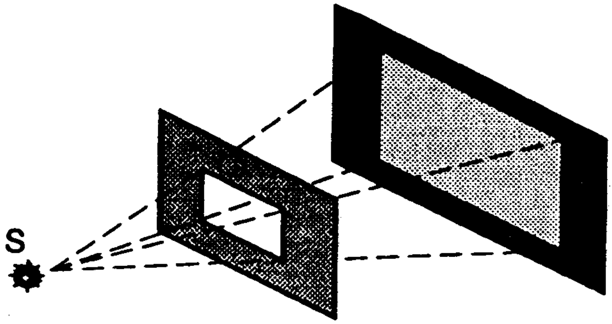

Figure 2. An illustration of Aristotle's argument.

However, having seen a round image instead of a rectangular one made him suggest that perhaps the sun's rays are cones with their apexes on the sun rather than straight lines. While observing a solar eclipse, Aristotle discovered again that the sun's image resembled the sun rather than the opening in a screen:

> Why is it that in an eclipse of the sun, if one looks at it through a sieve, or through the leaves of a broad-leaved tree, or if one joins the fingers of one hand over the fingers of the other, the rays are crescent-shaped where they reach the earth? Is it for the same reason as that when light shines through a rectangular peephole that it appears circular and cone-like? (Aristotle, *Problems*, 341).

The problem raised by Aristotle of why the image made by sunlight passing through an opening is similar to the luminous body and not to the opening, had baffled scientists for almost two thousand years.

Let us investigate this problem with the following simple supplies: index cards, masking tape, razor blade or scissors, paper or cardboard white screen. In each index card make two round holes with a paper-punch and several square holes of different size using a razor blade or by cutting pieces with scissors and pasting them together.

The teacher should explain the significance of each step of this procedure. The Preliminary Part (Table I) begins with background, which shows the origin of the problem, in this case a chance observation by Aristotle. The teacher should emphasize that although scientists do not rely on chance, sometimes they benefit from it. An accidental observation becomes a discovery only when a scientist recognizes something new and unusual.

TABLE II

An illustration of the strategy in action

PRELIMINARY PART OF THE INVESTIGATION

Background

Teacher. We begin this investigation with a problem suggested by Aristotle. The problem is that a rectangular hole produces a round image of the sun? We can repeat Aristotle's experiment by observing an image produced by sunlight passing through a square hole in a cardboard sheet. Incidentally, some 16th century astronomers also became interested in this problem, but their curiosity came not from reading Aristotle but from the needs of their science.

Initial experiments

Ruth. Our group discovered that Aristotle's conclusion is correct only when the screen is far away from the index card. He probably never tried to bring the screen close to the hole, for if he did, he would have seen a square image instead of a round one.

John. Distance is not the only thing that matters. We've found that at the same distance between the screen and the card a large square opening produced a square image, and a small square hole projected a circle.

Formulating a problem

Teacher. We see that Aristotle was only partially right. This finding suggests that we examine a more general problem than his: why does the image produced by sunlight coming through the same opening at some circumstances resemble the sun and at others, the opening?

Selecting variables

Mary. We found that two factors affect the shape of the image: 1) the distance from the hole to the screen, and 2) the size of the hole. These could be our variables.

The next stage (initial experiments) consists of reproducing the phenomenon a number of times to be sure it is real and not spurious. Also, by modifying the experimental conditions, the scientist tries to determine which factors affect the phenomena: these will be selected for further study as "variables." In addition to this, during the initial experiments, the scientist develops a satisfactory experimental procedure. Unlike the Main Part, in the Preliminary Part the experiments are conducted without any plan, and several factors can be changed simultaneously. For this reason, all conclusions made, for instance, about the choice of relevant variables, are tentative. In the Main Part, each variable is studied with other variables kept constant. The study of each variable begins with preliminary experiments, from which students deduce a hypothesis about how this variable changes. This hypothesis is tested by additional experiments. If different groups disagree on the conclusion about a specific variable, they conduct additional experiments until they reach a consensus.

TABLE III
The example continued

MAIN PART OF THE INVESTIGATION

Variable 1: Distance between an Opening and a Screen

Preliminary experiments

David. I would suggest placing the screen in the shadow and moving the index card to and from it.

Ruth. It looks as if all square holes produce square images when close to the screen.

Hypothesis

John. The closer the hole is to the screen, the more the image resembles the opening.

Mary. Why do you call this conclusion a hypothesis? Haven't we just proved it?

Teacher. We compared only two holes of a specific shape (square). Are we sure that holes of other shapes behave in the same way? Do we know that the result will not change if we make the hole either very large or very small? In both cases, the answer is "No." That is why we need additional experiments. The preliminary experiments are necessary to advance a hypothesis, but to prove it one has to perform more experiments and of a somewhat different kind.

Test

Ruth. Let us see how holes of different shape but about the same size behave at different distances. Instead of cutting additional holes we changed the shape of the original openings by covering them partially with tape. In our experiments the images of triangles and rectangles closely resembled the apertures when the screen was no further than 15 cm from the card.

John. We tried parallelograms and trapezoids. In our view, the similarity was preserved for distances up to 20 cm.

Conclusion

The image resembles a middle size opening only when the latter is close to the screen.

Variable 2: The Size of the Opening

Preliminary experiments

John. Let us watch the images of two different squares, first, when the card is close to the screen, and then when the card is far from it. Apparently, in both cases the larger square hole makes a sharper square image.

Hypothesis

Mary. The larger the opening, the closer its picture resembles the original, whatever its distance from the screen.

Test

John. We can check this in two ways: 1) by making the hole much larger and much smaller; 2) by studying openings of other shape (for instance, triangles of different size).

Conclusion

The hypothesis is true, and the conclusion of the previous part is confirmed again. Note: if there is a disagreement among different groups, all groups repeat the experiment at the conditions that produced the "different" result.

General Conclusion Formation

Sunlight reproduces the shape of any given opening only when the screen is close to it. On the other hand, at a sufficiently large distance any opening produces a round image. Perhaps at large distances we obtain the image of the luminous body. This hypothesis can be tested by experimenting with light sources of different shapes.

Again, as in the Preliminary Part, the teacher explains to students the necessity of various steps in the Main Part (see Table 1). In particular, students may argue that they have already obtained the necessary Hypotheses in the Preliminary Part, and thus no more Preliminary Experiments are necessary. The teacher explains that any hypothesis from the Preliminary Part is tentative, because the experiments leading to it were conducted without keeping everything but one variable constant. While the Preliminary Experiments are necessary for formulating a hypothesis, the Test aims at confirming it, which requires experiments different from those used to suggest the hypothesis.

To extend the importance of solving Aristotle's problem, the teacher notes that the rounding-off of the shadow's corners at large distances was not understood until the work of Johannes Kepler (1571-1630). The teacher can provide a geometrical drawing representing Kepler's ideas, which high-school students can follow. Since this drawing is based on straight lines representing light rays, the conclusion is made that Aristotle was mistaken about his phenomenon contradicting the concept of light rays being geometrical straight lines.

Then the teacher discusses with students several points this unit offers about the nature of science. First, we see that even famous scientists can err. If students wonder why they were able to get better results than Aristotle, the teacher may explain that the scientific method of Greek scientists somewhat differed from the modern one. The ancient Greeks were keen observers of phenomena in nature, but their experimentation was sporadic. If instead of limiting his observations to the "natural objects" (the shadow of a fence), Aristotle recreated this phenomenon artificially the way we did, he would have discovered the correct result. Second, we see that solving some problems require a tremendous amount of time (in this case about 2000 years!). Third, the case provides an opportunity to talk about the meaning of an experiment supporting a theory. Perhaps, some students will challenge the teacher's final conclusion that Kepler demonstrated the rectilinearity of light. The teacher answers that a theory is confirmed when none of the experiments contradicts it. To decide whether there is an agreement or a contradiction, a scientist must make certain assumptions about the phenomenon, which may be true or not. For instance, Aristotle based his conclusion on the idea of a point source of light, while the sun is not one because its angular size is quite large.

There may be other more generic questions as well, such as: 1) How many experiments are enough to test a hypothesis? 2) What would have happened if we picked a false variable? The teacher explains that repeating an experiment involves varying a parameter to be sure that its quantitative change alters the result. For instance, if an experiment is conducted with only two different sizes of the opening, one would never be certain of the results at much larger or smaller dimensions. If a false variable (the shape of an opening, for one) is selected, changing it does not affect the result. Since the time invested by a scientist in a given investigation is limited, an unlucky choice of a variable may lead to failure. Failure may also occur because of an inadequate experimental procedure. Aristotle, for instance, could not see a rectangular shadow if he never changed the distance between the aperture and the "screen." There are other difficulties as well. That is why, although all scientists use a similar research strategy, some of them make great discoveries, while others only minor ones.

It is worth noting that the plan of investigation described here was tested with such subjects as electricity and bioelectricity, optics and vision, acoustics and hearing, waves and vibrations, and graduates of our programs have applied it to topics in mechanics, chemistry, biology, astronomy, and car troubleshooting. By consulting an appropriate work on the history of science (see Appendix A for suggestions), the general strategy provided here could be used in any science discipline.

CONCLUSIONS

Teaching aspects of the "nature of science" through an historical approach appeals to teachers if it is intertwined with teaching science content so that it makes the latter more stimulating without taking additional classroom time.

Historical reading combined with investigative experimentation, especially of a historical nature, appears to be a promising way for students to learn the basics of the scientific method and understand some other issues of the nature of science even when this subject is presented unobtrusively. While reading and a discussion with a teacher may be sufficient for a few motivated and curious students, this will not work for the majority of them. Teachers may try to appeal to their practical sense, by explaining that their future job opportunities depend on their ability of systematic and critical thinking, but this is a too far-fetched perspective to many. On the other hand, involving any student on a daily basis in investigative experimentation where they can show their creativity without fear of being punished for errors, can gradually change their attitude toward science and learning it.

However, to teach students how to do investigative experiments, teachers must be trained in a similar way. This requires an investment of time and effort, but the benefits are considerable. This skill is applicable for life and may be used with any science subject and beyond science. Reading without experimentation, naturally, takes less preparation on the teacher's part, but its benefits are more limited; an experiment described in a book does not provide as much information as the real one, nor does it create a sense of participation.

Taking into account that few educators have an interest in experimentation and probably even fewer in the history of science, the value of my recommendations seems to be very limited. However, it is possible to split a course on the nature of science into two parts, theoretical and experimental, taught by two people. Moreover, the experiments must not necessarily be historical: one can find other experiments for investigations, the results of which are known and comprehensible to teachers (two important advantages of historical ones!). And it is very possible that some educators will decide to try the fruit of history and find it interesting, if not delicious.

Bakken Library and Museum, Minneapolis, Minnesota, USA

NOTE

The Bakken Library and Museum, founded by Earl E. Bakken, inventor of the first transistorized cardiac pacemaker, is a center for education and learning that furthers the understanding of the history, cultural context, and applications of electricity and magnetism in the life sciences and medicine. It holds a vast collection of rare books and scientific instruments relating to the historical role of "electricity in life." In addition to serving as a research center, The Bakken is a pioneer in using the history of science to enhance K-12 science education, through in-service training programs for science teachers, workshops for students in grades 4-12, publications and kits.

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APPENDIX A

This list of references, added by editor, addresses episodes from the history of science that may be useful in constructing scenarios for use with the strategy described in this chapter. This list was abridged from one originally developed by Robert Lovely and updated by HsingChi Wang. The editor sincerely appreciates the willingness of these two individuals to allow their work to be used here.

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