Science and Education **5**: 277–292, 1996.

The 'Historical-Investigative' Approach to Teaching Science

NAHUM KIPNIS

The Bakken Museum, 3537 Zenith Ave, So., Minneapolis, MN 55416, USA

ABSTRACT: The paper describes the author's experience in using the history of science in teaching physics to science teachers. It was found that history becomes more useful to teachers when explicitly combined with 'investigative' experimentation, which, in turn, can benefit from various uses of the history of science.

INTRODUCTION

The question of whether or not the history of science may be (or should be) used in teaching science has been debated for quite a while.[1] Teachers perceive a variety of needs for the history of science, beginning with the need to enliven their lectures and ending with a need to answer such students' questions as 'are we sure about what we know?' or 'is science good for people?' On the other hand, historians warn that the history of science is very complex, and its simplification can be detrimental to both the history of science and the science itself. The current consensus appears to be that a comprehensive historical approach to science teaching is neither feasible nor necessary, because selective case-studies can do the job.[2] Having agreed with this in principle, I have tried nonetheless to make the usage of the history of science as systematic and various as possible given my professional background and the job opportunity.

In 1985, I started developing programs for science teachers at The Bakken, a history of science and medicine library and museum in Minneapolis. As a historian of science and a physics teacher, I understood both the needs of teachers and concerns of historians. To me the question was not 'to do, or not to do?' but 'how to do it to maximize the benefits and minimize the damage?' I decided to try *internalizing* history, or making it a natural component in learning science. Initially, I followed Dr. Samuel Devons of Columbia University who created in the 1970s history of science courses with an emphasis on historical experiment for educating physics teachers (Devons and Hartmann 1970).

Usually, courses for teachers involving the history and philosophy of science aim at transforming the 'technical' science traditionally taught to students into the 'liberal' one (in Michael Matthew's terms). However, I found very soon that teachers' knowledge of even the 'technical' physics was very inadequate. Having no foundation to build on, I could only choose between teaching physics prior to history or teaching both at the same time. Then I asked myself: 'will students really benefit from the history of science? Currently, learning science is reduced to memorizing a certain number of facts (laws, rules, numbers). Will adding to this a few dates, names, and terms really help? If students are not accustomed to asking *why*? relative to the subject matter, will they be more curious about historical or philosophical issues?' It appeared to me that until the emphasis in teaching is shifted to developing thinking skills and a habit to use them, history will be out of place in a science course. That is how the third component – new techniques in teaching physics – came into the equation. Gradually, I transformed my history of science courses into physics courses enriched with elements of history and new teaching/learning techniques. The idea was to teach teachers in a way they could imitate in their classrooms.

A teaching technique must conform to the goal of teaching. Those vary: different teachers, students, parents, and social groups may have different goals. Thus, each teacher chooses the objective that appears the most important for him/her in a given situation and that is compatible with the teacher's own interests and limitations. For instance, a teacher who has no sense of history in general will not use the history of science. Some teachers may decide to concentrate on preparing future scientists, thus they will not pay much attention to less capable students. Others may believe that their duty is to prepare *all* their students to cope with real life, professionally and socially.

The meaning of 'learning' is not universal either, for it depends on the purpose of teaching. To prepare students for college, teachers make sure students know the laws of physics and can apply them to solve book problems. To prepare students for work in modern industry, students need to know how to apply physical laws to real problems. Of course, to learn how to operate a photocopier it is enough to memorize which buttons to push in different circumstances. But with an increase of machines in use more of the future operators will be required to service them if there is a problem, and those jobs will become more desirable as better paid and more interesting. Now, to fix a machine, one needs to understand the technical process involved (physics or chemistry) and basic rules of troubleshooting (the art of thinking scientifically).

In the past, physics has been considered in the USA to be necessary only to future physicists and engineers. Since these professions also require a considerable amount of mathematics, the presumption was that high-school physics must be totally mathematized. Consequently, only a small part of American high-school students have been taking physics. Now, however, there is a growing awareness that to compete in the modern industrial market it is necessary to have enough qualified workers not only at the top level (scientists and engineers) but also at the middle one (technicians). Technicians will be the backbone of a high-tech society of the next century, and they have to learn physics while in high school.

If we want the majority of students to learn enough physics to cope with their future jobs, we have to change the way we teach it. For many students, a future use of skills acquired now (in college or on a job) is not a motivator. An immediate application works much better. Thus, students should be taught to look at physics as a means for solving certain real-life problems.[3] One class of these problems is *troubleshooting*: find out why an electrical toy stopped singing, why the image in a wall mirror makes you bigger than life, etc. Another class is *making and improving* things such an electrostatic generator, an electrical motor, a mechanical telephone. The third class is *resolving a puzzle* not assigned by a teacher: 'why does a hair stick to a TV screen?', or 'how does a toy make a screeching sound?'

Thus, *physics for all students* should be based on experiment that requires thinking. Are teachers ready for this?

CLASSROOM EXPERIMENTS: HOW USEFUL ARE THEY?

The mainstay of experiments remains the classroom demonstration. Its character is *illustrative*: a theory comes first, and a demonstration follows to support it. Some time ago, demonstration was practically the only means of observing many physical phenomena. Nowadays, however, an abundance of pre-recorded audio-visual information considerably reduces the need for live demonstrations. Demonstrations leave students passive, which is a major shortcoming. Sometimes students are so bored that they concentrate not so much on the phenomenon as on the possibility of the teacher's failure. On the other hand, the activity is not threatening: if students do not learn much from a demonstration, they have nothing to loose either. To increase the effectiveness of demonstrations, teachers hunt for interesting experiments. The idea is that such demonstrations will attract students to science and motivate them to explore and learn. Yet, this works only for a tiny minority of highly motivated students.

In a lab, students' level of involvement is higher than in demonstrations, and they may be expected to learn more. Yet, this is not the case with a traditional lab whose purpose is again to *illustrate* a known physical law. It is organized so that students measure certain parameters, calculate the result and compare it with an equation. Such labs teach students some experimental techniques (for instance, measuring, making an electrical circuit, focusing a lens, etc.) and help memorizing a few equations. If that were labs' primary goal, the situation would be tolerable. In fact, teachers require their students to 'verify' a law, by obtaining an agreement between theoretical and experimental data within a rather narrow margin of error. Students seldom achieve such a goal, which breeds various negative emotions: students blame their instruments, or themselves as incapable experimenters. Some of them become frustrated with labs (and physics in general), while others resort to cheating, viewing a lab as just another boring obstacle on the way to a good grade. In addition to this, a 'cookbook' style of a lab procedure limits students' initiative and creativity.

To overcome this difficulty, a number of American teachers (primarily in middle school) began using the 'open-end problems', where students experiment without knowing the 'answer.' Students are free in designing their own procedures and choosing their own hypotheses. Teachers teach them the principal steps in the inquiry, such as 'hypothesis', 'test', etc. and their sequence. These labs are usually qualitative, and grading focuses on participation rather than result. Students like these labs, because they don't feel any pressure to produce a 'correct answer'. While they learn something about the phenomena they study and the instruments involved, this knowledge is quite limited. For instance, in static electricity they easily learn how to charge and discharge a Leyden jar, but very few understand how to go about *improving* this instrument. Teachers are so much concerned with involving students in an experiment, that they prefer not to say that answers obtained by some groups are completely erroneous. As the result, students leave the class without understanding whether the difference in their answers is of any significance. This does not bother teachers, who comfort their pupils with: 'All of you are right, you all did a great job.' Apparently, they want to show that physics is not for an 'elite' only, that physics can be fun and easy for anyone. The trouble is that playing games with 'hypotheses' and 'verifications' is just that: games. Students who came out of them with the idea that 'physics is easy' will be very disappointed later in life when they will have to face 'real' problems.

Both 'engaging' demonstrations and 'open-end' labs are based on the same presumption that a mere exposure of students to these experiments will motivate them to learn on their own. The teacher's role is reduced to that of a 'facilitator'. However, no more than a few percent of students justify these expectations. Some teachers believe that the 'open-end' experiments can teach students the inquiry method despite their errors in specific results. This brings up the question of assessing learning. In all professions and trades, the only valid criterion of learning is its successful application to a real situation. Why should it be different in science education? A student can go through all the right motions ('hypothesis', 'test', and so on) without solving a single problem. Until we judge the results rather than the motions, there will be no improvement in science education.

Such considerations prompted me to create a different method of teaching physics in secondary school that I call *historical-investigative*. I have been teaching it to teachers of both middle and high school for nine years, and described it in a book (Kipnis 1992). My main goals were: 1) to appeal to a broad range of students differing in their abilities and motivation, although not necessarily in the same way; 2) to make all students learn, although not necessarily the same; and 3) to make learning enjoyable intellectually and emotionally. To accomplish this, I use certain pedagogical devices. First, students are judged for their successes rather than shortcomings. For instance, some display more creativity in designing an apparatus, others are more inventive in testing hypotheses, and still others are more successful in generalizing the results. Such 'specialization' does not hinder team work, and eventually individuals not only develop their strengths better but, to some extent, learn the skills they are naturally short of. Secondly, there are assignments, such as home experiments, essays, or individual projects, where students may proceed at their own pace recapturing the credits lost in the classroom due to shyness or slower thinking. Thirdly, students are required to produce correct results. Finally, they are encouraged for achievements and not punished for errors.

The core of the method is *investigations* that simulate the 'real-life problems' mentioned above.

'INVESTIGATIONS'

I tried to find a middle ground between the 'verificational' labs, with their focus on the result and complete structuring of the procedure, and the 'open-end experiments,' where students are not guided at all and obtaining a correct result is of no importance. In investigations, students have enough freedom, but their ultimate goal is producing true results. The result is pronounced 'true' if all groups agree on it. The teacher's role is helping students to succeed. This includes training students to do an investigation before they can do it on their own, a proper selection of equipment, and periodical group discussions during the experiment.

The idea came from the history of science. I thought: 'When aiming at developing students' thinking skills, why can't we try to *imitate* scientists? Although scientists work independently of one another, they are not satisfied with their work until others confirm their results.' In an investigation, students follow a general plan, the main features of which are derived from scientists' routines.

PLAN OF AN INVESTIGATION

I. PRELIMINARY PART

1. Background (origin of the problem)
2. Initial observations/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

TABLE 1

Intermediary	Support	Effect
steel wire	styrofoam cup	yes
cardboard tube	plastic cup	yes
plastic tube	styrofoam block	no
cardboard strip	styrofoam cup	yes
steel nail	plastic container	yes
plastic ruler	styrofoam block	no
steel wire	styrofoam block	yes
plastic ruler	styrofoam cup	no
steel wire	wooden block	no

Variable 2

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

III. GENERAL CONCLUSION

To illustrate its usage, I will discuss an experiment 'Electrical conductivity.' Before doing it, students already know that certain bodies can be electrified by friction, and that the presence of electricity can be revealed by a thread electrometer, which works, though, only in the proximity of the electrified body. The origin of this problem is historical: it comes from experiments of Stephen Gray around 1730. After rubbing a glass tube, he observed that not only the tube itself attracted light bodies but so did the cork stopping it. He repeated the experiment with a nail inserted into the cork and found that the nail also acquired the property of attraction. Gray concluded that somehow the power of attraction was transferred from an electrified body through other bodies. I suggest to students to repeat some of Gray's experiments using a slightly modified original procedure. First, I show one as a demo: a 30 cm long wire is taped to the top of a styrofoam cup, and a thread electrometer is placed near one end of it. I rub a plastic tube and show that at such distance it does not act on the electrometer. However, when I bring the tube to the second end of the wire the thread moves towards the first one. Then I suggest they repeat this experiment with different 'intermediary bodies' placed on a styrofoam or plastic cup. This begins the section 'initial experiments.' In some cases, the electrometer reacted, in others, it did not (see the Table 1).

At this point, students have to formulate a problem to be solved. For instance, 'why in some cases does the intermediary body affect the electrometer, and in others it does not?' The next step is selecting *variables*, or parameters the change of which presumably changes the result.

TABLE 2

Intermediary	Support	Effect
steel nail	styrofoam	yes
steel wire	styrofoam	yes
wooden dowel	styrofoam	yes
wooden ruler	styrofoam	yes
cardboard strip	styrofoam	yes
cardboard tube	styrofoam	yes
styrofoam plate	styrofoam	no
aluminum tube	styrofoam	yes
aluminum wire	styrofoam	yes

TABLE 3

Intermediary	Support	Effect
steel	styrofoam	yes
steel	plastic	yes
steel	wood	no
steel	tin	no

Since only two objects are changed, the cause may be in either. Thus, we may try the intermediary body as one variable and its support as the other. Here the preliminary chaotic part of the investigation ends, and the main part begins where everything is planned and controlled. Students investigate one variable at a time, keeping everything else constant. The results of the initial experiments usually cannot be used in the main part, because they involve too many variables. However, in this case we have only two variables, and some preliminary results are usable. For the first variable, the hypothesis appears to be that the effect depends on the material of an intermediary body but not on its shape. To test it, we could add a few more materials and repeat some of the previous experiments, using in all cases the same support (see Table 2).

Conclusion: the hypothesis is correct – steel, wood, and cardboard transmit the attraction, while plastic and styrofoam do not. For the second variable, the preliminary results suggest that the shape of a support is not essential, the effect of the material being not clear: sometimes the same material produces different effects, while at other times different materials have the same effect. To formulate any hypothesis about the material of the support we need additional experiments. Now, we will keep the same intermediary body but vary the support's material (see Table 3).

The conclusion is that some support materials (styrofoam and plastic) help create the effect, but others (metal, wood) do not. At this point, a purely inductive investigation is over. However, its results appear to be contradictory, because the same materials help in transmitting an electrical

TABLE 4

Intermediary	Support	Effect
wooden dowel	wooden block	no
wooden dowel	pop can	no
steel wire	wooden block	no

attraction at a distance when used as intermediaries or prevent it when used as supports. To proceed, we need a theory.

There are several possibilities, and the simplest one is to assume that electricity can move, like water. This means that in our first experiment electricity traveled through metals, cardboard, and wood but was stopped by plastic and styrofoam. With this model in mind, we can explain the second experiment: if metal and wooden intermediary bodies conduct electricity, metal and wooden supports do the same, diverting electricity into the table and preventing it from reaching the electrometer. To verify this idea, we can do a few experiments with conductors serving in both capacities at the same time (Table 4).

The hypothesis is confirmed.

A full-scale investigation is time consuming to prepare and conduct, and a teacher cannot have many of them. Yet, each investigation teaches students more than many 'ordinary' labs, which fully justifies the efforts. We also use shorter investigative experiments that take only 5 to 20 min, conducted either as demonstrations or labs. These deal with one-two variables and serve in conjunction with short teacher's lectures and class discussions (5–10 min). The idea is to make the introduction of a new concept appearing as rediscovered right there by the joint efforts of students and the teacher.

WHY *HISTORICAL* INSTRUMENTS?

Physics for all students with its emphasis on labs requires many instruments, which means that the cost of a single apparatus must be very low. The history of science can help with this too. I am not speaking of reproducing *exact* replicas of historical instruments. That would be too time consuming, expensive, and not available for students' modifications. Instead, I retain the idea of an instrument, use modern materials, and sometimes simplify the design. I also preserve the historical sequence of experiments and limit the use of modern apparatus.

While it is obvious that an investigative lab does not have to be historical, the latter may have certain advantages. A teacher could study conductivity using a traditional circuit technique with batteries and wires. Yet, with a small incandescent bulb as a detector of electricity, the variety of conductors discovered would be meager, while replacing the bulb with a multimeter would improve the sensitivity but make the lab very expensive. The historical version produces better results at a much lesser expense, which makes the experiment feasible as a lab. And on top of this, a historical experiment shows how an important discovery was *actually* made.

INDUCTIVE OR DEDUCTIVE?

The approach used in the experiment described above is obviously inductive: students begin with observations; then they compare the results looking for something common in them; and finally, they try generalizing the results into a law or a rule. This is against the modern practice of teaching science in a deductive way where students are first presented with a general theory and then the theory is applied to specific phenomena.[3] In writing textbooks or lecturing, the deductive style provides certain advantages, such as generality, elegance, and economy of space or time. However, with the same certainty it kills students' curiosity about the origin of scientific knowledge. Besides, it distorts the image of science. Students get an impression from their textbooks that science is about general theories, and having been told that theories replace one another, they stop seeing much value in science. History is the only remedy for this disease.

The justification for introducing inductive experiments is simple: this kind of experiment in physics prevailed until well into the nineteenth century, and some important discoveries (for example, electromagnetism, electromagnetic induction, X-rays, and radioactivity) followed this mode even later. Physics teachers ignore inductive experiments because they do not lead directly to general (mathematical, of course) theories, which in many cases constitute not only the goal but even the content of physics courses. (A qualitative theory can be derived from inductive experiments, as shown above with electrical fluid.) What inductive experiments do produce is 'empirical' laws, such as Snell's law or the rule that violet light has a greater index of refraction than the red one. Empirical laws provide an important step leading to more general theories, thus we should not skip them. For instance, when thinking of a theory of light, physicists kept in mind a number of empirical laws (including the two mentioned above) that their theory had to explain. On the basis of empirical laws, physicists conceive a new general hypothesis. The experiments employed to verify it are deductive, because their outcome is predicted beforehand. Thus, both inductive and deductive experiments contribute to the making of a theory, but the process begins with the inductive ones. The experiment described above illustrates this because while its first part is inductive, the second one (after introducing the concept of a fluid and predicting the outcome of new experiments) is deductive.

From a practical perspective, there is no way for students to 'derive' the wave theory of light from their optical experiments, but they can infer from them some empirical laws instead. They will be happy to learn that this is no small achievement, because this is what most scientists can aspire to. Another way to dispel the myth of physics is to tell students that until quite recently, a dream of most physicists was a discovery of a new *phenomenon* rather than a theory. Grimaldi's diffraction, Galvani's effect, Øersted's electromagnetism, Röntgen's rays, all these discoveries were of new phenomena and not of theories. Of course, they received certain theoretical explanations after the discovery, but while theories replaced one another, the phenomena remained the same.

One may note that an inductive experiment can easily lead to an erroneous result. This is true, of course: following the best plan does not guarantee against mistakes. However, we have to specify the meaning of *error*. For instance, students investigate the image of an aperture produced by sunlight and find it to increase with the distance between the aperture and a screen. This is a correct result even if the teacher expected students to investigate other variables as well, such as the aperture's size and shape, and come up with some general conclusions. *A partial solution, if correct, is a solution.* Given time limitations and the endless character of an investigation, this is the only way to conduct such experiments in schools. A more complete solution may receive a higher grade (not necessarily!), but a less complete one will receive a positive grade, too. Moreover, this group will get an opportunity to extend its work at another time (in school or at home) and be graded on the cumulative merit of the final results regardless of the preliminary ones. The focus is on *quality*: a correct investigation of a single variable receives more appreciation than erroneous results concerning three variables.

An experiment may be fruitless, if the experimenter has a poor selection of variables. Even if the results are correct, nothing important will be discovered. For instance, in the experiment on conductivity, students could have spent the whole time focusing exclusively on metal intermediary bodies, studying the effect of their material, length, diameter, shape, etc. The partial result would have been correct, but no general idea of conductivity could come out of such an experiment.

A true error happens when the procedure is faulty, which means bringing in a hidden variable that masks the effect of the one under investigation. For instance, when using a plastic pipe as an intermediary body, students sometimes see it affecting the electrometer and conclude that plastic is a conductor. In reality, the pipe is either charged itself or too short, and the effect observed is due to the direct action of the charger.

In the beginning, when the focus is on teaching students how to investigate, the teacher must take special care that they succeed. By controlling the equipment available to students the teacher can reduce the number of possible variables. When seeing a faulty procedure, the teacher may suggest an additional verification. After students grasp the basics and became more confident, the teacher may let them fail more frequently.

The teacher will console them with stories of how many physicists (including the most famous) blundered or wasted time when they were out of luck in selecting variables or procedures. It is important to note that the main criterion of correct results is an agreement between different groups. Thus, the teacher should organize the class so that each variable be investigated by at least three groups. If they disagree on a result, they will conduct additional experiments until the results are the same. Even if students reproduce an historical experiment, it is better to withhold the results until the end: students will be happier to learn that they managed to obtain some results of famous scientists without any tips from the teacher.

Although the 'reproduction' of historical experiment is true only in a limited sense, its pedagogical value is considerable: students master the art of scientific experimentation and learn how scientists produce new knowledge. Not every experiment is suitable for 'reproduction': I preferred those that used simple apparatus, and connected with concepts and theories worth reviving so that the connection is not too complicated.

QUALITATIVE OR QUANTITATIVE?

The lab on conductivity is qualitative. This is another feature of the historical-investigative approach: to promote qualitative experimentation. Again, the justification comes from history. For about two thousand years physics remained primarily a qualitative science, with quantitative experiments coming to dominate only in the second half of the nineteenth century. I call here an experiment 'quantitative' if it leads to a mathematical law. The mere fact of measuring does not make an experiment quantitative. If the results of an experiment are expressed in terms 'greater or smaller', 'increase or decrease', etc., it is still a qualitative experiment.

How are qualitative experiments better than quantitative ones? The former focus on phenomena rather than on numbers, they provide a greater variety of phenomena accessible for a study, they are more engaging, and they can offer something to students of different abilities and interests. Actually, 'better' refers exclusively to the beginning in studying physics. After students have mastered the art of qualitative investigation, they can and should move to quantitative experiments that represent a higher level of experimentation. Of course, it is 'higher' only if properly organized. But how to do a quantitative investigation? An investigative component can be added even to an ordinary 'verificational' experiment by changing its purpose: instead of trying to obtain a small difference between experimental and theoretical values, try to identify the causes of this difference and reduce it. However, it is better to build up a quantitative part to a qualitative experiment In this way, students study a phenomenon first, and then derive its mathematical law. The idea is that a qualitative experiment can uncover a relation between its variables, such as 'when *A* increases *B* also increases'. What is left is to find the mathematical function connecting *A* and *B*, which is achieved by collecting enough measurements and plotting *A* vs. *B*, a procedure quite familiar to students.

Moving away from traditional quantitative experiments to qualitative ones is equivalent to replacing the *theory-first* approach to learning physics with the *experiment-first* one. One can say that the change is not necessary, because generations of students, including future physicists, succeeded with the *theory-first* method. They learned to experiment later, in a research or industrial lab. This is absolutely correct when speaking of those who overcame a fear or boredom of 'theoretical' physics and after graduation managed to get a job with some amount of 'practical' physics. But many others either never took physics (hearing the 'horror' stories from others) or did but hated it and subsequently avoided any job where some physics was needed. For a well-motivated mathematically-prepared student, perhaps it does not matter which way to go. Yet, for the majority of students it does. To produce enough intelligent technicians, we have no choice but to teach *experiment-first* physics in secondary school.

BACK TO NATURE

Observing phenomena is the first part of inductive experiments. It is an art little practiced in a modern secondary school, and it is worth reviving. Whenever possible, I promote observations and experiment outdoors and outside the classroom. Repeating historical experiments in such an environment will remind students that science is about *Nature*. They will also understand that science is an activity not limited to manipulating special 'scientific' instruments in special places called 'laboratories'. This is important because students will be required to do many experiments at home using household items as physical apparatus.

SCIENCE AS 'DRAMA OF IDEAS'

One of the best ways for understanding a concept is through studying its history. Historical controversies are very helpful because they show that there is always more than one interpretation of an experiment. The controversies are especially valuable if students can repeat some of the experiments involved. One instance is the debate on the nature of electricity in a 'frog's circuit' between Galvani and Aldini on one side and Volta on the other. Another example is Kepler's correction of Aristotle's meaning of the *rectilinearity* of light. When studying arguments for and against the hypothesis of 'animal' electricity students will better appreciate the difficulties and complexities of introducing new ideas. They will see that a choice between competing theories is a very complex business, which may have a personal line in it. They will also realize that there are no crucial experiments against a theory: every time Aldini advanced a new 'crucial' objection to Volta's theory, Volta modified his theory so as to conform to the new experiment. There was a price to pay, however, for each increase in the theory's generality reduced its predicting power, and its last version never found any use. I also use more technical debates about specific laws, such as the one between Galileo and Huygens on whether the period of an isochronous pendulum depends on its amplitude. This debate teaches students that sometimes precision of measurements is very important. In this case, fortunately, improving the precision is easily achievable because the only thing it requires is extending the time of observation. To make it more interesting to students, I withhold the result: they have to decide themselves who was right.

ARE OLD THEORIES USABLE?

Bringing up old theories serves several purposes. In the case of Galvani and Volta, students can see an interplay between a theory and experiment: new experiments to refute the opponent's view, new counter-arguments, both theoretical and experimental, to defend the theory in question and attack the other one, etc. Naturally, a teacher cannot follow all historical convolutions, for there is no time for that, and not all pieces of the historical puzzle are equally instructive.

Another application for old theories is more practical: explaining phenomena. The 'modern' theories dominating physics texts are not really new: the electron theory is about 100 years old, and the wave theory of light is about 175 years old. A 'modern' theory is simply a newer theory, but like its predecessors, it has a limited range of applicability. From a pedagogical perspective, within its range an older theory can be as usable as the newer one, sometimes even more so. For instance, the theory of electricity based on the analogy with water works beautifully in both static and current electricity. Using it, students can easily figure out, for instance, what happens when you connect two capacitors, one of which is uncharged. Similarly, the emission (corpuscular) theory of light is excellent in explaining such phenomena as rectilinear propagation, reflection, and refraction of light. On the contrary, the wave models of these phenomena are much more difficult for students, both mathematically and conceptually. Teachers concerned with preserving the 'theoretical consistency' ('either waves of light or nothing') get around this obstacle by leaving rectilinearity of light unexplained, or even by skipping this fundamental concept altogether. However, this works only with students who do not ask questions.

CONCLUSION

The historical-investigative approach is one of several possible techniques for developing physical thinking and 'scientific thinking' in general. It was conceived for educating teachers, but later it was redesigned so as to allow teachers to transfer it to the classroom. It finds its users among teachers who are interested in history and have a certain philosophy of teaching. This approach is based on two presumptions: 1) certain trends in the historical development of science can inspire new teaching techniques; and 2) with a proper combination of freedom and guidance, students not only learn science better but also discover in themselves more creativity, curiosity, initiative, and ability to think than they had suspected. The implementation of this method in schools increased students' enjoyment of learning and their interest in experimenting, improved their understanding of scientific concepts, and enhanced their ability to think (Lawrenz and Kipnis 1990). It was also found that the method appealed to a range of students of different academic standing, naturally, for different reasons (Preskill 1991, pp. 11–12).

Most teachers put the investigative component in first place, history in the second, which corresponds to their perceived relevancy to the majority of students. The ultimate goal of investigations is to show students another way of acquiring new knowledge: when faced with a problem, try finding the answer through an experiment instead of asking the teacher or looking in books.

The purpose of the historical part is to give students a *sense* of how new scientific knowledge comes into being. This is achieved by combining a description of a discovery with its experimental reproduction. When experiencing first-hand how difficult it is to make even a minor discovery, students will better appreciate the achievements of scientists. While the 'reproduction' is only partial, it is sufficient to teach students the art of scientific investigation and to give them an idea of the profession of a scientist.

As with any teaching technique, this one is only as good as the teacher using it. Both components of the method require time to learn, although teachers began using it after studying for one month in summer. Three summer courses and two years of practice in between made them quite confident. Not all survived the first challenges in the classroom, but those who did are now trying to apply the method to *new* topics and subjects. Of course, they do not realize yet all the possible pitfalls awaiting them, especially in history, when they start selecting materials on their own. It would be very helpful thus if more historians of science participated in preparing curriculum materials for teachers.

While this experiment in science teaching was not conceived to prove or disprove any educational theory, its results are useful for evaluating certain recommendations. While detailed analysis should be done elsewhere, I will make one brief comment about requiring students to 'understand the nature of science'. It took three summers for teachers to become comparatively proficient in conducting an historical research and applying its results to their individual experimental projects. However, they are still far from being able to analyze historical information on the subject of the 'nature of science'. If we mean *understanding* this notion rather than memorizing pre-selected examples, let us forget students for a while and concentrate on teachers first. Without properly prepared teachers there will be no revolution in science education of any sort.

NOTES

[1] See, for instance, Brush and King (1972), Shortland & Warwick (1989), Jenkins (1990), and Matthews (1994), chpt. 4.
[2] Here are examples of various uses of the history of science at secondary school level: old theories, Carvalho (1990) and Steinberg (1992); historical experiments, Sanchez (1990) and Teichmann (1986); original texts, Galdabini and Rossi (1993); 'historical' dialogs, Lochhead and Dufresne (1990); in multimedia, Bonera et al. (1992).
[3] Unless otherwise specified, 'problem' in this article refers to an experimental problem rather than a pencil-and-paper exercise.

REFERENCES

Brush, S. G. and King, A. L. (eds.): 1972, *History in the Teaching of Physics*, University Press of New England, Hanover, New Hampshire.

Bonera, G., et al.: 1992, 'Reconstruction of Historical Experiments: A Multimedia Approach', in S. Hills (ed.), *History and Philosophy of Science in Science Education* (Proceedings of the Second International Conference on the History and Philosophy of Science and Science Teaching), vol. I, The Mathematics, Science, Technology, and Teacher Education Group and The Faculty of Education, Queen's University, Kingston, Ontario, pp. 127–134.

Bybee, R. W., et al: 1991, 'Integrating the History and Nature of Science and Technology in Science and Social Studies Curriculum', *Science Education* **75**(1), 143–155.

Carvalho, A.: 1990, 'The Influence of the History of Momentum and its Conservation on the Teaching of Mechanics in High Schools', in D. Herget (ed.), *More History and Philosophy of Science in Science Education* (Proceedings of the First International Conference), Science Education and Department of Philosophy, Florida State University, Tallahassee, Florida, pp. 212–219.

Devons, S. and Hartmann, L.: 1970, 'A History-of-Physics Laboratory', *Physics Today* **23** (2), 44–49.

Galdabini, S. and Rossi, O.: 1993, 'Using Historical Papers in Ordinary Physics Teaching at High School', *Science & Education* **2**: 239–242.

Jenkins, E.: 1990, 'The history of Science in British Schools: Retrospect and Prospect', *International Journal of Science Education* **12** (3), 274–283. Reprinted in M. Matthews (1991), 33–41.

Kipnis, N.: 1992, *Rediscovering Optics*, BENA Press, Minneapolis.

Lawrenz, F. and Kipnis, N.: 1990, 'Hands-On History of Physics', *Journal of Science Teacher Education* **1**(3), 54–59.

Lochhead, J. and Dufresne, R.: 1989, 'Helping Students Understand Difficult Science Concepts Through the Use of Dialogues with History', in D. Herget (ed.), *History and Philosophy of Science in Science Education* (Proceedings of the First International Conference), Science Education and Department of Philosophy, Florida State University, Tallahassee, Florida, pp. 221–229.

Matthews, M. R. (ed.): 1991, *History, Philosophy, and Science Teaching: Selected Readings*, OISE Press, Toronto.

Matthews, M. R.: 1994, *Science Teaching: The Role of History and Philosophy of Science*, Routledge, New York.

Preskill, H.: 1991, 'Final Evaluation Report on Bakken Summer Institute on Vision and Optics', unpublished.

Pumfrey, S.: 1991, 'History of science in the national Science Curriculum: a critical review of resources and their aims', *British Journal for the History of Science* **24**, 61–78.

Sánchez, L.: 1989, 'On the Implicit Use of History of Science in Science Education', in D. Herget (ed.), *History and Philosophy of Science in Science Education* (Proceedings of the First International Conference), Science Education and Department of Philosophy, Florida State University, Tallahassee, Florida, pp. 306–312.

Shortland, M. and Warwick, A. (eds.): 1989, *Teaching the History of Science*, Blackwell/British Society for the History of Science, Oxford.

Steinberg, M.: 1992, 'What is Electric Potential? – Connecting Alessandro Volta and Contemporary Students', in S. Hills (ed.), *History and Philosophy of Science in Science Education* (Proceedings of the Second International Conference on the History and Philosophy of Science and Science Teaching), vol. II, The Mathematics, Science, Technology, and Teacher Education Group and The Faculty of Education, Queen's University, Kingston, Ontario, pp. 473–480.

Teichmann, J.: 1986, 'The Historical Experiment in Physics Education: Theoretical Observations and Practical Examples', in P. V. Thomsen (ed.) *Science Education and the History of Physics*, University of Aarhus, Denmark, pp. 189–221.