History as a collaborator of science

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I am very much obliged to for the invitation, and the honor, to talk to you about so unpromising a subject as the collaboration of history and science. According to the authoritative opinion of the most influential modern theorist of science, Thomas Kuhn, science progresses by abandoning its history. At every scientific revolution, at every shift of paradigm, the victors replace the old textbooks and dethrone the old heros just as the ancient Romans tore down the statues of overthrown dictators. The deeper the revolution, the more thorough the purge; and that, according to Kuhn's theory and most standard science texts, is as it should be. The Roman poet Lucan sighed over what had been the city of Troy, *etiam periere ruinae*, "even the ruins have perished." The routine pedagogue of science looks with satisfaction at a present without a past.

Many academic scientists, though not many from leading universities, and some historians, believe that science students fed only the latest paradigms will grow up savages; that the history of science should be used to inculcate an understanding of the practice, nature, and institutions of science, and therewith, perhaps, some culture, ethical awareness, social concern, and modesty. Despite the ever increasing body of scientific knowledge and the ever sharper competition for fellowships, research positions, and professorships, time must be found for something other than scientific ideas, problem sets, and laboratory work in the science curriculum. I have in mind here and thoughout my talk students concentrating on science, not students wanting to know a little about science to broaden their educations.

There are now several international organizations and many national ones that preach the importance of history in the science curriculum and offer advice about course ingredients. But in my opinion their approach too often suffers from their failure to take into account either Kuhn's theoretical arguments about the character of scientific revolutions or the practical problems faced by textbook writers and classroom teachers. Historical material should have a prominent place in the pedagogy of science; but not to recall the past for itself, or for anecdotes or sugar coating, but because, for some purposes, history may be the best way to teach science.

If historical materials do not promote understanding of current science and the acquisition of knowledge and skills still believed to be correct, their use in science courses is hard to justify. However, once admitted for their value in teaching currently held facts and ideas, historical materials offer many opportunities for references to significant social and cultural topics. The science teacher should not develop these topics in class; that would distort the curriculum and unduly challenge the teacher. Rather, the teacher should refer students to appropriate books and courses in history and political science or sociology where the the wider topics are studied properly.

There is very good reason to believe that the history of science used in science courses in the manner suggested creates deeper understanding and wider perspectives. The evidence is, of course, historical. As our modern division of scientific disciplines began to take shape around 1800, the history of science had an honorable place in the teaching of science. The connection was genetic as well as substantive. Modern general history and classical experimental science jelled at the same time, during the later Enlightenment and the Napoleonic period.

Both of them -- both history and natural science -- had acquired new forms and purposes during the 18th century. In 1700 natural knowledge, to use the term the Royal Society of London devised to designate its pursuits, was largely a bookish subject, qualitative in character, expressed in more or less the same terms as the rest of human experience. In 1800 the physical sciences had become experimental and quantitative, and had taken as their goal the establishment of mathematical laws and theories that could summarize and predict the outcome of measurements. During the same time, history was transforming itself from its traditional functions as chronicler of Christianity, recorder of European dynastic relations, handmaiden of classical philology, and exemplifier of moral principles into an independent empirical inquirer into all aspects of human activity throughout the world. The new natural science incorporated some of the new universal history in its teaching.

These observations set the framework for the balance of my talk. I'll begin with a few historical examples of the use and value of history in the teaching of science. Then come a few indications of the ways in which, today, historical materials can be valuable additions to the science curriculum. By "additions" of course I mean substitutions; for the curriculum is crowded already, and historical materials can only be given time to do their work by replacing other, less effective, units. Finally I shall mention a few initiatives underway in Europe that might help to implement curricular change. I regret that owing to faults in my education, most of my examples come from the physical sciences.

1. History and Science

A standard Christmas present for a student of physics 100 years ago was a copy of Ernst Mach's *Die Mechanik in ihrer Entwicklung, historisch kritisch dargetstellt* (1883). It has had at least nine German and six English editions, and several in French and Italian as well. It is not strictly a history, but a selection of problems important in the development of mechanics together with instructive analyses based on the solutions proposed at the time. Some very important people profited from studying Mach's *Mechanik*, Planck and Einstein among them, though, to be sure, both later repudiated him. If critical history helped form Planck and Einstein, we are well advised to find a place for it, suitably updated, in our curricula.

An earlier example of the inspirational use of history in science is Joseph Priestley's *History and present state of electricity*, first published in 1767, which had five English editions and several translations during his lifetime, when very few books on electricity appeared more than once in any language. Priestley's approach was entirely different from Mach's. Priestley prepared his readers not by incisive analysis of selected problems but by laying out the course of discovery of the entire inventory of electrical knowledge of the mid 18th century. The method was as suited to the rude state of the science of electricity in Priestley's day as Mach's treatment was to the advanced state of mechanics in his. Perhaps no more need be said about the value of Priestley's history for students of science than that it guided Volta to several of his discoveries.

A third example comes from the teaching of modern physics. Max Born's book, *Die Relativitätstheorie Einsteins* (1920), still offers a royal road to neophytes via historical-critical accounts of a range of problems, such as the aberration of starlight and Fresnel drag, implicated in the thinking that eventuated in the theory of relativity. Born's book went through at least three German and two English editions and several reprintings. In some respects it is a supplement to Mach's *Mechanik*, which Born acknowledged as his principal reference. Born's recourse to history has counterparts in a few good introductory texts in quantum physics, which lends itself particularly well to historical treatment since it still employs the concepts it overcame, although in limited and often mysterious ways.

These modern texts make a different use of history from Priestley's and Mach's. Whereas Priestley presented his information historically so as not to lose information that was not yet known to be unimportant and to give credit to discoverers in fields just forming; and whereas Mach exploited historical examples to deepen and broaden principles already regarded as models of clarity and reason; Born and the others turned to history to explain why physicists had been forced to base their discipline on concepts that do not appeal to the intuition.

Further to this theme, I can offer my own experience that exposure to old astronomy can materially assist students of modern astronomy. That is because, as in the previous examples, the old science is not entirely outmoded: anyone who understands the full geocentric accounts of the motions of the sun, moon, and stars knows as much about their appearances as the naked-eye astronomer requires even now. The geocentric accounts relate immediately to the observable world -- the changes of season, the times and places of sunrise and sunset, the lengths and directions of shadows, and so on. This sort of material is not always taught in astronomy departments, where students are thrown into black holes as soon as possible. They can come to the historian to learn how much of what they see in the heavens can be modelled and mastered by the ancient theory of the sphere.

From these few indications let us take heart that historical materials can be useful, even indispensable, in science education provided -- and this is a major qualification -- provided that they are used to inculcate science, not history or sociology.

2. The Examples

The obliquity of the ecliptic

From ancient times astronomers have worried that the inclination of the earth's axis to the plane of the sun's apparent motion, the so-called obliquity of the ecliptic, is not constant. The fundamental data for answering the question are the sun's altitude at noon on the day of the summer solstice and the latitude of the place of observation. For well over two thousand years, until the 17th century, measurements of the obliquity even in one place varied so much that no unambiguous decision about the constancy of the ecliptic could be made. One reason for the wide scatter in the data was that the instruments did not remain intact and in place; another was that astronomy then was ignorant about matters essential to a solution of the problem.

Around 1600, following the lead of Tycho and Kepler, astronomers routinely corrected their observations for atmospheric refraction and parallax. But since the observations contain these effects intertwined, and since the corrections required have opposite signs, the old astronomers could err greatly in their estimates of one effect and compensate by fiddling with the other. For example, Tycho made the solar distance grossly too small, by a factor of 20, and hence the solar parallax 20 times too large; an excess that had to be killed by exaggerating the amount of refraction. Since refraction is more serious for objects close to the horizon than for ones near the zenith, the corrections changed with altitude; and since the height of the midsummer sun is different from that of the stars used to determine latitude, the question of the change in the obliquity could not be resolved before both the parallax and the refraction were known separately as functions of altitude. The errors in these quantities, which often amounted to over two minutes of arc, vastly exceeded the size of the secular change in the obliquity, which, in 1700, amounted to around 45 arc seconds a century.

The establishment of accurate tables of refraction and parallax was the work of Gian Domenico Cassini, who used the cathedral of San Petronio in Bologna for the purpose. Cassini's successors at Bologna continued his observations for over half a century. After 1700 they could compare their results with ones obtained at a second church observatory built in Santa Maria degli Angeli in Rome, at the order and the expense of the pope. The churches spoke equivocally in favor of a negative change of around -1" a year. (The negative sign means a diminishing obliquity, that is, a straightening up of the earth's axis; if the process existed and continued unabated, in only 1000 centuries it would be perpetual spring.)

In the mid 1750s a new church observatory came on line to settle the matter. Its builder, a Jesuit mathematician named Leonardo Ximenes, spared no pains in leveling the line, measuring the height of the hole, and laying out a scale against which to record the position of the sun's midday image. He had two precious advantages over previous measurers. For one, the church in which he laid out his instrument -- none other than the great Florentine cathedral, Santa Maria del Fiore -- had a bronze plate in its floor on the exact spot on which the solstitial sun shown in 1510. Ximenes had only to measure how far the midsummer sun fell from the image of 1510 to settle the rate of change of the obliquity.

The second advantage Ximenes had over his predecessors was the knowledge that previous measurements would not have been intercomparable even if they had been made with the accuracy -- a second or two of arc -- at which he worked. A decade or so before Ximenes began at Santa Maria del Fiore, the astronomer royal of England, James Bradley, had delivered the second of two body blows to the corpus of secure observations. The first blow was that all stars execute a little circle around their average position during the course of a year. The maximum value of this excursion from the average is about 10 arc seconds; hence observations of the same star, even if made with exquisite accuracy, can differ from time to time by as much as 20 seconds.

The second blow was that, in addition to this annual dance, the stars oscillate up and down. The oscillations take 19 years to complete and have an amplitude of 9 seconds. The dance, called the aberration, is explained as the result of the earth's motion and the finite speed of light; the oscillation, called the nutation, arises from gravitational forces that cause the earth's axis to bob. The bobbing of course changes the obliquity; but that was not the long-term change astronomers had sought for a millenium.

To obtain comparable data, Ximenes had to correct both his and the 1510 measurement for refraction, parallax, aberration, and nutation; to be safe, he also corrected for the settling of the church, atmospheric conditions that might change the length of the *meridiana*, and other things truly negligible. After much massaging of the data, he could announce that the difference of four centimeters, which he had found between the images of 1510 and 1755, indicated a secular change in the obliquity of the ecliptic of -30 seconds a century. He repeated his operation 19 years later, at the same phase in the nutation cycle, and got the same result. His measurement was in fact extremely good, about the best possible with the intrument he used.

That of course did not settle the matter. A *meridiana* set up in the church of Saint Sulpice in Paris obtained no change in obliquity. The best telescopic measurements made at the Paris Observatory when combined with what appeared to be the most reliable earlier observations gave values of 0", 45", 60", and 100", all values negative. The better the instruments, the more knowledgeable the users, the subtler the corrections, the worse the agreement.

At this point -- we are now in the 1760s -- the mathematicians began to speak. Without looking at the sun, Leonhard Euler announced from his study that interplanetary gravitational forces caused a slow shift in the axes of rotation of all the planets. He made various estimates and settled on -45"/century for the shift for the earth. Pierre Simon de Laplace confirmed the result and also that the change is periodic. We cannot expect perpetual spring.

Did the measurements confirm the theory, or the theory the measurements, or neither the other? Ximenes thought that, since 45 does not equal 30 and since he had worked to sublime accuracy, taking all known disturbances into account, there must be something wrong with the gravitational theory or with the calculations. But Newton's laws had proved too successful to be upset by so subtle and uncertain a matter as a discrepancy of 50 or 100 percent in measurements of the change in the obliquity. Astronomers soon brought theory into agreement with experiment. They employed a technique often practiced in science. They changed instruments.

By 1750 the church heliometers were outmoded. Their advantages over telescopes -- stability and size -- were negated by improved mountings and single-metal constructions, achromatic lenses, and much improved graduation. Without the competition of the church observatories, astronomers armed with telescopes came closer to the mathematicians' value as observational protocols and instrument design improved and routinized. This convergence was no doubted assisted by the belief that English telescopes, especially instruments made by Jesse Ramsden, gave the best results.

There you have a story that delivers sound lessons in epistemology, measurement, and instrumentation and, at the same time, imparts important information, which, I must again insist, is not out of date, about the universe. The imagery and the unexpected part played by cathedrals give openings for lessons of an entirely different kind, to which I shall return.

The motion of the moon

One reason that mathematicians declined to consider seriously Ximenes' suggestion that the discrepancy between his measurements and their calculations might be blamed on the theory of gravitation was that they had recently tried a similar move and had ended in fiasco. In 1747 Alexis Claude Clairaut, frustrated by the shortfall between his calulations of the the moon's motions under the gravitational pulls of the earth and the sun, announced that Newton's law of the inverse square was not the entire story of gravity. To save the phenomena, Clairaut proposed to alter the law by adding a term involving the inverse cube of the distance. The effect of the new term was to cause the moon's orbit to precess in its plane. Clairaut calculated that the slow precession thus introduced would put the moon where it was observed to be and also clear up an apparent difficulty in the shape of the earth brought to light by then up-to-date geodetic surveys. Clairaut had the support of two other powerful reckoners, Euler and Jean le Rond d'Alembert. It appeared that Newton had found only the first term in the gravitational force between mass points. It was just the possibility of this sort of finagling that made the first French reviewer of the *Principia* reject Newton's approach as unphysical; for how, he asked, could the underlying physics be found if the law could always be amended to cover apparent violations? The great defender of Newton in the Paris Académie des Sciences, the Comte de Buffon, insisted on the inverse-square as the only reasonable and rational relationship. Clairaut rejected his opinion as ignorant and metaphysical.

The mathematicians made ready to amend the universal law of gravitation. But at the moment of truth, even Clairaut did not want to change Newton's law merely because it disagreed with the facts. So he returned to his computations. He had not made a mistake. But neither had he been right. He had stopped too soon in his approximations. When carried further, they accounted for the motions of the moon without invoking the r^{-3} precession. D'Alembert and Euler reached similar happy conclusions.

Once again the story carries methodological lessons -- in this case the malleability of mathematical description, the trickiness of approximations, and the danger of premature defeatism (or, as the quantum physicists used to say, renunciation) -- along with information about the moon's motion and some good exercise on the three-body problem.

"Relativistic" fine structure

The spectrum of the two common one-electron atoms -- hydrogen and ionized helium -- differ from tone another in two respects that, briefly, were of the first importance in the development of the quantum theory of the atom. For one, some lines in hydrogen fall very close to, but do not coincide precisely with, corresponding lines in ionized helium. Niels Bohr explained the disparity as a consequence of the greater mass of the helium nucleus and, by a literal application of an elementary mechanical principle to a situation in which, as he said, mechanics does not apply, he calculated the displacement to many places of decimals. The perfect agreement with observation caused many important physicists, including Einstein, to take Bohr's quantized atomic model seriously.

The other significant difference between the spectra of hydrogen and ionized helium was that the helium lines had a fine structure while the hydrogen lines did not. (In fact, hydrogen lines have the same strucure as ionized helium's, but spectroscopists had not resolved it when Bohr promulgated his theory.) Bohr could not find the source of the helium fine structure. Arnold Sommerfeld came to the rescue with the observation that the radiating electron must travel at relativistic speeds. Analytically, the relativistic correction is equivalent to adding a little inverse cube to the Coulomb force, introducing the sort precession invoked by the 18th-century moon men to control the lunar orbit. The frequency of the precession depends upon the eccentricity of the orbit, which is fixed by the so-called azimuthal quantum number k. Applying his version of Bohr's theory, Sommerfeld could calculate the energies allowed precessing ellipses and thence the frequencies of the lines making up the fine structure. They agreed exactly with precision measurements of the satellites of ionized helium. Physicists rejoiced; the agreement reached to five or six places of decimals. That was a remarkable achievement since Sommerfeld's theory lacked what is now the essential factor in the analysis of the fine structure, the inner quantum number *j*.

Using the same relativistic formulas, Sommerfeld calculated the energy difference between the two levels in the L region of the atom -- that is, the second ring of electrons counting from the nucleus -- allowed by his theory. This energy difference agreed perfectly with measurements of absorption edges of x rays associated with the L region. It appeared therefore that the doublet -- the two L edges -- arose from orbits of different eccentricities, characterized by different values of *k*; to be explicit, from a circle ($k = 2$) and a very eccentric ellipse ($k = 1$).

Alas, the L region has three, not two absorption edges. Sommerfeld's dynamical theory supplied only one circle and one ellipse. To label the third, he invoked *j*, which he had introduced, without dynamical significance, to classify the multiplets in optical spectra. Thus he had a "relativistic" doublet he could calculate arising from the diference in the precessional energy between a circular and an elliptical orbit, and a supernummerary level he could not explain arising also, somehow, from the ellipse. To achieve his impresssive agreement, however, Sommerfeld had had to assume that the effective nuclear force in the $k = 2$ circle was exactly the same as that in the $k = 1$ ellipse. That did not seem plausible to those who took the orbital picture literally, since the circle lies entirely outside the innermost electron shell and the ellipse penetrates it. Also, certain analogies between optical and x-ray spectra suggested that Sommerfeld had got his attributions backward; the terms in the relativistic doublet should have the same *k*, but different *j* values. Those who preferred general qualitative analogies to isolated exact quantitative agreements were left without a way to reproduce Sommerfeld's remarkable achievement.

They were almost saved by the invention of the concept of electron spin, which allowed two energetically different orbits with the same value of *k* (and thus the same effective nuclear charge). Unfortunately, calculations of the difference in energy between the levels in these "spin doublets" continually differed from observation -- and therefore from Sommerfeld's successful computation of the "relativity doublets" -- by an apparently irreducible factor of two. Many physicists thought that a good ground for rejecting electron spin. As in the motion of the moon, however, those who pushed the established mechanical theory another step won out. A new relativistic effect connected with the spinning electron, the so-called Thomas precession, supplied just what was needed to bring the spin doublets into agreement with Sommerfeld's old calculations. The striking connection between spin and relativity thus revealed soon found its explanation in Dirac's theory of the electron.

Fundamental principles in relativistic, atomic, and quantum physics can be elucidated by this story, which, of course, also contains a warning against believing in a calculation just because it agrees with observation to seven places of decimals.

The virtual oscillator

A final example illustrates the power of simple means and models. The harmonic oscillator has played a noble part in physics since Robert Hooke first announced in the 1670s, in an undecipherable anagram, *ut tensio sic vis*, the extension of a spring is proportional to its force. During the 18th century, analysis of simple harmonic motion, of coupled springs, pendulums, small excursions from equilibrium, and so on, materially assisted the development of classical mechanics. In the 19th century, with the acceptance of the wave theory of light, the simple harmonic oscillator became a model for the emitter, absorber, and scatterer of radiation. Its use led to astonishingly grand results. H.A. Lorentz made it the basis of his explanation of the magnetic splitting of spectral lines discovered by Pieter Zeeman, and so established the presence of electrons in ordinary atoms. Max Planck's resonator, which drove him to and from and then to the invention of quantum theory, was an electron tied to a harmonic oscillator.

With these successes in mind, subsequent theorists turned to the old harmonic oscillator when they needed a brand new theory. Werner Heisenberg invoked it in the invention of quantum mechanics, to devise the rules for matrix multiplication. The simple harmonic oscillator vibrated in the background throughout the last days of the old quantum theory. The penultimate step in Heisenberg's path to quantum mechanics was a paper he wrote in collaboration with Bohr's assistant Hendrik Kramers. The paper models dispersion using simple harmonic oscillators. It followed a paper by Bohr, Kramers, and the American physicist John Slater that replaced radiating atoms with collections of virtual oscillators as a convenient if unrealistic means to evade the wave-particle duality. This catalogue does not exhaust the tale of the simple harmonic oscillator. To mention only one further inspired application, Enrico Fermi had recourse to it in setting up his form of quantum electrodynamics.

An entire course of physics could be organized around the history of the harmonic oscillator. It would deliver not only more physics than most students and instructors could easily handle, but also point the tough question, why simple models work. Does the fact say anything about the world or does it merely confirm, to paraphrase Francis Bacon, that any step out of a theoretical muddle is likely to in the right direction?

Crossing the bridge

Students who are not jaded or brain dead should develop a curiosity about the people, institutions, instruments, and other circumstances mentioned in the examples just given. The unexpected appearance of cathedrals as solar observatories may be a particularly good hook with which to draw science student across the cultural bridge that supposedly separates them from students of the humanities.

The science teacher can offer tidbits to encourage crossing the bridge. For example, in the case of the obliquity, he or she can point to the apparent discrepancy between the Catholic church's condemnation of heliocentrism in 1633 and its initiation, some twenty years later and within its own cathedrals, of investigations into precisely the same question that had landed Galileo in trouble. Interests thus raised should not be pursued within the science curriculum, however, but in history courses. Similarly, interests in philosophy, art, architecture, and, maybe, history of science, awakened in science courses should be pursued on the other side of the bridge.

Crossing the bridge can bring substantial advantages to science students not only in personal cultivation but also in professional formation. The careers of scientists and engineers outside of academia suggest that replacement of a few technical courses by non-technical ones would not only be harmless, but even beneficial. People seldom get jobs that call for exactly what they studied during their professional training. They learn on the job, the more quickly and effectively the better they understand general principles and procedures. Those who rise the furthest tend to have a broader culture than those who remain at the bench.

3. Present State

Straws in the wind

People who see promise in the collaboration of science and history may take some encouragement from a world-wide survey conducted in 1995/6 during the Third International Mathematics and Science Study (TIMSS). Topics in the history, philosophy, and sociology of science (HPSS) occupied a place in the guides, textbooks, and classroom teaching of most of the forty or so countries surveyed. No less than 15 percent of the space in textbooks used in the eighth grade -- the last year of primary school -- in Canada and the US concerned HPSS; Spain came in at about half that, and the rest of Europe averaged around 5 percent. The amount of class time given over to HPSS by the many teachers who taught it reached 5 percent in Canada and the US; the world average was 3 percent and Spain's 2 percent. The upbeat inferences from these facts are, first, that several countries deem HPSS important for science edcation up to (and indeed including) the secondary level, and, second, that students who learn their lessons in high school would be prepared to profit from further exposure to the history of science in college or university. Evaluations of the survey results suggest that students do well in HPSS also do well in their science courses. Of course they may just be better students in general.

That, unfortunately, is suggested by the fact that Japan, Korea, and the Czech Republic, whose students do best in the world on science examinations, gave relatively little time to HPSS. The significance of this finding is hard to judge, however, since Japanese, Koreans, and Czechs also did well on the HPSS part of the exam. The reports I've used do not provide enough information to test my hypothesis that the HPSS taught in the countries that did best in science was the fertile sort of history of science I've recommended. The North American countries stressed the social and institutional practice of science; Japan, Korea, and the Czech Republic may have chosen examples that furthered understanding of the content of science.

Various groups in the US continue to insist on the importance of the history of science in primary and secondary education. The most influential of these bodies is the American Association for the Advance ment of Science (AAAS). Its "Project 2061" aims to revamp the curriculum in primary and secondary schools to make all Americans scientifically literate by the middle of the century. History of science was built into the reform from the beginning, implicitly in the title of the project, which began under Halley's comet and will terminate when it next returns; and explicitly, in a set of "historical perspectives" or vignettes.

The AAAS gave two reasons for including history. One is grandiose: "some episodes in the history of science are of surpassing significance to our cultural heritage." They mention the shocks to common ideas associated with the work of Galileo, Lyell, Darwin, and Pasteur. The second reason is closer to practical pedagogics. "Generalizations about how the scientific enterprise operates would be empty without concrete examples." Take the assertion that new ideas are limited by the context in which they arise and advance through refinement and development by many individuals. "Without historical examples, these generalizations would be no more than slogans." This reasoning gives ground for hope. The process of refinement and development of scientific ideas in response to new discoveries and well-taken objections has left particularly valuable historical material for teaching the substance of science.

Without waiting for the return of Halley's comet, the European Physical Society, through its History of Physics and Physics Teaching Division, began to support biennial conferences on the use of history in science pedagogy in 1983. An International History, Philosophy and Science teaching Group formed in 1989 around a special issue of the journal *Synthèse* and has continued to generate rhetoric and scholarship on science education, much of which is published in the international journal *Science and education*, founded for the purpose in 1992. In 1996, the All European Academies network (ALLEA) decided to convene a meeting on the role of history of science in university education. The conference took place in Strasbourg in 1998. Its proceedings include reports on the state of the history of science in the various European countries.

The first and last of the ALLEA reports indicate the the range of possibilities. The Austrian respondents could not point to a single chair in history of science in any of their universities. They found a small unit for the history of science in the University of Vienna and one on the history of physics in the Institute for Experimental physics in Graz. At the other extreme both substantively and alphabetically, the United Kingdom boasted 24 universities that offered undergraduate courses in history of science or history of medicine and 27 that offered postgraduate courses and research degrees; they employed more than 100 professional historians of science. Other professionals work at the Royal Society, the Wellcome institutes, the great museums, and so on. Spain falls between the extremes, with 17 chairs and associate professorships in history of science, and 46 in the history of medicine. The field is strong at the graduate level and should be able to help produce the teachers required for bringing history to bear on the teaching of science.

Spain has a good start on the necessary infrastructure. Not much money is required to make a difference. An indication of what can be done with relatively little is the program of the Fundación Canaria Oratava de la Ciencia, set up in Tenerife in 1999 by a group of university professors and secondary school teachers who had been working together for a decade. They saw that history of science could be an important tool for improving the teaching of science and promoting understanding of the application and misapplication of science to technological innovation. The Foundation obtains support from various local institutions for its studies of the history of science and its efforts to integrate the subject into teaching at all levels. To jump start the process, it holds courses on history of science for teachers and professors, who bring what they learn back to their own classrooms. The Founation has prepared materials for courses on history of science at the secondary level to be used throughout the Canaries, perhaps the widest such offering in the history of science in Spain.

There is an even larger amount of useful material in the many journals for the history, philosophy, and sociology of science and technology published around the world, and in the books and periodicals dedicated to science education in schools and colleges. It is there for exploitation free of charge by any teacher with sufficient energy and purpose.

A test

It should be easy to test the claim that the use of materials from the history of science can strengthen science teaching. All that is needed is to set up courses with and without the historical materials, assign students at random to them, and examine all the students on the same scientific questions. To insure a persuasive outcome, the questions should be set by scientists and the materials materials from the history of science must be prepared in collaboration with historians. Scientists do not have the time to search for the most instructive episodes; for those are just the ones most likely to be suppressed by the advance of science. Let me give you one example of what might happen without the collaboration of informed historians.

The tireless popularizer of modern physics, John Gribbin, has just published a big book entitled *Science: A history, 1543-2001*. It is the first single-volume general history of science to appear in English for many years. It would be churlish to criticize Gribbin's wide-ranging, good-natured book for errors in history and neglect of documents; but it is fair to fault him for bad physics. For example, he writes of Rutherford's famous experiments bouncing alpha particles off gold foil, that "because the alpha particles carry two units of positive charge, this could only mean that occasionally they were being repelled by approaching head on other concentrations of mass carrying positive charge." The statement and conclusion are false.

Had Gribbin looked up the historian's literature, he would have discovered that for a time Rutherford thought that the atomic scattering centers might be negative. Assuming, as Rutherford did, that Coulomb's law holds throughout the interaction, the rebounding alpha particles described hyperbolic orbits; and hyperbolic orbits occur under an attractive as well as a repulsive inverse-square law. In the attractive case, the incident alpha particle goes around the scattering center as an eccentric comet in the solar system goes around the sun. A tightly bound atomic electron could backscatter an alpha particle if the collision were close enough. Rutherford's argument in favor of a concentrated scatterer or point nucleus, whether plus or minus, was statistical: from the latest findings of J.J. Thomson, Rutherford could work out that the atom did not contain enough electrons to turn around alpha particles in the proportions observed. Rutherford's invention can be used to teach and enforce important facts about motion under central forces and to illustrate the use and inevitability of probabilistic considerations in microphysics. But to do that, the story of the invention must be got right.

Let us prepare the right materials and the teachers to use them, try the test, and determine whether or not, in our age as three centuries ago, history has something to offer as a collaborator of science.