A HISTORY-OF-PHYSICS LABORATORY

A laboratory in which students can reproduce historically significant physics experiments provides them with a useful change of viewpoint.

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DURING THE PAST FEW years we have been developing, at Columbia and Barnard Colleges, a somewhat unorthodox vehicle for teaching physics, a combination laboratory and library designated a History of Physics laboratory. In it some of the experiments that have played a major role in the development of physics, for example those of James Joule, Heinrich Hertz, Michael Faraday and Charles Coulomb, are being reconstructed, with proper attention to their significant historical features. The methods and materials used in these experiments are essentially those used originally. We want to provide students with an opportunity to repeat these experiments and to appreciate the significance of each in its own historical context.

When, after much deliberation, we decided to embark on this venture, we met with the expected reaction (at times our own as well as our colleagues'): "Not another new approach to physics? Surely there are already enough new courses and systems and experiments in the educational hopper to satisfy any appetite for innovation. Is not now the time to exploit and improve, in practice, as teachers, rather than advocate and reform, as educators?" Even the most ardent reformer must feel the timeliness of this exhortation although he may believe himself exempt from its restraint. Under the circumstances we could not but feel some diffidence in proposing even some modest innovation.

We started, however, not by asking whether or not there was now sufficient variety of developed courses in physics to suit all tastes and purposes, but rather why there has been among this generation of physicists (and scientists generally with physicists in the vanguard) such sustained zeal for educational reform.

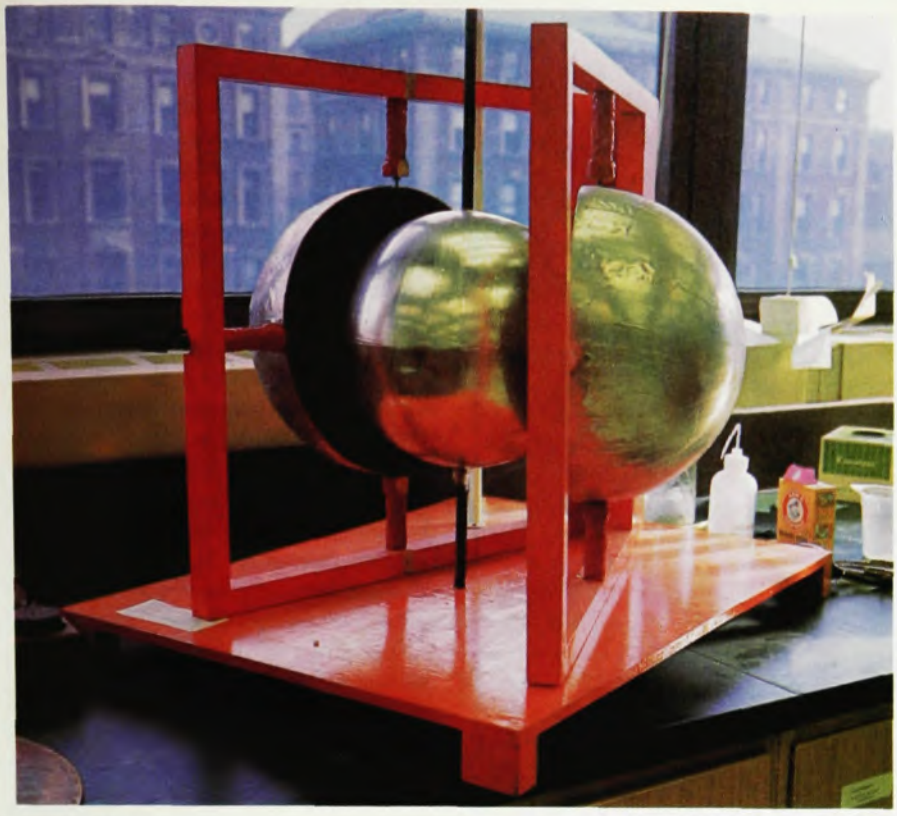
Physics has changed vastly and perhaps those who would or should learn it have also changed. Have the advocates of reform found that the methods of a generation ago, the regimen on which they themselves were reared, are totally inadequate for the needs of today? Yet, paradoxically, among the reformers are some of the most distinguished physicists, those who display an outstanding understanding of the subject they may have been so inadequately taught!

The paradox is not very profound. Who, after climbing to a level of understanding where a whole subject can be seen in full perspective, does not see alternative pathways that lead to this vantage point? And who, having achieved such perspective, does not feel that the path would have been easier had he acquired this perspective from the start? But some shortcomings of the earlier approach that appear in retrospect may be illusory; enhanced understanding derives not only from substitution of the view from the top for that from the ascent, but also from combination of the different viewpoints. No matter how clear the picture afforded by a single viewpoint, a view from a different one can throw the whole picture into new relief. By occasionally standing on one's head, one may be better able to appreciate what supports one's feet.

Our concern as teachers is primarily with teaching contemporary physics, whether it be to those who wish to understand its place in the larger scheme of things (physics as part of contemporary knowledge, or physical science as a cultural or social force) or to those for whom an understanding of physics will be essential in professional life. We assume that these purposes will be served, for the most part, by a systematic presentation of the subject at whatever level is appropriate. And this we expect would be predominantly theoretical and conceptual. The historical and practical aspects of the subject traditionally play an uncertain and subordinate role. Why have we focused our attention on the instructional value of these two aspects and their interrelation? For an answer, it is useful to examine the usual instructional laboratory.

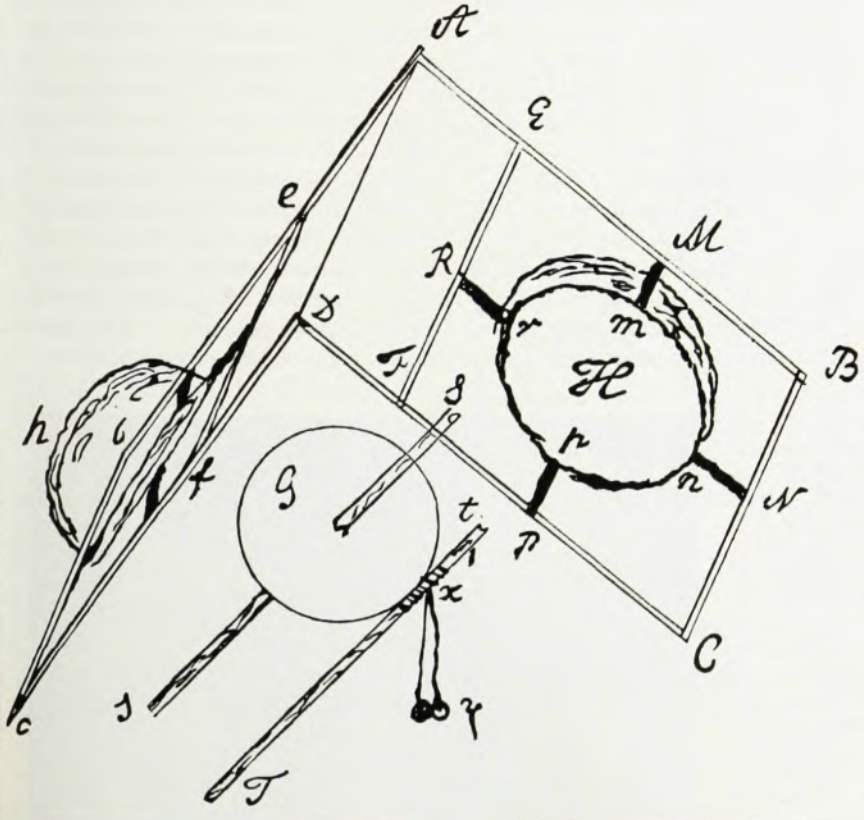
The instructional laboratory

As a supplement to other physics courses, the laboratory offers a means of illustrating physical principles and their application in "real" situations. It can provide an introduction to the art of experimentation, a training in precision measurement, an opportunity to develop skill in observation or to gain familiarity with the properties and limitations of actual materials and techniques. It might be a place simply to observe interesting and unusual physical phenomena. There are,



CAVENDISH

Concentric-sphere apparatus that Cavendish used to demonstrate the inverse-square law of electrostatic force. He verified that, when the outer sphere is closed and the surfaces of the two spheres are connected electrically, the "electricity" resides wholly on the outer surface. Cavendish's analysis of the results led him to conclude that the law of force was an inverse-square law similar to the Newtonian law of gravitation. Drawings are from Cavendish's notebooks.



however, severe limitations to all these opportunities.

Consider first the art of experimentation. This should include the conception of an experiment as well as design of the apparatus that materializes the concept; in the instructional laboratory the apparatus usually must be set up beforehand. Precision measurement? Potentialities of the apparatus are limited, and even these can not usually be fully exploited in the time available. Critical observation? The student must be told what he should observe, or too much is left to chance. Properties of materials and instruments? The equipment is ready-made, and the student does not usually know how or why.

In times past the laboratory did, no doubt, afford a unique opportunity to observe and study many physical phenomena; sophisticated physical artifacts were rare outside it. But now, with transistor radios, television tubes, tape recorders, photoelectric-range-finding instant image-forming cameras and orbiting satellites all familiar objects, spectacular manifestations of physical science are as abundant outside the laboratory as within it.

And yet most of us persist in the belief that laboratory instruction, with all its limitations, retains some value. We compromise with the ideal of the laboratory as an avenue for free initiative and spontaneous discovery, but only because of the inescapable recognition that "ars longa, vita brevis." This we can not change, but we can perhaps be more aware of what the compromises are. What, in fact, is the rela-

tionship between laboratory exercises and the actual process of experimental investigation and discovery?

Frames of reference

No matter how we arrange an instructional laboratory then, any observations, measurements, or discoveries made therein are not simply objective exercises in physics. What is done must in some degree reflect the scope of the resources and opportunities provided, and what is learned must, whether one is aware of this or not, depend on available techniques and some assumed framework of concepts. Whatever the emphasis, whether it be measurement, observation or interpretation, the proper significance of an experiment emerges only when it is related to this actual framework of concepts and accessible techniques and methods. This practical and conceptual framework is not always, perhaps not even usually, fully recognized. And even when it is, to delineate it precisely is not a simple matter.

In *principle*, explicit delineation should be most straightforward for a significant experiment in some contemporary aspect of physics. The proper conceptual framework would then be all relevant current concepts, theories and methods. Choice of experimental techniques would be limited only by the immense range of contemporary sophisticated instrumentation. (In principle, local budgetary considerations should not enter!) We are describing, of course, the setting, knowledge and understanding that are a basis for research. This corresponds to the goal of education, rather than to some step on the way.

At early stages of learning, or when an understanding of only some particular part of the subject is being developed, a more restricted framework may be invoked. One can, for example, assemble a very modest set of simple techniques and materials, associated with a limited range of possible phenomena, and leave elementary "discoveries" to be made spontaneously. This method may be an excellent one for introducing science to the very young, but for a more sophisticated level of instruction it has, as already remarked, severe limitations. Another approach is to circumscribe sharply a specific part of the subject matter, to furnish the relevant conceptual, analytical and technical background for this restricted part of the subject and then to do exercises within this context. In such approaches, where the framework is far less than the full contemporary one, the restriction is always to some degree arbitrary or ill defined, so that the purpose of what is attempted and the nature of what is achieved are obscured.

In the instructional laboratory that we have been developing, the special feature is an emphasis on the relationship between the "great" experiment and its historical context. In the repetition of some historically important experiment there are present many of the ingredients of any instructional experiment, and in addition an illustration of how some particular combination of imaginative perception, observation, measurement and deduction can make a pronounced impact on the development of physics. Such experiments invite an approach in which the conceptual and technical framework is explicitly delineated; the framework is the actual historical context.

Repetition of the experiment is only part of the exercise; equally important is some appreciation of the state of development of physics at the time when the experiment made its significant impact. Preliminary historical study is a necessary and integral part of every laboratory experiment, hence the associated library.

Historical versus logical

Elementary instruction can fail to exploit the full significance of historical development not only by ignoring it but also by assuming implicitly that logical development always follows the historical path. Or, to put the matter more frankly, many an elementary exposition creates the impression that history has followed the path of development chosen by the expositor, implying, perhaps, that little further is to be gained by explicit historical study. Maybe this attitude is encouraged by an analogy from science itself, the old dictum "ontogeny recapitulates phylogeny." There are certainly parallels between the development of a science as it presents itself to a learner and the historical evolution of the science. But there are also, especially nowadays, many disciplines in which the two developments stand in marked contrast. And independently of this reason, awareness of historical evolution can throw valuable light on the contemporary logical structure.

Could the advantages to be derived from occasional adoption of an historical viewpoint be obtained more simply from literary activity alone? Is this close juxtaposition of historical and practical of special value? The answer to this question might depend on whether one regards the combined activity in terms of the influence of the historical viewpoint on the laboratory work or vice versa. These influences are distinct; both may be valuable.

Insofar as many of the exercises performed in a physics laboratory are intended to demonstrate physical *principles* themselves (as distinct from limited exercises in problem solving with assumed principles), they often have an air of triviality quite incom-

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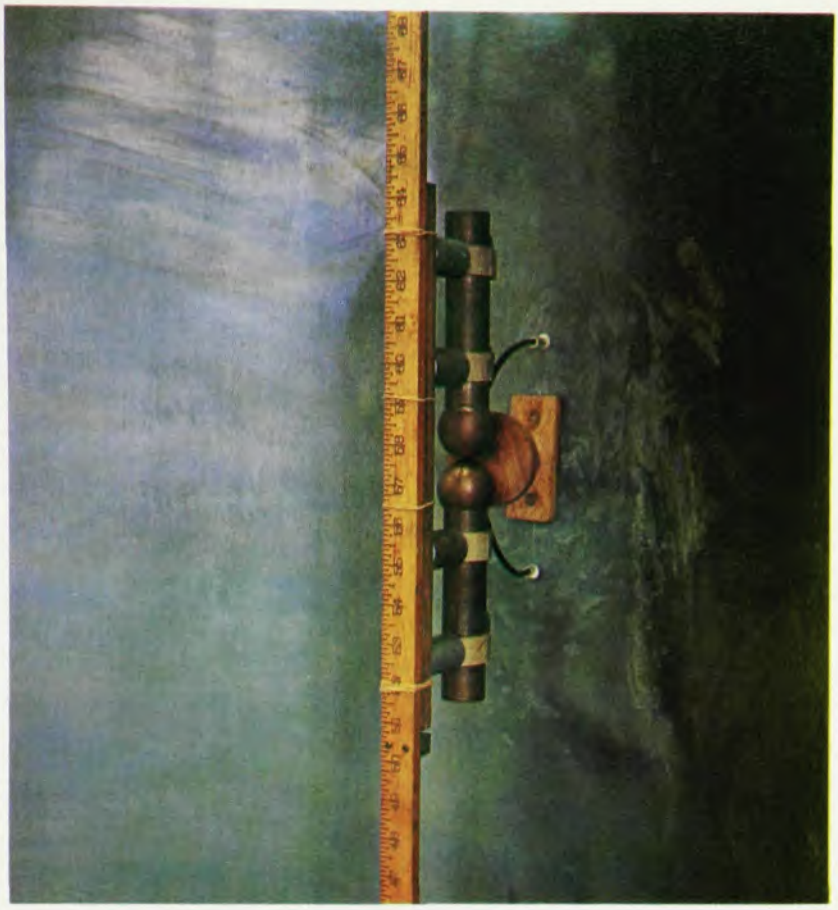
mensurate with the imposing nature of the principles at issue. This is surely because the principles themselves are often thoroughly well known, their validity accepted on impressive authority of their discoverer and confirmed by numerous applications. Which student setting out to "measure" e or e/m does not know that e is quantized and that the value of e or e/m is tabulated in every text? And, if his experiments yield a different result, is the student willing to challenge weighty authority with his own findings? After all, he probably used some standardized "educational" equipment labeled "oil-drop experiment" or "e/m apparatus" (whose relationship to Robert Millikan or Joseph J. Thomson may be obscure), so that what he discovers may reflect as much on his equipment as on physics or its history.

If, however, he attempts to repeat these experiments using only techniques available to Millikan or Thomson, with a clear picture in mind of just what was known and understood at that time, his experiments will no longer appear trivial, nor need the results themselves be regarded as measurable against the standard of what appears in textbooks today. His own observational powers and experimental skill may fall short of that of the illustrious predecessors, so that he may not learn even as much as they did. He will, however, surely appreciate something of the magnitude of their achievement both in the concept of the experiments and in their outcome.

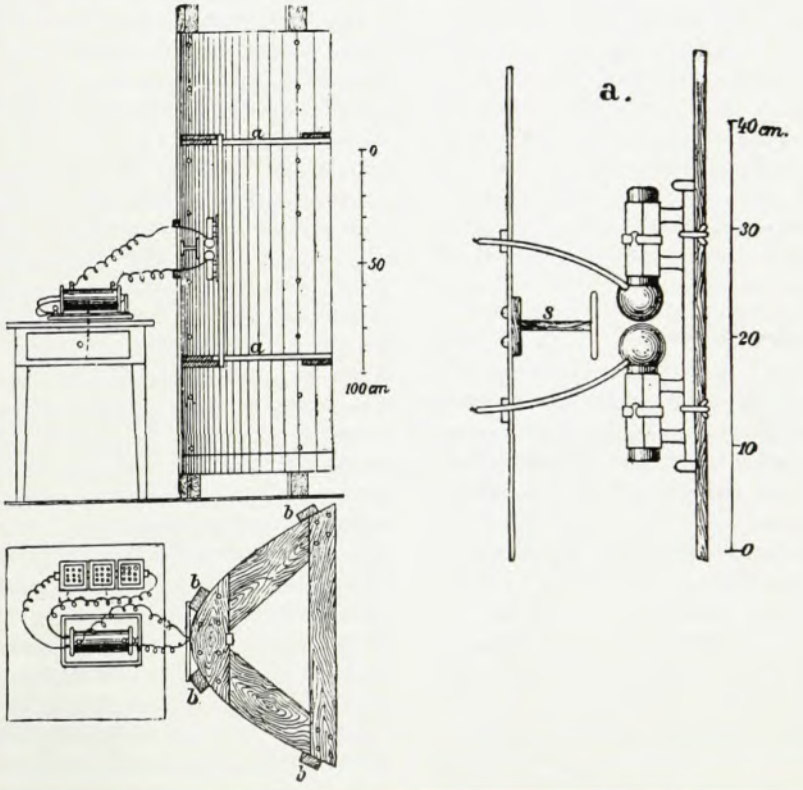
If the student were to summarize his findings, they might read: "With the techniques and concepts of physics of 1895 (and with no greater resources than might have then been available) I have found that the ratio of charge to mass for all cathode rays appears to be the same universal quantity, some 2000 greater than that of the lightest atom." It would certainly not be a simple didactic assertion about the value of e/m for the electron. In brief, the student will be well aware that doing exercises in physics and doing physics, although related, are two distinct activities.

From the standpoint of historical appreciation, there are also real advantages in relating historical development to laboratory experiment. A tendency in exclusively verbal and written exposition is to dwell on the narrative or to overemphasize the theoretical, conceptual aspects of the sub-



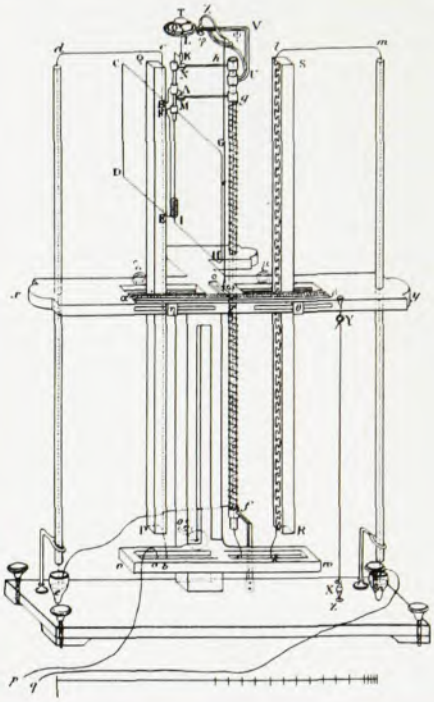
HERTZ

Detail of Hertz's transmitter, as reconstructed in Barnard laboratory from Hertz's drawings. Engraving shows the Hertzian dipole connected to the Ruhmkorff coil used to excite it. With a similarly mounted receiver, one studies optical properties of electromagnetic radiation.



AMPERE

Demonstration of the vector properties of a current element. Reconstructed apparatus was built from a description and engraving in Ampere's published works. This is one of an elegant series of experiments. Austerely simple, impeccably logical, and with apparently unequivocal implications, these experiments have more the character of steps in a mathematical proof than of actual experimental findings.



ject. That all experiments are conceived, executed and interpreted within some conceptual framework, that experiments can be designed only within limits of technical possibilities, that familiarity with certain types of technique and artifact both proscribe and extend the range of theoretical ideas—all these are aspects of historical development that can be very forcefully exposed by performing and scrutinizing actual experiments in their proper setting.

Selecting experiments

Not all (nor even most) historically interesting experiments are suitable for a history of physics laboratory. Some experiments are technically impractical, others too time-consuming. Many do not, in their historical setting, particularly illumine the logical structure or context of the subject. (Technical scale elaboration as well as conceptual sophistication are, incidentally, factors that mitigate against the choice of many important contemporary experiments for instructional purposes, and so lead one to seek illustrative material from the past.) But many of the experiments important in the development of physics *are* suitable. They range from the most elementary to the quite sophisticated. We have chosen some 25–30 experiments or groups of experiments that were of major importance in advancing the physics of this day.

Consider, for example, the significance of Hertz's experiments for their own time. Few physicists have equaled the outstanding combination of experimental skill and ingenuity and great analytical power that Hertz brought to his researches. This research was not only decisive in placing James Clerk Maxwell's electromagnetic theory beyond the range of controversy, but was also seminal for the whole new technology of electromagnetic-wave propagation (see box page 47). In his brief life (1857–94), Hertz set out to test Maxwell's theory and its major prediction, free electromagnetic waves with velocity equal to that of light. He succeeded at this task in a remarkable series of experiments, but first he developed the essential techniques for generating and detecting very high-frequency electromagnetic-wave trains. Making quantitative measurements, inferring frequencies (in the range 10^9 cycles/sec), measuring wavelengths and verifying and relation $\lambda\nu = c$ were quite spectacular accomplishments at a time when techniques for quantitative measurements were common only at frequencies many, many orders of magnitude lower.

The experiments that we have reconstructed or plan to reconstruct span the development of physics from the 16th (Galileo, William Gilbert) to the 20th (Ernest Rutherford, Max von Laue, the Joliot–Curies) centuries. These will not comprise a complete coverage of the whole development of physics; they are intended to be illustrative rather than exhaustive. The general spirit of the laboratory is that it be not a self-contained course of physics but a complement to one. Admirably suited to our purpose are many of the basic discoveries in the development of electromagnetism, from the mid-18th to the late-19th century. We have set up, essentially in their original form, a whole sequence of the seminal experiments of

Benjamin Franklin, Henry Cavendish, Coulomb, Allessandro Volta, André-Marie Ampere, Faraday, Joseph Henry, Georg Ohm, Maxwell and Hertz, all of which seem capable of providing valuable lessons, even now.

One of the groups selected is the elegant series of experiments by which Ampere demonstrated the mathematical form of the force between "current elements"; these studies are among the most famous in electrodynamics (see box, page 48). Their conception, style and execution as well as the account of them by Ampere, are extraordinary if not unique. Austerely simple, impeccably logical and with apparently unequivocal implications, they have more the character of steps in a mathematical proof than of actual experimental findings.

Interpretation of his experiments led Ampere to believe he had analyzed electrodynamics on sound Newtonian lines, and this analysis provided in turn a solid basis for his conviction that he had reduced magnetism to a manifestation of electricity. Assessment of Ampere's achievement has varied with time and circumstance. Faraday, in 1821, said "the experiments . . . are few, and theory makes up the great part of what M. Ampere has published, and theory is in a great many points unsupported by experiments." (Quotation is from S. Ross.[1]) Many years later, however, Maxwell would write that "the experimental investigations by which Ampere established the laws of mechanical action between electric currents is one of the most brilliant achievements in science . . ."[2]

Another experiment we have chosen to reproduce is Cavendish's demonstration of the inverse-square law of force, now commonly known as Coulomb's Law. Cavendish did his investigations more than a decade before Coulomb's but, because they were largely unpublished, their significance was not fully appreciated. More than 100 years later (1879) this remarkable series of experiments became known through a publication edited by Maxwell. Cavendish's method of investigating the law of force between charges is, although less direct, capable of far higher precision than Coulomb's (see box page 45).

In each case the equipment is more or less a copy of that described in the original publications, although not with all the minutiae that might be considered important for museum exhibits. We have tried, however, not to err by modernizing techniques or materials to the extent that a historically essential feature could be misrepresented. Where small, but not physically trivial, changes must be introduced, for example to reduce the time (or skill) demanded of the student, we have drawn attention to these changes and their purpose. More importantly, one can not in most cases expect a student to retrace all the actual steps, the whole sequence of searching, probing, trial and error to which so often, the "historic" experiment was a crowning climax. Here we rely on documentary material to provide the necessary setting.

Selecting literature

The familiarization with both immediate background and general historical context is perhaps the most difficult part of the enterprise, both for student and teacher. How can we recreate the atmosphere of physics—the accepted concepts, technical possibilities and limitations, salient issues of controversy and the ideas held sacrosanct, as well as the broader intellectual and social environment of some past epoch? How can we present this succinctly, so as not to make unreasonable demands of time and effort, and yet avoid the pitfalls of canned histories, which falsify by oversimplification? This problem has occupied much of our attention.

Some contact with scientific literature of the period, both original papers and memoirs as well as expository material of the period, seems essential. We hope that a judiciously chosen sequence of short extracts from such sources, connected by a thread of commentary and combined with a carefully compiled bibliography for the more adventurous, will provide, in return for a reasonable effort, a reasonably faithful picture of the historical setting. This background will form a major part of the instructional material furnished for each experiment.

There will be brief guidelines to help the student in the actual experimentation, in interpretation of the outcome of the experiment, and in assessing its impact on the physics of its time. The more sophisticated student will, we hope, be encouraged to complement his contemporaneous assessment with a review in retrospect; one that exploits the wider historical perspective that subsequent developments permit.

We have, with the cooperation of a few interested students and the generous support of the National Science Foundation, prepared sufficient material, both written and practical, for a modest and preliminary trial of the instructional laboratory, in which students from Barnard and Columbia Colleges have participated. We can not conclude from this limited experience that our efforts and expectations have been justified, but we do have some reassurance that we are not entirely mistaken. *Some* students, at least, do find in this approach and emphasis an interest they do not associate with more orthodox laboratory instruction. Especially for those who have no intention of becoming professional scientists, the emphasis on historical context does seem to evoke a response that the formal science itself does not. For these students the methods of science are usually unfamiliar and alien to their intellectual concerns and aspirations. Close juxtaposition of the historical, conceptual and practical helps to connect elements so often divorced, the human and the scientific. In the history of physics laboratory the student is confronted not only with the formal contents and potentiality of science but also with a glimpse of historical actuality, the thoughts and aims, as well as the achievements, of individual persons working in a particular social and intellectual environment.

There are also students whose appetite for physics (or science) demands nourishment rather than stimulation. For these students the novelty of the viewpoint adopted does seem, at least occasionally, to throw familiar concepts into a new relief. This contrasting viewpoint often provides the stimulus for a more critical and thorough understanding.

What evidence we have of the value and viability of our approach is meager but encouraging. It does seem possible that one can, through a history of physics laboratory, make a modest contribution to the better understanding of both physics itself and its significance as a part of human endeavor. For some students, at least!

References

1. S. Ross, *The Search for Electromagnetic Induction, Notes and Records of the Royal Society*, **20**, 203 (1965).
2. J. C. Maxwell, *Treatise on Electricity and Magnetism*, **1**, 162 (1873). □