The Role of Experimental Work*

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The difficulties in making the physics laboratory truly a part of the education of students are considered. The tendencies toward the use of less standardized equipment and toward allowing more freedom to the students are resulting in improvements, but they, in turn, introduce new problems—those of cost, of the preparation of laboratory assistants, and of the prevention of over-specialization at an early stage. Among the activities that offer hope for the improvement of our laboratories are the work of the AAPT Committee on Apparatus, especially the Apparatus Drawing Project. Broad specifications of the requirement for good instructional apparatus and laboratory instructions are outlined, and instructors are encouraged to engage in a continuous process of change in their laboratories. Finally, some of the educational achievements of well-run experimental work are listed and discussed.

IN a recent contribution to the series of articles on "Adventures of the Mind," appearing in the Saturday Evening Post, John Wain, an English writer, has this to say. "Education is essentially a process of launching. An education of whatever kind has failed if it has not managed to stimulate in the student that kind of intellectual curiosity which will naturally lead him, year by year, to extend his knowledge. And also, it should give him the necessary basic information to build on, not only factual information but skills of a kind that do not show themselves in a parade of facts."

A student physics laboratory should, I believe, be part of a student's education. To design and operate such a laboratory to meet the requirements laid down in the above statement so that it becomes part of a student's education is not easy. I have come to the conclusion, as I am sure many of you have also, that the basic ingredient entering into the satisfactory running of such a laboratory is hard work.

Let us look at this item a bit—this important ingredient of effort. I recall vividly my senior year in college when I was in charge of a physics laboratory at Pomona College. Professor Tileston was an excellent teacher, a hard worker, and demanding of his students and assistants alike. This was my first experience in running a laboratory and the first time I had seen most of the experiments, although I did have quite a bit to do with setting up the apparatus. There was a number of subtle points in regard to the proper manipulation and operation of the apparatus that I just was not familiar with. I remember Tileston coming in nearly every laboratory period, sensing out where there were difficulties, and in a quiet, unobtrusive way, leading the students as well as the instructor along a carefully explained path so that the difficulties melted away.

It isn't everyone who has the gift to teach that some are blessed with, but I am sure that Tileston would never have sent on the dozens of students he did to graduate work and would not have been chosen for the Oersted medal were it not for a lot of hard work.

I have been running laboratories for 35 years and do not regard myself as having achieved great successs in all that time. Somehow I think everyone else so engaged has difficulties similar to my own. In the larger schools, the mere numbers involved become a problem of major proportions. How does one give a meaningful laboratory experience to 800 to 900 students? We have a serious enough problem at Caltech with a class of 160 to 180. As much as many of us would like to run all the laboratory ourselves, this is physically not possible, and we must rely upon teaching assistants. Here is one of the biggest problems, I believe, and one that is the most serious with us. How do we train graduate students to be effective laboratory instructors?

With the physics laboratory of 40 years ago—and I suspect the same applies even to some laboratories today—the instructor in charge could sit back at a desk in one corner of the room, see that order was maintained, and watch his student grind through the directions for his ex-

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periment as written up in some laboratory manual. At the end of two or three hours the student finishes, he writes up a report during the week, he hands this in, and does a similar cookbook experiment next week. In such a case a laboratory was usually regarded as a necessary evil.

But the days of simple, standardized experiments and apparatus are passing. Even the elementary laboratories are becoming more sophisticated. Oscilloscopes, amplifiers, and photocells for timing and various other complex, auxiliary equipment are becoming part of the modern, introductory physics laboratory. For some time my own tendency was to resist the introduction of such items. The reasoning was that nothing should be used in an introductory laboratory that the student did not understand. But if one is consistent about this, then one would rule out such things as stopwatches, clocks, electric motors, magnets, induction coils, and a host of other items. True the oscilloscope is more complicated than the induction coil, but the black box is there in each case. The chief difference such new items make is in the cost involved.

Such equipment makes it more imperative that teaching assistants be instructed in the proper use of such apparatus.

Graduate assistants may not even be familiar with much of the apparatus used in a more advanced laboratory. In our sophomore year such experiments as the Zeeman effect, isotope shift in the spectral lines of hydrogen and deuterium, the L lines of the x-ray spectrum of tungsten, the Franck-Hertz experiment, and others use apparatus that they may not be familiar with at all, and they will need special instruction before they attempt to run such a laboratory.

A conference on the training of college physics laboratory assistants was held at Northwestern University in 1954. I think it is well to get together and compare notes once in a while to get ideas and stimulate our own thinking.

So much for the personnel running the laboratory—a person in charge who is dedicated to seeing that the laboratory is run properly and his student assistants whom we would all like to see dedicated also.

Now as to the laboratory itself. There are, as you know, two extremes which have been tried. There is the standard cookbook variety of laboratory in which apparatus is purchased from one of the apparatus concerns, and a standard set of directions is used in performing the experiment. This kind of laboratory has been alluded to above. To run such a laboratory puts the *least* demands on those in charge. Then, there is the so-called "free-lab" that various institutions have tried at one time or another. Such a laboratory is *most* demanding of those in charge.

From the student's point of view, the free-lab has many advantages. It gives him freedom to use his imagination, ingenuity, and often his time as he wishes. For the right student this can be a very valuable experience. His interest runs high, and he does much of his thinking and planning outside his laboratory. He tries to put into practice his ideas. He is the one who then must see that the equipment he has gotten together actually works. He has no written instructions. He talks with his partner or his fellow students on how best to do what is needed, either in the way of constructing the apparatus or procedures in using it. This is wonderful and constitutes an experience long to be remembered. All this is on the credit side of the ledger.

On the debit side are some rather serious holes that more than likely will result. Among these may be listed:

(1) The student may never really learn to use such simple tools as micrometer calipers or to read scales, of one kind or another, properly.

(2) He may never learn the important rules for keeping a notebook—tabulating data and drawing graphs.

(3) His experience will undoubtedly be very limited. He may learn more and more about less and less until he knows everything about nothing.

(4) Unless the student is quite gifted in devising his own experiment and procedures, his time may be pretty much wasted.

(5) Unless the instructor in charge is himself a good experimentalist, he may not have the interest or know-how to guide the student properly.

(6) Often neither the student nor the instructor knows what apparatus is available, and much time may be wasted and disappointments occur because equipment cannot be found.

(7) To really carry out such a free-lab program much equipment must be provided which may or may not be used. In other words, such a program is expensive in material as well as time.

I believe that most departments that have tried the free-lab principle have retained it in a modified form. Used properly, it can be a great stimulus to the proper student and can be applied to every laboratory that is available throughout the college course.

Many students have not had a pre-college interest in physical phenomena, some develop it the first year or two in college, some develop it later, and some never develop any interest in the way nature behaves. What we would like to see is for students to become sufficiently interested in the behavior of something or other that they will take the time to perform an experiment for their own satisfaction.

There are many things of this sort. I remember a story Feynman tells about an experiment he once performed. He considered the usual rotary lawn sprinkler with curved arms that rotates when water is forced through it, thus sprinkling the lawn. He asked himself the question as to what would happen if he put this sprinkler in a barrel of water? He thought he knew the answer to this one. Then he asked himself, what would happen now, if instead of forcing water out of the nozzles, he sucked on the hose and drew water into the nozzles—which way would the sprinkler turn, if indeed it turned at all? I wonder how many here would have a ready answer to this question. A simple experiment would easily decide.

I wonder if it would not be worth while trying to capitalize on the ingenuity of students. As far as I know, there is no organized program to award prizes to college students who devise experiments or make apparatus. Most of the programs apply to high school students, I believe, and often are on a local level. There is a Westinghouse program, but I believe this applies to high school or perhaps junior college students. The AAPT has sponsored an apparatus competition on several occasions and plans to continue this. I wonder if it would be worth while to somehow sponsor a program that would award prizes for ingenious apparatus or experiments for the college student. I would think it could well be on a national level, but with local screening to end up with say 25 good experiments. The experiments would be designed either to demonstrate some principle of physics or to be capable of yielding data that could be used to arrive at a result of physical interest. If the prize were worth while, and it could be, for example, a travel prize to some laboratory of the world or a scholarship, I am fairly sure some good results would come out.

We have discussed the free-lab idea, but most institutions will probably find that such is not practical on any large scale for their particular institution. Our next concern then is to discuss how to stimulate interest in the performing of experiments with apparatus that has already been designed and built.

I think we will all agree that, whatever is done, we must manage somehow to stimulate interest. I am convinced that, given the right instructor, interest can be created, and a meaningful laboratory experience for the students will be guaranteed. I have seen this kind of laboratory in operation. It was such a laboratory that if you had removed the instructor, the laboratory would have fallen to pieces. The apparatus was simple but effectively used. Again, few of us are so gifted, and we must rely upon other things to create interest.

There is considerable effort being expended in this country to devise and make available new and better pieces of laboratory equipment. One of the stated aims of the Commission on College Physics is to stimulate interest in making new equipment. The American Association of Physics Teachers, together with the American Institute of Physics, has a very active Apparatus Committee that is working hard at trying to improve the apparatus situation in the physics departments of the country. A number of institutions individually have programs going for improving and devising new apparatus. If nothing comes out of these efforts, there has been and will be much time wasted.

Those of you who have seen the apparatus competitions that have been run by the Apparatus Committee at the annual meetings in New York will agree, I think, that there is a number of good ideas that have been worked up into workable apparatus. Also, those of you who have followed the Apparatus Drawings Project operated jointly by AIP and AAPT will appreciate, I think, that not only are there interesting pieces of apparatus in various departments of the country, but drawings now exist so that other departments can go ahead and have similar apparatus made up. It would be desirable if some of these were available commercially, and we of the Apparatus Committee are trying to interest commercial concerns. But, as you know, the wheels grind slowly, and few companies are willing to gamble on a market.

Let us try to analyze what constitutes an interesting experiment. I submit that each piece of apparatus must meet one or more of the following requirements:

(1) It must have a good appearance—eye appeal if you wish, i.e., it must look new or well looked after.

(2) It must be unusual in some way. One way is for it to be capable of giving results with a small error. Another way to stimulate interest is to operate in an unusual way—contrary to the students' preconceived ideas. The air pucks and air troughs and air-bearing devices are good examples. Even unusual size often makes what might be an ordinary piece of apparatus one of more appeal.

(3) The apparatus under study must come apart so that the student can see the essential parts. With modern-day plastics many pieces of equipment can now be made so that one can see what is inside.

(4) It must perform as advertized.

(5) It must be capable of occupying the student's attention for more than the full laboratory period.

What I am trying to say is that somehow the apparatus must command the respect of the student, otherwise he will probably not get interested. Here again the instructor becomes all important. An instructor with a lot of enthusiasm can make any piece of apparatus sound much more appealing than the drab variety many of us have to deal with.

I do not maintain that every piece of equipment must meet all the above conditions, but I believe one or more must be met. To do better than some of the commercial manufacturers in these respects is one reason many of us have undertaken to design and make our own equipment. I may say here that NSF has had a program of financing the development of apparatus, and I understand that next year this program is to be expanded.

I should also like to make a few comments about laboratory directions. These fall between two extreme categories—(a) the cookbook variety and (b) no directions, i.e., the student is turned loose and asked to come up with a result. In choosing between extremes most people in charge of an undergraduate laboratory choose a middle course. In general, however, the best procedure is to give as few specific directions as your students can take. In other words, leave something for their imagination and ingenuity. I have often suggested to my students that they leave their mimeographed lab notes at home and figure out their own procedure of arriving at numerical results.

I believe another essential in keeping a laboratory alive is to always keep it in a state of flux. Each year old experiments should be re-evaluated, some thrown out, and others introduced. This means a re-evaluation of the laboratory instructions as well as the apparatus used. Psychologically this is desirable from both the instructor's and students' points of view. If they have the feeling that something is being done, changes are being made, and effort being put in to keep the laboratory up to date, there is an added reason for morale to be high.

Sometimes I think that it is not as important, as far as students are concerned, that the changes made in any given situation are intrinsically better. The important thing seems to be that the students should feel that changes are being made.

We next come to the maintenance of a laboratory. With more electronic devices and other complicated equipment, maintenance is bound to go up. Most student laboratories do not use a research type of oscilloscope (although I have been surprised to see some of the latest Tektronix models in some schools), but repair on the usual variety can be expensive. We recently sent in a Tektronix oscilloscope for general reconditioning at the price of $400. Administrations must become aware of the fact that to maintain a well-equipped laboratory is expensive business.

Lastly, I would like to discuss the general question of "Why have a laboratory at all?" A few years ago, many institutions in the country were de-emphasizing the laboratory. Being an experimentalist myself, I am encouraged and happy to find that the present tendency is in the opposite direction. The policy of the NSF and other organizations should be sufficient evidence to anyone that those concerned with the national picture really have a high regard for good physics laboratories in this country. People have a vague feeling that laboratory is a good thing, but I suspect few have really sat down to try and come up with some good reasons. Perhaps this would be a fit topic for discussion in some of the sessions to follow. Perhaps I can throw out a few suggestions that you can be thinking about and evaluating in the meantime.

(1) Most people learn with their hands as well as with their heads. By this I mean that one can learn about some physical phenomenon in class but it really doesn't soak in, in many cases, until one handles a piece of apparatus with which one can demonstrate to one's own satisfaction that it is really true. We all like to get our hands on things, and the psychologists tell us this is a major way of learning. One also should get a better feeling for the magnitudes of physical quantities, e.g. lifting a weight, etc.

(2) A good laboratory should develop the student's experimental ability. This means that he should develop a sense of what is important in a given situation and what is not—also what the order of procedure should be to arrive at a reliable result. A person with a sense of good experimental technique using the same piece of equipment may, in the same time, comes up with an answer which is ten times as reliable as that arrived at by the inexperienced person.

(3) Many experiments illustrate physical principles that are very difficult to grasp from classwork alone. I have in mind particularly some experiments in electrostatics that we do in one of our labs. How does the electric charge get onto this conductor, and how much is there? How is it possible that a spark can be drawn from a completely insulated conductor each time it is moved from one location to another? If the student can really satisfy himself about many of these questions, he certainly knows a lot about electrostatics.

(4) Part of the education of any individual is a training in skills, as our quotation at the beginning of this lecture pointed out. Skills are many and varied. One important skill is learning to make calculations without making mistakes. This involves training in the use of slide rules, calculating machines, and the like, until confidence is developed in their use. I have come to the conclusion that the limitations in the accuracy of results in the student use of such apparatus as the Busch tube for determining e/m of the electron are not the limitations imposed by the statistical accuracy possible with the use of the apparatus itself, but are most often determined by the mistakes made by the student in reading scales and meters and by his lack of skill in making adjustments. In principle, these are experimental skills and techniques that should be passed on from teacher to pupil, just as technique at the piano is passed on from teacher to pupil.

(5) There are certain accepted ways of doing things that are also best taught in a laboratory. Many of our students will be going into technical work. They should know how to keep a notebook, get habits of tabulating data, treating their data, and arriving at an estimate of the reliability of their result. The plotting of curves in an acceptable manner can also be taught best in a laboratory.

There are certainly other reasons for having a laboratory. The above may serve as a basis to get started on a discussion. As teachers we must ourselves have very clear ideas as to the purposes of a laboratory, i.e., its role in the teaching of physics, if we are to pass on to our students its importance in their training. Such convictions on our part will help in formulating policies and guide lines in the future development of our laboratories.