DEMONSTRATION EXPERIMENTS IN PHYSICS

INTRODUCTION

This is a "cookbook" for teachers of physics, a book of recipes for the preparation of demonstration experiments to illustrate the principles that make the subject of physics so fascinating and so important to our understanding of the world about us. The skillful cook takes cognizance of the equipment of her kitchen, of the number of persons she is to feed, and even recalls their individual capabilities of digestion; she adapts her recipes accordingly. Likewise, the teacher of physics must adapt his experiments to the needs of his class and to the equipment of his lecture room and laboratory.

The cookbook seldom tells how good a particular dish tastes, and it never insists that any dish must be served at least once a week. Fortunately, some latitude is left to the discretion of the cook. Likewise, in the preparation of demonstration experiments much is left to the individual teacher. This book aims to furnish him with numerous suggestions so that his menu of experiments can be satisfying even if his larder of apparatus is meager. Many recipes in a cookbook end with the admonition, "Season to taste." The same remark would be appropriate after each of the experiments described herein. The teacher himself must decide what seasoning of language he will use to accompany his demonstrations, so that his students will take to them with relish.

Physics, more than any other science, can be demonstrated principle after principle by direct and simple experiments. The implements of the present attack upon the unknown are great cyclotrons, stratosphere balloons, 200-in. telescopes, and 10-million-volt generators, but the basic principles of our physical knowledge are demonstrable with inclined planes, pendulum bobs, electroscopes, and other pieces of homely apparatus to be found in any laboratory. Logic and insight transform the commonplace rolling of a ball down an incline into a profound experiment. Both students and teachers need to realize that great discoveries may still be made with the common appliances found in the humblest laboratory, where there are far better facilities than were available to those who laid the foundations of our science. Faraday made a great advance in his understanding of electricity when he performed what is now known as the "ice-pail experiment" with the most elementary equipment.

In the study of physics, there is no substitute for experimental observation. In the laboratory students receive training in precise observation and acquire respect for the experimental verification of principles. However, neither time nor equipment permits a student to perform more than a score or two of the countless experiments that contribute to a thorough understanding of the subject. There are a great many important physical phenomena that he may miss altogether unless he is introduced to them. Hence we turn to demonstration experiments, which by their very number and variety fill a real need in the physics course and at the same time provide the instructor with one of the most helpful methods of "selling" physics to a class of students. When demonstration experiments are used in proper proportion, particularly in the introductory stages of the course, there is no more potent way to maintain interest, to make principles concrete and vivid, and to stimulate discussion and active thinking. Since most of this book is concerned with describing *what* to demonstrate, a little space is devoted here to suggestions from a number of sources on *how* to demonstrate.

PRINCIPLES OF DEMONSTRATION

Demonstrations are for the student and not for the instructor. If this simple truth were kept constantly in mind, many of the major crimes of the physics lecture room would be eliminated. The student in the back row, as well as the student in the front row, should see and hear what is going on. The instructor must examine critically every experiment to be demonstrated with this thought in mind; he should consider the value of an experiment by judging what the student sees and understands rather than by his own personal enjoyment and satisfaction in performing an operation that may be perfectly clear from his vantage point but perfectly invisible to most of the students in his class. After an experiment is set up, the instructor may be astonished to see what it looks like from the back of the room.

"The impact of an experiment upon the student's mind is proportional to the solid angle which the apparatus subtends." With this thought in mind, the instructor must adapt his methods to the size of the group before him. Large-scale apparatus, adequate facilities for projection, clearly visible indicators, and readable charts and drawings are essential. Projection of small-scale apparatus by optical methods is necessary in some cases, but at best it is a makeshift.

Simplicity (but not crudity) of arrangement and manipulation is paramount. Teachers often avoid simple experiments, favoring those which require elegant and elaborate facilities. By such displays, the student may be impressed and even overawed, but it would be a mistake to consider that he is better instructed. He deserves to see as much of the working arrangement of every experiment as he can understand without being confused by unnecessary detail. It might be stated as a corollary that the experimental arrangement should be more easily understood than the concept that it is designed to illuminate.

The foremost purpose of any demonstration experiment is to *clarify* a physical principle or to show some interesting application of a principle. If, at the same time, it can amaze and intrigue the student and cause him to do some independent thinking, it more than fulfills its mission. But its primary purpose is not to mystify. Whenever a physics instructor presents a demonstration, he becomes a showman; some of his experiments are as clever as any magician's tricks, and he should make the most of their "show" qualities. His purpose, however, is very different from the magician's: the latter makes every effort to conceal and to mystify; the former makes every effort to expose and to clarify the underlying physical principles.

Of the many principles taught in elementary physics courses, almost every one is reducible to a mathematical statement that involves three or four symbols only. Yet students constantly stumble over these mathematical expressions which might be made vivid and meaningful if illustrated concretely by simple experiments. Every statement of a physical principle embodies (at least implicitly) a set of operational procedures by which it can be verified. Every mathematical formulation of a principle can be translated into an experiment, and the skillful teacher will constantly resort to simple demonstrations to emphasize the relationships involved. $F = ma$, $pv = RT$, $Q/V = C$, $E/I = R$, and numerous other forbidding expressions are *alive* with possibilities for demonstration. These are not algebraic equations alone but shorthand statements of physical relationships, and the symbols take on new meaning when they are translated, one by one, into their equivalents as parts of a working experiment.

METHODS OF DEMONSTRATION

There are as many ways of presenting demonstrations as there are instructors of physics. Each instructor develops special methods of his own that have merit for his own situation. The following are some suggested methods; no single one is sufficient.

Each experiment should be accompanied by a large-scale drawing of the apparatus employed. The drawing may be made while the instructor explains the function of each part. Chalk of different colors adds clarity and life to such a diagram.

Student assistance in the performance of an experiment may be called for from time to time, *e.g.*, in the reading of thermometers and small scales. In experiments such as M-110 and E-228, the class as a whole may be asked to share in taking data. Observation of phenomena is more important than accuracy of result, unless the experiment is used as a substitute for a laboratory experiment where greater precision of measurement is required. Such a substitution is necessary in some institutions where the lack of time or facilities prevents individual experimentation.

Demonstration experiments frequently lead to interesting problems, and conversely, many problems may be translated into experiments. There is danger, however, of killing interest in the experiments themselves if they are turned into problems too frequently.

In many experiments, the expected result is by no means obvious to the class, even after the proposed procedure has been described exactly. Class interest may be whetted by calling for a vote on the various possible outcomes of the experiment. M-112 is a good experiment of this type.

The element of surprise should not be neglected; something may be left untold before the experiment is performed. As the class observes the demonstration, new aspects not yet considered will appear, and class discussion can center on the interpretation of unexpected results. As a very simple example, suppose the instructor has shown step by step how to charge an electroscope by induction (E-23). If after the electroscope is so charged the charging rod is brought toward it, the leaves collapse; but if the rod is brought still closer, the leaves diverge. The interpretation of this apparent duplicity of effects from a single cause calls for original thought and interesting class discussion.

An occasional hoax, such as those described in M-104 and M-161, deliberately introduced without complete explanation in advance, arouses both mirth and thought. In this connection, it is useful to keep a class in suspense now and then while leading them forward to a satisfactory physical interpretation of what they have just witnessed.

Demonstrations may be employed effectively in presenting material by the "method of contrast," since different final results may be shown to come from initial conditions that are similar though not identical. M-100 and M-209 are examples of experiments of this type. Freezing mercury and then burning iron with liquid air, lighting a fire with an ice lens, etc., are processes that offer strong contrasts.

Paradoxical results are often of great value in emphasizing principles. After a class has reached the point where its members feel complacent about their mastery of a principle, it is well to show some striking experiment that leads to a result unlooked for on the basis of their knowledge. Such a method necessitates renewed thinking about the principle from another viewpoint. M-24, M-186, S-134, E-97, and E-98 are examples of this method.

Now and then the apparatus for an experiment can be assembled and set up as the class watches. After discussing the problem or principle to be examined, the instructor may arrange a suitable experiment *under class direction,* asking frequently for suggestions as to the next step or the next piece of apparatus required. Thus the experimental arrangement takes form under student observation and, in part, under student guidance. Evidently, the instructor must have all of the necessary facilities close at hand so as to avoid undue confusion during the progress of such an "assembly technique." Those who know what painstaking preparation and adjustment are required for many experiments will rely upon this device only as an occasional variant of the usual method, in which experiments are completely arranged ahead of time.

One instructor suggests that a good experiment involves a maximum of manipulation and a minimum of explanation. He goes so far as to suggest giving a demonstration lecture of selected experiments without saying a word!

The inspirational value of experiments depends so much upon the manner in which they are presented that the instructor cannot give too much attention to planning his experiments so that they will be given in the proper setting. There is an appropriate time at which to perform an experiment: to show it too soon is to find a class unprepared to appreciate its importance; to delay it by prolonged explanation is to diminish its effectiveness. Thought should be given to exposition, and the lecture should move steadily forward toward some climax. The physics instructor needs to develop a sense of what on the stage is called "timing."

Each class hour or lecture period may be regarded as a unit, complete in itself, which fits into the larger pattern of a carefully planned course. Having settled upon some significant principle or group of principles to be treated during the hour, the instructor can plan his experiments so that they help to develop the subject by logical steps. The hour may close with the showing of some final experiment that gives beautiful and striking confirmation of the principles under discussion.

It is generally more profitable to show a few experiments carefully during a class hour than it is to run hastily through a great number of those bearing upon the topic under discussion. Nevertheless, an occasional "show" raises the class morale. For example, an annual liquid-air display with 20 or 30 experiments presented in rapid succession is worth while. (In many cases, of course, it is obligatory to show liquid air in a single hour because of the cost and inconvenience of securing the air.)

At the beginning of any general subject, an introductory lecture with numerous experiments may serve to arouse interest and to create a predisposition toward the new study. This preliminary lecture should be designed to raise questions but not to answer them. Many of the experiments may then be repeated when the class is better informed. There is a danger that this practice will take the edge off student interest, and it must be used sparingly, reserving some of the best experiments for a later showing so that the instructor's repertoire is not exhausted before the study is well begun.

The lecture table should present a well-ordered aspect; it is not meant to look like an African jungle scene. The instructor who gives a little thought to his experimental arrangements can convey by the pleasing appearance of his lecture table something of the quality of orderly thinking that he expects of his students.

In many cases, it is a good plan to keep the center of the table clear and to move pieces of apparatus to this space as they are needed. The attention of the class is thereby directed to a single point, and the confusion is thus avoided that arises in the student's mind when he tries to isolate the parts of a demonstration apparatus from a maze of surrounding pieces, which have, at the moment. no relation to the experiment being performed.

TOOLS OF DEMONSTRATION

It is well to acquaint the student with the "tools of demonstration" so that he may acquire confidence in interpreting what he sees. It is not necessary that a student know all about the physical principles of an instrument in order to appreciate the effects shown by it in experiments in which its use is an incidental means to an end and not an end in itself.

The lecture thermometer (H-6) may be introduced and used freely for the measurement of temperature, even though the student may be quite ignorant of the underlying principles of thermoelectricity.

The cathode-ray oscilloscope may be used as an indicator of numerous phenomena, even though the student may know little about its operation as a whole.

The stroboscope offers a means of apparently "stopping" rapid periodic motions and of studying them under "slow motion" conditions (*e.g.*, see M-149, S-36, and S-49). Its principles are simple, and its effectiveness as a tool of demonstration is great.

Shadow projection is useful for enlarging small pieces of apparatus. It is accomplished by illuminating the object with light from an intense source (carbon arc or concentrated filament lamp without lenses) and casting its shadow upon the screen where the size of silhouette obtained may be varied by changing the distance from source to object.

In many cases, the instructor may prefer to project an image of a piece of apparatus, by either the vertical or the horizontal arrangement described in L-1. The student may become acquainted with the inversion of image in this type of projection and may thereafter take proper account of it in the interpretation of what he sees. However, an inverting prism may be used to show an erect image of the object.

Projection equipment for showing slides and for shadowing or for projecting apparatus should be available at all times. In one laboratory, the arc lamp housing is in an adjoining room, with its condensing lens set in the lecture-room wall, in such a manner that the light beam runs longitudinally above the lecture table at a convenient height. This arrangement is especially helpful for showing experiments in which even small amounts of stray light may be confusing.

In addition to the usual screens for projection, flashed opal glass (milk glass) is very desirable. It works equally well for projection by transmission or by reflection; images may be seen clearly even though the screen is viewed obliquely. A piece of this glass in a frame may be set vertically upon the lecture table as a screen on which to project, for example, the leaves of an electroscope. Both student and instructor can see the image, although they are on opposite sides of the glass screen. This arrangement has the further advantage that the student looks in the same direction to see both the apparatus and its image. Thus he is saved from the bothersome shift of attention that is one of the greatest objections to the use of projection in lecture demonstrations.

Electric meters may be arranged for projection by cutting away the backs of their cases and equipping them with glass scales either drawn by hand or photographed. Such meters are in many ways preferable to the more expensive large-scale wall meters. The mechanism of the meter should be carefully protected from dust at all times.

Electrical arrangements should be made as simple as possible and should be set, in most cases, on vertical panels with large, plainly visible connecting wires.

The lecture room should contain a wall galvanometer with lamp and scale permanently mounted and ready for immediate use.

It is better to err on the side of making things too large than too small. Large models, large pointers, strong contrasts of color (preferably black and white), and *strong* illumination are important. Floodlights over the lecture table or desk lamps properly placed to illuminate apparatus without obscuring it are helpful.

A large box with opal-glass front, within which several 60-w lamps are housed, makes a good background of diffused light against which pieces of apparatus may be shown. In other cases, especially with apparatus painted white, contrast is enhanced by exhibiting experiments under strong illumination before a dark background such as a piece of black velvet.

It is beyond the scope of this book to describe the architectural features of a physics lecture room. A well-designed room has adequate lighting and ventilation, elevated seats, blackboards, screens for projection, a convenient lecture table with water, gas, and electric connections, and electric outlets for alternating current and direct current from generator or storage batteries. It should be possible to darken the room completely. Numerous window-shade controls are in use, some electrical,[1] some mechanical, some hydraulic. These controls and those of the lights should be arranged so that the lecturer has easy access to them. A simple convenience is a push button on the end of a cord by which the lecturer can control the room lights from any part of the lecture table. An electric clock set face upward in the lecture table and covered by a piece of plate glass flush with the table top is an inconspicuous reminder of the passage of time.

In a lecture room with high ceiling, a trap door or a balcony above the lecture table may be of use in numerous experiments. Such an arrangement makes it possible to suspend objects from the ceiling of the room, which is a convenience in certain experiments with falling bodies and pendulums (M-80, M-98, M-124, etc.).

Adjacent to the lecture room should be a room in which apparatus may be stored in glass cases. Orderliness of storage is a virtue to which the instructor may well give thought and in which he should train his assistants. The habit of returning

[1] One laboratory reports a simple method in which the springs are removed from the shade rollers, and each shade is controlled by a separate d.c. reversible motor.

apparatus to its proper place is a rewarding one, for it saves much time in lecture preparation, besides the obvious contribution that it makes to the order of the laboratory. Movable tables on casters or rollers are a great aid, especially in institutions where several instructors must use the same room. Experiments may be arranged and adjusted on such tables, which are rolled into the lecture room when needed. There is no quicker way to "change scenes." The rolling tables may be locked in position by ordinary doorstops fastened to one or more of the legs and used as lecture tables.

GENERAL CONSIDERATIONS

A book such as this cannot specify the exact piece of apparatus required for a given experiment; its purpose is to outline a variety of useful experiments that may be adapted, both in number and in difficulty, to the needs of a particular institution. Since so much time is consumed in setting up apparatus, it is desirable to keep a card catalogue or a notebook of experiments giving details of apparatus and its arrangement. Such a catalogue or notebook that records successful arrangements will, in the course of a few years, become invaluable.

Apparatus for showing many of the demonstrations described in this book is procurable from scientific supply houses. Most instructors will doubtless secure ready-made apparatus, but those who desire to construct their own will find the details given here of material assistance. Good apparatus can rarely be made without the facilities of a well-equipped shop. Apparatus for a number of the experiments described herein is not commercially available and must be specially constructed; in a few cases, considerable skill is required, but in most cases the apparatus may be assembled from the common appliances ordinarily at hand. A trip through any 5-and-10-cent store will discover dozens of humble and inexpensive articles that can be turned to good advantage in the physics lecture room. If a few new experiments are assembled each year, the departmental facilities will steadily increase.

Above all, the instructor should investigate the possibilities of new commercial products as they appear on the market. Many new materials and new devices have remarkable properties that make them useful in lecture demonstrations. Low-voltage neon lamps, amplifier tubes and photoelectric cells, cathode-ray oscilloscopes, polaroid sheets for polarizing light, plastics for showing photoelasticity, cellophane, cobalt-steel magnets, and numerous other products have appeared in recent years and have found great usefulness in the lecture room and the laboratory. It would be impossible to enumerate them all or to point out all the possible uses of any one of them.

In large institutions where the physics class is divided into sections and different instructors must use the same apparatus, orderly storage of the equipment is imperative. In this regard, the system in operation at one large state university is worthy of comment. Demonstration is a departmental undertaking. Each lecture demonstration is thoroughly discussed by the staff and perfected to the point where it shows just what is desired. A set of apparatus is assembled in a box or built up on a panel or framework, and each set is accompanied by a list of parts and a summary of directions for the conduct of that experiment. Much time is spent in organizing the work so that the time required of any one instructor in arranging a particular lecture is greatly reduced. Each instructor is obliged to see that the apparatus is returned to its proper place in readiness for the next instructor. The advantages of this system are to some extent offset by the cost of duplication of apparatus and the increase in storage space demanded.

If each one of the experiments described in this book were accompanied by a full discussion of the physics involved and by a detailed account of what to say, it is evident that *six* volumes would scarcely suffice. The instructor is assumed to have sufficient knowledge of physics to interpret the observed results of experiments and to know which ones he cares to use. Any good college text will supply the background against which nine-tenths of these experiments may be shown. There is an accompaniment of fact and theory that is logically associated with each experiment, but bare fact and theory are not sufficient to carry a class along. There must be life and action, and to attain them, the instructor himself must be alive and alert, enthusiastic and imaginative. His manner of presentation is important, but this is a quality that cannot be acquired solely from books. It comes best from a keen awareness of his class and their capabilities and from a well-developed ability to express his thoughts in clear and forceful language. Observing successful lecturers helps to suggest ways of improvement, but no two men use just the same technique.[1] Expertness of manipulation and agility on the part of the lecturer are never-failing sources of satisfaction to a class.

In a sense, the instructor should start fresh each year and not rely too much upon what he has done before. This applies especially to his mental approach to an experiment, although the physical setup may be very similar from year to year. He must keep in mind that an experiment that may seem old and hackneyed to him may be new to his students.

Every experienced lecturer has had experiments fail at the crucial moment. Some experiments are, by their very nature, reproducible only by starting afresh, but one should make as certain as possible that everything is working properly before the class arrives. Such preparation acquaints the demonstrator with the vagaries of apparatus and the pitfalls to be avoided. When Ernest Fox Nichols, while preparing a lecture in England, remarked that he was trying out his experiments, Sir William Dampier-Whetham replied, "Do you think that is quite sporting?" The sporting element is large enough in any case without augmenting it by inadequate preparation! Unexpected events, when they occur, can help to make or mar a lecture, depending upon the lecturer's skill in turning failures to good account. In any physics experiment, what actually happens is what *ought* to happen under the existing conditions; it may not be what the lecturer *expects* to happen, but if he is on his toes, he can make excellent use of apparent upsets.

Any experiment is commonplace if it is presented in a dull and commonplace manner. As a single example of the kind of treatment that can be given to an average experiment to make it outstanding, consider M-18. The lecturer draws the attention of the class to the forces acting upon a car resting on an inclined plane and kept from rolling down the plane by a block in front of its wheels. First he adds weights to the end of a string attached to the car and passing over a pulley at the top of the plane, until

[1] The instructor may find inspiration in the writings of great experimenters and lecturers like Faraday and Tyndall. A number of the Christmas Lectures of the Royal Institution (Great Britain) are in print (see bibliography in Appendix A).

the car ceases to press against the block. "Now we no longer need the block." Then he adds weights to a second string, which passes over another pulley in such a manner as to exert a force on the car perpendicular to the plane (Fig. 6) until the pressure of the car upon the plane is reduced to zero. "Now we no longer need the plane." There the car hangs in midair as if still ready to run along an imaginary inclined plane of the same slope. Simple? Yes, but not easily forgotten. Such picturesque presentations are possible with great numbers of these experiments if the instructor will but use his imagination.

MUSEUMS

In recent years, a number of large scientific museums have been established. They serve a useful purpose in acquainting the public with the place of science in modern technical, industrial, and social life. An excursion to any one of these great institutions is a rewarding experience for either student or instructor. In many of them, apparatus for showing fundamental physical or chemical phenomena is so arranged that the individual observer can operate it by pushing a button.

The essential features of such a museum are not beyond the reach of any physics department in high school or college, where a small museum can fill a very important place in the teaching of science. Exhibits that work are so arranged that the student may operate them at his leisure, thus allowing him to observe effects at close hand, to vary conditions of performance within limits, and to ponder deliberately over what he observes. Several institutions have devoted rooms to such exhibits in which numerous experiments, arranged in an orderly and attractive manner, are set up permanently, each accompanied by a brief description of its purpose and operation.

The museum method is particularly desirable for those experiments of the "peep-show" type (diffraction, interference, Brownian movements, etc.) which are best seen by individual observation. Others (*e.g.*, Cavendish balance, M-128) require so long to perform that it is better to allow the interested student an opportunity to carry out such experiments by himself. Students should be directed to particular exhibits from time to time, and they may even be asked to make use of the apparatus in the exhibits for quantitative measurements or for the solution of problems.

A slight variant of the physics museum that has several advantages is to be found in some departments, where a display case or a table is arranged to make one or two experiments available at a time. The success of this method depends upon frequent change of exhibits. Some experiment that relates to the current work of the class may be on display, perhaps one designed expressly to mystify the student and arouse his curiosity.

Such an exhibit table is well worth the effort expended upon it. There are many experiments that should be set up for student operation, the purpose of which is qualitative observation rather than precise or quantitative measurement. Sturdy apparatus is required, and the experiment should be as foolproof as possible. This restriction eliminates experiments in which there is any element of danger or those requiring critical adjustment, unless the adjustable parts are out of reach of the observer. If electrical circuits are used, each circuit should be protected in such a way that no damage can be done by any possible combination of switch connections. Some student, perhaps more curious than others, is sure to try unconventional combinations of switches. At best, there is considerable wear and tear on apparatus in such exhibits; for if there are n usual ways of using a piece of apparatus, some student will discover the $(n + 1)$th way!

Descriptions of physics museums at two large universities[1] are to be found in *The American Physics Teacher*. These institutions consider them a great asset in their teaching program, because of the valuable collateral experience that they give to individual students.

[1] INGERSOLL, L. R., *Am. Phys. Teacher*, **4**, 112, 1936; LEMON, H. B., *Am. Phys. Teacher*, **2**, 10, 1934.