32/

~~12-10~~ 7

Reprinted from AMERICAN JOURNAL OF PHYSICS, Vol. 32, No. 3, 220–225, March 1964
Printed in U. S. A.

A Library of Experiments

FRANK OPPENHEIMER AND MALCOLM CORRELL
The University of Colorado, Boulder, Colorado
(Received 17 October, 1963)

A new concept in physics laboratory instruction is described in which the experiments are available to the student in much the same fashion as books in a library. The general nature of the experiments is explained and the philosophy underlying the use of the laboratory for instruction is discussed.

THE University of Colorado is developing a new concept of physics laboratory instruction for lower-division physics courses. We are constructing a "library of experiments" in which the apparatus for an experiment is nearly as accessible as are the books in the stacks of a university library. Our library at present contains about sixty-five different experiments, two-thirds of which have at least one duplicate. Eventually we hope to have between eighty and ninety different experiments.

These experiments are set up permanently on metal tables which can be moved from one location to another by means of a specially constructed dolly. The tables containing the experiments in most active use are located in a single large room whose area is about 3200 sq ft, while the remainder of the tables are stored in an adjacent room. The library-laboratory is open regularly from 8:30 a.m. to 9:00 p.m. and the scheduled laboratory classes meet in this room. Moreover, individual students are encouraged to return to perform experiments on their own. The laboratory sections are conducted by the regular teaching staff of the Physics Department, and a technician who is thoroughly familiar with the experiments is on hand during all open hours of the library.

Under this concept of laboratory instruction the students may be expected to do two or three experiments in the course of a 2-h period. In general, of course, students get more out of a laboratory session if the experiments have been discussed and if the procedures have been demonstrated during a previous session. Ways in which this may be handled are discussed below.

THE PEDAGOGICAL PURPOSE OF THE LABORATORY

The experiments in our library are not research projects and we make no pretense that the student is led to discover the laws of physics or even to establish them firmly. Moreover, since the setups are ready made for the student, we cannot claim that one of the objectives of the laboratory instruction is to teach laboratory technique by assembling apparatus for an experiment.

The experiments, however, are designed to be both *exercises and demonstrations* which are closely related to the content of the course. In one sense they can replace some or nearly all of the regular lecture demonstrations, although in our view this is neither necessary nor desirable. The big advantage from the demonstration standpoint is that the student is much more intimately associated with the apparatus than in a large lecture-hall situation and he can see for himself just how the components of the apparatus coordinate in order to display the phenomenon. Moreover, in performing the demonstration for himself, or as a part of a small group, he can more readily comprehend the quantitative aspects of the phenomenon.

The experiments also serve as exercises which are assigned for the same purpose as problems: to stimulate thought on the part of the student and to make him more familiar with the structure of physics. While discovery is not a principal aim of our experiments, they contain elements of discovery just as well-designed problems do. In addition to following the main theme of the experiments, the students find effects and aberrations which were not necessarily designed into the experiment but the explanations of these effects may present an exciting challenge to the experimenters' knowledge.

For the most part new experiments are designed after the following questions have been asked:

(a) Which parts of this chapter are difficult to understand from the text alone?

(b) Which parts could be understood more fully if the students had some quantitative and qualitative experience with the phenomena involved?

We have then tried to design experiments in which these aspects of the underlying physics were demonstrated most clearly and simply. Experiments which are "cute" in that they embody a subtle or esoteric way of measuring a constant of nature have generally been given less priority than their more straightforward counterparts. Also, there are no experiments whose major aim is to provide practice in laboratory techniques.

We have also tried to couple the simple physical gear of the experiment with fairly modern measuring techniques. For example, frequent use is made of type 561 Tektronix oscilloscopes. With practice, the students become quite adept at using oscilloscopes although no time is spent in studying the design of the instrument itself. Electronic interval timers and counters, photocell gate-circuits, and stroboscopic cameras are also used. Since only one or two copies of a given experiment are required, a higher cost per station is justifiable in pursuit both of higher reliability and lower maintenance cost.

There are other advantages to a laboratory program in which only one or two copies of a given experiment are necessary. Firstly, it is possible to modify experiments as needed and to incorporate suggestions for new ones as they are made by students and staff. Even though the experiments are permanently set up on tables and are not dismounted after use, we anticipate that the laboratory will tend to be less static. The sense of development and newness which has been stimulating for our present teachers and students should be a permanent aspect of the laboratory. Secondly, since there are fewer multiplicates of a given experiment, there can be greater variety in the total library of experiments.

Each experiment is usually performed by a group of four or five students. The use of such large groups is frowned upon by many because invariably some of the students hang back and do not get the full benefit of the experiment. We have found that this disadvantage is partially offset by the fact that the experiments are generally sufficiently interesting and complicated to provoke considerable discussion and argumentation among the participants. Furthermore, the manipulations frequently involve several students. Some students are not satisfied with this group experience. Many of them *do* return after class hours to repeat the experiment, or some part of it, in peace, quiet, and greater privacy.

THE EXPERIMENTS

We are in the process of providing a wide variety of experiments which cover the bulk of the material of the lower-division physics. As the introductory courses are revised to include more of the physics that has been developed during the twentieth century, we develop appropriate experiments for the laboratory.

Many of the experiments are quite standard introductory experiments. They include the potentiometer, the Wheatstone bridge, and acoustical resonances in variable length tubes. We have built Leighton–Neher air troughs for one-dimensional kinematic, dynamic, and collision experiments. There are standard PSSC ripple tanks. Lenses on optical benches illustrate the principles and the operation of the microscope and the telescope, and in the latter case, the limitations to the quality of the image are investigated from the standpoints of both geometrical and physical optics.

Other experiments are adaptations of standard measurements. There is an electrostatic balance constructed from a commercial triple-beam balance with which the force between charged plates can be measured. The balance uses up to four kV between the plates whose spacing is variable; moreover, the dielectric material between the plates can be easily changed. The students also measure the force between two currents by using a torsion balance whose principal element is a large single-turn loop which carries up to 50 A dc. The moment of inertia of the loop can be easily calculated and its period of oscillation can be determined. From this information the torque constant of the balance can be found and absolute determinations of the force between the currents follow.

We have constructed several experiments on oscillations and waves. The position as a function of time in simple harmonic motion is measured by means of a spark trace on waxed paper or by stroboscopic flash photography or by photocell timers. A very simple, well-controlled experiment on forced and damped harmonic motion can be set up by letting a PSSC cart oscillate on a glass plate, the restoring force being provided by two long rubber bands, one of which is attached to a variable-speed crank. There are coupled pendulums which are driven by a relay that receives its energy from a multivibrator whose frequency is variable. The driving frequency can be adjusted so that the system resonates at each of its normal modes and so that it displays both the transient and steady-state behavior of the oscillations. A long Slinky as well as microwave and optical apparatuses are used to display interference and polarization effects.

We have two arrangements which are models for wave- and group-velocity effects. One is a mechanical model using two bicycle wheels and knitting needles; the other is an electronic model which uses the superposition of waves from two audio oscillators displayed by a dual-trace Tektronix oscilloscope.

Many other experiments are probably new to the sophomore laboratory both in purpose and design. For example, the students measure the viscosity of air as a function of pressure. Also provided are two commercial versions of equipment for studying nuclear magnetic resonance.

A list of all of our experiments, complete as of the opening of the 1963 fall semester, is given below. Since the laboratory is still in its most active stages of development, there are some notable omissions from the list.

THE UNIVERSITY OF COLORADO LIBRARY OF PHYSICS EXPERIMENTS

I. Mechanics

A. Motion and Forces

PSSC carts with tapes
Acceleration measured with accelerometer
(a) on inclined plane (b) on rotating table
Air trough experiment I
Equilibrium of a rigid body
Circular motion and centripetal force

B. Energy Motion and Momentum

Atwood machine
Peg-board pendulum
Potential energy
Loop-the-loop
Kinetic and potential energy
Friction
Air trough experiment II
Conservation of momentum in an inelastic event
Impulse
Moment of inertia and conservation of angular momentum (angular momentum part doesn't require moment of inertia)
Moment of inertia
Rotational motion of a rigid body
The gyroscope
Scattering

II. Measurement

Significant figures (done at home)

III. Electricity and Magnetism

Electroscope
A study of Coulomb's law
Force of attraction between charged parallel plates

Capacitance and energy of a parallel-plate capacitor
Magnetism
Force between two wires carrying a current
Magnetic field near a current in a wire
Potentiometer
Wheatstone bridge
Time constant of a capacitor
Long solenoid
A study of the L–C–R circuit

IV. Optics

Snell's law using the optical disk
The telescope
A pin-hole magnifier (short experiment)
The compound microscope
Simple magnifier and the location of virtual images (short experiment)
Multiple images from plane mirrors
Interference fringes from thin film (short experiment)
Single and multiple slit diffraction-cornell plates (2 sets of lights; 6 plates)
The grating and prism spectrometer
Polarization (long experiment)

V. Harmonic Motion and Wave Motion

Simple harmonic motion I
Simple harmonic motion II
The physical pendulum
The driven harmonic oscillator
Coupled pendulums and normal modes of vibration
Polarization study on oscilloscope
Wave motion—traveling waves on a Slinky
Wave machine
Study of addition of SHM and phenomenon of beats
Waves in a ripple tank
Resonant air columns
Study of Lissajou figures on oscilloscope
Microwave as an example of wave phenomena

VI. Heat and Kinetic Theory

Model gases: the velocity distribution
Specific heat constants of a gas
Ideal gases and the temperature scale
Viscosity of air as a function of pressure
Electricity energy and heat

VII. Modern Physics

A study of ferromagnetism
Michelson's interferometer (long experiment)
Hall effect and force on current in a magnetic field
The determination of the true average number of events in a given time interval from a measurement of the actual number of events
Millikan oil drop
Charge to mass ratio of the electron
Nuclear magnetic resonance
The continuous cloud chamber
Rest mass of the Λ^0 hyperon (done at home)

ORGANIZATION OF THE LABORATORY INSTRUCTION

All of the experiments are accompanied by instruction sheets which are distributed to the students. At present the instruction sheets make reference to one particular text: Halliday and Resnick, *Physics for Students of Science and Engineering*. Instructors using other texts provide the appropriate change in reference. These instruction sheets briefly discuss the procedures and the theory of the experiments. They also ask questions to stimulate thought and discussion by the students. We have tried to keep the instructions brief and to avoid the detail necessary in a kit-construction manual. However, since many of the experiments involve quite new techniques, the students are frequently not able to cope with the apparatus on the basis of the instruction sheets alone.

A brief demonstration of the apparatus including the required manipulations can provide the missing instruction without the need for detailed printed description of cut-and-dried procedure. We hope that later this instruction can be accomplished by three-to-four minute motion pictures. We have started making such movies and plan to have them made up into cartridges suitable for the Technicolor silent projectors. These films will be particularly helpful to the individual student who is using the laboratory as a library. We plan also that the students in laboratory section will be able to view the films well in advance of performing the experiment; they can thus come to the laboratory having prepared by instruction sheet, suggested reading, and short film.

In the meantime, for some of the classes, until the films have been prepared, we have adopted a procedure which has proved to be quite satisfactory. We designate about six experiments which cover the class material for a two-week period. During the first 2-h period of this 2 weeks, all six of these experiments are demonstrated and discussed by the laboratory instructors and, in some cases, sample data are collected. The students take notes on all six demonstrations. After the demonstrations are concluded, the class is divided into groups. Each group is told which two or three experiments it is to do during the 2-h laboratory period of the following week. Also, after the demonstrations there is usually some time left in which students can work briefly with the apparatus. They are asked to come to the next class with data sheets and procedural outlines prepared in advance and the data sheets are initialed by the instructors before the students start the experiments. In this way we have found that the students become familiar enough with the experiment and the apparatus to appreciate the experiment while they are doing it. The preparatory demonstrations tend to whet rather than to dull the interest of the students.

Not all classes are conducted according to this schedule. In some, the demonstration is given during the same period which the students use for the experiment; in others, no demonstration is given and the students are given more time to find out about the experiment.

In one particular three-semester hour course for freshmen, no laboratory has been scheduled or officially approved. In this course, one of the recitation periods has been extended to two hours. The experiments are demonstrated with partial participation by the students and then they are discussed much as are the problems at the end of a chapter in a text. Although such an arrangement is far from ideal, these recitation–demonstration periods for 25 students provide more understanding than would the traditional lecture-demonstration before a class of three hundred students. In this case as in others, the experiments remain available for the interested student to explore on his own.

From our experience thus far, it would seem that this library of experiments can be adapted to various procedures satisfying diverse pedagogical tastes and diverse types of courses.

As yet we have not adequately solved the problem of the students' reports of the experiments. The students are asked to minimize their reports including only the data, the physical implications of these data, and brief discussion concerning their validity. However, the students still spend more time in reporting than they feel that they can afford or than they find to be profitable. Their reports continue to be concerned too largely with matters that have no clear pedagogical value. Part of the difficulty stems from the fact that the data frequently are confusing and take a long time to disentangle and understand. In addition, many of the instructors who grade the reports continue to favor polish as against content.

FACILITIES

At the outset of this project it was estimated that it would require about 6000 sq ft of floor space. Until new construction is accomplished we will not be able to house the laboratory on the requisite amount of floor area. At present we are using one room 3200 sq ft with less than 1000 sq ft of storage area in an adjacent room. Table I below gives the approximate utilization of the available area.

In the present laboratory, gas, water, and 110-V ac power is available along the walls on three sides of the room. Three overhead continuous trolley ducts supply ac power to the tables in the working area. Two similar continuous trolley ducts supply dc power from nearby generators and rectifiers to the working area. The general room illumination is provided by fluorescent lights. However, overhead incandescent lights can be attached to the trolley ducts so that individual tables can have concentrated light even though some of the nearby experiments may require low level illumination. A convenient arrangement with movable opaque screens is being developed for obtaining dark areas.

There are of course both advantages and disadvantages to having all the experiments set up in one large room. The one large room has a very appealing and exciting atmosphere, since it displays such a large variety of interesting equipment. In addition the library aspects of the laboratory are easier to organize, since one curator can supervise the entire room. Also, the students are stimulated to browse and to excite their curiosity by examining other experiments.

TABLE I. Space allocation for the library of experiments.

Working area per table		50 sq ft
Storage area per table with easy access (tables are $5\times2\frac{1}{2}$ ft)		20 sq ft
Working experimental area		1500 sq ft
Class room area		500 sq ft
Curator area		200 sq ft
Storage area	in main room	1000 sq ft
	in adjoining room	600 sq ft

The noise level in each room is adequately suppressed by the acoustic tile on the ceiling. One can foresee, however, that some experiments may require sound or light proofing beyond that which can be obtained in the one large room. It may probably be desirable, therefore, to provide a few small adjoining rooms for special experiments.

SOME STATISTICS CONCERNING THE LABORATORY

The project of developing the library of experiments first commenced in September 1961. At that time the administration of the University of Colorado made a $12 000 grant under its program for experimentation in educational improvement. The National Science Foundation through its Undergraduate Instructional Equipment Program provided further stimulus by a grant of $20 900 which was, of course, matched by an equal sum from the University.

Table II below gives in summary the approximate investment of the University of Colorado in this project to improve undergraduate instruction in physics.

Table II does not include certain other investments by the University in the project. For example, one additional full time laboratory curator has been added thereby doubling the staff of curators.

We conclude this report with Table III which gives some statistics concerning our use of the laboratory during the spring semester of 1963.

We may note that a duty cycle of 12 h/day, five days/week with no more intensive use than outlined by Table III would accommodate a maximum of 1500 students. Even allowing for the unpopularity of, say, Friday evening laboratory sessions, our present facilities could accommodate between 1100 and 1200 students. However, it is desirable to avoid this kind of use in the present space so that browsing and other independent work by individuals can prosper.

Table II. A summary of sources of support.

Apparatus:		
U. of C.	1961–62 grant	$12 000
NSF	1962–63 grant to U. of C. Physics Dept.	$20 900
U. of C.	1962–63 matching grant	$20 900
NSF	1962–63 (U. of C. Engineering superior student program)	$ 4 000
U. of C.	1962–63 matching grant	$ 4 000
Facility:		
U. of C.	1962–63 finishing of attic room	$29 000
U. of C.	1962–63 tables, cabinets, stools, etc.	$ 4 000
U. of C.	1962–63 production of films	$ 1 500
		$96 300

Table III. A summary of laboratory uses.

Number of different experiments	65
Number of additional duplicates (approx)	35
Number of different courses holding lab	5
Average number of students per lab	25
Number of two hour classes scheduled per week	28
Maximum number of simultaneous classes	2
Total number of students in lab per week (approx)	700