Millikan Lecture 1996: Promoting active learning based on physics education research in introductory physics courses

P. W. Laws,[a] Coordinator, Workshop Physics Project
Department of Physics and Astronomy, Dickinson College, Carlisle, Pennsylvania 17013

Early in his career Robert Millikan experimented with a laboratory-based method of teaching introductory physics that bears close resemblance to Workshop Physics.® In this talk, key elements of Workshop Physics are summarized. Some Workshop Physics activities are described which involve apparati that are used for rapid observations of conceptual aspects of physical phenomena as well as for equation verification experiments. Challenges are discussed that must be faced if recently developed activity-based approaches to teaching based on the outcomes of physics education research are to provide a foundation for a major paradigm shift in physics teaching.

I. INTRODUCTION

A few months ago when Karen Johnson invited me to give this lecture, I only knew two things about Millikan: First, that he was the inventor of the famous oil drop experiment that I repeated as an undergraduate at Reed College, and second, students at Caltech thought he had a big ego. Walter Michels, who chaired the Physics Department at Bryn Mawr College where I did my graduate work, was a student at Caltech when Millikan served as its president. Michels used to tell the Bryn Mawr graduate students about an irreverent student prank. In 1936, during Millikan's early years at Caltech, he helped raise money to build the Crellin Chemistry Laboratory. A steam shovel on the Crellin construction site invited three rounds of graffiti. The first graffito was "Roosevelt for King." This was followed by "Jesus Saves." Finally an anonymous Caltech graffiti artist couldn't resist adding the phrase "But Millikan Gets Credit." My husband, who is a Caltech graduate, recalls that Millikan had to borrow money in order to complete the building, giving the phrase another meaning.

Fortunately, Millikan does deserve credit for a great deal. His biographers wrote about his impressive record as the "complete academic—teacher, writer, Nobel Prize-winning researcher, administrator, entrepreneur, and sage."[1,2]

II. MILLIKAN'S EDUCATIONAL PHILOSOPHY

As an underclassman at Oberlin College, Millikan concentrated in mathematics and Greek. At the end of his sophomore year, Millikan had also completed a single 12-week course in physics, which he felt was a "complete loss."[3] However, his Greek professor invited him to teach introductory physics. And so, Robert Millikan found himself teaching physics in his junior year with no additional course work—a task he prepared himself for by spending the summer working every problem in an elementary text.

Several years later after Millikan completed his Ph.D. at Columbia University, he joined the staff at the University of Chicago. It was now 1896, and there was a pressing need to reform the freshman physics course. Millikan describes his approach to this task in his autobiography:

> "I had become thoroughly disillusioned by the ineffectiveness of the large general lecture courses of which I had seen so much in Europe and also in Columbia, and felt that a collegiate course in which laboratory problems and assigned quiz problems carried the thread of the course could be made to yield much better training, at least in physics···I started with the idea of making the whole course self-contained···I abolished the general lectures···This general method of teaching···has been followed in all the courses with which I have been in any way connected since."[4]

Millikan's conclusions about the ineffectiveness of lectures in introductory physics courses have been reconfirmed by Donald Bligh's research on the impact of lectures in over 200 college-level courses of all types. Bligh concludes that lectures are best for inspiration and for the transmission of information but that they are not effective for teaching concepts.[5] Millikan's conclusions are reconfirmed once again by Ohmer Milton, an outstanding introductory psychology teacher from the University of Tennessee. Milton found that the half of his class who were selected at random to stay away from his lectures did just as well as the half who were required to attend them.[6] Further, Millikan's conclusions have been reinforced by current educational research: Lillian McDermott's insight, "Teaching by telling is an ineffective mode of instruction for most students··· [They] must be intellectually active to develop a functional understanding,"[7] and the University of Maryland's recent study of the comparative effectiveness of lectures and active engagement in microcomputer-based laboratories.[8]

During the past ten years the Workshop Physics project team members have developed computer tools, apparatus, and curricular materials. These materials allow instructors at the college and high school levels to achieve Millikan's goal of *teaching introductory physics courses without lectures.* The wisdom of experience garnered from the Workshop Physics project[9] has provided additional reinforcement for Millikan's educational ideas. Workshop Physics, with its laboratory orientation and its abandonment of formal lectures, is certainly a reinvention of Robert Millikan's educational legacy.

The facts about Millikan's "Workshop Physics" approach to teaching are not well known, and it is apparent that they did not take root at either the University of Chicago or Caltech. I think there are many reasons for this. Millikan worked alone without the support of colleagues. He also was leading a dual life in which he reported working six hours a day on teaching and curriculum development and six hours on his Nobel Prize-winning research. There are other factors. There was no AAPT and no body of physics education research to support Millikan's ideas. Without computers to fa-

Table I. Workshop Physics goals.

1. To develop a conceptual understanding of physics phenomena and to be able to relate that understanding to a mathematical representation of phenomena.
2. To achieve wider scientific literacy (cf. Arons—Ref. 10).
3. To develop skills in the use of contemporary apparatus and computer tools for the collection and analysis of scientific data.
4. To be motivated to learn more science both formally and informally.

cilitate the more time-consuming and tedious task of data collection and display, laboratory-based learning was slower and more difficult. In fact, it was the existence of computer tools that catalyzed the Workshop Physics curriculum and the development of other related activity-based laboratory curricula in collaboration with Ronald Thornton and David Sokoloff. It is my hope that with the support of physics education research, the collaborative work of many active physics teachers, sustained support from funding agencies, and the continued improvement of microcomputer tools and apparatus, the trend toward active physics learning will grow and evolve to produce a sweeping paradigm shift in the methods we use to help students learn physics.

III. WORKSHOP PHYSICS

Let's look more closely at Workshop Physics and some examples of how new apparatus and computer tools used in the program can facilitate activity-based learning.

We're often asked, "If you don't lecture, what is a typical Workshop Physics class like?" The short answer is that it consists of a series of related activities that help us achieve several educational goals, which are summarized in Table I.

A longer answer to the question of what a typical class is like includes the fact that classes are divided into 2-hour periods. In these longer sessions, students engage in a series of activities that approximate elements of a learning sequence distilled by David Kolb from findings in cognitive psychology and educational research. This sequence is summarized in Table II.

Activities include discussions with instructors and classmates, qualitative observations, data gathering, guided-equation derivations, problem solving, as well as the use of spreadsheets, computer-based laboratory tools, and video analysis tools for the collection and analysis of data as well as for both analytical and numerical modeling using spreadsheets.

IV. APPARATUS THAT CAN BE USED FOR CONCEPTUAL AND QUANTITATIVE ACTIVITIES

The two-semester calculus-based introductory Workshop Physics sequence at Dickinson College begins with the prediction and measurement of the speed of a pitched baseball; proceeds through classical mechanics, thermodynamics, and electricity and magnetism; and ends months later with the numerical integration of the forces on a chaotic oscillator. Today I would like to share with you a few of my favorite pieces of physics apparatus that are used in activities included in the *Workshop Physics Activity Guide.*[11] These activities, along with many others, serve as conceptual and mathematical stepping stones that carry students on a yearlong journey from baseballs to chaos.

Table II. The Workshop Physics learning sequence.

1. Prediction
2. Observation
3. Reflection
4. Theory
5. Application

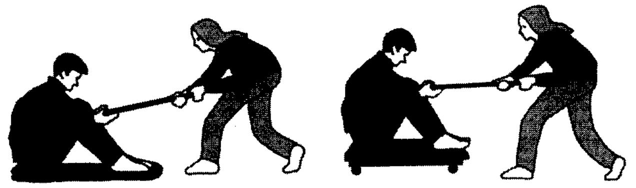


Fig. 1. Being pulled with a constant force under two circumstances: (a) sliding along a smooth floor on a plastic garbage bag and (b) rolling along a level floor on a low-friction Kinesthetic cart. (Illustration courtesy of John Wiley & Sons.)

The pieces of apparatus I have chosen serve to illustrate the learning sequence. Among other things, physics is the art of idealization, as physicist John Harte, author of *Consider a Spherical Cow*, so aptly noted.[12] In this spirit, each piece of apparatus devised for the activities invites initial observations and reflections about a basic, idealized physical phenomenon that can be made quickly and easily. Also, each piece of apparatus developed for these activities can also be used for the application phase of the learning sequence. In the application phase, quantitative measurements, often made using flexible computer tools, can be analyzed to verify theoretical equations and mathematical relationships.

Activity Set 1 on Force and One-Dimensional Motion: This set of activities is taken from Unit 5 on One-Dimensional Forces, Mass, and Motion.

(1) Constant Force: In general the idea that a constant force leads to a constant acceleration is not obvious to most nonphysicists. In these activities we assume that students intuitively accept the notion that a rubber band stretched to a constant length exerts a constant force. Students are asked to sketch graphs predicting the motions that would result if someone was pulled with a heavy-duty rubber band held at fixed length under two conditions—sliding on a smooth floor on top of a plastic garbage bag and rolling on a smooth floor on a low-friction Kinesthetics cart (see Fig. 1).[13]

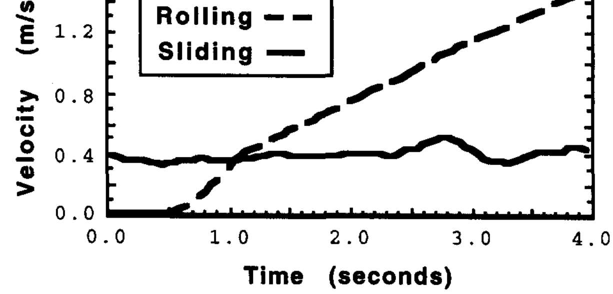


Fig. 2. An overlay graph showing velocity vs time data for a sliding motion and a rolling motion based on data taken using a computer-based laboratory system with a motion sensor.

Slope=	0.75	[kg]
Intercept=	0.00	[N]
	Force[N]	Force[N]
a [m/s/s]	Data	Model
-3.20	-2.30	-2.40
0.09	0.17	0.07
2.60	2.00	1.95
1.20	0.97	0.90
-0.99	-0.44	-0.74

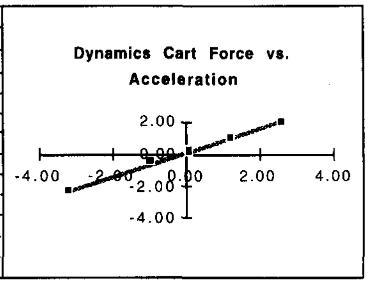


Fig. 3. Sample of plot of a few data pairs and corresponding Excel model constructed by students showing a proportionality between force and acceleration.

Next, the motions are demonstrated, and then students can compare velocity vs time graphs of the motions generated by an ultrasonic motion detector attached to a computer-based laboratory system. In this case students can move rapidly from qualitative to graphical representations of motion for a constant horizontal applied force. They see that in the absence of significant friction, a constant applied force results in a constant acceleration, as shown in Fig. 2.

(2) Variable Force: Observing and acknowledging the relationship between constant force and constant acceleration doesn't always lead students to conclude that acceleration and force are proportional on a moment-by-moment basis when the force varies. This observation can be made graphically by pushing and pulling on a low-friction dynamics cart with a force sensor attached and tracking the motion with a motion detector. The idea for this observation comes from Bob Morse of St. Alban's School in Washington, DC. Some students who predict that velocity will be proportional to applied force can see iconographically that it is acceleration and not velocity that matters on a moment-by-moment basis. Some students who don't recognize the relationship by graph shape see it better when they plot several force and acceleration data pairs that they select. A graph of actual student data and an analytic spreadsheet model for this exercise is shown in Fig. 3.

Once the proportionality between force and acceleration is firmly established, students turn their attention to devising logical procedures for measuring gravitational mass using a simple equal arm balance. Finally, they revisit the cart push and pull exercises with different masses on the cart to find that the total gravitational mass of the system being pushed and pulled is approximately the same as the slope of the real-time graph of force vs acceleration that emerges, as shown in Fig. 4. This establishes an equivalence between gravitational and inertial mass in a very straightforward manner and leads to the conclusion that Newton's second law, $F = ma$, holds for an applied force in the absence of significant friction.

Activity Set 2 on Force and Two-Dimensional Motion: This next set of activities is taken from Units 6 and 7 of the *Workshop Physics Activity Guide.* Those units involve the application of Newton's second law to two-dimensional motions. (1) The first activity is adapted from a one-dimensional Bowling Ball Mechanics sequence originally developed by Edwin Taylor when he visited the University of Maryland one summer as part of the FIPSE-funded M.U.P.P.E.T. project. In Bowling Ball Mechanics, students emulate the action of a constant applied force by using a rubber-tipped baton to apply a series of rapid taps to a bowling ball. A student can simulate the gravitational forces that we presume govern the motion of a projectile that is shot horizontally off a cliff. This is done by tapping a massive rolling ball continuously in a direction that is always perpendicular to its initial velocity. If another student trails along and drops small bean bags at the ball's location at regular time intervals, the trail of the bean bags can display the parabolic path of the "projectile." This part of the activity involves predictions and qualitative observations. However, the coordinates of each bean bag can be measured so that the data can be subjected to analytic mathematical modeling using a spreadsheet, as shown in Fig. 5.

(2) The next activity enables students to experience centripetal forces kinesthetically. A student sits on a cart with high quality furniture casters under it and grips a rope that is tied to a bearing fixed to the middle of the floor area. Another student pulls the circular rider in a direction that is tangent to the circular motion. The tangential pull cancels the friction forces in the cart bearings and keeps the rider moving at a constant angular velocity. If the angular velocity is increased or if the radius of the rope is decreased, the rider experiences a noticeably stronger central pull in her shoulders and arms. The experiment is shown in Fig. 6.

This experience establishes the qualitative conceptual ideas that centripetal force increases with increasing tangential speed and decreases with increasing radius. After students do a guided derivation of a relationship between centripetal force, rotational speed, and turning radius, the same

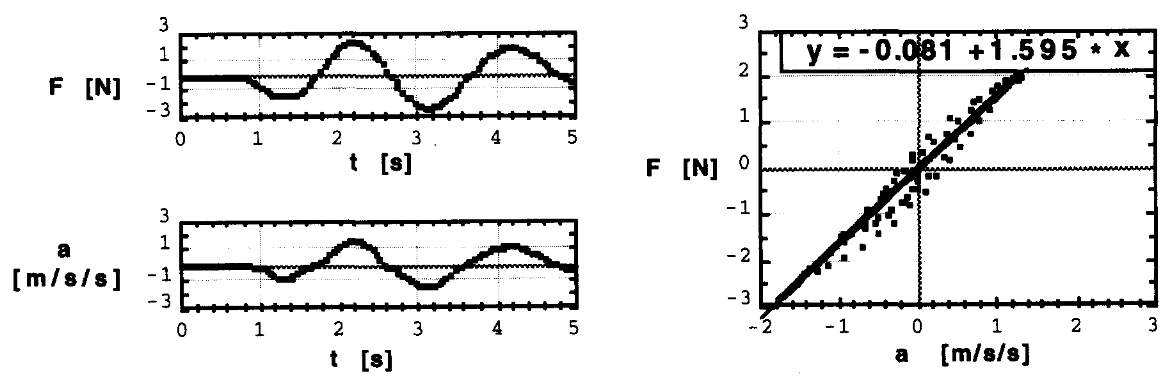


Fig. 4. Simultaneous display of F vs t, a vs t, and F vs a. This latter plot yields a slope that is equal to the mass of the cart and force sensor demonstrating an inverse proportionality between acceleration and mass.

a=	-0.24	[m/s/s]
voy=	0.00	[m/s]
yo=	0.00	[m]
2D Bowling Ball Motion		
y[m]		
t[s]		
t[s]	y-data [m]	y-model
0.00	0.00	0.00
2.00	-0.25	-0.48
4.00	-2.56	-1.92
6.00	-4.85	-4.32
8.00	-7.50	-7.68
10.00	-11.55	-12.00

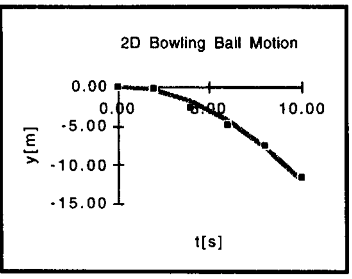


Fig. 5. Student data showing the displacement of a bowling ball in the y-direction (parallel to the direction of the "constant" force applied to the ball) as a function of time. An analytic spreadsheet model reveals that an acceleration of about -0.24 m/s/s and an initial velocity of 0.00 in the y-direction are consistent with the data.

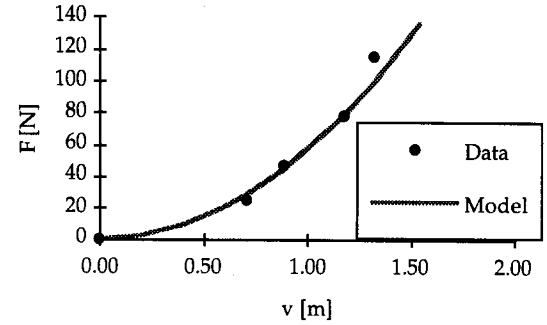


Fig. 7. Student data showing the centripetal force on a student-cart system as a function of the tangential speed of the system. The results are consistent with the centripetal force equation of $F_c = mv^2/r$.

observation can be turned into an excellent equation-verification experiment. For example, if a strong spring scale is placed in the rope and the rate of rotation of the student is measured, the mathematical relationship between central force and velocity of rotation can be determined; see Fig. 7.

Activity Set 3 on Coulomb's Law: This next set of activities is derived from Unit 19 of the *Workshop Physics Activity Guide*. Two ping-pong balls that are covered with conducting paint can be stroked with a fur-charged rubber rod and touched together to equalize their charges. One of the negatively charged balls is hung from a long bifilar pendulum and the other, which serves as a prod, is attached to an insulated rod, as shown in Fig. 8.

The hanging ball is pushed to larger angles and rises higher as the prod is brought closer to it. This experiment demonstrates qualitatively that the force exerted by the prod on the hanging ball is greater when the distance, r, is smaller between the centers of the two charged balls. However, new technology allows us to take this experiment a step further. The slow motion of the prod inching forward can be captured with a video camera and digitized, as shown in Fig. 9. Then the VideoPoint™ software can be used to perform a frame-by-frame analysis of the angular displacement of the hanging ball and of the distance between the balls. This yields the information needed to find the magnitude of the Coulomb force, F_c, as a function of r.

As shown in Fig. 10, when the video analysis is done carefully, the inverse square relationship is revealed.

Activity Set 4 on Parallel Plate Capacitors: Unit 24 on Capacitors and RC Circuits begins with the construction of a simple parallel place capacitor. This capacitor consists of two sheets of aluminum foil wedged between the pages of a textbook. Arnold Arons once noted that the use of the textbook here is a "transformation of dialectic into dielectric." In the first activity students are asked to use what they have already learned about the interaction between charges in their study of electrostatics to predict the simplest possible relationships between the capacitance of the plates and the plate spacing and area. Once the qualitative considerations are completed, then students can use a digital multimeter that has capacitance reading capability. The capacitances are on the order of a nanofarad. It is possible to determine that capacitance is proportional to area and inversely proportional to spacing. Once students have done a guided derivation of capacitance as a function of spacing and area using Gauss's law, they can determine the dielectric constant of the book they have used. A typical result for C vs d is shown in Fig. 11.

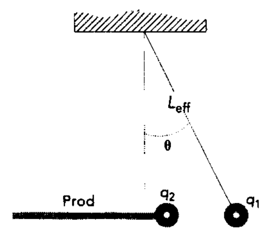
Activity Set 5 on Faraday's Law: The last activity in Unit 27 involves a verification of Faraday's law. The apparatus sketched in Fig. 12 is based on a design originally developed by Christopher Jones at Union College.[14] It consists of a large field coil that can have a time varying magnetic field at its center when driven by a function generator. According to Faraday's Law an emf can be induced in a small pickup coil placed in the center of the field coil. Faraday's equation is

$$\epsilon = -\frac{d\Phi_m}{dt},$$

where ϵ represents the emf and Φ_m represents the magnetic flux through the pickup coil due to the magnetic field generated by the field coil.

By measuring the voltage from the function generator and the emf induced in the pickup coil with a dual trace oscilloscope, it is obvious on a qualitative basis that the emf is

Fig. 6. A student rotates in a circle due to the centripetal force. A constant angular speed is maintained by a tangential force applied by another student which balances the force of friction that opposes the direction of motion. (Illustration courtesy of John Wiley & Sons).



4. Coulomb force (unit 19)

Fig. 8. A charged ping-pong ball is repelled from an equally charged prod. At equilibrium, the vector sum of the gravitational force, the tension in the string, and the Coulomb force on the hanging ball is zero.

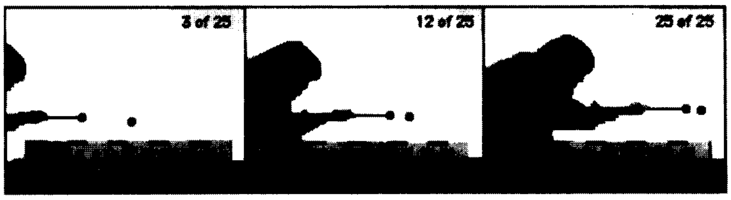


Fig. 9. Three of 25 digitized video frames depicting the forces between two charged balls. The thread holding up the hanging ball is not visible.

proportional to the negative of the time derivative of the current delivered to the field coil by the function generator. An example of this is shown in Fig. 13 for a situation in which a triangular wave is fed into the field coil and the emf induced in the pickup coil has the form of a square wave and hence is proportional to the negative time derivative of the triangle wave.

If the frequency of the triangular wave is increased so the magnitude of the time derivative of the magnetic flux through the pickup coil increases, students can immediately see an increase in the amplitude of the square wave. If the pickup coil is turned ± 90 degrees with respect to the field coil, students can quickly observe the amplitude of the emf go to zero. Thus students can observe the relationship between flux and induced emf. The next step is to try other wave forms and see if the new emf wave form still has the shape of the derivative of the field coil wave form.

Finally, Faraday's law can be verified quantitatively if the number of turns, areas of coils, and the current fed to the field coils are known. Sample data showing the linear relationship between the pickup coil wave amplitude and the driving frequency is shown in Fig. 14. Figure 15 shows the linear relationship between the pickup coil wave amplitude and the cosine of the angle between the field coil and the pickup coil. Another quantitative experiment involves using the pickup coil to measure the magnitude of the magnetic field as a function of distance along the axis of the field coil.

Activity Set 6 on the Heat Engine: Unit 18 deals entirely with the heat engine. A typical nineteenth century heat engine is a complicated device full of chambers, pistons, levers, and gears. These trappings obscure the essential physical features of a heat engine. With the help of PASCO Scientific, we designed a simple engine whose function is to lift masses from one level to another. The engine consists of a hollow cylinder with a graphite piston that can move along the axis of the cylinder with very little friction or air leakage as long as the total pressure on the gas in the cylinder is within a few percent of atmospheric pressure. The piston has a platform attached to it for lifting masses. A short length of tubing connects the air in the cylinder to a canister that serves as an air chamber. When the canister is moved from a vessel of cold water to a vessel of hot water, the expanding air causes the piston to rise. Thus, a mass placed on the platform can be lifted and removed. When the canister is returned to the cold reservoir, the platform descends and is ready to receive a new mass. The basic mass lifter engine cycle is shown in Fig. 16.

Students can predict and observe what happens during each stage of the cycle. A good equation-verification experiment is to make the measurements needed in various stages of the cycle to develop a $P-V$ curve and to compare the area it encloses to the useful work done in raising the mass. Thus, in the next activity students are asked to calculate the pressure on the air column with and without a mass of several hundred grams. They can also determine the volume of air in the system at each stage of the cycle using geometric considerations and measurements of the height of the piston. If the calculations and measurements are performed carefully, then the thermodynamic work and the useful work are the same within 1% or 2%. Since it is easy to prove, using the equations needed for the calculations, that the two calculations should be the same, this is actually a tautological experiment. A typical $P-V$ curve along with calculations is shown in Fig. 17.

Although it may seem like gilding the lily, it is also possible to use a computer-based laboratory system outfitted with an ultrasonic motion detector and pressure sensor to track the cycle automatically. The motion detector can be placed above the platform that has a low-mass canopy added, to allow for the addition of a mass between two surfaces, and a motion detector can register the changes in the canopy height and hence the cylinder volume correctly. A typical

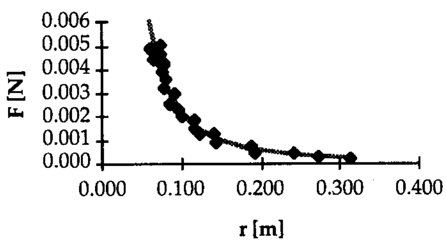


Fig. 10. A graph of the Coulomb force vs the distance between two charged ping-pong balls. The gray line is based on a fit of $F_c = \text{const}/r^2$ that shows that the inverse square law holds quite well. Assuming that Coulomb's law holds, it can also be shown that each ball carries about 5×10^{-8} C of excess charge. The VideoPoint™ software was used to obtain the data from video frames.

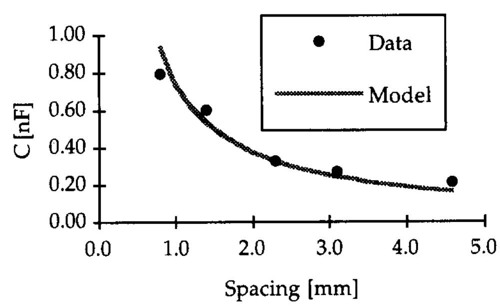


Fig. 11. A graph of the capacitance vs the spacing between two pieces of aluminum foil separated by the pages of a book. C is measured with a digital multimeter. A model that predicts an inverse relationship between capacitance and spacing gives an excellent fit to the data.

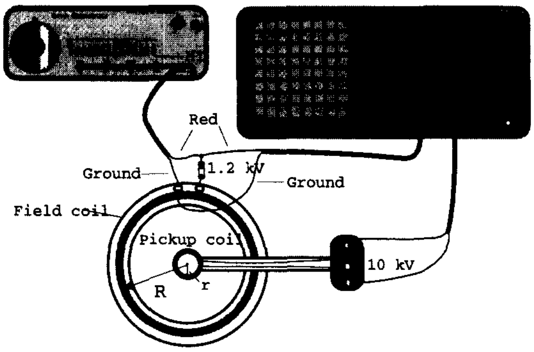


Fig. 12. Faraday's law apparatus (Illustration courtesy of John Wiley & Sons.)

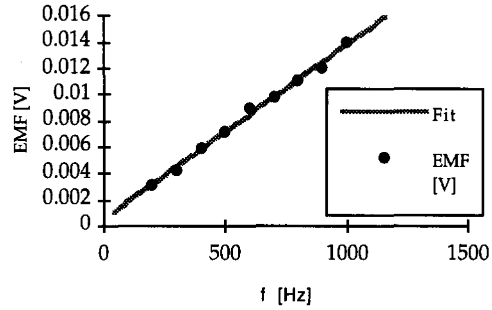


Fig. 14. Amplitude of the pickup coil emf as a function of the frequency of the wave form impressed on the field coil.

$P-V$ curve generated based on motion detector and pressure sensor measurements is shown in Fig. 18. Although this method of collecting and displaying data in real time is very impressive, we don't start students' quantitative engagement with the heat engine on this level as it appears to the novice like an animated movie and the elements of the cycle happen a bit too fast for real conceptual understanding.

Obviously in the Workshop Physics context, the apparatus, computer tools, and activities all serve to reinforce each other. Many of the prototypes and ideas for the apparatus that I have been talking about come from fellow physics teachers. I hope that this brief introduction to a few of my favorite pieces of apparatus will serve to inspire you to continue inventing new ways to enable students to observe physical phenomenon without unnecessary complexity. These basic observations can act as seeds which eventually germinate into conceptual and mathematical understandings of a host of related physical phenomena.

V. INTRODUCTORY PHYSICS TEACHING CHALLENGES

An exciting new mood of change pervades our physics teaching community. In addition to Workshop Physics there are a number of new curricular developments for teaching introductory physics that are based at least in part on the outcomes of physics education research and that seek to replace passive learning with active experiences. New activity-based teaching methods and curricular materials are currently available for most student audiences including nonscience majors and future teachers as well as the more traditional physics students taking algebra-based and calculus-based introductory courses. Some of these new approaches to teaching have been designed to make lecture sessions more interactive and engaging for students. Other curriculum developers have designed conceptual tutorials and also quantitative tutorials to replace conventional recitation sessions or to augment lectures. Others have developed new sequenced laboratory programs that combine new understandings from physics education research with powerful microcomputer tools.

All of us who want to keep Robert Millikan's educational legacy alive by engaging in physics education research or by developing and testing new methods for teaching activity-based physics courses face many challenges. Two of these are particularly noteworthy.

The hardest challenge for me personally is to find that each year some students who have, according to objective tests, learned much more in the Workshop courses than they would have in traditional courses but are still frustrated by their experience. Many of these students remain convinced that they have learned little, and that a good clear set of lectures would be more educational and require less work. We are continually striving at Dickinson to refine and improve activities and explore new approaches to students who cling to the notion that passive learning is easier and better. In fact, in a new book entitled, *The Captive Audience*,[16] educators Pat Cross and Mimi Harris Steadman have used some of our experiences teaching Workshop Physics at Dickinson to introduce readers to an extensive body of research on student-learning styles.

However, I am afraid that the attitudes of some of our frustrated students toward the study of physics are symptom-

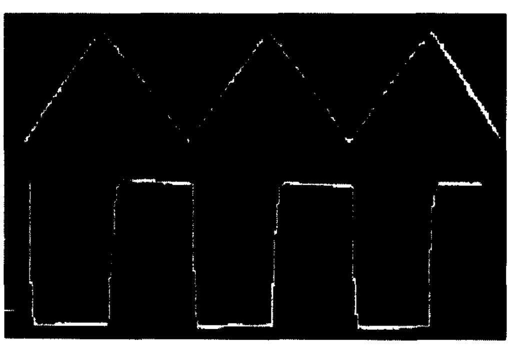


Fig. 13. Dual trace oscilloscope signals showing a relationship between the current in the field coil and the emf induced in the pickup coil that obeys Faraday's law.

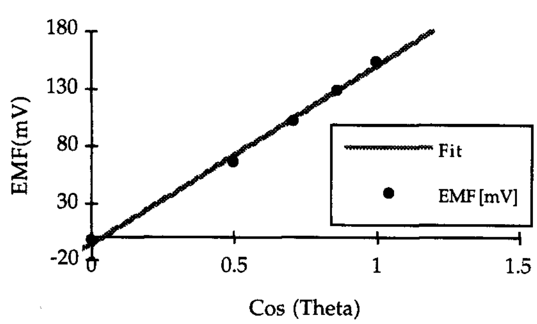


Fig. 15. Amplitude of the pickup coil emf as a function of the cosine of the angle between the field coil and the pickup coil (Ref. 15).

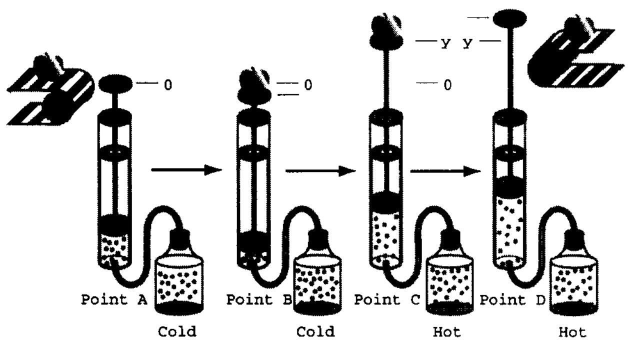


Fig. 16. A simplified diagram of the mass lifter heat engine at different stages of its cycle. (Illustration courtesy of John Wiley & Sons).

atic of cultural phenomena that we have little control over. First of all, many college students have had little practice in the art of logical reasoning in their previous schooling. Although these students are often very capable intellectually, many of them find thinking and taking intellectual risks to be a painful process. Students who contend that they prefer lectures say they resent having to "teach themselves everything."[17]

A second cultural phenomenon is revealed in a national study which indicates that the average full-time college student spends less than 25 hours a week on activities related to academics.[18] So the fact that a typical introductory physics course, including Workshop Physics, requires a total of about 12 hours of a student's time each week, is viewed by many students as an unreasonable time demand.[19] This student cultural phenomenon is at odds with a tradition strongly imbedded in the culture of physics teaching. Most physics teachers feel that a respectable year-long introductory physics course sequence should cover mechanics, geometric and physical optics, thermodynamics, electricity and magnetism, and some modern physics. Our attempts as introductory physics teachers to cover the expected topics frustrate students no matter what methods we use to teach.

Those working on curricula for future K-8 teachers and nonscience majors are not burdened with demands that a full range of topics be covered in depth. Our initial attempts to use a blend of Workshop-style guided inquiry and student-directed projects in the Workshop Physical Science courses being pilot tested at Dickinson College are encouraging. Our nonscience majors seem to be less frustrated, yet they are achieving a mastery of topics, learning techniques that should allow them to master new topics in the future, and learning more about the processes of doing scientific research.[20] Why can't introductory physics students share this experience?

We and many of the client programs we serve, including engineering and pre-medical programs, are locked into an expectation of complete coverage. I personally feel trapped by these expectations and feel that we as members of AAPT must discuss coverage issues as a community.

An equally daunting challenge is that the implementation of computer-enhanced, activity-based physics courses takes

Can Dimensions:		Hose Dimensions:		Added Mass:	
D=	5 cm	d=	0.5 cm	m=	0.255 kg
L=	7 cm	l=	50 cm	Piston & Platform Mass:	
V=	1.37E-04 m^2	V=	9.82E-06 m^2	M=	0.0387 kg
Cylinder Diameter:		Cylinder Area:			
D'=	3.254 cm	A=	8.316 cm^2		

a->b: adiabatic
b->c: isobaric
c->d: adiabatic
d->a: isobaric

Useful Work (mgh): W= 0.170 J

Mass Lifter Heat Engine
Pressure [Pa]
Volume [m^3]

	Added Mass [kg]	Total Mass [kg]	L' [mm]	Vtotal [m^-3]	ΔP [Pa]	P [Pa]
a:	0.000	0.0387	13.6	1.59E-04	456.12	1.018E+05
b:	0.255	0.2937	7.8	1.54E-04	3461.5	1.048E+05
c:	0.255	0.2937	75.7	2.10E-04	3461.5	1.048E+05
d:	0.000	0.0387	81.5	2.15E-04	456.12	1.018E+05

ΔP= 3.01E+03 [Pa]
ΔV= 5.65E-05 [m^3]

Thermodynamic Work: W= 0.170 J

$$W_{useful} = ma_g(h_c - h_b)$$

$$W_{therm} = \oint PdV \approx \Delta P_{ad,bc}\{\tfrac{1}{2}[(V_c + V_d) - (V_a + V_b)]\}$$

$$V_{cylinder} = \pi\left(\frac{D'}{2}\right)^2 L' \quad V_{hose} = \pi\left(\frac{d}{2}\right)^2 l \quad V_{can} = \pi\left(\frac{D}{2}\right)^2 L$$

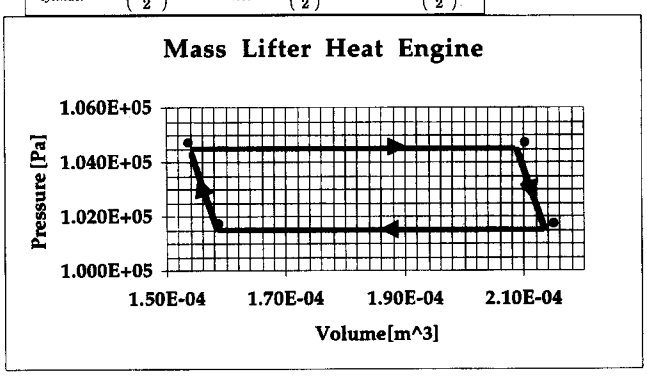


Fig. 17. $P-V$ curve and calculations of work associated with one cycle of a mass lifter engine which is lifting a 255 g mass.

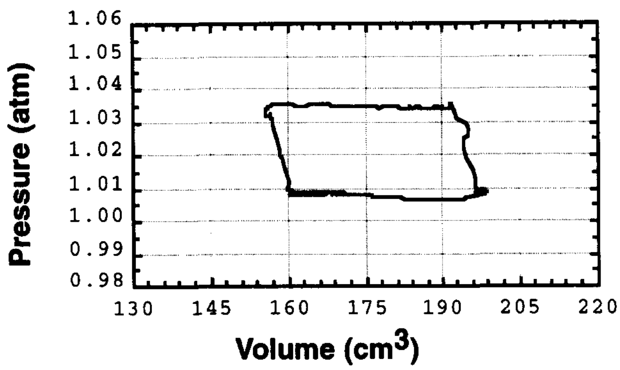


Fig. 18. $P-V$ curve associated with one cycle of a mass lifter engine created using a computer-based laboratory system with a motion detector and pressure sensor.

more time, energy, and resources than traditional courses do. Although we have evidence that the additional effort and expense is very cost-effective when student learning gains are assessed, it is not easy to garner the resources and muster the energy to use new methods in each of our classrooms. Change demands that each of us be creative about the adaptation and continued refinement of activity-based methods to our own environments. In addition, each of us must become an entrepreneurial advocate for our teaching dreams and garner the resources needed to make them realities. Millikan's lifetime efforts to obtain the resources needed to transform Caltech into a leading institution serve as a fine example of the spirit of advocacy each of us needs.

I look forward to these challenges because I think if enough of us work together with a renewed sense of dedication, a paradigm shift in physics education can be achieved. I look forward to these challenges because the continued interplay between physics education research, curriculum development, and informed classroom testing offers us endless opportunities to deepen our understanding of basic physics and the ways in which students from all backgrounds and walks of life can learn better. I look forward to these challenges because I love doing physics and teaching it to others. I look forward to these challenges because they allow me to continue working with all of you who belong to this extraordinary AAPT community. I can truly say one more time "I'm proud to be a physics teacher!"

ACKNOWLEDGMENTS

We thank Lillian McDermott and Arnold Arons for inspiration and support; contributing authors of the *Activity Guide* Robert Boyle, Patrick Cooney, Kenneth Laws, John Luetzelschwab, David Sokoloff, and Ronald Thornton; Dickinson colleague Hans Pfister for collaboration on apparatus design; staff members and student interns who have worked with the project during the past ten years as well as staff members at Vernier Software, PASCO Scientific, Lenox Softworks, and John Wiley and Sons for helping us refine our equipment, computer tools, and written materials; major funding agencies—FIPSE and NSF; and my immediate family and the family of AAPT members who will continue to share experiences with me.

[a]Electronic mail: lawsp@dickinson.edu

[1]J. R. Goodstein, *Millikan's School* (Norton, New York, 1991), p. 88.

[2]R. H. Kargon, *The Rise of Robert Millikan: Portrait of a Life in American Science* (Cornell U. P., Ithaca, NY, 1982).

[3]R. A. Millikan, *The Autobiography of Robert A. Millikan* (Prentice-Hall, New York, 1950), p. 14.

[4]In Ref. 3, pp. 40–41.

[5]D. Bligh, *What's the Use of Lectures* (ADB, Devon, England, 1978).

[6]O. Milton, *Alternatives to the Traditional* (Jossey-Bass, San Francisco, CA, 1972).

[7]L. McDermott, "How we teach and how students learn—a mismatch?," Am. J. Phys. **61**(4), 295–298 (1993).

[8]E. F. Redish, J. M. Saul, and R. N. Steinberg, "On the Effectiveness of Active-Engagement Microcomputer-Based Laboratories," Am. J. Phys. (to be published).

[9]P. W. Laws, "Calculus-based physics without lectures," Phys. Today **44**(12), 24–31 (1991).

[10]A. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990), Chap. 12.

[11]P. W. Laws, *Workshop Physics Activity Guide* (Wiley, New York, 1997).

[12]J. Harte, *Consider a Spherical Cow* (University Science Books, Mill Valley, CA, 1988).

[13]PASCO Scientific Kinesthetics cart (SE-8747), (PASCO Scientific, Roseville, CA).

[14]C. C. Jones, "Faraday's law apparatus for the freshman laboratory," Am. J. Phys. **55**(12), 1148–1150 (1987).

[15]See Ref. 14.

[16]P. Cross and M. Harris Steadman, *The Captive Audience* (Jossey-Bass, San Francisco, 1996).

[17]P. W. Laws, P. J. Rosborough, and F. J. Poodry; "Women's responses to an activity-based introductory physics program," New Directions for Teaching and Learning **61**, 77–87 (1995).

[18]T. L. Wingard, E. L. Dey, and W. S. Korn, *The American College Student, 1990: National Norms for 1986 and 1988 College Freshmen* (Higher Education Research Institute, University of California, Los Angeles, 1991).

[19]Based on unpublished student survey data collected on 17 introductory physics courses at 14 colleges as part of the Workshop Physics project.

[20]D. P. Jackson and P. W. Laws, "Workshop Physical Science: Project-based Science Education for Future Teachers, Parents and Citizens," in *Proceedings of the 1996 International Conference on Undergraduate Physics Education* (University of Maryland, College Park, MD), 31 July–4 Aug 1996.

AESTHETIC JUDGMENTS

In this century, as we have seen in the cases of general relativity and the electroweak theory, the consensus in favor of physical theories has often been reached on the basis of aesthetic judgments before the experimental evidence for these theories became really compelling. I see in this the remarkable power of the physicist's sense of beauty acting in conjunction with and sometimes even in opposition to the weight of experimental evidence.

Steven Weinberg, *Dreams of a Final Theory* (Pantheon Books, New York, 1992), p. 130.