Millikan's Influence on Undergraduate Teaching

DUANE ROLLER

Wabash College, Crawfordsville, Indiana

RECENTLY I had occasion to make an analysis of current problems in undergraduate instruction and of the steps that might be taken to solve them.[1] Afterwards, while preparing the present paper, I reread a number of Professor Millikan's papers on physics education and was impressed to find that many of the points covered in my analysis had been discussed and stressed by Millikan in papers published at various times throughout the last half-century. Since my analysis was based not merely on personal experiences in teaching but on numerous articles on physics instruction that have appeared during the past 15 years, I must conclude that a good deal of the current educational thought of physicists has been strongly influenced and often anticipated by Millikan. As has been said elsewhere:[2]

> Millikan's career is in rather striking contrast to the conventional career in science in that he devoted the early years of his professional life mainly to teaching and to reforming the teaching of physics. Instead of being chiefly an investigator of pure science, with teaching as a side line, he was primarily a teacher during this phase, although at the same time working, as is now apparent, toward fundamental research.

Moreover, during these later years of research he has always retained a deep interest in educational matters.

The contents of Millikan's educational writings show that, in general, the conditions of school and university life in the time of his youth were not greatly different from those prevailing today. Hence a study of these writings is still rewarding. One problem, however, seems to have changed to some extent. Even as late as World War I, this country, with its large population and ambitious program of public education, appeared to be producing many good physicists, but too few of the very first order. It was sometimes contended that this situation would eventually correct itself, that it existed merely because the country was new and had not as yet had time to produce its share of eminent scientists. However, that this was the complete explanation seems doubtful. Millikan's views on it, voiced shortly after World War I, are worth summarizing.[3]

> It is to our eternal credit that the two most significant and important technical advances of the half-century preceding 1920 had their inception in the United States: one was the conquest of the air by man after centuries of failure; the other was the initiation of the science and art of electrical transmission of speech. Nevertheless, at the beginning of and during World War I, we were far behind other countries in the art of aviation, and for two reasons—because the American public was not sufficiently appreciative of the possibilities and needs of this sort of scientific work to support it adequately, and because we had not developed a sufficient number of men of outstanding ability in this field to enable us to cope with our European competitors. The story of the application of the vacuum tube to the purpose of the war is remarkably similar, and so is that coming from many other fields of activity—for instance, the development by American chemists of gas masks for chemical warfare.
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> Furthermore, consider comparisons that had nothing to do with the war. When we count up the world's outstanding physicists, the number of American names is not more than a half or a third of what it should be in proportion to the population. Similarly, in chemistry one would scarcely think of comparing the group of men we produced in the 30 years preceding 1920 with those who have honored Germany.
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> As evidence that this deficiency is not due to poor native capacity of men born on American soil, we long ago learned at the University of Chicago to expect an exceptional man when we got an honors student from Toronto or McGill. Yet the population of Canada is very similar to that of certain portions of our own country. Apparently the British honors system has been more successful in one respect than has our own educational system, namely, *in selecting and training the exceptional man.*

Even if this defect has now been partially overcome, it is a problem that must be carefully

[1] Unpublished paper presented at the Iowa Colloquium of College Physicists, June 1947, under the title, "The role of nuclear physics in undergraduate instruction."

[2] Citation upon occasion of the award to Professor Millikan of the 1940 Oersted Medal, Am. J. Phys. 9, 39 (1941).

[3] Digest of parts of an address by Millikan at Indiana University; published in *Centennial memorial volume*, Indiana University (1920).

watched in order to secure and extend the progress made. For instance, a way in which our future scientists might be selected is discussed by Millikan in a recent article devoted to opportunities of the physics teacher, especially those teaching on the secondary and lower division college levels.[4] Millikan asserts that vocational guidance from the age of 13 years on is the most important job of any universal educational system; that, for testing analytic aptitude and capacities of the student, physics is admittedly the best subject in the whole curriculum; that, as nearly as possible, equal opportunity should be given to every youth up to the age of from 16 to 18 to find the vocation in which, in this probationary period, he has shown himself best adapted to succeed and most content.[5] In brief, young people should be encouraged to continue their schooling at least through the secondary school level, not merely so that they may have a more extensive education, but because it is in this later period that they can pursue studies, such as physics, that make possible judgments as to whether they are likely to make a success of any of the analytical pursuits—the sciences, law, medicine, engineering, and so on. This also means, as Millikan points out, that on the secondary and lower college levels, selection and vocational guidance are the teacher's chief job.

> Talking entertainingly to a hundred or two hundred students is a wholly subordinate and trivial requirement of a good teacher. The great, indispensable requisite is conscientiousness in watching carefully and discriminately the way students solve problems, the way they do their laboratory work, the way they answer examination questions, the way they pose questions of their own. This job cannot be delegated to anyone else without abdicating the main job of the teacher.[4]

This conception of the teacher's function not only differs from the ordinary one, but implies an interest in and devotion to elementary teaching that too often are lacking in college and university physicists of good ability—and it is only such physicists that should be teaching elementary courses or any other courses. Much of the weakness in our teaching of elementary physics—or, for that matter, of any of the sciences—can be attributed to the fact that such teaching has little or no career value so far as the able scientist is concerned. To say that the able physicist should be unselfish enough to disregard the effects of such interests on his own career is merely being unrealistic. Instead, there must somehow be set up conditions within the profession that will make it possible for able people to give earnest attention to elementary teaching without detriment to their careers as physicists.

IMPROVING UNDERGRADUATE WORK

One of Millikan's early students at the University of Chicago, who afterwards made a notable record at a small liberal arts college in sending physics students on to successful graduate work, has this to say about Millikan's influence on his undergraduate teaching:[6]

> When I started teaching, some 40 years ago, Doctor Millikan helped me to arrange my courses. I used his two books—*Mechanics, Molecular Physics and Heat*[7] and *Electricity, Sound and Light*[8]—in my sophomore courses and consider that what success I may have had as a teacher of physics was largely due to the start the students had in these courses prepared by Doctor Millikan.

Many of Millikan's former students could tell a similar story about his influence on their teaching.[9]

The establishment of the experimental physics courses at Chicago in 1898, soon after Millikan's arrival there, helped to initiate a wave of renewed interest in the science of physics in this country. His reorganization of the undergraduate courses was based on a close correlation between laboratory and classroom work, and it was around a series of experiments, which Millikan insisted must be made significant and capable of yielding precise results, that his two textbooks were built.

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[4] R. A. Millikan, Am. J. Phys. **9**, 81 (1941).

[5] According to S. S. Visher [Am. Scientist **35**, 543 (1947)], data on 860 of the 2607 scientists starred in *American men of science* show that almost a quarter decided to become scientists before they were 15 years of age, and more than another third decided while they were 15 to 18 years old. Of the physicists in this group, roughly a third chose their science before attaining the age at which most students enter college.

[6] In a personal letter to the writer.

[7] (Ginn and Company, 1901.)

[8] Written in collaboration with John Mills (Ginn and Company, 1908).

[9] See, for instance, L. B. Loeb, *A laboratory manual of electricity and magnetism* (Stanford University Press, rev. ed., 1941), preface.

> Attempts to secure a satisfactory articulation of the laboratory and classroom phases of instruction were not prevalent at the time, although the objectives thus to be realized do not differ essentially from those that guided the pioneers of physics in training small groups of workers in the early laboratories; but Millikan was convinced that this was the way in which the student could most readily gain genuine insight to the methods of physics and I had a thorough grasp of its foundation principles.[2]

In 1921 Millikan went to Pasadena, and since then has devoted much of his time to building a scientific institute with a strong research atmosphere, but again with the teaching function at the base of the organization. Consequently, he insisted that a four-year undergraduate college be maintained, and not neglected, in this great productive center of scientific research; and he took the position that all research men should do some undergraduate teaching and that all teachers should engage in some research.

Perhaps no greater improvement could be made in undergraduate instruction than to have all of it carried out in an atmosphere similar to that existing in the good graduate schools. A. W. Hull[10] has made the rather arresting assertion that it is not so much the extra knowledge gained in graduate school as the changed attitude toward study that enables the man who has done graduate work to advance while those with only the undergraduate degree often reach a ceiling. Hull lists four qualities sought in the hiring and retaining of personnel for industrial research, these being, in order of importance, *character*, *aptitide*, *attitude*, and *knowledge*. Certainly, if the development of proper character traits and attitudes are of primary importance in the training of undergraduate physics students, then they should be made prime educational objectives; and such objectives are not likely to be realized merely by prescribing a set of courses intended primarily to impart knowledge. Examples can be cited of undergraduate professors who are rated by their students as poor classroom teachers and yet have sent numerous young people on to successful careers in physics. The ability to impart knowledge is important; but, both Hull and Millikan contend, there are other factors in undergraduate instruction that are essential in selecting and training people for a successful career in physics.

Carrying out undergraduate training in an atmosphere similar to that of the graduate school also means putting greater emphasis on the creative outlook. Possibly the undergraduate student should be started on creative work of a modest character almost from the beginning. The manpower shortage during the war taught us that very young people of high native ability and good attitudes can carry on creative work of a modest character without benefit of much formal training. As J. J. Thomson once said,[11] a certain degree of healthy ignorance is an asset to a research worker.

Of the various reasons for fostering creativeness in a student as early as possible, a most important one is the desirability of getting the student seasoned in research well before he reaches the average age of maximum creative productivity. American physicists, on the average, receive the doctorate when they are about 30 years of age,[12] but studies[13] indicate that this is not far from the average age of greatest creativeness in physics. Thus it appears that most American physicists do not get deeply into research until they have passed the average age for highest creativeness. In this connection it should be mentioned that the average lapse of time between receipt of the bachelor's and doctor's degrees in this country is *eight* years.[12] Evidently, a greater effort should be made to encourage and assist very able students to go from undergraduate to graduate work without delay.

As for the formal courses in physics to be taken by undergraduates, mention has already been made of Millikan's insistence that these show a close correlation between laboratory and classroom work. Today it is becoming clear that there is also a need for reformulation of these courses so as to cut across old subject-matter boundaries and set up new areas more in keeping with modern trends.[14] Most undergraduate courses still follow the nineteenth-century pat-

[10] A. W. Hull, Science **101**, 157 (1945).

[11] A. L. Hughes, Am. J. Phys. **15**, 49 (1947).

[12] R. M. Bell, Am. J. Phys. **14**, 396 (1946).

[13] H. C. Lehman, Sci. Mo. **43**, 151 (1936); Science **98**, 393 (1943).

[14] As suggested, for example, by Caswell and Gordy, Am. J. Phys. **13**, 315 (1945), and A. L. Hughes, reference 11.

tern of mechanics, heat, sound, light, and so on; and these, moreover, are often presented as almost separate disciplines. Such a classification of physics subject matter is essentially phenomenological in character and is necessary and appropriate only so long as there is no theoretical structure that permeates the field as a whole. Today, instead of putting in one course all topics previously concerned with, say, optics, we should try to integrate topics that lead to, or illustrate common, fundamental principles.

This reformulation would not only effect savings in student time and effort, but would serve to discourage the practice of adding a new course to the curriculum every time that a new area of physical knowledge comes into prominence. Moreover, it would reduce the tendency to include courses on specialized technics, such as photography, x-ray technology, shop practice, and so on, all the essential parts of which can be absorbed in the lecture or laboratory work of the basic courses.

Other needed reforms in instruction will not be mentioned here, for most of them should be obvious when we remember that physics, of all major areas of knowledge, is probably the one most adaptable to a compact and efficient plan of instruction. No other field presents more opportunities for effecting economy of thought and learning. None has a better developed theoretical structure, so that a relatively few principles and procedures knit together a great array of facts. None has a methodology so explicit and clear-cut. None puts greater emphasis on productivity and use of knowledge as contrasted with passive learning. The efficiency in instruction that we seek is inherent in the science, if we can only find the time and energy needed to make the most of it.

PHYSICS IN GENERAL EDUCATION

Defining the fundamental aim of all public education to be that of giving the rising generation the best possible preparation for perpetuating and improving upon the civilization that it inherits, Millikan has enumerated, in order of importance, the following factors as contributing best to this end:[15] (*a*) the development in the young of high ethical standards and ideals; (*b*) the development of the power of self-control as it manifests itself especially in industry and application to the mastery of difficult situations; (*c*) implanting in the rising generations a knowledge of, and ability to use, the materials and the tools by means of which our civilization has been built up.

Millikan points out that the first of these factors—the ethical—is the responsibility of the individual teacher, and herein lies an incomparable opportunity to pass on the best ideals of the past to the generation that is to follow. This can be done in connection with all studies, but, as Millikan notes, physics offers especial opportunities for impressing the lesson of scrupulous honesty in observation and statement, and for inculcating habits of accuracy, reliability, conciseness, and orderliness. Thus the first need in utilizing physics for purposes of general education is to have the right sort of teachers—men who realize that the greatest need of the schools is an increasing appreciation among educators that "the building of character is the real aim of the schools" and that the tendency of the youth of today "toward a weak appreciation of the demands of duty, and a disposition to follow pleasure and interest rather than obligation and order" constitutes a "condition which demands the earliest thought and action. . . ."[16]

With regard to the second factor—the disciplinary one—the different subjects of the curriculum have obviously different values as means of giving students control over their different faculties; and Millikan believes it will be generally conceded that physics is of peculiar value in developing and discipling the *reasoning* faculty. In physics the problem method is particularly easy to apply. In it the memorizing, textbook habit is particularly easy to eradicate. Indeed, from the intellectual standpoint, the main object of the course in physics is to teach the student to begin to think for himself. The old method of teaching merely by authority, the memory being crammed with undigested subject matter, and the more modern method of omitting everything bothersome, and serving up to the students delectable dishes of predigested thought

[15] Sch. Sci. and Math. (Dec. 1908, Jan. and Feb. 1909).

[16] Resolution adopted by the National Education Association in 1908, quoted in reference 15.

lead to the same *result*—an emasculated physics, entertaining, no doubt, in the latter case, and dry and uninteresting in the former, but well-nigh valueless in both.

Turning to the third educational aim, namely, that of developing the ability to understand and to meet the situation of modern life, Millikan points out that it would be difficult to find any subject in the curriculum that can lay claim even to equality with physics. Here the chief need of the general course in physics is the sort of teaching that gives to the student not only a knowledge of and an ability to apply a few of the most fundamental principles of physics, but that opens his eyes to the *method* of physics, that inculcates in him the scientific attitude, that leads him to appreciate the nature of evidence and the hypothetical character of all our great generalizations. In accomplishing this aim, Millikan thinks that physics must be given some sort of historical setting, so as to show the student how and when the great generalizations of physics have been set up, modified, and, in some cases, discarded, as the science has grown.

> I can conceive of no better way of showing a boy the folly of cock-sureness, and of implanting in him the seeds, at least, of the scientific attitude toward all the relations of life, than by giving him a glimpse of how Galileo, and Newton, and Volta, . . . , and the other great makers of physics have themselves worked.[15]

It could be added that, if character development and use of scientific methods are to be taught effectively in the general physics course, they must be taught consciously and explicitly. A student can spend many hours in the laboratory, and still be unable to render verbal the difference between observation and experiment. He can spend the year learning the definitions of many technical terms and still not be conscious of the attributes of good definitions, the general desirability of knowing the meanings of the words that he uses, or of the economy of thought that can be effected by inventing new concepts or improving existing terminology. He may be able to apply simple algebra with facility and yet be unaware of the role of symbolism in promoting economy and clarity of thought, ready manipulation of ideas, and increased ability to generalize. And unless he does verbalize and become functionally conscious of these various ideas, he will not put them to much use outside of the immediate situation in which they were learned.

As Millikan implies, physics *could* be made highly significant and indeed almost indispensable as a means for preparing able people for life in a culture that is coming to be predominately scientific. But that we have failed thus far to do this seems to be the opinion prevailing among college students and faculty members in general. College scientists are becoming increasingly aware of this failure, as seems evident from the numerous articles and even books on the subject that have appeared in the last several years. An examination of these publications will show, I think, that many of the reforms advocated are along lines similar to those which have been emphasized by Millikan and a very few other scientists over a period of at least half a century. It is the impending social crisis that has finally forced us to consider these reforms seriously and to try to put them into effect as quickly as possible.