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THE TEACHING OF PHYSICS TO ENGINEERING STUDENTS.

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I have been teaching physics to college and university students for nineteen years and I now have a few ideas on the subject which can, I think, be expressed independently of the subject-matter and which may be helpful to others.

Some time ago, in talking with a practical engineer on the teaching of physics, I stated that in my opinion the ultimate object of the teaching of physics to technical students is to lead the young man by a shortened route to that familiarity with physical things which is possessed by such a man as John Fritz. The shortening of the route which leads to this result depends upon the fact that the teacher of physics has to do largely with an *epitome* of real knowledge, and consequently the primary object of physics teaching is, in my opinion, to develop in the young man's mind a logical structure consisting of the aggregate of physical conceptions and theories.

Since beginning the teaching of physics, I have never devoted any of the time of my classes to the discussion of the history of the subject. The best way to study an organic structure is to study its history, through the medium, say, of embryology, but this is the worst possible way to study a logical structure.

I have never on any occasion apostrophized the Wonders of Nature to any class of mine. The ability to measure electricity and the ability to calculate magnetism are really very simple and prosaic things, and any writer or teacher who for a moment allows himself to speak of these things otherwise than in explanation or in application, may be set down at once as attempting to lend an element of mystery to knowledge he claims to possess. It seems to me a very significant fact that in most of the cases that have come to my notice, the appeal on the part of a scientific writer to the reader's wonder-sentiment has been associated with very hazy, or entirely faulty, notions on the writer's part. I know of a text-book on physics which introduces the discussion of the doctrine of the dissipation of energy in the chapters on Mechanics: this text-book actually would have it appear that the degradation of energy is *essentially the change from the potential to the kinetic form*, and the whole discussion ends as follows: "Tait calls available energy *Entropy*. The inevitable conclusion is that *entropy tends toward a value of zero*. In the beginning, then, points to a period when all energy was available. With no less certainty, physical science points to a time when entropy shall become zero. All the processes of nature must then cease. Even the earth itself, as lifeless as the moon, can no longer circle round the glowing sun, but both and all together, in one dead mass, must hang in everlasting silence in the boundless night of space." Now, what I want you to keep in mind, is that this wonderful view adown the corridors of Time is ostensibly based, in the book in question, upon a succession of egregious blunders.

I never have allowed the slightest speculative tendency to enter into any of my teaching, oral or written, and the extent to which many of our elementary text-books in physics indulge in imaginative nonsense and in weak phases of speculative philosophy is distressing to me. Nearly every text-book on physics that I know of defines the mass of a body as "the quantity of matter the body contains." I had the pleasure thirteen years ago of listening to a course of lectures by von Helmholtz on theoretical physics, and the first eight weeks or more of this course was devoted to the origin and meaning of our quantitative methods in physics. I thought at the time that von Helmholtz's statements were so simple and so apparently remote from the usual complications of physics that most of his hearers were likely not to appreciate what he said. Those lectures, however, stand in my mind as the most complete outline of the philosophy of the mathematical sciences ever given. All our notions of length and angle arise from and are defined by the fundamental geometric *operation* of congruence. The definition of mass, likewise, is a *physical operation*, the verbal definition is the briefest possible specification of this operation. The result of this operation on a given body is an invariant number, and by a feat of the imagination we are led to adopt this number as a measure of the "amount of matter the body contains." This is a notion of some mental utility although strictly it is mere imaginative nonsense. Several years ago I had occasion to review a well-known French book on "Electrical Measurements," the authors of which say "Une grandeur est une quantité susceptible d'augmentation ou de diminution. Une grandeur est dite mesurable quand on peut la comparer à une grandeur de méme espece et qut la résultat de la comparison donne à notre esprit une satisfaction compléte."

As an example of weak speculation, what do you think of the use in a *secondary school book* on physics of the following quotation from Maxwell as a means to clear up an inadequate discussion of energy? "We are acquainted with matter only as that which may have energy imparted to it from other matter, and which may in its turn communicate its energy to other matter. Energy, on the other hand, we know only as that which in all natural phenomena is continually passing from one portion of matter to another." What do you think of the following from an elementary English text-book on physics? "The fundamental property of matter, which distinguishes it from the only other real thing in the universe, is inertia. * * * We are now in a position to give one or two provisional definitions of matter—provisional because we cannot yet say, possibly may never be able to say, what matter really is. It may be defined in terms of any of its distinctive characteristics. We may say that matter is that which possesses inertia, or again since we have no knowledge of energy except in association with matter, we may assert that matter is the Vehicle of Energy." I wonder if any of you really doubt that every notion in physics, definite or indefinite, is associated with and derived from a physical operation, and that absolutely the only way to teach physics to young men is to direct their attention to that *marvelous series of determining operations which bring to light those one-to-one-correspondences which constitute the abstract facts of physical science.* If you do doubt this, I am bound to say that I do not think much of your knowledge of physics. I think that the sickliest notion of physics, even if a student gets it, is that it is the "science of masses, molecules and the ether." And I think that the healthiest notion, even if a student does not wholly get it, is that physics is the science of the ways of taking hold of bodies and pushing them; that it is the aggregate of all things that can be "by handling known."

In my opinion, the characteristic feature of science study, especially of the study of physical science, is *a determining objective constraint upon the processes of the mind.* I am surprised that this one important feature of science study is never mentioned in the many estimates that have been made of the value of science study in education, for as a matter of fact, that *complete definiteness* which is usually urged as the characteristic and valuable feature of science study is the fundamental condition of every psychological process, you say this or you say that, you go or you do not go, and even the classic mule standing midway between two similar loads of hay is in no danger of starving from indetermination. The psychological processes which are brought into play in the study of science do not differ from other psychological processes in regard to definiteness.

I say again that it is the completeness of objective constraint that chiefly differentiates the study of the physical sciences from all other studies and which makes the study of the physical sciences so important an element in any correct scheme of education. The importance of this objective constraint upon the mental processes in scientific work is most strikingly shown by the entire absence of any such constraint in all of our crank scientific literature. I think that the full realization of this objective constraint in the teaching of physics depends first of all upon the making of one's teaching utterly and absolutely simple and homely, *and devoid of all appeal to anything but the rigors of the scientific imagination.* Anything beyond this is, in my opinion, idolatry.

I think that the ability to learn science by reading is a highly specialized faculty and that among average young men this faculty is nearly zero. I know many men who are quick to receive knowledge by experience, and quick to catch, from verbal description, manifold variations of their empirical knowledge, but whose imagination is wholly unresponsive to that abstract kind of writing which is so necessary in a concise treatise on the elements of physics.

Nevertheless, I think that the development of the student's imagination to the extent that is necessary to enable him to follow concise writing is one of the chief objects in the teaching of physics, and I do not believe that this result can be accomplished without requiring the student to use a text-book of the severest kind.

My idea of the teaching of physics is to use a sharply, clearly and concisely written text-book, to give explanatory lectures of such character as to appeal properly to the student's imagination (*theoretical lectures*, in fact, illustrated by the simplest kind of experiments), to require of the student a large amount of numerical calculation, and to give a laboratory course based upon highly generalized printed directions supplemented by a vanishing series of verbal suggestions from an instructor.

I think that the chief object in a course in physics for technical students should be to give conceptual and analytical knowledge of the most important facts of physics. It is certainly better to know a little by reason, than much by rote. There is nothing in the teaching of physics so important as to develop in the student the ability to express physical conditions in mathematical form, geometrical or algebraic as the case may be, to reproduce or re-present the conditions of a problem adequately as a geometrical construction or as an algebraic formula. Nothing, I think, is so important as this for technical students. It is the very essence of effective knowledge of physics, and every bit of attempted instruction in physics which does not contribute directly or indirectly to facility in this re-presentation of physical fact in terms of our mental tools is in my opinion futile.

Many students, and even teachers of physics raise the objection that a rigorous mathematical presentation of physics is highly unsatisfactory and uninstructive. They like such a book as the excellent new book of Edser's on *Light* which abounds in descriptions of phenomena and of the most recent researches on light pressure and the cause of comet's tails. Now, I am really interested myself in comet's tails, but I would feel like thrashing a young student who concerned himself about comets' tails but held his imagination unresponsive to a discussion of stationary wave trains and of reflection with and without change of phase. I have a contempt for a student who thinks he understands the formation of a comet's tail but admits that such things as the kinematics of wave motion are beyond him. I recommend such a student to be honest with himself and study physics under the instruction of Jules Verne. Then he need not trouble himself about foundations, but he may follow his teacher pleasantly on a careless trip to the moon and with easy improvidence embark on a voyage of ten thousand leagues under the sea.

In my teaching of physics I have come to distinguish two distinct phases of laboratory work. One phase is that which is intended primarily to vivify algebraic formulas—I think it is silly to talk of the verification of Nature's Laws(!) by a student—and the other phase of laboratory work consists of elaborate and precise measurements carried out with every possible precaution for the elimination of error.

I take pleasure in distributing to the INSTITUTE members here present a small pamphlet which I have had printed for this occasion as an illustration of the vivifying phase of laboratory work. The eight experiments described in this pamphlet apply to the direct current dynamo, and I think that every technical student who studies physics to any extent should perform these experiments just to see the equations of the dynamo become alive. No one really knows much physics who is not able to look at an equation and see the manifold activities which the equation is intended to represent.