tva-6
WAS

Reprinted from the January Number of Vol. XIX, 1919,
School Science and Mathematics.

THE ROLE PLAYED BY GENERALIZATIONS IN LABORATORY PHYSICS.

By W. A. Shewhart,
Western Electric Co., New York City.

Reflection upon the history of civilization reveals at once that [illegible] of the chief [illegible] the human race has been a search for things or principles that remain invariant. If we study the history and philosophy of man, if we thoughtfully look about us, if we reflect upon the cravings of our own mind, we shall see that in every department of human interest and activity the supreme enterprise has been the quest for constance in a world of change, a search for permanence in a world whose law is variation. This is natural, for consider man plunged into the depths of the sense world of force and matter, surrounded by innumerable and apparently unrelated phenomena, torn and tossed among the elements of the cosmic stream which originates he knows not where, and flows he knows not whither. The aim of man has been to gain some everlasting vantage ground, some abiding rock from which to view and study the great ebb and flow of material events.

Look, if we please, at what we call science, philosophy, theology and art, and it is evident that these are greater forms under which various conquests for abiding realities have been carried on by previous generations. Confining ourselves to the domain of only a fragmentary element of the far greater domain of science, that is, considering the subject of physics, we find that the same aim has spurred on human endeavor that has underlain advancement in general. Lives of all great physicists remind us that theirs has been a search for permanence, a groping for abiding principles which would serve to correlate the great mass of worldly phenomena. Amid the infinite variety of nature many things appear as common, others as perplexing and seemingly unexplainable. The search for the elements which remain the same throughout the great multiplicity of phenomena has resulted in the real progress that has been made in physics.

It is the common observation of the teaching profession that the young student usually finds difficult those same points which have proven stumbling blocks to the greater physicists. Each adventurer, in his struggle to attain this vantage ground from which to view the phenomena, must expect to often slip and lose his footing even at the beginning of the course, even though the generations which have trod before him discovered and pointed out many well established principles which serve as guide posts. He must acquire for himself the skill of recognizing the permanent elements throughout the greatest range and variety of phenomena. "This ability," to quote Professor E. Mach,[1] "leads to a comprehensive, compact, consistent, and facile conception of facts."

The first period in the study of science may be designated as the period of survey and discovery in which the student must needs become acquainted with a large mass of facts. He must read of experiments and make experiments for himself, gathering all the while a store of concrete and vivid perceptions from which to draw in his later work, but it would be a hopeless task to undertake to remember and keep in mind this great body of data. Many physical quantities, such as velocity, mass, force, energy, etc., have been given names and in order that a new adventurer in the domain of physics may profit by the written and spoken words of others, he must memorize the accepted definitions of these terms as he would the vocabulary of a foreign language.

It is true, however, that physics is often taught as a heterogeneous body of unrelated facts and the student who has taken an elementary course, either in high school or college, looks back upon his work and remembers only a number of isolated facts, for he has not formed a conception of the principles relating these facts, and cannot think physics.

Therefore, the next step in scientific advancement is to pick out the common elements in the various experiments and include these under certain generalizations or, to again quote E. Mach,[2] "Thence is imposed the task of everywhere seeking out in the natural phenomena those elements that are the same and that, amid all multiplicity, remain the same."

The third step should be a critical study of the generalizations and a discussion of their applicability to all phenomena. Many such principles have practical limitations, as in the case of the general gas law, $pv = RT$, where p is the pressure, v the volume, T the absolute temperature and R a constant. As has long been known, this applies only approximately for real gases, and a study of its limitations is necessary for a thorough appreciation of the principle. In fact, as has often been pointed out, what we sometimes call physical laws are not laws in the sense that they present the whole truth of nature, but that they represent only a generalization based upon a finite number of observations.

---

[1] Mach, *Science of Mechanics*, page 5.

[2] E. Mach, *Science of Mechanics*, page 5.

Thus, we must note the difference in reasoning from principles based upon experiment and postulates of pure reason, for in the limit we do not know whether nature is based upon a rigorous or chance basis.

If the study of physics is to lead ultimately to a critical study of generalizations, then the laboratory work must lend itself to this end, by acquainting the student with physical quantities and phenomena which should give him clear-cut perceptions which, under the leadership of the teacher, should form the groundwork for the conceptions which may be gathered together as generalizations. Furthermore, it should lead the student to acquire the proper viewpoint from which to approach an investigation, be it either scientific or technical, and the ability to recognize the essentials of the problem at the outset.

In the laboratory, we must choose between the two-horned lemma—performing a large number of experiments in a cursory way, or of performing a fewer in a more thorough manner. The former gives a student a chance to gather a few facts; the second develops the student's individuality and encourages him to make generalizations and to discern the abstract principles underlying the concrete phenomena and in the end encourages the student to think.

For example, in the group of experiments ordinarily performed under the general heading of elasticity, it is not sufficient to know that the stretch l of a wire of length L and cross section πr^2 subjected to a tension F is given by $l = \frac{cFL}{\pi r^2}$ where c is a constant, depending upon the material of which the wire is made, or similarly that θ, the angular twist in radians for a rod of uniform cross sectional area πr^2, and length L, fastened at one end and subjected to a torque FR at the other is equal to $\frac{2FRL}{\pi r^4 k}$ where k is a constant called the coefficient of torsional rigidity.

A study of experiments of bending and twisting rods or stretching springs is incomplete unless in addition to such concrete facts, certain generalizations are made, as indicated below.

Such a study should lead to a definite conception of strain and stress and of the general relation between them, called elasticity, for this is a vantage ground from which to view most elastic phenomena. For instance, the general terms may be defined in the following manner: Whenever a body undergoes change in size or shape it is said to be strained. If the strain is of the simplest class, where two equal straight parallel lines go over into two equal parallel lines, it is called homogeneous; the most general type of such a strain being resolvable into a strain which changes the size but not the shape and one which changes the shape but not the size. If we consider the body under strain, the forces per unit area resisting the forces producing the strain are called stresses. The most general stress can be resolved into a tangential and a normal component, both of which are measured in terms of force per unit area. The relation existing between these two quantities is given by Hooke's Law, which states that stress is proportional to strain, within the elastic limit, or that when the load increases or diminishes the measured strain increases or diminishes in the same ratio, and when the load is reduced to zero no strain can be measured.

Thus we may write: stress = c strain. The student should grasp the generalized meaning of the constant c, for he should see that the types of stress and strain may be defined in different ways, and that we may express the strain of any of these types that accompanies a stress of the corresponding type, when there is no other stress, by the above equation, where c is called a modulus of elasticity. If the strain is a change in size but not shape, and the stress is a uniform normal pressure, the constant c is called the bulk modulus of elasticity, but if the strain is one of shape only, the constant of proportionality relating this strain to its accompanying stress is called the modulus of simple rigidity.

Since any homogeneous strain may be decomposed into a shear changing the shape and a single contraction or expansion changing the volume, if we know the two moduli of elasticity corresponding to these we may calculate all others, such as Young's Modulus, which may, for example, be shown to equal $\frac{9nk}{3k+n}$.

In generalized terms, Hooke's Law may be stated thus: "Each of the six components of stress at any point of a body is a linear function of the six components of strain at that point." From this statement a group of equations may be set up which form the basis for our present mathematical treatises on elasticity. From a critical viewpoint it should be noted that there is much room for future work, for the present theory of elasticity does not hold beyond the elastic limit nor does it rest upon the ultimate nature of the structure of materials. The student of physics should therefore gain a clear conception of principles involved in experiments which he is performing in the laboratory in addition to gaining a hold on facts, and the teacher should have these same conceptions when teaching.

If the chief aim of the human race as reflected in the collected works on science, theology, etc., has been a search for invariance in a world of change, then as progress in physics is but a single unit of the progress of civilization, it must reveal a search for invariance, the somewhat satisfactory heights of attainment being marked by such principles as conservation of energy, conservation of linear and angular momentum, a generalized statement of Hooke's Law, etc. In order to see physics as a single unit we must endeavor to attain some vantage ground from which to view all physical phenomena in their relation one to another. Many and far-reaching though the known principles of physics are today, lending an insight into a multitude of physical phenomena on every side of us, guiding us onward amid the flux of things material, yet we must recognize, perhaps more than ever before, the height of the wall of unknown and unrelated facts which surround us today.

In every field of physics much has been done, but there remains much more for the future generations to do. Just insofar as a student acquires a definite and clearly defined conception of the principles of physics and is enabled by these to relate and show the interconnection and interdependence, he has fitted himself to force on towards the final goal of science.