was able to prove experimentally that his deductions were correct. The discoveries of Newton, Faraday and others are very striking in that they propounded fundamental laws on what would now be considered very meager data. I am inclined to believe that their profound knowledge of mathematics was a great aid in arriving at the conclusions they did with so little data. Darwin, however, went to the opposite extreme and amassed a large amount of data over a long period of years before he announced his theory of the origin of species. One could cite numerous examples of the thought that was given to the interpretation of data before it was offered for publication.

The present tendency is to accumulate a superabundance of facts and data and devote too little time and effort in the proper correlation and interpretation of them. It is high time that we do relatively more thinking and less investigating if we are to maintain the high standards which have been set up for us by the past masters of science.

How are we to attain the goal of creative research? This question can not be answered any more easily than one can explain the production of a masterpiece in art, music or literature. However, it is possible to discuss some of the avenues which might lead to creative research. I am sure that when we began our careers in the sciences we were prompted to do so either through curiosity, humanitarianism, personal vanity, imitation or some such motive. Whatever this urge might have been originally, without it I doubt if any of us would spend the energy we do in research. In more ways than one this incentive is like a mirage, always in the distance, but for some reason or other we are never quite able to catch up with it. This failure to catch and hold a creative thought is partly due to the fact that we are not real dreamers or good philosophers. We are so busy collecting facts that we fail to give them much thought. Have you ever analyzed where your ideas originate? You will frequently find that it is during moments of relaxation, when the problems demanding your working energy are farthest from your thoughts. It is seldom that the most constructive thinking is done while busily engaged in the laboratory. More relaxation and reflection would be much more advantageous in solving problems than the mere collection of more data. With relaxation and reflection our subconscious mind might function and flash to us in an instant the clues which we were vainly groping for while in the laboratory.

Even if we ourselves fail to do creative research we can stimulate the rising generation of scientists to hunger for the goal and in this fashion make our contribution to the advancement of science. It should be the chief aim of the teacher in his contact with students to direct and stimulate them to thinking, rather than to fill their minds with masses of unrelated facts, which are always available, providing they have been taught where to find them. Convenient and accessible libraries should be built up, even at the expense of the laboratory, and students taught to use books constantly, as they would indispensable methods in the laboratory. Our graduate students for the most part have access to too much work and thought evading equipment. It is really surprising what can be done in the way of substantial research without costly apparatus. It is only necessary to refer back to the old masters of science to substantiate this statement.

Let us therefore stop deluding ourselves. The aim of research is not solely the accumulation of facts for immediate publication, so that we may in vainglory point to our output for the year. We must strive to do more constructive thinking and especially give our minds an opportunity to function through proper relaxation. We shall not advance fundamental science if we are simply busy collecting data. With more constructive thinking on our problems there would be fewer but better publications, an era without doubt we should all sincerely welcome.

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RECENT DEVELOPMENTS IN QUANTUM MECHANICS[1]

THE fundamental fact for quantum physics which has emerged from experimental investigations in the field is a double duality of wave and particle concepts. The wave theory of light, firmly grounded by the wave explanations of interference and diffraction and by Maxwell's electromagnetic theory of light waves, is now recognized as giving but one aspect of the nature of radiation. The corpuscular aspect of radiation is revealed in the photoelectric effect and in the Compton effect. In these effects Planck's constant appears as a universal constant which connects the wave and particle modes of description of the same radiation.

The radiation which functions as a wave disturbance of frequency ν waves per unit time, and as having a wave number of σ waves per unit length, when interference and diffraction phenomena are being discussed, also functions as a mechanical corpuscle of definite energy, E, and momentum, P, when effects like the photoelectric and Compton effects are considered. The connection between the quantities, ν, σ,

[1] Based on a lecture delivered on July 19, 1928, before the summer school for engineering teachers of the Society for the Promotion of Engineering Education at the Massachusetts Institute of Technology, Cambridge.

E, and P, given by experiment is contained in the equations:

$$E = h\nu, \quad P = h\sigma.$$

(Note that the equations are made more symmetrical by using σ, the wave number, instead of its reciprocal, the wave-length, which is more commonly used.)

The duality is made double by recent discoveries concerning the electron. The most direct are those of Davisson and Germer, reported in the *Physical Review* for December, 1927. In their experiments a beam of electrons is scattered from the direction of normal incidence on a single crystal of nickel. It is found that there are certain directions of strong scattering and that the location of these directions can be quite closely represented by assuming the scattering to be governed by laws of wave interference, exactly parallel to the wave interpretation of the diffraction patterns formed when X-rays are scattered by a crystal. The association of wave and particle concepts which holds for radiation is also seen to hold for electrons in these experiments, for when the mechanical momentum is varied the wave-number or wave-length effective for diffraction of the electron beam varies in just the manner given by the equation, $P = h\sigma$.

Instead of trying to go back of this duality, quantum mechanics is attempting to give a self-consistent mathematical development to the phenomena of quantum physics, which recognizes the duality as fundamental. The recognition of a wave-length associated with the motion of electrons really antedates the Davisson and Germer experiments, going back to de Broglie's wave interpretation of Bohr's rule for picking out the stationary states in atoms. In Bohr's theory of the hydrogen atom, it is postulated that circle orbits of just certain discrete sizes are possible, the rule being that the angular momentum of the orbit must be equal to an integral multiple of $h/2\pi$. De Broglie recognized in this rule an analogy with the discrete modes of vibration of a stretched string. Such a string when fastened at the two ends may vibrate only in ways which make the wave-number of the standing waves be an integral multiple of the length of the string or in a superposition of several of these modes of vibration. If there is some kind of wave motion associated with a moving electron, it is then natural to suppose by analogy that the wave-number of the waves must be an integral multiple of the circumference of the orbit. One may readily see that this leads to the same choice of orbits as did Bohr's rule, when the fundamental connection, $P = h\sigma$, is assumed. It has the advantage that it gives some inkling of the reason for the existence of stationary states.

Schrödinger's contribution lay in the mathematical development of this idea. Working by analogy with the theory of propagation of elastic waves he set up a partial differential equation for the propagation of the waves associated with an electron which has had extraordinary success in dealing with quantum phenomena. His work was in no way a derivation by strict logical steps from previous knowledge of what this equation must be. In fact, it is now recognized that his equation is a simplified form of other equations for the waves discovered by Dirac this year. The correction given by Dirac is a small one so far as numerical magnitudes go but an important one in that it puts the magnetic effect of the electron spin into the theory in a rational way.

Whenever there are waves having a wave amplitude propagated in space and time one must have a physical understanding of the wave amplitude or quantity which does the waving. In the electromagnetic theory of light this wave amplitude consists of two vectors, the electric and magnetic forces, which are recognized physically by the forces which they exert on electrified or magnetized bodies placed in the field. When physical reality is attributed to the corpuscular light quanta, one must still find a way in which the wave field is important. Einstein suggested that the electromagnetic field determines the relative probability that the quanta go to different places. In a set of interference fringes, the wave amplitude is strong at some places and weak at others. The quanta go to the different places with a relative probability that is given by the wave measure of the intensity, namely, the square of the wave amplitude.

In attempting to provide an interpretation for the wave amplitude Schrödinger supposed that when in an orbit an electron does not remain a little particle of negative electricity whose radius is of the order of 10^{-13} cm, but spreads out and fills a larger region of space with a volume distribution of charge. The total amount was just the charge on an electron, but the electricity was thought of as being actually smeared out over a region of space which is of the same order of magnitude as the orbits on Bohr's theory, therefore more like 10^{-8} cm. Against this view can be urged that in dealing with the free particle, the wave associated with a freely moving electron on Schrödinger's theory fills all space uniformly: there is not much left of an electron which is so smeared out that it fills all space uniformly.

Recognizing this difficulty in connection with problems involving the motion of electrons free from atoms, Born carried over Einstein's idea concerning the electromagnetic field as a probability field for the positions of the light quanta. He supposed the square of Schrödinger's wave function to give not the actual charge density arising from a smeared-out electron, but the probability of finding the corpuscular electron in the different parts of space. This view has been the basis of the developments due to Dirac and Jordan which have given a much more general form to the mathematics of quantum mechanics.

This interplay of wave and particle concepts which makes the wave field serve as giving the probability of different positions of the particle or particles governed by the wave field implies a fundamental limitation on the precision of certain physical quantities, a point which has been emphasized by Heisenberg and by Bohr. (See especially Bohr's article in *Nature* for April 14, 1928.) A plane wave of infinite extent is to be associated with a particle of which the momentum is exactly known. The infinite extent of the wave in turn means that the particle is equally likely to be anywhere in space. That is, exact knowledge of the momentum implies absolute ignorance concerning the position of the particle. By superposing waves of different wave-lengths, it is possible to have the different waves interfere everywhere except in a certain small region of space. Such a group of waves is taken as the wave representative of a particle *of which it is known* that the particle is in this region of space. It follows from the laws of wave interference that the smaller the region in which the waves do not destructively interfere, the greater the range of wave-lengths which must be represented in the different plane wave constituents which are superposed to make up the group. Recalling the connection between wave-length or wave number and momentum, it is seen that such a group of waves, which represents a particle known to be in a certain region, implies a range of values of the momentum or a lack of precision in the knowledge of the momentum. The size of the region in which the particle is known to be located may be thought of as the uncertainty of our knowledge of the position of the particle. The range of wave-numbers in the constituent waves of the group measures the associated uncertainty in the momentum of the particle. Calling Δx, Δy, Δz the uncertainties in positional coordinates and Δp_x, Δp_y, Δp_z the uncertainties in the momentum components, the laws of wave interference, together with the quantum law of association between the concepts of wave number and momentum, give the equations:

$$\Delta x \, \Delta p_x \geqq \frac{h}{2\pi}, \quad \Delta y \, \Delta p_y \geqq \frac{h}{2\pi}, \quad \Delta z \, \Delta p_z \leqq \frac{h}{2\pi}$$

If the laws of wave interference really do govern the motion of particles this implies that our simultaneous knowledge of the position and momentum of a particle may never be so precise that the product of the uncertainty in a coordinate multiplied by that in the associated momentum component that the product of the two uncertainties is less in order of magnitude than Planck's constant, h. A consideration of various methods of measuring simultaneously the position and momentum of a particle has indicated that all physical measurements are really subject to this fundamental limitation. This point is likely to prove of considerable interest to philosophers. It appears that in the concepts of position and momentum we are confronted with two quantities, either of which may be given a precise definition when considered alone, but when considered together there is a correlated vagueness about their magnitudes which appears as a fundamental law of nature.

In conclusion, it may be well to point out that the reason that the classical laws of mechanics prove to be so satisfactory for macroscopic things is that the wave-lengths of the wave phenomena for them are so small that diffraction effects are negligible, just as in many problems concerning light it is admissible to ignore the wave nature of light, as is done in geometrical optics. The laws of classical mechanics bear the same relation to those of quantum mechanics as the laws of geometrical optics bear to the wave theory of light.

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SCIENTIFIC EVENTS

CONFERENCE OF THE BRITISH ASSOCIATION ON THE PRESERVATION OF SCENERY

THE London *Times* says that the detailed work of the British Association is carried out in 13 sections, lettered from A to M, and one "conference," a gathering of delegates from 160 societies in correspondence with the association. Partly owing to the accident that this gathering is not named and lettered as a section, its proceedings have hitherto received something less than their due share of publicity. On the occasion of the Glasgow Meeting of the British Association the conference will constitute itself in fact, if not in name, a section dealing with the Science of Scenery.

Dr. Vaughan Cornish in his presidential address pointed out that the special responsibility of learned societies in regard to the preservation of scenery is to discover and define the combinations which result in scenic beauty, and thus provide a secure foundation for an esthetic of scenery.

Mr. C. R. Gibson, representing the Royal Philosophical Society of Glasgow, will move that it is