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THE ROMANCE OF THE NEXT DECIMAL PLACE[1]

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IN the year 1896 the *Beiblätter zu den Annalen der Physik* devoted 1,032 pages to reviewing the literature of physics. In 1930 the corresponding journal required almost five times that amount of space.

The *Physical Review* for 1896 contained 490 pages of text. Computed on the basis of the same size and form of page, the *Physical Review* for 1930 contains over 5,000 pages—an increase of over tenfold.

At the present rate, graduate schools in America are granting ten times as many doctorates in physics as they did at the beginning of the century.

If we take into account the large amount of research in technical, industrial and governmental laboratories which is never published, and if we ignore the still larger amount of work in engineering which has grown directly out of physics and is published in engineering journals, we should probably be justified in making the statement, which I believe to be conservative, that there is now in progress from twenty to twenty-five times as much research in physics as there was a third of a century ago.

Physics in 1931, however, differs from the physics of, say, 1895 not only in volume of activity, great as that is to-day, but also in basic theories and viewpoint, as well as in underlying factual content. The physicist of 1895, in his wildest imagination, could not have dreamed of x-rays and radioactivity, each to be discovered within a year; of the quantum theory, to be proposed before the century ended; or of the rôle which the then hypothetical electron was to play not only in altering completely the whole framework of physical theory but in making possible inventions and other developments which were to revolutionize certain important phases of our economic and social life. Indeed we of to-day are so impressed with both the quantity and the fundamental nature of our contributions that we are wont to think, and even sometimes to remark, that the progress which physics has made since 1895 exceeds that of all preceding time.

But if we view our science objectively and in

[1] Address of the retiring vice-president of Section B—Physics, American Association for the Advancement of Science, New Orleans, December 30, 1931.

unbiased historical perspective we must conclude that this extravagant evaluation of the prowess of the twentieth century physicist is hardly justified. The generation of physicists immediately preceding ours likewise took giant strides. When silhouetted against historical background Maxwell's electromagnetic theory and its remarkable experimental confirmation by Hertz loomed up as large to the physicist of 1895 as the de Broglie-Schrödinger wave theory of matter and its experimental confirmation by Davison and Germer does to the physicist of to-day.

Stepping back another 30 years from 1865: With what pride must the older contemporaries of the young Maxwell have viewed such outstanding achievements of their generation as Faraday's discovery of electromagnetism. What could be more fundamental and far-reaching, even outside of physics proper, than the law of conservation of energy firmly established by the experiments of Joule in 1846? Had not one of their number, Foucault, with unsurpassed experimental skill, actually settled for all time the two-century-old conflict between the corpuscular and the wave theory of light by showing that light actually travels slower in water than in air?

And to all these claims of preeminence we can imagine the shades of the next older generation protesting: "Ah, but you forget that Joule was but completing Rumford's work begun in 1798; that the starting point of Faraday's researches was Oersted's discovery of the magnetic effect of an electric current (in 1819); that Young and Fresnel in the first two decades of the nineteenth century really established the wave theory of light, which was merely confirmed by Foucault's experiments."

If we trace this story still farther back we find that, except for the more or less sporadic contributions of the ancient and medieval world, the science of physics arose almost asymptotically out of comparative nothingness only a short time ago, at least as measured on the time scale used by the historian to mark the progress and development of human society. Whether we say that physics began with Galileo, or with Copernicus, or with Roger Bacon is relatively unimportant. Of great importance is that fact that since its beginning physics has increased, with each generation, in geometrical ratio. If there is anything remarkable in our twentieth century physics it is perhaps not so much because of the fundamental nature of the changes since 1900, as because of the number of those changes which have taken place in a single generation—a remark which has probably been made by each of the generations which has preceded us!

Now, what are the factors which have made this accelerated growth possible? Volumes have been written in attempts to answer this question for all science, as well as for each science in particular. It is generally agreed that it is no accident that the beginnings of modern science were contemporaneous with the discovery of the art of printing; and that the rate of growth of science has followed closely improvements in that art. When permanent records of the works and thoughts of one generation could be quickly and cheaply made, not only for ready exchange among the members of that generation but for passing on to the next, progress became possible.

Further, increased speed in the transmission of intelligence, both by development and improvement in systems of transportation and by such agencies as telegraphy, cable and telephone, have reacted to speed up scientific research. It is said that within forty-eight hours after American newspapers had printed the cable dispatch reporting the discovery of x-rays by Roentgen, at least six x-ray photographs had been made in laboratories on this side of the water. On the contrary, Henry did not learn of Faraday's experiments on electromagnetism until several months after the announcement was made in England.

Then, too, there is the reaction which has come from the application of science in so many aspects of modern life. The present great volume of scientific research is made possible in very large part because society believes such research is useful.

We must not forget, also, that, probably because of this demonstrated usefulness, the work of the scientist is no longer viewed with suspicion and intolerance. He is free, except for here and there a backward community, to hold such theories and to perform such experiments as he pleases. No longer need a Galileo abjure, nor a Roger Bacon spend half of his life in prison because he had made discoveries that proved to him that previous theories were untenable.

This freedom to experiment and to interpret the results of experiment has been a determining factor in the development of the so-called laboratory sciences. Observation merely of the phenomena in the world about us would be quite ineffective in advancing such a science as physics.

Now, broadly speaking, laboratory research in physics falls under two classifications. First, there is the pioneer work of exploration and of rough measurement as a result of which phenomena are discovered and classified. Second, there is the precise measurement and study of these phenomena in an attempt to set up physical relations as exact as the technique at hand may permit. It is this latter type of measurement which has given to physics the name "exact science"—an appellation which those of us who attempt to make so-called "precision" measurements know to be entirely unjustified! Otherwise expressed, we may say that the purpose of making such careful measurements is, to borrow Rowland's famous phrase, "to investigate the next decimal place."

Now why should one wish to make measurements with ever-increasing precision? Having measured the velocity of light to four significant figures, why should one wish to know what the next "decimal place" is? "Because making such measurements is great fun," the late Professor Michelson is said to have remarked. "Because only by making such measurements can we establish exact physical laws," will be another obvious answer. To these two answers I wish to add a third: "Because the whole history of physics proves that a new discovery is quite likely to be found lurking in the next decimal place." If the making of a new scientific discovery is thrilling to the discoverer, and if a romance is a human event which thrills the participants, then we may justly speak of the "romance of the next decimal place." To devise methods of making measurements with greater precision than has ever been attained before; not only to establish so-called exact laws, but possibly to discover new and unsuspected phenomena furnish both fun and thrills not surpassed by any other quest in scientific research.

A well-known industrial physicist once remarked that no physical measurement was worth making which required a precision in excess of one per cent. Let us examine a few typical cases to see what sort of structural members would be lacking from the framework of modern physics if investigators had been content with one per cent. as a limit of precision.

One of the most conspicuous examples of the importance of precise measurements is to be found very early in the history of physical science. In 1543 Copernicus revived the long-discarded heliocentric theory of the universe, postulating that the planets move round the sun in circular orbits. Possessing a qualitative rather than a quantitative background, the theory made slow headway. Had no further evidence been obtained, there is no *a priori* reason to believe that Copernicus would have been more successful in convincing a skeptical world than was his predecessor Aristarchus eighteen centuries earlier.

But then came Tycho, a man to whom, as to our own Michelson, the making of fine instruments and their utilization in research was "great fun." Further, Tycho's own theory of the universe, quite at variance with that of Copernicus, could be established only by observing the motions of the planets with much higher precision than had yet been attained.

And so Tycho began to investigate the "next decimal place." After twenty-five years of the most painstaking devotion to the design and use of his instruments he had accumulated a series of observations on planetary motion not only by far the best in existence at the time but still regarded with wonder and admiration when we consider the crudeness of his apparatus as compared with our own. It is said that in the delirium of his death-bed Tycho prayed that his life might not have proven useless. We can well imagine that his prayer arose from a realization that his life work consisted only in a mass of observations and that he had failed to prove his theory of the structure of the universe. What would posterity think of him for having done nothing but observe?

Such questions are still asked to-day. Not only men of the town but not a few of even those of the gown are wont to belittle the endeavors of those whom they call "hair-splitting scientists," who devote their lives merely to devising and to using instruments and methods intended to make four significant figures grow where only three grew before.

How completely was Tycho's prayer answered during the century following his death (1601)! Kepler's use of Tycho's data is too well known to require extensive comment. After years of the most intensive study Kepler finally found that the hypothesis of circular motion as applied to the planet Mars was inconsistent with Tycho's observations, there being at certain points in the orbit of Mars a discrepancy between the predicted and observed position of as much as eight minutes of arc—the angle subtended by the lead of an ordinary lead pencil at some twenty feet!

Accordingly, Kepler rejected the principle of circular motion, a principle assumed by Copernicus and held unquestioned for 2,000 years. After various trials and failures, he was finally led to try an ellipse. By placing the sun at one focus, Tycho's observations were satisfied. Conjecture as to the nature of the planets' paths had given way to proof that the paths of the planets were ellipses. A most important law of planetary motion had thus been discovered. "These 8 minutes (of arc) alone," Kepler later wrote, "have led the way towards the complete reformation of astronomy."

But not only astronomy! One may trace a direct path from Kepler's proof of the elliptical nature of the planetary orbits to Newton's proposal and ultimate proof of the inverse square law of gravitation. Thus Tycho's study of the next decimal place had not only led to the acceptance of the Copernican theory of a heliocentric world, but had influenced most profoundly both physics and philosophy. For, without such careful measurements, the true paths of the planets must ever have been a source of conjecture, confirmation that the law of gravitation extends at least to the boundaries of the solar system would have been wanting, and man would not have been able to envision a universe governed by immutable laws.

The century which followed Newton did not see much attention paid to the making of precise measurements, at least by physicists. Nor, in turn, were there many significant advances recorded. It may be not without point, however, to make mention of the fact that Newton's failure to investigate the next decimal place, in his study of the relation between index of refraction and dispersion, led him to the erroneous conclusion that these two quantities are proportional and that therefore achromatic optical systems are impossible, an error which persisted for many decades.

It is generally agreed that the first two or three decades of the nineteenth century mark the beginning of a new era in the history of physics, in that during this brief period there were introduced basic concepts as to the nature of light, heat, electricity and magnetism which provide the foundations of so much of modern science. It is by no means a mere coincidence that this period saw also the general recognition of the important part which precise measurements were to play in the development of physical theory. Thus, Young's discovery of the interference of light, although not technically "in the next decimal place," was essentially the result of precise adjustment of apparatus and of careful observation. In this class also falls Faraday's discovery of electromagnetic induction, since his observance and interpretation of the minute deflection of his galvanometer led the way to further study and to the establishment of the laws of electromagnetism. Rumford's qualitative theory of the nature of heat was no more convincing than was Aristotle's theory of the solar system. But when Joule actually proved that 772 foot pounds of mechanical energy are required to raise the temperature of one pound of water one degree Fahrenheit the quantitative relation thus established provided an argument as cogent as were Kepler's elliptical orbits.

Indeed, one outstanding characteristic of nineteenth century physics is the extent to which the making of precise measurements, *merely for the sake of securing data of greater accuracy,* became a recognized part of research in physical laboratories. This point is aptly illustrated by Lord Rayleigh's determinations of the absolute density of gases in the early nineties.

Proust's law demanded that the ratio of the respective densities of oxygen and hydrogen should be 16 : 1. The measurements of this ratio by Regnault as early as 1845 yielded 15.96 : 1, a result in agreement with Proust's law almost within experimental error. In 1888 Rayleigh attacked the problem anew, and, after a long investigation described by him as "unusually tedious," found that the ratio was 15.882 : 1, thus proving untenable the theoretical value of 16 : 1.

Having thus developed an improved technique for measuring the density of gases with great accuracy, Rayleigh, for no apparent purpose other than to satisfy his curiosity, decided "before leaving the subject (to ascertain) not merely the relative but also the absolute densities of the more important gases." In the course of this investigation he found that nitrogen, prepared from its chemical compounds and thus presumably pure, had a density of 1.2505 grams per liter, while that prepared by removing oxygen from ordinary air had a density of 1.2572 grams per liter, a difference of about ½ per cent. which previous and less precise determinations had failed to detect. After eliminating one by one the various possible sources of contamination with known gases, Rayleigh concluded that the difference in density must be due to the presence in the atmosphere of a hitherto unknown gas more dense than nitrogen. This clue led Rayleigh, in collaboration with Ramsay, directly to the discovery of argon. Subsequently the whole series of noble gases was discovered.

Seldom has a discovery been more fruitful. Occupying, as they do, unique positions in the series of the elements, these noble gases may be said to provide the very foundation stones for that elaborate and beautiful edifice which we call "atomic structure." The use of helium, neon and argon for so-called practical purposes is commonplace. Whereas Rayleigh with great difficulty prepared a few cubic centimeters of argon in 1894, to-day that gas is produced in large quantities for commercial purposes. "Bigger and better" dirigibles are made possible through the use of helium. Even the legal profession is reaping a rich harvest from the crop which grows out of Rayleigh's fifth significant figure, for it is said that more than a million dollars has been spent in litigation over the neon-sign patents!

That last decade of the nineteenth century, one of the most fruitful and romantic in the whole history of physics, provides a close parallel to the discoveries of Tycho and Kepler. For, just as the century was closing Planck, analyzing the data of Lummer and Pringsheim on temperature radiation, announced the quantum theory, which was destined to revolutionize the whole trend of physics and, though perhaps to a lesser extent immediately, of philosophy. Just as Tycho's observations agreed with the theory of circular orbits except for certain small differences in parts of the orbit, so the data of Lummer and Pringsheim agreed with Wien's law of temperature radiation, except for certain small discrepancies at long wavelengths. In both cases the theorist, placing confidence in the accuracy of the observations, was led to propose a new and a very fundamental theory.

This principle of the importance of the next decimal place, in leading to new discoveries is, though perhaps unconsciously, given recognition in the fact that one expressed purpose underlying so much of our modern research in physics is to increase the precision with which physical phenomena may be observed. For 25 years attempts to observe the refraction of x-rays failed. About 1920 Siegbahn and Larsson, pushing measurements of wave-lengths of x-rays to higher and higher precision, found that the wave-length of Cu Ka radiation, as measured in first order reflection from a mica crystal, differed from similar measurements in the eleventh order by about 0.15 per cent. They correctly attributed this difference to refraction of the rays as they entered the crystal, a phenomenon hitherto unobserved. To-day indices of refraction for x-rays (strictly speaking, the difference between the index and unity) are measurable with a precision in excess of 1 per cent. Until a few years ago no one had succeeded in producing an x-ray spectrum by reflection from a ruled grating. Recently, by use of such a grating, Bearden has reported measurements of x-ray wave-lengths with an estimated probable error of 0.01 per cent. As is well known, the slight discrepancy between the values so obtained and those yielded by use of a crystal grating has necessitated a critical reexamination of the whole technique of x-ray spectroscopy, and perhaps requires some fundamental modifications in our concepts of crystal structure.

In 1900 Drude, in his "Theory of Optics," remarked that "this (radiation) pressure is so small that it can not be detected experimentally." Almost before Drude's book was released from the press, Lebedew in Europe announced the experimental discovery and rough measurement of this phenomenon; and within three years Nichols and Hall in America reported measurements of radiation pressure with an estimated probable error of about one quarter of 1 per cent. The bearing of these measurements on theories of radiation is too well known to need comment.

In a little over a decade, Thomson's apparatus for studying positive rays evolves into Aston's precision mass-spectrograph, in which the relative masses of atoms can be measured with a precision of the order of one part in 10,000. After observing the "fine structure" of spectral lines the spectroscopist goes on to observe "hyperfine structure." A recently reported critical examination of existing data leads to the conclusion that the most probable value of "e," the charge carried by the electron, is 4.7721×10^{-10} as e.s.u. instead of 4.774×10^{-10} as previously used. From each such extension of the precision of measurement there results either a significant modification of theory, or not infrequently a new discovery. So frequently has this happened in the history of physics that to sum up what I have said I am disposed to conclude by paraphrasing a famous saying: "Look after the next decimal place and physical theories will take care of themselves."

RESEARCH AND INDUSTRIAL ORGANIC CHEMISTRY[1]

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I EXAMINED a short time ago the advertisements in a copy of *Industrial and Engineering Chemistry* to see to what extent the pages reflected the recent development in this country of industrial organic chemistry. I found 42 organic compounds advertised which are available for large scale use. Many of these are new substances; the rest have been used but are produced now at lower prices and in a purer condition than in the past as the result of the application of new synthetic methods. In the list were several compounds of importance on account of their use as intermediates in the preparation of a great variety of technical products. A study of the methods by which these results have been reached shows clearly that chemical research of a high order is the foundation upon which the achievements rest. A broader survey of the present condition of the organic chemical industry leads to the same conclusion.

The division of engineering and industrial research of the National Research Council has as one of its important activities the study of the relation between research and industry and has demonstrated in its publications the controlling significance of this relation.

The chemical industry of the United States has grown rapidly since the world war. It stands high in the list of industries arranged according to the number of men employed, returns and capital invested; it is thus an important factor in the economics and well-being of the country. I shall limit myself in this address, however, to organic chemistry, the field in which my knowledge and chief interest lie.

The supply of many important chemical compounds used in a variety of industries was suddenly cut off when the country entered the recent war. It was

[1] Address of the retiring vice-president and chairman of Section C—Chemistry—American Association for the Advancement of Science, New Orleans, December, 1931.