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CONTENTS

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THE NEW OUTLOOK IN CHEMISTRY[1]

Your Excellencies, Your Magnificence, Ladies and Gentlemen:

To-day there has come together here, to welcome a new guest to your noble university, a group of chosen spirits from among the best in this highly cultivated center of learning and civilization. I see before me many men whose names will go down to the future as leaders in their respective widely different fields of work, and rejoice to be in their presence. The opportunity of addressing a gathering so notable could not but be esteemed by anyone as an especial privilege and honor; and to me, whose debt to German scholarship is so exceedingly great, the occasion brings peculiar pleasure.

You are here not only to welcome graciously a newcomer, but also to hear the first lecture of a course concerning one of the most recent developments of human learning. As is well known, the logical process of inductive reasoning based upon carefully planned experiment is relatively a new manifestation of the power of the human intellect. The philosophers of old imagined, observed and reasoned, but neglected experimentation; the artisans, who alone came into close contact with realities, were unable except in the crudest fashion to generalize concerning their results. Because of this separation of thought and deed, man's knowledge of his

[1] Inaugural lecture delivered on May 4, 1907, in the Aula of the Royal Friedrich Wilhelm University of Berlin.

environment remained for thousands of years in a wholly undeveloped state.

From this dormant condition natural science emerged but slowly, although with steadily increasing pace. Little by little, in spite of occasional pauses of inactivity, or apparent forgetfulness, human acquaintance with the fundamental laws of the universe has grown. Each century has added something to the total; and usually each century has added more than any century before. What a contrast such a development presents to that of sculpture, for example, which reached nearly if not quite its highest point of perfection more than two thousand years ago!

In chemistry especially has the acceleration been great; and the effect of recent growth is so remarkable, that, looking back, one is inclined to deny the existence of any real science of chemistry a century and a half ago. If the accumulation of chemical knowledge is depicted diagrammatically in relation to the progress of time, measuring one in the vertical and the other in a horizontal direction, an upward-pointing curve with steadily increasing inclination is obtained. The curve stops at the present day; but unless a cataclysm annihilates the earth's population and its libraries, this line is bound to be continued. Whither will it lead? What further insight into his own constitution as well as that of his environment may man attain? The answer to these questions is fraught with weighty significance as regards the future of the human race.

All the manifold experiences of the human mind are intimately connected with the presence of that which we call material, enlivened by its association with that which we call energy; and the ultimate deciphering of the great mystery of life will depend as much upon the understanding of these as upon the study of the mind itself. Thus modern chemistry should be regarded not only as bringing to medicine and the useful arts its obvious and multifarious contributions, but also as occupying an essentially important place in the realm of intellectual speculation.

First among the influences which have affected the growth of chemistry may be named that kind of insight which may be called the scientific imagination. As this quality of mind has sometimes been assumed to be incompatible with exactness, a brief discussion of its nature will not be out of place. All who have intelligently followed a really original research in chemistry will agree in maintaining that an active and far-seeing imagination is required. Even the gleaner in the field of matter and energy who seeks merely for the facts, without especially concerning himself with the meaning and bearing of these facts, needs imagination, if his work is to be useful. He who lacks imagination will see only that which he is told to see. In any but the simplest scientific task, the mind of the investigator must conceive of many underlying conditions and possible modifying circumstances which are not apparent at first sight, and which demand imagination for their detection and proper adjustment. The highest type of scientific man—he who compares and generalizes his facts, who frames hypotheses concerning their ultimate nature, and who from these tentative speculations evolves new experiments to expand his knowledge—needs an imaginative mind in a yet higher degree. Dealing with impersonal things, instead of with personal emotions, this imagination is indeed of a somewhat different type from that exercised by the poet or artist; but it is none the less fitly to be considered as true imagination, and it likewise yields the singular delight of creative power to its possessor.

Not always have the two types of imagination, the scientific and the poetic, been separated in individuals. Indeed the occurrence of the two in the same individual is so often to be noticed that the two types might well be supposed to be really the same in essence and to differ only in their field of development. History furnishes many a proof of this twofold exercise of originality. For example, Leonardo da Vinci furnishes striking evidence of the manifold working of a powerful imagination. Leonardo was no less eminent as a geologist and engineer than as an artist and a poet. Chemistry too was profoundly interesting to him. His extraordinary writings manifest the fruitfulness of an imagination which has rarely been equaled. His few paintings, which show surpassing insight into human nature and unusual technical skill, were the expression of the same imaginative force. If Leonardo were living to-day, he might be as well known for his investigations into pure and applied science as for his artistic preeminence, since these fields of thought now have much more to offer to the imaginative mind than they had in the days when their scope was more restricted and less appreciated.

In more recent times, Goethe furnishes one of the most brilliant examples of a truly poetic mind which found joy in scientific studies. Goethe was not only one of the greatest poets of all times; he made also notable contributions to the science of his day. The imaginative quality which gives the pervading charm to one product of his genius gave insight to the other.

These are examples of men primarily known for their ability in the directions commonly recognized as imaginative, who have possessed also ability which was or might have been developed in a scientific direction. One may find likewise many cases of the dual use of the imagination among those who are known chiefly for their scientific productions. For example, von Helmholtz's interest in sound was not purely mathematical in its expression; the great physicist loved music for itself, having a wide knowledge of its literature and keen pleasure in its performance. Robert Wilhelm Bunsen's delight in the beauty of the Italian landscape, especially of the country around Naples, will be remembered by any one who knew him; this poetic appreciation, artistic in feeling if not in expression, persisted even to his old age, after pain and disability had caused his interest in chemistry to wane.

The case of Charles Darwin, which is the one example usually cited to prove the supposed incompatibility of the scientific and poetic imaginations, is perhaps rather to be referred to another category. One can hardly follow his long combat with ill-health without feeling that this misfortune, not his scientific interest, was the cause of the apparent atrophy of his literary and artistic sympathy. Darwin in his youth was extremely sensitive to every imaginative impulse; and years of suffering were needed to deaden this intense sensibility.

There is no need of multiplying the many possible examples of this kind, however, for the best place to find evidences of the imaginative insight of a scientific man is in his own work. Here, where his mind has dwelt longest, his mental vision will find its widest scope. Perhaps the most easily traceable record of this immediate effect of the scientific imagination is to be found in the life of Faraday, because he committed his wildest dreams to the pages of existing notebooks. Faraday's originality ranged at large over the whole field of chemistry and physics; to him nothing seemed too strange to be possible, no relation too unlikely to be unworthy of thought. But with this extraordinary disposition to dream things before undreamt, he possessed the steadying power of judgment which enabled him to dissociate his dreams from the reality. He always sought to test each hypothesis by actual experiment, and cheerfully recorded every overthrow when he was convinced of its finality. Experiment served to keep him scientifically sane, and day-dreams inspired his enthusiastic nature to undertake further experiment. Thus each helped the other, with a rare cumulative effect. Without imagination, Faraday could not have made most of his discoveries; but without profound common sense, he would have ended in a madhouse.

The example of Faraday serves also to emphasize the indisputable fact that imagination alone is not a sufficient intellectual outfit for the scientific man. At least one other attribute is essential, namely, good judgment, or common sense, to select between the various possible interpretations of fact and theory presented by the imagination. So emphatically is this true that Huxley maintained science to be nothing more than systematized common sense.

Imagination, then, and good judgment, are necessary, if science is to grow. But both of these admirable qualities were possessed in large measure by some of the ancient philosophers, who nevertheless made but little real progress. What was lacking, that so little advance should have been made in the 400 years between Democritus and Lucretius, and so little more in the succeeding centuries?

To-day, in the light furnished by any successful scientific investigation, the answer, given a few minutes ago, is manifest. This answer is so important that its substance may be repeated. The philosophers with all their intellectual greatness and insight, were too far removed from realities. More thorough observation, more consistent study of the actual operation of the law of cause and effect, and above all more frequent reference of each doubtful case to the almost neglected test of actual experiment should have supported their too vague speculations.

Accurate observation and well-planned experiment, then, besides imagination and good judgment, are needed if science is to advance. But long ago all these essentials were at the command of a few of the best of the alchemists, and yet chemical science loitered in its ever-onward way.

Chemistry began really to become a science and to enter upon the phenomenal growth of recent years only a little over a century ago. Since then its development has been one of the most remarkable features of human progress, and its results are among the most important of human intellectual possessions.

What was the reason for this striking transformation? What was the key with which modern chemistry has opened the door to her treasure house? The answer is easily found. Measurement, the accurate evaluation of the numerical relations of things, has been the "open sesame" whose magic influence has slowly disclosed the hidden wealth. As van't Hoff has pointed out, each new instrument for measuring a given phenomenon of nature led immediately to a greatly accelerated development in that particular field.

No wholly new idea exists under the sun, it is said. Certainly the perception in general of the importance of measurement is almost as old as the hills, although its effect upon chemistry was so long postponed. Plato over two thousand years ago put into the mouth of Socrates the equivalent of these words: "When measuring and weighing and the idea of number are taken away from an art, how little of that art is left!" Essentially this conviction led

Kant to exclude chemistry from the list of true sciences. In Kant's day, as he rightly maintained, chemical inferences depended so little upon any data capable of mathematical treatment, that the experimenter was liable to fall into extraordinary errors of interpretation. The world-wide prevalence of the oddly inverted theory of phlogiston, which imagined that a metal in rusting lost something of its substance is evidence of this defect. Such a theory became untenable as soon as measuring, weighing and the idea of number removed the cause of Kant's reproach.

Measurement, then, revolutionized chemistry—but what forms of measurement? History tells no equivocal tale on this score; every form of measurement whose careful application has laid the foundations of the present science of chemistry is quickly seen to belong to the domain of physics. This is not surprising, since only two of the traditional five human senses, namely, taste and smell, are purely chemical in their action; and these are not easily amenable to precise quantitative treatment. All the other senses, sight, hearing and touch, through which man obtains knowledge of the outside world, depend upon the interposition of physical energy; and the methods of measuring must correspond to this fact.

Thus, Joseph Black brought the balance, an essentially physical instrument, into requisition in order to demonstrate the nature of the caustic alkalies. Lavoisier used the balance to prove the fundamental laws of conservation of mass. The same instrument alone afforded Dalton a sound basis for his laws of combining proportions and of multiple proportions, and therefore the first unimpeachable argument in favor of the ancient atomic theory in which he had believed from childhood. The study of the densities of vapors, of the specific heats of solids, and of the forms of crystals, all found by processes of physical measurements, were the foundations upon which by degrees a logical system of chemical notation was built. The discovery of the quantity-dimension of electrical energy led in Faraday's hands to the new definition of chemical equivalents. The spectroscope, a physical instrument, in the hands of Bunsen and Kirchhoff made possible the detection of new chemical elements. Physical measurements of osmotic pressure led van't Hoff to a new conception of the phenomena of chemical relations in solution; and electrical conductivity was used by Arrhenius as the basis of the generally accepted theory concerning a large majority of the ordinary reactions between inorganic substances. Both the free energy change and the total energy change of a system undergoing a chemical reaction are measured by physical methods, and the proof of Nernst's equation depicting the mechanism of the galvanic cell depends upon the precise evaluation of small electromotive forces. Again, Lord Rayleigh's exact quantitative determinations of the densities of gases with Ramsay's help led to the discovery of a whole series of new elements possessing extraordinary properties. Still more recently physical methods of research are used in identifying the yet more extraordinary radioactive substances, and in endeavoring to solve the unanswered riddle of their possibly transitory existence. Finally, exact analysis, based upon weighing, alone made possible the exceedingly complex syntheses of organic compounds carried on by a long line of brilliant chemists culminating in Emil Fischer. These are only a few striking instances of the discoveries in chemistry which are essentially dependent upon physical processes.

Thus if the various methods of measurement borrowed from physics were taken away from the chemistry of to-day, but little would be left of the science. Chemistry would then become a purely qualitative observational study; she could penetrate but superficially into the hidden world. Therefore it would not be an extreme statement to call all quantitative chemistry *physical* chemistry, with the understanding that by physical chemistry in this sense is meant the application of physical methods of research to the study of chemical problems.

Indiscriminate measurement will lead nowhere, however. The results of the numerical determination of chemical phenomena are by no means all of equal importance. They may be divided into two classes: the first class comprises those which are variable and accidental, depending upon the relatively unimportant conditions of the special case, such as the analytical composition of a piece of granite; and the second class comprises those which are invariable and general, recurring almost or quite unchanged under widely varying conditions. Such results as the latter may be called "physicochemical constants." They claim our immediate attention.

A "physicochemical constant" is a numerical magnitude expressing one of the numerous apparently permanent quantitative relations of mass or energy which seem to be essentially associated with the elementary substances, or chemical elements, and their compounds; it is a fundamental fact, a unique number which touches very closely the ultimate structure of material. As examples, the atomic weights stand out strikingly. Whether or not these quantities, representing the relative weights in which elementary substances combine with one another, are to be referred to the weights of hypothetical atoms, they are certainly concerned in determining the composition of every compound substance in the heavens above, on the earth beneath, or in the waters under the earth. Every proteid in each muscle of our body, every drop of liquid in the ocean, every stone on the mountain top bears within itself the stamp of the influence of this profoundly significant and impressive series of fourscore numbers.

The heat evolved during any chemical combination typifies a different kind of physicochemical constant. Coal on burning sets free a quantity of heat which mankind uses in exceedingly divers ways, deriving therefrom the major part of the energy of manufactures and transportation as well as that needed to warm his habitations. The evolution of quantities of heat in this and other chemical reactions indicates a decrease in the total energy of the substances during the reaction involved; therefore from the point of view of the chemical philosopher, as well as from that of the practical engineer, these figures also are of great importance.

Many other examples of other types of constants might be cited, such as densities, compressibilities, or electrochemical equivalents; all are not of equal significance, but each in its way is fundamental. These properties although undoubtedly somewhat connected with one another, can not yet be safely predicted; each must be ascertained for itself. Thus a colossal task is involved in their accurate determination.

How nearly has this task been completed? The comparative study of the existing accumulation of experimental data concerning chemical phenomena affords reason for congratulation that so much has been done within a single century; but it also reveals the fact that much remains to be done. For in spite of the fact that physical measurements are the basis of all quantitative chemistry, we find, upon comparing the probable accuracy of most results in chemistry with the probable accuracy of many results in physics and astronomy, that chemistry is at present far in the background. In physics or astronomy results attaining an accuracy of one part in a hundred thousand are by no means uncommon, and often a much higher degree of precision than this is reached. For example, in weighing it is easy to detect one tenth of a milligram in a kilogram, a fractional part of only one in ten million. Again, the length of the year in terms of the length of the mean solar day is probably known to within one part in a hundred million. On the other hand, in chemistry few results are to be relied upon to within one part in 500, and many investigations, even of the atomic weights, have yielded results which are not to be trusted within one per cent. Such an error is 100,000 times as great as the possible error of the process of weighing alone.

Why is chemistry still so much behind physics and astronomy in quantitative consistency, when all three sciences depend upon the same methods of measurement? Are the supposed constant magnitudes to be measured in chemistry really variable, that their range of uncertainty should be so large? If they are thus variable, is it worth while to expend much labor in determining the values which they happen to possess at any one time under any one set of conditions?

The question as to whether or not the supposed constants of physical chemistry are really not constants, but are variable within small limits, is of profound interest and of vital importance to the science of chemistry and to natural philosophy in general. If this latter alternative is true, the circumstances accompanying each possible variation must be determined with the utmost precision in order to detect the ultimate reason for its existence. As Democritus said long ago, "the word chance is only an expression of human ignorance." No student of natural science who perceives the dominance of law in the physical universe would be willing to believe that such variation in a fundamental number could be purely accidental. Every variation must have a cause, and that cause must be one of profound effect throughout the physical universe. Thus the idea that the supposed constants may possibly be variable instead of invariable, adds to the interest which one may reasonably take in their accurate determination, and enlarges the possible field of investigation instead of contracting it.

Possible variability is by no means the only reason for being interested in the more accurate determination of the physico-chemical contents, however. Many considerations show that whether the constants are changeable or not, more time and care may be profitably spent upon them than has been spent in the past. The argument may be epitomized by referring back to the theorem of Plato, and somewhat extending it. Plato said: when measuring and weighing and mathematics are taken from an art, there is little left of that art. May we not add that the more efficiently weighing and measuring are used in any art, the more valuable that art becomes? If, as Kant has it, a subject becomes truly scientific only when its facts are susceptible of mathematical treatment, then an extrapolation enables us to say that a subject becomes the more scientific the more accurately the mathematical premises are ascertained. Huxley was wont to say that mathematics might be compared to a mill which would grind exceedingly fine all that was placed within it, but was incapable of making wheat flour out of porscods. Interpreting the simile to suit the present case, it may be said that the accuracy of a quantitative conclusion must depend upon the accuracy of the data upon which it is based.

For example: it has long been surmised, because of the undoubted periodic relations of the elements, that the atomic weights have some fundamental numerical connection with each other. Many acute thinkers have attempted to discover such relations, and some regularities have indeed been found. Obviously, however, if the data are sometimes as much in error as a whole per cent., nothing but vague conclusions can be drawn from such numerical speculations; the time spent upon them is little better than wasted. Before the real numerical relations between the atomic weights can be discovered, it is safe to say that the magnitudes of many of them must be known far more exactly than this. Thus for such speculations the precise determination of these physicochemical constants is essential.

But this case is only an example of a series of similar cases. In general, it is not an exaggeration to say that in order to obtain the ultimate understanding of the mysteries with which chemistry is concerned, all the fundamental data must be determined as accurately as possible. From the point of view of the chemical philosopher no pains is too great for determining these data upon which all his really scientific conclusions must rest.

Thus it is clear that exact experimentation, instead of being as some of the earlier philosophers supposed incompatible with imaginative impulse and unworthy of a true thinker, furnishes the only basis upon which the imagination has a right to build. No hypothesis which disregards the results of measurement is worthy of a moment's consideration; but given these results, fancy may exercise itself at will within the limits thus imposed. The restriction is salutary, because speculation basing itself upon reality is much more likely to reach a useful hypothesis than when unrestricted; and there is plenty of room left for fancy. The quantitative results direct, but do not really hamper imagination.

These lectures will discuss the theory and practise of exact physicochemical measurement. It will be shown that much of the uncertainty affecting the present data of physical chemistry is due neither to the variability of the fundamental phenomena themselves nor to the inability of the physical methods of measurement to yield constant results, but rather to the superposition of other inessential phenomena upon the fundamental ones which it is desired to measure. The discovery and elimination of these inessential phenomena, chiefly chemical in their nature, are really the difficult parts of the measurement; it is their successful accomplishment which makes all the difference between success and failure, and offers a task demanding the ablest knowledge and insight, both chemical and physical, theoretical and experimental. Whether perfect constancy will have been reached when all inessential phenomena have been eliminated, no one can certainly say.

But after all, one may ask, is it worth while in a world filled with burning practical problems demanding speedy solution to expend so much valuable time and energy merely in adding another certain decimal place to a collection of rather dry figures for the sake of abstract scientific learning?

When answering such a challenge, in a manner convincing to the practical man, one must recall to mind again the fact that chemistry serves the world in a twofold fashion, partly as an essential factor in our mechanism for directly obtaining and preparing most of the material comforts of modern living, and partly as one of the most intimately searching of the available rays of intellectual light on the philosophy of nature. The usefulness of the science in its former capacity is easily traced, and any one can see that as methods of manufacture are improved and competition increases, the numerical data involved must be more accurately known. Nevertheless, this manner of helping mankind, although the most direct and obvious, is by no means the most effective way in which increased precision in scientific work may be of service. A much greater gain is ultimately made, although indirectly, through the vastly augmented clearness of view which is given to the science as a whole by the increased stability and trustworthiness of the fundamental basis of facts. The resulting growth of either physical or chemical science as a whole not only brings with it increased satisfaction, and respect for man's intellect; it may also at any time lead to wholly unexpected and unforeseen developments of practical usefulness about which man could not otherwise have dreamed. Thus Liebig and Soubeiran, when they found chloroform, little thought of the priceless boon which the new substance would bring with it to suffering humanity. Faraday, in studying the behavior of wires and magnets, never dreamed of the miracles to be wrought by the modern dynamo. Röntgen was striving only to advance scientific knowledge and not to furnish a sure guide to the puzzled surgeon in his crucial task, when the almost incredibly penetrating rays were discovered.

These records of the past lead us to look forward towards the beckoning future. Has the advantage to humanity to be gained by furthering pure science come to an end? No, a hundred times no! Not until man really understands himself and his environment, will the possibility of the discovery of some new blessing be ended. Prophecy is inevitably uncertain; and yet when one realizes that our frail and often jangling human mechanism is actuated essentially by a series of chemical reactions, and that every material thing connected with our life is a chemical substance, one feels that chemistry must still have vast treasures in store for the human race. What may she not accomplish for the comfort of living, for a rational practise of medicine, for a profound philosophy of nature! One can not but believe that as yet her mission is scarcely begun; and if this mission is to be fulfilled, the great result must be wrought not by superficial, but by fundamental understanding, built upon the solid foundation of exact knowledge.

THEODORE W. RICHARDS

SCIENTIFIC BOOKS

The Warblers of North America. By FRANK M. CHAPMAN, with the cooperation of other ornithologists. With 24 full-page colored plates, illustrating every species, from drawings by LOUIS AGASSIZ FUERTES and BRUCE HORSFALL, and half-tones of nests and eggs. New York, D. Appleton & Company. 1907. Pp. x + 306. Cloth, $3.00.

Few groups of North American birds are of such general interest as the wood warblers, and this attempt to bring together the information concerning them is a welcome addition to ornithological literature. Its title, however, would much better have been "The Wood Warblers of North America," for the true warblers, family Sylviidæ, also represented in North America, are not treated at all.

Following an "Introductory" chapter, in which the plan of the work is outlined and a