SCIENCE

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IDEALS OF CHEMICAL INVESTIGATION[1]

LESS than three centuries ago an outspoken student of nature sometimes faced the grim alternatives of excommunication, imprisonment, or death. To-day he no longer needs to conceal his thoughts in cryptic speech or mystic symbolism. Although the shadow of incomprehensibility may still darken the language of science, mystery is no longer necessary to protect the scientific investigator from persecution. The generally recognized value of the truth with his domain gives him the right to exist.

The courage needful for the task of addressing this august assembly on a topic concerning chemistry is, therefore, of a different order from the courage required for such a task in the days of Galileo. The problem to-day is not how to obscure the thought, but rather how to elucidate its inevitable complications.

Modern chemistry has had a manifold origin and tends toward a many-sided destiny. Into the fabric of this science men have woven the thought of ancient Greek philosophers, the magic of Arabian alchemists, the practical discoveries of artisans and ingenious chemical experimenters, the doctrine of physicists, the stern and uncompromising logic of mathematicians, and the vision of metaphysical dreamers seeking to grasp truths far beyond the reach of mortal sense. The complex fabric enfolds the earth—indeed, the universe—with its far-reaching threads.

[1] Oration delivered before the Harvard Chapter of the Phi Beta Kappa in Sanders Theater, Cambridge, Mass., on June 19, 1916.

The history of the complicated evolution of chemistry is profoundly significant to the student of human thought. Long ago, at the very dawn of civilization, Hindu and Greek philosophers were deeply interested in the problems presented by the nature of the universe. They speculated intelligently, although often with childlike naiveté, concerning energy and the structure of matter; but they forbore to test their speculations by experiment. They builded better than they knew; their ancient atomic hypothesis, ardently supported but very inadequately applied two thousand years ago, now finds itself installed in the innermost recesses of chemical theory. Independently, ancient artisans and medieval alchemists, dealing with the mysterious actual behavior of things, acquired valuable acquaintance with simple chemical processes. After much chemical knowledge of facts had been gained, alchemy sought the aid of philosophy. Thus, little by little, order was brought into the chaos of scattered experience. But strictly chemical knowledge alone was inadequate to solve the cosmic riddle; it had to be supplemented by knowledge of heat and electricity—agencies which produce profound alterations in the chemical nature of substances. Thus the study of physics was combined with that of chemistry. Again, since mathematical generalization is essential to the study of physics, this discipline also was, of necessity, added to the others. All these powerful tools taken together having failed to penetrate to the ultimate essence of things, imagination is invoked, and physiochemical dreams to-day conceive a mechanism of infinitesimal entities far beyond our most searching powers of direct observation.

Chemistry has not grown spontaneously to its present estate; it is a product of human mentality. The science which we know to-day is but an echo of the eternal and incomprehensible "music of the spheres," as heard and recorded by the minds of individual men. Impersonal and objective although matter and energy may be, their appreciation by man involves much that is subjective. The history of science, like all the rest of human history, is, as Emerson said, "the biography of a few stout and earnest persons."

Robert Boyle, self-styled "the skeptical chymist," a gentle spirit skeptical only of the false and vain, pure-minded aristocrat in an age of corruption; Mikhail Lomonosoff, poet, philosopher, philologist and scientific seer, far outstripping contemporary understanding; Antoine Lavoisier, whose clear mind first taught man to comprehend, after thousands of years, the mighty stolen gift of Prometheus; John Dalton, Quaker peasant, who found convincing chemical evidence for the ancient atomic hypothesis; Michael Faraday, a blacksmith's son, whose peerless insight and extraordinary genius in experiment yielded theoretical and practical fruits beyond the world's most daring dreams—these men and a few score others are the basis of the history of chemistry. The science has not come into being, Minerva-like, full-grown from the brain of Jove; she has been born of human travail, nursed and nourished from feeble infancy by human caretakers, and she sees the universe to-day through human eyes.

The diversified origin of chemistry has shaped the varied contemporary application of the science and its many-sided destiny in the years to come. Chemistry has wide theoretical bearings, but at the same time is concerned with the crudest and most obvious affairs of manufacture and every day life. Chemical knowledge must form an essential part of any intelligent philosophy of the nature of the universe, and alone can satisfy one manifestation of that intense intellectual curiosity which to-day, no less than of old, yearns to understand more of the fundamental nature of things. On the other hand, rational applied science to-day must follow in the footsteps of the swiftly advancing strides of theory. The laws of chemistry can not be adequately applied until they have been discovered. Chemical insight, concerned with the intimate changes of the substances which are all about us as well as within our bodies, furnishes us with the only means for employing material things to the best advantage. Chemical processes appertain in large degree to medicine, hygiene, agriculture and manufacture; these processes depend upon laws of which the perfect understanding is essential to the full development of most of the activities of civilized life.

However oblivious we may be of the inexorable laws of chemistry, we are ever under their sway. Our consciousness is housed in a mortal shell, consisting primarily of compounds of less than a score of chemical elements. The physiological behavior of our bodies is inevitably associated with the chemical changes or reactions among highly intricate chemical unions of these few elements. The driving tendency or immediate cause of the reactions which support life is to be found in the chemical affinities and respective concentrations of the several substances. Our bodies are chemical machines, from which we can not escape except by quitting our earthly life. The nature of the chemical elements and their compounds therefore presents one of the most interesting and important of all problems offered to mankind. That the study of chemical problems of life is consistent with the study of man in a biological, a psychological, or a spiritual sense is obvious. To-day the epigram, "The proper study of mankind is man," must be greatly broadened in order to correspond with modern knowledge.

These words regarding the origin and significance of chemistry serve as an introduction. Your committee has honored me by the request that I should tell you something about the object and outcome of my own endeavors, and these could be made clear only by reviewing the peculiar nature of chemistry. In my case the incentive to the pursuit of science was primarily that intense curiosity concerning the nature of things which echoes down the ages from the time of the ancient philosophers. To the feeling of curiosity, as time went on, was added the perception that only through a knowledge of the fundamental laws of chemistry can men use the resources of the world to the best advantage. Any further gain in this knowledge must, sooner or later, directly or indirectly, give mankind more power. Even an abstract chemical generalization must ultimately be of priceless service to humanity, because of the extraordinarily intimate relation between theory and practise.

The field is wide, and it is traversed by many paths. Among these one must be chosen and persistently followed if progress is to be made; and in my case that one was the study of the fundamental attributes or properties of the chemical elements, and the relation of these properties to one another. The work was undertaken with the hope of helping a little to lay a solid foundation for our understanding of the human environment.

What, now, are the fundamental attributes of the elements? First and foremost among these stands *weight*—the manifestation of the all-pervading and mysterious force of gravitation possessed by all forms of matter. Hand in hand with this attribute of weight goes the equally inscrutable property of inertia—that tendency which causes a body once in motion to keep on moving forever in the same straight line, if not acted upon by some new force. The idea of inertia, conceived by Galileo and amplified by Newton, was one of the starting points of both modern philosophy and modern physics. So far as we know, weight and inertia run parallel to each other. Of any two adjacent bodies, that having greater weight has also greater inertia. Hence they may be determined at one and the same time, and this Siamese-twinlike conjunction of properties establishes itself at once as perhaps the most fundamental of all the attributes of matter. Next perhaps comes volume, the attribute which enables matter to occupy space, with the corollaries dealing with the changes of volume caused by changes of temperature and pressure. Other fundamental properties are the tendency to cohere (which has to do with the freezing and boiling points of the liquids) and the mutual tendency of the elements to combine, almost infinite in its diversity, which may be measured by the energy-changes manifesting themselves during the reaction of one substance with another.

These are only a few of the important properties of the elements, but they present an endless prospect of further investigation, in spite of all that has been done during the past hundred years. For as yet we know only the surface of these things, and comprehend but little as to the underlying connections between them and the reasons for their several magnitudes. Why, for example, should oxygen be a gas, having an atomic weight just four times as great as that of helium, and why should it have an intense affinity for sodium and no affinity whatever for argon or fluorine? No man can answer these questions; he can discover the facts, but can not yet account for them. The reasons are as obscure and elusive as the mechanism of gravitation. But we shall not really understand the material basis upon which our life is built until we have found answers to questions of this sort.

In order to correlate the properties of the elements, and to attain any comprehension of their significance, one must first exactly ascertain the facts. Therefore, my endeavor has been to institute systematic series of experiments to fill the gaps in our knowledge of the actual phenomena. In much of this work I have had the invaluable aid of efficient collaborators, for which I am grateful.

The atomic weights were the first of the fundamental properties of the elements to receive attention in carrying out this plan. These, as every one who has studied elementary chemistry knows, represent the relative weights in which substances combine with one another. They are called atomic weights rather than merely combining proportions because they can be explained satisfactorily only by the assumption of definite particles which remain indivisible during chemical change. Even if some of these particles or so-called "atoms" suffer disintegration in the mysterious processes of radioactive transformation, the atomic theory remains the best interpretation of the weight-relations of all ordinary chemical reaction. Indeed, it is entrenched to-day as never before in man's history.

The determination of atomic weights is, primarily, a question of analytical chemistry—a question of weighing the amount of one substance combined with another in a definite compound—but its successful prosecution involves a much wider field. First, the substances must be prepared and weighed in the pure state, and next, they must be subjected to suitable reactions and again weighed with proof that in the process nothing has been lost and nothing accidentally garnered into the material to be placed on the scale pan. These requirements involve many of the principles of the new physical chemistry, so that the accurate determination of atomic weights really belongs as much in that field as in the field of analytical chemistry.

At Harvard during the last thirty years the values of the atomic weights of thirty of the most frequently occurring among the eighty or more chemical elements have been redetermined. From data secured here and elsewhere is compiled an international table of atomic weights, revised from year to year by an authoritative committee composed of representatives of various nations. The values thus recorded are in daily use in every chemical laboratory throughout the world, serving as the basis for the computation of countless analyses performed by the analytical chemist, whether for technical or for scientific purposes.

This practical utility of atomic weights, although not forgotten, was not the prime incentive in the work under discussion. The real inspiration leading to the protracted labor of revising these fundamental quantities was the hope of finding some clue as to the reasons for their several magnitudes, and for the manifest but incomprehensible relationships of the elements to one another.

The unsolved cosmic riddle of the meaning of the atomic weights may have far-reaching significance in another direction, because the atomic weights may be supposed to hold one of the keys to the discovery of the mechanism of gravitation. The mutual attraction of the earth and sun, for example, must be due to the countless myriads of atoms which compose them, each atom possessing, because of its own appointed relative atomic weight, a definite if infinitesimal gravitational force attracting other atoms. If we could discover the reasons for the individual atomic weights, we should probably gain a far better understanding of the all-embracing force built up of the infinitesimal effects represented by their individual magnitudes.

Among the striking facts to be considered is the constancy of gravity (and, therefore, of the sum total of the weights of all the atoms concerned) as shown in many ways. Moreover, not only is the sum total of the weights of the atoms remarkably constant, but also in many cases the values for the individual elements are found to be numbers of amazing constancy. Silver from all parts of the world and from many different ores yields always the same value; copper from Europe has the same atomic weight as the native metal mined under the bottom of Lake Superior; and yet more wonderful, the iron which falls from the sky, in meteorites having their birth far beyond the terrestrial orbit, has precisely the same atomic weight as that smelted in Norway. Many atomic weights, therefore, must be supposed to be constant, whatever the source of the elements.

Although thus we know only one kind of copper and iron and silver, evidence has recently been discovered which points towards the existence of at least two kinds of metallic lead. Every sample of *ordinary* lead always has exactly the same atomic weight as every other sample; but lead from radioactive minerals—lead which seems to have come from the decomposition of radium—has neither the same atomic weight nor the same density as ordinary lead, although in many of its properties, including its spectrum, it seems to be identical. This recent conclusion, reached only two years ago at Harvard, has been confirmed in other laboratories, and it now seems to be beyond question. Whatever may be the ultimate interpretation of the anomaly, the solution of this cosmic conundrum must surely give us a new idea of the essential nature of matter. Indeed, the fascinating subject of radioactivity bids fair to give us in many ways an entirely new insight into the innermost structure of the atom.

During the progress of the study of the combining proportions of the elements, it became more and more evident to me that the atomic weights should be considered not only in relation to one another, but also in relation to many other essential distinguishing properties of the elements. This wider problem involved a great extension of the experimental field.

Among other attributes of the various forms of matter, compressibilities, surface tensions, densities, dielectric constants, heats of reaction and electromotive forces have begun to receive attention, and already many new data have been accumulated. The explanation of the nature of these researches would take us far beyond the scope of this present address, but their object deserves attention. This object is the correlation of the various properties into a consistent whole, in the hope of tracing the unknown physical influences which determine the nature of the elements.

The rigorous science of thermodynamics enables us to predict in logical and precise fashion some of the relations between physical properties. My hope is not only to aid in providing accurate experimental basis for calculations of this kind, but also to achieve the correlation of different properties, apparently independent of one another from a thermodynamic point of view, thus, perhaps, enabling one by inductive reasoning to penetrate further into the causes which lie back of all the attributes of matter.

In attempting to follow this inductive path comparisons of the properties of the elements have been made in two different ways.

On the one hand a given property of one element has been compared with the same property of another. For example, the question, "Which of the two elements, cobalt or nickel, has the heavier atom?" was answered by parallel determinations, using the same methods, conducted side by side in the laboratory. Cobalt was found to possess the higher atomic weight.

On the other hand, the attempt has been made to discover a relation between the different, apparently quite distinct, properties of a single element. For example, one may ask: "Have the low melting and boiling points of phosphorus any connection with its small density and its large compressibility?" Here one compares various properties of the same element, and one seeks to discover if all are based upon some common, ultimate characteristic of phosphorus, of which the properties are merely symptoms.

The inductive methods used in comparisons of this sort can not be explained here to-day. They are partly statistical, partly mathematical and partly graphical. From the nature of the problem, which involves many unknown variables, perfect mathematical exactness is not to be expected. Nevertheless, little by little, one may hope to trace the conflicting tendencies, and ascribe them to a few common causes.

With the help of these methods the tentative conclusion has been reached that the space occupied by the atom and molecule in solids and liquids is highly significant. The actual atomic bulk or volume is diminished but slightly by moderate mechanical pressures, and by cooling even to the absolute zero; but it is very greatly affected, apparently, by the mutual attractions of the atoms, called cohesion and chemical affinity. Usually the less volatile a substance (that is to say, the more firmly it is held together by cohesion) the greater is its density and the less is its compressibility, other things being equal. Greater cohesion is associated with greater compactness. Likewise the existence of powerful chemical affinity between elements forming a compound is usually associated with great decrease in volume during the act of combination, and consequent increase in the density of the product in relation to the average density of the constituents. Thus we can hardly escape the inference that both cohesion and affinity, by pulling the atoms together with enormous pressure, actually exert a compressing effect upon the atoms, or at least upon the space which they demand for their occupation. The result of each of these compressing agencies is found to be greater the greater the compressibility of the substances concerned—a new evidence of the reasonableness of the inference. Not always are these effects easily traced, because the situation is often complicated, and the several effects are superposed. Nevertheless, enough evidence has been obtained to leave but little doubt, at least in my mind, as to the manner of working of the essential agencies concerned.

But we need not dwell upon this tentative hypothesis. Many more data and much more thought are necessary to establish it in an impregnable position, although no important inconsistency has thus far been pointed out in it. At present it may be looked upon as valuable because it, like other hypotheses of this type, has stimulated thought and experiment concerning the fundamental facts with which it deals.

As the years go on, the recent contributions to the study of atomic weights and volumes and other properties will be sifted and tested; and such contributions as may stand the test of time will take their places among the multifarious array of accepted chemical facts, laws and interpretations accumulated by many workers all over the world.

But we may well ask: What use, in the years to come, will mankind make of this knowledge gained step by step through the eager study of many investigators?

Chemistry has, indeed, a many-sided destiny. A mere catalogue of the countless applications of the science, which underlies many other sciences and arts, would demand time far exceeding the limits of this brief discourse. Some of the more obvious uses of chemistry have become daily topics in the public press. America is gradually awakening to the consciousness that, because every material object is composed of chemical elements and possesses its properties by virtue of the nature of these elements, chemistry enters more or less into everything. We perceive that chemical manufactures must be fostered, and also that chemical knowledge must be applied in many other industries not primarily of a chemical nature. Although chemistry plays so prominent and ghastly a rôle in war, her greatest and most significant contributions are towards the arts of peace. Even explosives may be highly beneficent; they may open tunnels and destroy reefs, furthering friendly communication between men; dig ditches for irrigation; help the farmer in his planting; and in many other ways advance the constructive activities of mankind. Again, poisonous gases, confined and harnessed within safe limits, may render valuable aid to humanity in preparing precious substances otherwise unattainable.

Such obvious and well recognized offices of chemistry need no further presentation to this intelligent company. Neither is it necessary for me to call your attention to the services which science may render to agriculture through the chemical study and enrichment of the soil in preparing it for the development of those subtle chemical mechanisms called plants, upon which we depend for our very existence.

There is a further beneficent possibility worthy of more than passing mention—namely, that which arises from the relation of modern chemistry to hygiene and medicine. Already your attention has been called to the indisputable fact that the human body is, physiologically considered, a chemical machine. For this reason, future knowledge of chemical structure and of organic reaction may perhaps revolutionize medicine as completely as it was revolutionized by the devoted labors of Pasteur—not by doing away with his priceless acquisitions of knowledge, but rather by amplifying them. Chemistry may show how germs of disease do their deadly work through the production of subtle organic poisons, and how these poisons may be combated by antitoxins; for both poisons and antitoxins are complex chemical substances of a nature not beyond the possible reach of chemical methods already known. In that far-off but not inconceivable day when the human body may be understood from a chemical standpoint, we shall no longer be unable to solve the inscrutable problems which to-day puzzle even the most learned hygienist and physician. Is not a part, at least, of the tragedy of disease a relic of barbarism? A race which could have put as much energy and ingenuity into the study of physiological chemistry as mankind has put into aggressive warfare might have long ago banished many diseases by discovering the chemical abnormalities which cause them.

May not the study of subtler questions, such as the nature of heredity, also lead us finally into the field of chemistry in our search for the ultimate answer? Even psychology may some time need chemical assistance, since the process of thinking and the transmission of nervous impulse are both inextricably associated with chemical changes in nervous tissue; and even memory may be due to some subtle chemical effect. In the realm of thought there can be no question of the blessed service already performed by science in dispelling grim superstitions which haunted older generations with deadly fear.

In brief, more power is given mankind through the discoveries of chemistry. This power has many beneficent possibilities, but it may be used for ill as well as for good. Science has recently been blamed by superficial critics, but she is not at fault if her great potentialities are distorted to serve malignant ends. Is not this calamity due rather to the fact that the spiritual enlightenment of humanity has not kept pace with the progress of science? The study of nature can lead an upright and humane civilization ever higher and higher to greater health and comfort and a sounder philosophy, but that same study can teach the ruthless and selfish how to destroy more efficiently than to create. The false attitude toward war, fostered by tradition and by the glamor of ancient strife, is doubtless one of the influences which have held back mankind from a wider application of the Golden Rule.

There is, in truth, no conflict between the ideals of science and other high ideals of human life. With deep insight, a poetic thinker on life's problems, in the opening lines of a sonnet, has said:

> Fear not to go where fearless Science leads,
> Who holds the keys of God. What reigning light
> Thine eyes discern in that surrounding night
> Whence we have come, . . .
> Thy soul will never find that Wrong is Right.

Our limited minds are confined in a limited world, with immeasurable space on all sides of us. Our brief days are as nothing compared with the inconceivable æons of the past, and the prospect of illimitable ages to come. Both infinity and eternity are beyond our mental grasp. We know that we can not hope to understand all the wonders of the universe; but, nevertheless, we may be full of hope for the future. Step by step we gain in knowledge, and with each step we acquire better opportunity for improving the lot of mankind, and for illuminating the dark places in our philosophy of nature. Although we shall none of us live to see the full development of the help which science may render to the world, we rejoice in the belief that chemistry has boundless service still in reserve for the good of the human race.

Theodore W. Richards
Harvard University

THE ONE HUNDREDTH ANNIVERSARY OF THE U. S. COAST AND GEODETIC SURVEY[1]

The honor of being one of the speakers on this memorable occasion is highly appreciated, in spite of a perfect realization of the fact that it comes to me solely because I have had the fortune, good or bad, to survive my predecessors. To live long, according to a well-known proverb, is to prove that one is not a favorite of the gods; on the other hand, to live long is to furnish fairly good evidence that one has not been found guilty of a capital crime.

During the past two days the various activities of this service have been so thoroughly discussed by competent critics that there is little room for further comment. As I am, in a way, representing the men who directed these activities during the century of its existence, I choose to speak, not for them, but of them, the superintendents of the Coast and Geodetic Survey, with some reference to their share in the development of the work.

To the republic of Switzerland American science is enormously indebted. Thence came Agassiz, Guyot, Lesquereux, and others who stirred us into scientific activity fifty years ago, and more than a half century earlier came Ferdinand Hassler, organizer and first superintendent of the Coast Survey. No brief sketch can do justice to Hassler's personality or to his all-powerful influence in molding the character of the new organization, the first of the so-called "scientific bureaus" of the United States government. Educated in the best schools of Europe, intimately acquainted with the most eminent scientific men of the Old World and with experience in the trigonometrical survey of his native country, he possessed exactly the qualifications necessary to a successful launching of the new enterprise. Not the least of these qualifications was one rather rare among men of science, though common enough in the so-called "learned professions." With intellectual power and technical skill of the highest order he combined an equally high appreciation of his own merits. It is related that when invited to organize and direct the survey of the coasts, which had been strongly recommended to Congress by Thomas Jefferson, he demanded and received a salary equal to that of the head of the department to which the new bureau was assigned. *Tempora mutantur!* There is also a tradition that when the President objected, saying, "Your salary is as large as that of my Secretary of the Treasury, your superior officer," he replied: "Any president can make a Secretary of the Treasury but only God Almighty can make a Hassler."

Visiting Europe to purchase the necessary instruments and standards of measure, he was detained in England as an alien enemy until 1815 and thus a period of nearly ten years elapsed between its authorization by act of Congress and the actual inception of the Survey.

Hassler's plan of organization, broad and thoroughly worked out, is still the funda-

[1] Address given at the banquet, April 6, 1916.