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A CENTURY OF PROGRESS IN CHEMISTRY[1]

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WHOEVER considers the history of the past 100 years can not but conclude that its outstanding feature has been the progress of mankind in science, that is, in the ordered knowledge of the world about us. In agreement with this, Mr. Dawes and his able co-workers have made the scientific sections of this exposition of unexampled completeness and excellence. Never have the achievements of science been so adequately portrayed at any exposition. Never anywhere has such a galaxy of scientific exhibits been gathered together, as is housed in this brilliant Hall of Science where we are now assembled.

Three thousand of the 18,000 members of our American Chemical Society have convened this week in Chicago from every corner of our country, to present and to discuss the most recent results of their researches. At this evening meeting of our Society, within the confines of the Century of Progress Exposition, it is eminently fitting that the contributions of chemistry to the advance of science during the past one hundred years should be set forth. It is, then, all but inevitable that I should address you this evening on

A CENTURY OF PROGRESS IN CHEMISTRY

In 1833 chemistry was, so to speak, still in her swaddling clothes. Less than fifty years had elapsed since Priestley and Scheele had discovered oxygen and chlorine; since Volta had discovered how to produce electricity by chemical means; since Lavoisier had elucidated the age-old problem of the nature of fire, and since Dalton had demonstrated the existence of atoms and had shown how their relative weights could be ascertained.

In 1833, chemistry was a small and compact science.

[1] A popular address (The President's Address) delivered at an evening meeting of the American Chemical Society at the Century of Progress Exposition in Chicago, September 14, 1933.

It was concerned chiefly with mineral substances and with a number of so-called organic substances derived from vegetable and animal sources, only one of which, namely urea, had been made in the laboratory from inorganic, lifeless materials. A chemist of that period could be expected to be well informed about every branch of his science. Indeed, Berzelius, each year in his "Annual Reports," discussed with intimate knowledge and with authority every important chemical contribution of the past twelve months.

During the succeeding century, chemistry has changed from a single science to a collection of sciences, no one of which can be fully mastered by a single intellect. The sciences of thermochemistry, electrochemistry, photochemistry, radio chemistry, chemical dynamics, chemical statics and biochemistry have come into being. They are almost exclusively the products of the past one hundred years.

It will be impossible for me to give even an outline of these vast developments. I shall, therefore, only undertake to describe, in language which I trust will be sufficiently free from technicalities so that people who are not chemists can understand, a few typical and significant chemical achievements of the past one hundred years.

The most patent of these achievements are those which minister directly to the material welfare of mankind; better and cheaper supplies of old and known materials, or wholly new and superior materials. I shall speak of these achievements first, and specifically of new inorganic substances.

Since 1833, forty new elements have been recognized, most of them present in only minute amounts on the earth. All but three of these new elements have been isolated and studied. I shall mention four of them specifically.

First, helium, discovered in 1893 by Ramsay as an infinitesimal constituent of the atmosphere. Excessively rare on our earth, it is a major constituent of innumerable giant stars. Although its only important commercial use is for the inflation of airships—where its non-inflammability coupled with its lightness makes it invaluable—it has been of the greatest importance in theoretical chemistry.

Second, neon, also discovered by Ramsay, resembles helium in many respects and is even more rare. It finds its chief commercial application as a gaseous filling for the brilliant glow lamps that enliven our thoroughfares and adorn the towers of the Hall of Science.

Third, radium, that marvelous element discovered by Madame Curie in 1898, which has been of incalculable value to the physician and, as we shall shortly see, like a magic wand, has unlocked the secrets of the structure of matter.

Fourth, heavy hydrogen, discovered about a year ago by Urey, Brickwedde and Murphy. This variety of hydrogen is present in minute amounts along with ordinary hydrogen, in water, petroleum and presumably in the myriad other compounds of this element. Washburn showed how to concentrate it and Lewis has prepared pure samples of it and has shown, for instance, that water made from oxygen and this new variety of hydrogen has very different physiological properties from ordinary water.

The discovery of these four elements alone would have been sufficient to make any century illustrious!

Of even greater practical importance are the striking improvements that have been wrought since 1833 in the preparation of many common substances. I shall again cite four examples:

First, iron and steel. The small blast furnaces of 1833 have grown into the huge structures of to-day nearly one hundred feet high, turning out 600 tons of pig iron a day. The old process of making steel by prolonged heating of wrought iron in contact with charcoal has been replaced, for instance, by the Kelly-Bessemer process, where sixteen tons of pig iron is converted into steel in almost as many minutes.

In 1833 American steel sold at wholesale in New York for $180 a ton on the currency basis of 1926. To-day finished steel on this same basis sells for $28.00 a ton. I need not tell you that our whole industrial civilization rests upon the abundance and cheapness of this indispensable metal!

Aluminum is my second example. In 1833 this metal was a museum rarity, for only a few grams of it had ever been made. In 1854 it sold for $100 a pound. In 1886 Charles Hall, then a student at Oberlin College, working with a make-shift apparatus in the obscurity of a garret, discovered how to prepare aluminum easily and cheaply by an electrolytic method. Independently Héroult in France discovered the same method at almost the same time. This method, in its essentials, is still in use to-day, producing huge amounts of the metal selling at about 23 cents a pound.

My third example is sodium carbonate. This substance, often called soda, has been known since prehistoric times and has a thousand uses in the industries and the arts. Chief of these is in the manufacture of glass and of soap. In 1833 soda had long been made from certain plants that grow in marshy land near the sea. They were burned, their ashes leached with water and the liquors evaporated. To-day sodium carbonate is made by the Solvay process on a huge scale from limestone and coal. It is of remarkable purity and sells for about one-tenth of its price in 1833.

My final example is ammonia. In 1833 this gas was obtained almost exclusively as a by-product of the distillation of coal. It has long been used in great quantities in the manufacture of ammonium sulfate, one of the two important nitrogenous fertilizers. The other important nitrogenous fertilizer is sodium nitrate, obtained from natural deposits in Chile.

In 1898, Crookes pointed out that the supply of ammonia and hence of ammonium sulfate was relatively limited, and that at current rates of consumption the Chilean nitrate deposits would be exhausted in a few decades. As a consequence, chemists eagerly sought ways of making nitrogenous fertilizers out of the limitless supply of inert nitrogen in our atmosphere. Haber, in 1905, by the application of the principles of physical chemistry, succeeded in demonstrating the possibility of forcing the nitrogen of the air to combine directly with hydrogen to form ammonia. Shortly afterward Bosch developed the active and robust catalysts which were required to make this process a commercial success.

Never was a discovery more timely! The world war was just breaking and Germany was soon shut off from the supply of Chilean nitrates. The synthetic ammonia factories were rushed to completion and greatly enlarged. The ammonia there made was easily converted into the nitric acid and the nitrates required in the manufacture of explosives. Thus throughout the war, Germany was able to keep her armies adequately supplied with ammunition.

Since the war there have been many further improvements in this process and it is now practised on a large scale in several countries. Nitric acid and nitrates can be made so cheaply from this ammonia that they compete successfully in the world markets with the Chilean supply. Clearly the threat of a nitrogen famine no longer exists.

More important, however, than the cheap and abundant ammonia which this process now provides are the contributions it has made to the technology of high pressure and of large scale catalysis. It has opened up a new realm of chemical manufacture of immense promise for the future.

I wish now to turn to the material achievements of organic chemistry; to the improvements in the manufacture of already known, and to the discovery of new, organic substances.

Since 1833 the refining of sugar has been highly perfected, so that commercial sugar is now of astonishing purity and cheapness. Petroleum has been refined and separated into hundreds of products indispensable to our modern life. In particular, the manufacture of gasoline and of lubricating oils has become a great industry. Even the synthetic manufacture of these substances from coal has been accomplished and, in favorable localities, put into commercial operation. The refining and hardening of edible oils and fats is another organic chemical industry that has originated during the past century and become of great economic importance.

More impressive than all these developments are the myriads of new substances that the organic chemist has fashioned in his laboratory. As contrasted with the relatively few organic substances known in 1833, it is estimated that there are now more than 300,000 of these new substances; substances which, so far as we know, never before existed in the world!

Almost countless in number, these substances are almost endless in their variety. They comprise dyes, perfumes, flavors, foods, fabrics, resins, plastics, explosives and innumerable drugs, to mention only a few of the larger classes.

I can speak in greater detail of but two of these classes. First, dyes. In 1833 dyes were nearly all extracted from plants and trees. The two most important, madder and indigo, were produced synthetically in 1868 and 1889, respectively, and are now exclusively manufactured in this way. More important, Perkin in 1856 discovered the first aniline dye which he christened "mauve." Thousands of such dyes derived from aniline or related substances have now been made. They are almost infinite in the variety of their colors. The best of them are more brilliant than the natural dyes of similar hues and are much more permanent.

Second, medicines. Although only a small fraction of the 300,000 organic substances known have been tested from this point of view, thousands of them have been found to possess valuable medicinal properties: antiseptics, stimulants, sedatives, hypnotics, anesthetics. Perhaps most interesting of all are the specific drugs that in a few instances have been developed to combat definite diseases. In the search for such a specific a likely organic substance is selected as a starting material, and its molecule is systematically altered by the removal and introduction of different atoms, until a substance is obtained that is highly and peculiarly poisonous to the particular bacteria or other organisms responsible for the disease. The first great success of this kind, achieved after years of research, was "salvarsan."

Another was "Bayer 205," a specific for African sleeping-sickness. Such purposeful and systematic search for definite specifics holds great promise for the future of medicine.

So much for the material contributions that chemistry has made, during the past one hundred years, to the welfare of mankind. Without them our present civilization would be impossible. They impinge upon mankind in every corner of his world and at every moment of his existence. They have profoundly affected most of his manifold fabrications; his houses, his means of transportation, his implements, his weapons, his medicines, the very clothes he wears and the food he eats!

I now turn to what is still more significant, namely, the advances in chemical knowledge during this period. I shall discuss, as typical of these advances, the progress that has been made in our knowledge of the structure of matter.

In 1833 Dalton had already demonstrated that matter was composed of atoms, but the greatest confusion still prevailed as to the relative weights of the atoms and as to the formulas of the compounds they formed. Actually, Avogadro in 1811 had already shown how the relative weights of the smallest particles or molecules of gases could be ascertained, and how by assuming that the molecules of the common gaseous elements contained two atoms, a consistent set of formulas for all gaseous substances could be established. Unfortunately this discovery remained either neglected or unappreciated for nearly forty years. In 1858 Cannizzaro called attention to this work of his countryman, and its importance was promptly recognized. Like a ray of sunshine, it dispelled the uncertainties and confusion in Dalton's atomic theory. In 1874 the correctness of Avogadro's fundamental assumption of the doubled formula for the common elementary gases was established by independent and indubitable evidence.

Meanwhile, the organic chemist, in spite of the handicap of uncertain atomic and molecular weights, had made important advances in ascertaining the structure of his substances.

His problem was, however, a most difficult one. The formulas of organic substances were usually very complicated, even though they consisted of remarkably few elements, namely, carbon, hydrogen, and in addition usually oxygen or nitrogen or both. During the first twenty years after 1833 little progress was made in unraveling their structure, although certain characteristic groups of atoms were recognized as occurring in many different substances and some classification of organic substances was achieved. Indeed, the perplexity increased rather than decreased during this interval, for chemists were already learning how to convert one original organic substance into dozens of new ones. As a consequence, the number and variety of organic substances multiplied prodigiously and organic chemistry was threatened with asphyxiation in a deluge of her own progeny.

Most perplexing of all were the numerous pairs and groups of organic substances, called isomers, such as the silver fulminate of Liebig and the silver cyanate of Woehler, which, though quite different in their properties, nevertheless were identical in their composition; that is, their molecules contained exactly the same number of atoms of the very same elements.

To the chemist of the 50's these multitudinous organic substances with complicated and at times indistinguishable formulas presented a puzzling, indeed a bewildering array!

Then in 1852, within a few months of each other, Frankland in England, Couper in Scotland, and Kekulé in Germany found the key to this locked door. This key was the idea of valency, or the number of other atoms that any one atom can attach to itself. Thus the hydrogen atom which can attach to itself but a single other atom, has a valence of one. It has, speaking symbolically, but a single hand with which it can grasp the hand of some other atom. The oxygen atom has a valence of two, the carbon atom a valence of four; that is, the oxygen atom has two hands, the carbon atom four hands with which they can grasp the hands of other atoms. Two carbon atoms can unite by each grasping a hand of the other, leaving each atom with three other hands with which it can grasp hydrogen, oxygen, additional carbon atoms, or indeed almost any other atoms it may desire.

Adhering to this idea of fixed valencies, atomic structures could be pictured which not only corresponded exactly with the numerical formulas of organic compounds but also with the numerical formulas of the groups of atoms whose presence in the compounds had already been established. The key fitted.

The diagrams which the organic chemist could now draw of his innumerable substances showed that they usually consisted of chains of carbon atoms, where each carbon atom grasped the hand of a neighboring carbon atom on his left and right. These chains were like the human chains used to rescue drowning people, except that each carbon atom had two extra hands, one in front and one behind with which it grasped other atoms, usually of hydrogen, oxygen or nitrogen.

"Very pretty," you say, "but how about isomers, those different substances with the same numerical formula?" The answer is simple and illuminating. First, in thousands of cases where the valencies permit but a single arrangement, only a single substance of this formula is known; there are no isomers. Second, in thousands of cases where the valencies do permit a certain number of different arrangements of the atoms, and therefore indicate the existence of that number of isomers, chemists have been able to prepare exactly that number of isomers and no more. In other words, the facts of isomerism, instead of presenting a difficulty, are an emphatic confirmation of the structural formulas based on valency.

A few undeniable exceptions to these generalizations still remained. And this brings me to the final step which organic chemists took in deciphering the structure of molecules.

Pasteur, in 1860, had found pairs of substances with identical structural formulas, that is, substances whose molecules contained exactly the same atoms apparently arranged in exactly the same way which, although alike in other respects, nevertheless behaved differently toward polarized light. One member of each pair rotated the plane of polarized light to the right, the other to the left. Here was a more subtle and elusive kind of isomerism not explicable by the simple principles of valence.

In 1874 Van't Hoff and LeBel both pointed out that this isomerism only occurred when there was in the molecule an atom of carbon each of whose four valencies held a different atom or group of atoms. They pointed out that in such an asymmetric assembly of atoms there can be both a right-handed and a left-handed arrangement of the four different atoms about the central carbon atom and that two such isomers should rotate the plane of polarized light in opposite directions.

This explanation has been confirmed by all subsequent investigation and indeed has been extended to cover asymmetric atoms of other elements. Thus even this delicate type of isomerism found an explanation on the basis of structure.

Van't Hoff went still further. He showed that these phenomena indicated that the four valencies of the carbon atom were fixed at the corners of a regular tetrahedron whose center was the center of the carbon atom. In other words, carrying our anthropomorphic analogy a little farther, and considering the valencies of atoms to be represented by legs as well as by arms, the carbon atom can be pictured as a man standing with his legs spread widely apart, his shoulders turned squarely to one side and his arms pointing diagonally upward, one arm toward the front and one toward the rear. A man who achieved this somewhat trying posture by turning toward the right would represent one isomer; he who did so by turning to the left would represent the other isomer.

Subsequent investigation has confirmed this tetrahedral conception of the carbon atom, and recent measurements of the electromagnetic properties of carbon compounds have established it beyond question.

Chemical molecules can no longer be thought of as arrangements of atoms in a single plane—they are structures in three-dimensional space.

Thus the organic chemist by extraordinary industry and acumen has deduced the number, arrangement and geometry of the atoms even in very complicated organic molecules. He makes diagrams of these atomic structures just as an engineer makes blueprints of his buildings. He sees with his mind objects a thousand times too small for his eye to see, even under the most powerful microscope.

Meanwhile, an attack was launched from a wholly different quarter that was to lead to a knowledge of the structure of the very atoms themselves. Newlands and others about the middle of the past century observed that the properties of the elements were recurrent; that is, if the then known chemical elements were arranged in the ascending order of their atomic weights, nearly every eighth element exhibited marked similarities. That is, the eighth element resembled the first, the ninth the second, etc. However, there were so many exceptions that this observation was hardly given serious consideration by other chemists. In 1869 Mendeléeff independently made the same observation as Newlands and further showed that by leaving a number of blank spaces at appropriate points in the series of elements, the regularity became surprisingly exact. He prophesied that new elements would be found whose atomic weights would correspond to these blank spaces and whose properties would be similar in each instance to the eighth preceding and the eighth succeeding element. He was so confident of the validity of this relationship that he predicted minutely and numerically the properties of a number of these as yet undiscovered elements. Within ten years half a dozen new elements were discovered. They not only fitted neatly into the blank spaces, but their properties were precisely what Mendeléeff had foretold!

All the thirty additional elements since discovered have fitted equally well into the remaining blank spaces. There can be no question as to the reality of this periodicity in the properties of the elements.

Moreover, it was certain that this regularity reflected some genetic relationship among the atoms—a veritable "family tree" of the elements. The atoms could not be inchoate particles of fortuitous, unrelated, different kinds of matter; they must be built up of a more fundamental unit or units of matter according to a scheme of architecture which found its reflection in the periodic properties of the elements.

This inference was confirmed by a rapid succession of discoveries. In 1897 J. J. Thomson, from studies of the passage of electricity through gases, showed that the unit charge of electricity, which Faraday in 1833 had found chemical atoms to carry in the process of electrolysis, was capable of free existence, and that it behaved as an atom of negative electricity with a mass only about 1/2000 of that of the hydrogen atom, the lightest of the chemical atoms. These atoms of negative electricity were called "electrons."

The very next year Madame Curie made the momentous discovery of radium. Rutherford and others demonstrated that a minute fraction of the atoms of this remarkable element were continually exploding with astounding results. Rays were emitted similar to x-rays; atoms of helium charged with positive electricity were expelled from the exploding atoms at speeds of thousands of miles per second, while electrons were shot out at speeds ten times as great, comparable with the velocity of light. In addition, atoms of lead were found among the debris of these atomic cataclysms. Soon it was found that other chemical elements exhibited this same instability, though in a less degree than radium.

Here was conclusive proof that the atoms of our chemical elements are not simple and inalterable particles, but are complex structures made up of simpler and smaller units and subject to disintegration.

The most important of the units, or building stones of the atoms, are the electron and the proton, the proton being the positively charged nucleus of the hydrogen atom, that is the hydrogen atom minus its single electron. The positron, an almost weightless unit of positive electricity, and the neutron, a coalesced electron and proton, have been discovered recently but their importance in the construction of atoms is still uncertain.

The architecture of most of the atoms, and particularly of the larger atoms, is still imperfectly understood. The architecture of the simplest of the atoms, namely hydrogen and helium, is somewhat better known. In the hydrogen atom the extremely minute proton comprising most of the mass of the atom occupies a central position and the electron appears to revolve rapidly about it at a relatively great distance. The properties of hydrogen, such for instance as the wave lengths of the light it emits under different conditions, can be calculated on the basis of this structure with truly astronomical precision.

The term "astronomical" is appropriate, for actually when the distance between proton and electron is compared with the diameters of these units themselves, the atom is seen to resemble the solar system where the distances between the planets and the sun are very great in comparison with their diameters.

As regards the larger atoms, it is known that their mass, like that of hydrogen, is all concentrated in a minute central nucleus. This nucleus is made up apparently of protons and about half of all the electrons in the atom. The remainder of the electrons appear to circulate about this nucleus, their orbits lying in a series of concentric shells comparable to the successive layers of an onion.

As soon as these discoveries as to the structure of atoms had been made, chemists and physicists tried to break up the ordinary, stable chemical atoms, or to make them explode as radium atoms do on their own initiative. At first, all these attempts were in vain. Finally, by bombarding them with the positively charged helium atoms shot out of exploding radium atoms, a number of these stable atoms were shattered and helium and hydrogen atoms were found among the debris. Similarly, by bombarding, for instance, lithium atoms with protons shot out of an electric cannon, atoms of helium were produced.

Thus, on a small scale and at great expense the goal of thousands of years of human effort has been reached—the transmutation of the elements! To be sure the particular dream of the alchemist, the transformation of base metals into gold, is still unrealized, but this no longer appears impossible or, thinking in centuries, unlikely.

Another possibility which these discoveries have afforded is even more alluring. The helium atoms obtained from the bombardment of lithium and other atoms with protons are endowed with enormous energy, thousands of times that of the bombarding particles. Here is a source of energy which, if it could be practically and efficiently utilized, would surpass by a thousand times the energy obtainable from all the coal in the world!

There is one final observation that I should like to make. These contributions of chemistry during the past one hundred years that I have recited, these better and cheaper materials, this wealth of wonderful new substances, this deeper understanding of matter, profoundly affect the heart and the soul of man. As he contemplates these new disclosures of the extent, the intricacy, the wonder and the beauty of this, his universe, he can but exult at the glorious opportunity of mankind. As he considers these innumerable intellectual achievements, these repeated decipherings of an all but inscrutable scroll, he can but thrill with pride at the fertility and power of the human intellect.

Ladies and Gentlemen, except in the inconceivable event of a complete eclipse of our civilization, these contributions of the past one hundred years to human welfare are lasting. Material wealth may come and go, governments may rise and fall, systems of human society may evolve and disappear, but these additions to human knowledge that I have described this evening, this "Century of Progress in Chemistry" is a permanent asset of the race!