Chemistry is all around us. Everyone can and should understand basic chemistry. Apart from those wanting to become chemists, students wanting to become doctors, nurses, physicists, nutritionists, geologists, and pharmacists all need to study chemistry. It is important to remember that the importance of chemistry would not be diminished over time; rather it will continue to remain a promising career prospect.

International Year of CHEMISTRY 2011

The Central Science Chemistry

BIMAN BASU

RIGHT from the moment we get up in the morning till we go to bed at night, we come intimately close to chemistry and things related to it. The toothpaste we use to clean our teeth, the toilet soap, shampoo, and plastic buckets we use to take bath, the plastic comb we use to comb our hair, the melamine cups and plates we use at breakfast, the cooking gas our mother uses in the kitchen, the iodised salt she uses to cook food, the ink in the pen we write with, the inks this magazine is printed with, the beautiful dyes that brighten up our dresses, the polyurethane foam mattress that makes our sleep at night comfortable, and a host of other items of daily use are all products of chemistry.

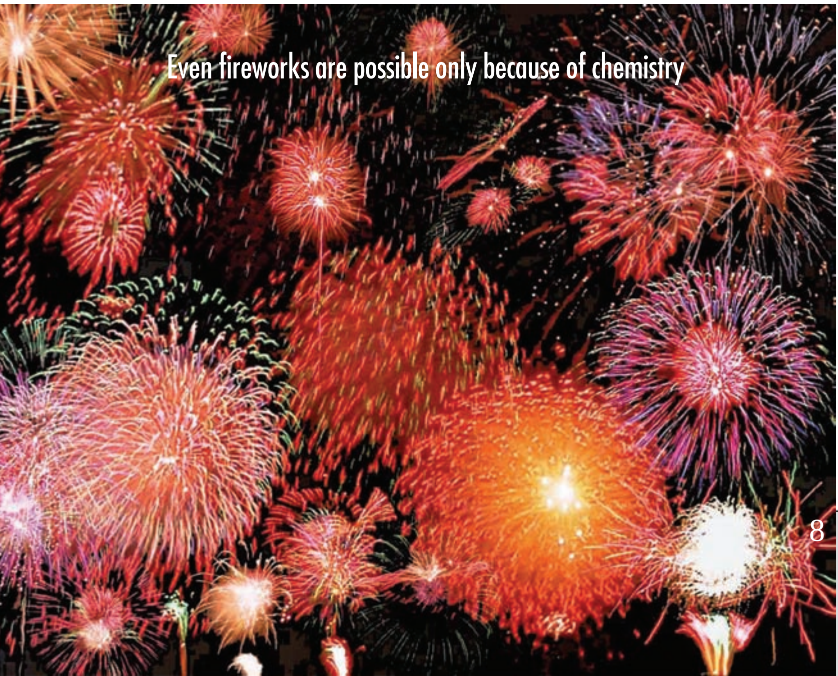
That is not all. There would be no drugs – painkillers, antacids, or antibiotics – no polyester fibre or nylon stockings, no stainless steel, no sugar-free soft drinks, even no Diwali illumination and fireworks without chemistry. Without chemistry, we would not have such items as computers, CDs, DVDs, iPods, fuel for vehicles, oil to cook, refrigeration units, radios, televisions, batteries, and so much more. So, then, what is chemistry?

Chemistry Around Us

In brief, we can say, chemistry is all about the nature of all matter around us – air, water, metals, plastics, drugs, everything – about how they behave, how they react, and how they change. It is about changing one kind of material into another.

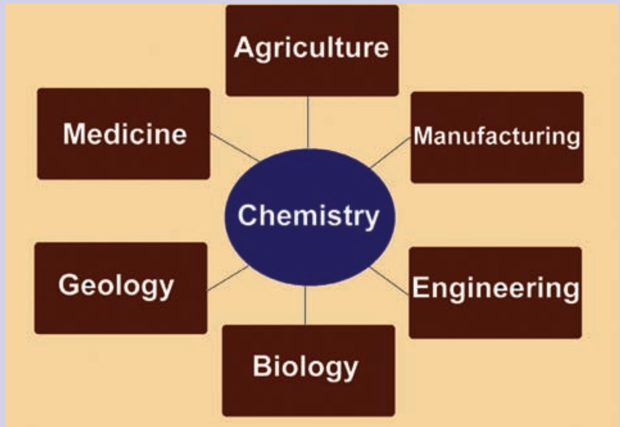
In fact, the practice of chemistry started thousands of years ago, but not as a science. It was primarily directed at efforts to turn all kinds of substances into the precious metal gold by early chemists, who were known as alchemists. We have heard about the "philosopher's stone" using which the alchemists sought to turn any metal into gold. Of course it was a silly thought, because no one can really turn one element into another by mere touch! Still, the alchemists made important contributions to chemistry; they developed many of the techniques used by modern chemists like distillation, filtration, etc., and were also the first to use symbols for some common elements like gold and mercury.

The real importance of chemistry stems from the fact that it serves as a common interface between practically all of the other sciences – medicine, biology, engineering, geology, and manufacturing – as well as between many other areas of



Even fireworks are possible only because of chemistry

Chemistry serves as a common interface between practically all of the other sciences



There would be no drugs, stainless steel, sugar-free soft drinks, CDs, DVDs and iPods, televisions and a host of other things without chemistry

Apart from those wanting to become chemists, students wanting to become doctors, nurses, physicists, nutritionists, geologists, and pharmacists all need to study chemistry.

human endeavour such as art and culture where paints, colours, dyes and fabrics – all products of chemistry – play a key role. For this reason, chemistry is often called the "central science". (The phrase was popularised in a textbook by Theodore L. Brown and H. Eugene LeMay titled *Chemistry: The Central Science*, which was first published in 1977, with a 12th edition published in 2011.)

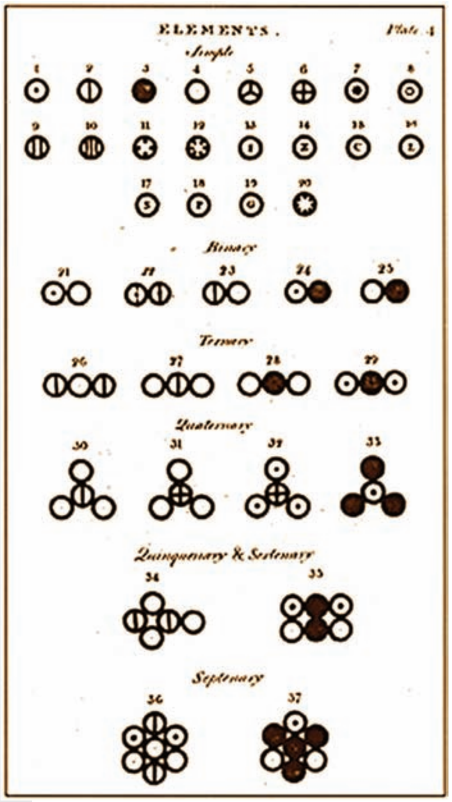
This is not an overstatement, because a student with a solid background in chemistry would find it far easier to migrate into other fields as his/her interest develops. But, unfortunately, many science students find chemistry boring, and some find it a very hard subject to understand. But that need not be so.

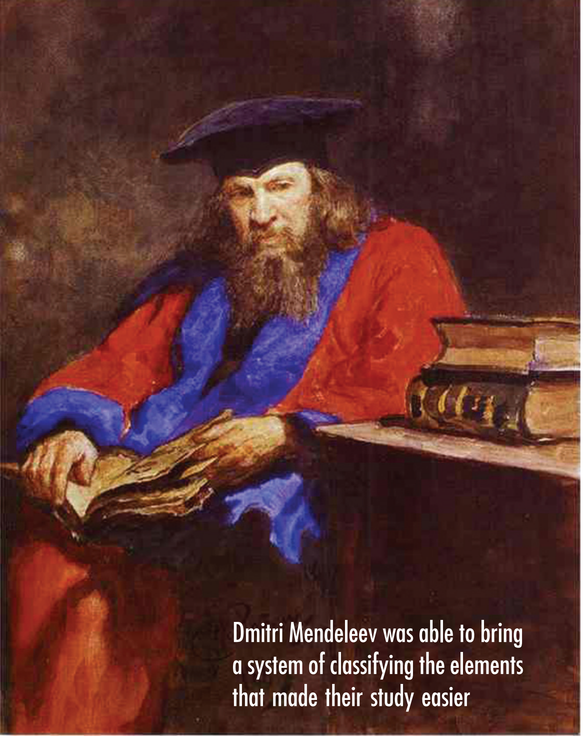
Chemistry is primarily concerned with chemical elements – the simplest substances into which ordinary matter may be divided – and the way they react with each other. As early as 1660, Irish-born chemist Robert Boyle recognised that the Greek definition of element (earth, fire, air, and water) was not correct. Boyle proposed a new definition of an element as a fundamental substance, and we now define elements as fundamental substances that cannot be broken down further by chemical means. But Boyle did not elaborate on the nature of the elements or compounds.

The 118 chemical elements known today constitute the "alphabet" of matter because everything else is made of some combination of these. (Of course, many of the transuranium elements do not occur in nature; they are artificially produced.) The elements can combine by reacting together to form a multitude of compounds that make up everything in this universe, including us. Everything around us is formed by a combination of two or more of these elements.

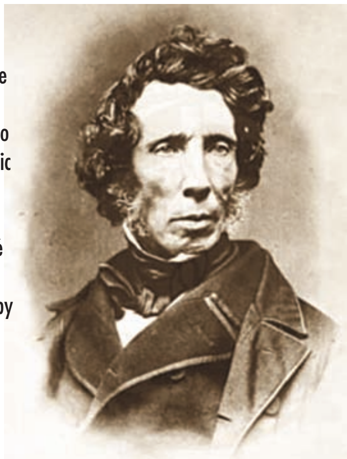
So, in order to understand chemistry one has to know about the chemical elements, about their properties, about how they react, and about why they react the way they do. But doing that is not as difficult a task as it may sound. It is possible

John Dalton's atomic theory could explain the facts of chemical combination as they were then known (below), Various atoms and molecules as depicted in John Dalton's *A New System of Chemical Philosophy* (1808) (right)





Dmitri Mendeleev was able to bring a system of classifying the elements that made their study easier



Friedrich Wohler overturned the vitalism theory by converting the inorganic salt ammonium cyanate into urea, which is an organic compound (right);

Friedrich August Kekulé brought in a revolution in structural chemistry by suggesting a ring structure for benzene (extreme right)

to learn about the elements even without memorising complex equations and formulae. Of course, getting familiar with the chemical symbols can be of great help in understanding the subject better, as would a little understanding of how chemical formulae and equations are written.

Laws of Chemistry

The real joy of learning chemistry comes from understanding its basic laws. If we look at the history of science we will come across numerous instances where a sudden spark lit up a dark tunnel leading to the solution of a long-sought problem. Chemistry also evolved in small steps, each marked by a unique discovery.

One of the first big breakthroughs in our understanding of chemistry came in 1803 when English physicist, meteorologist and chemist John Dalton proposed a rational atomic theory to explain the facts of chemical combination as they were then known. The idea of atoms had been proposed much earlier. The ancient Greek philosophers had talked about atoms, but Dalton's theory was different in that it was supported by careful chemical measurements. It was not just a philosophical statement.

Dalton's atomic theory specifically stated that elements consisted of tiny particles called atoms. It further said that the reason an element is pure is because all atoms of an element were identical and that in particular they had the same mass. It also said that the reason elements differed from one another was that atoms of each element were different from one another; in particular, they had different masses. Dalton's theory also said that compounds consisted of atoms of different elements combined together. He used his own symbols to visually represent the atomic structure of compounds.

There are millions of chemical compounds formed by elements in different combinations; yet all of them are guided by three simple laws of chemical combination, which were propounded between 1785 and 1806.

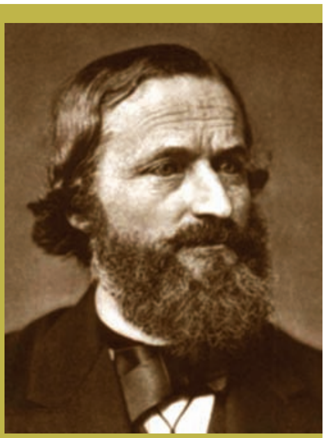
The law of conservation of mass was discovered by French chemist Antoine Laurent Lavoisier about 1785. It states that during any physical or chemical change, the total mass of the products remains equal to the total mass of the reactants. John Dalton formulated the law of multiple proportions in 1803. According to this law, if two elements form multiple compounds, the ratios of the masses of the second element combining with a fixed mass of the first element will be in ratios of small whole numbers. Three years later, the French chemist Joseph Proust stated the law of constant proportion, which states that a chemical compound always contains same elements combined together in the same proportion by mass.

These were great achievements in understanding how the chemical elements combine. All the three scientists formulated their laws after careful and extensive experimentation – an essential prerequisite of chemistry.

Periodic Properties of Elements

Before the Russian chemist Dmitri Mendeleev came up with the periodic table of elements in 1869, understanding and remembering the properties of all the 63 chemical elements known at that time was a stupendous task. Mendeleev was able to bring a system of classifying the elements which made the job easier. Although Mendeleev arranged the elements in order of increasing atomic mass, which was incorrect, his periodic table brought some order in an apparently random collection of elements.

Mendeleev also did a few things that made his table useful. He realised that the physical and chemical properties of elements were related to their atomic mass in a 'periodic' way, and arranged them so that the elements with similar properties fell into vertical columns, or 'groups', in his table.



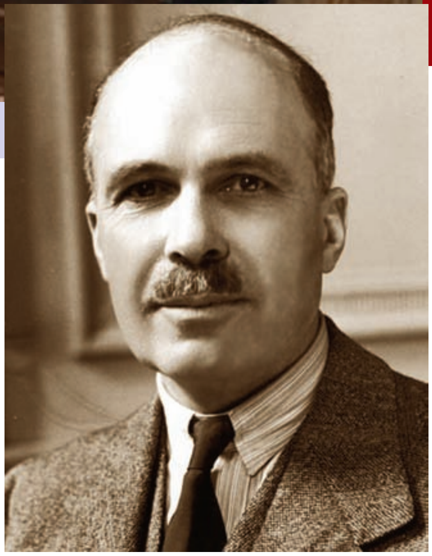
Gustav Kirchhoff

Carrying matters further, the French chemist Pierre Eugene Marcelin Berthelot went about synthesising organic compounds systematically, turning them out in scores during the 1850s.

A major turning point in chemistry was the refutation of the long held 'vital force' theory

Robert Bunsen

The work of William Lawrence Bragg created a new science of X-ray crystallography. Here he is seen delivering a lecture.



William Lawrence Bragg, who was 22 years old, realised that X-rays could be used to detect the arrangement of individual atoms inside solid crystals.

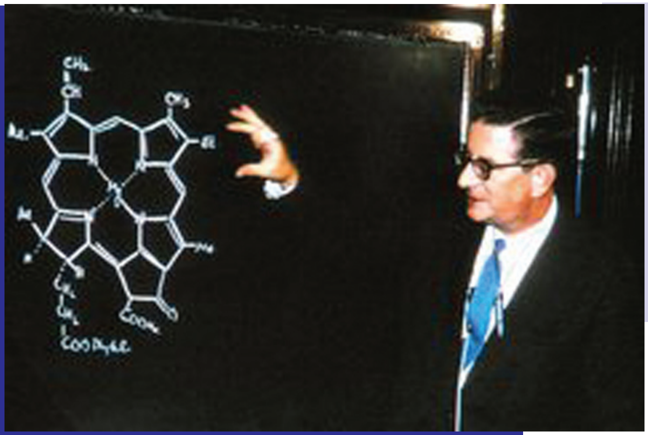
In Mendeleev's table there were gaps in the horizontal rows or 'periods' where no known element could be placed. But instead of seeing this as a deficiency of his table, Mendeleev thought it simply meant that the elements which belonged in the gaps had not yet been discovered. He could also work out the atomic masses of the missing elements, and so predict their properties. When the unknown elements were discovered, Mendeleev turned out to be right. For example, he predicted the properties of an undiscovered element that should fit below aluminium in his table, which he called *ekaaluminium*. When this element, called gallium, was discovered in 1875 its properties were found to be close to Mendeleev's predictions. Three other predicted elements – *ekamanganese* (technetium), *ekasilicon* (germanium), and *ekaboron* (scandium) – were later discovered, lending further credit to Mendeleev's table. Suddenly the properties of the elements not only became rationalised but also predictable.

Mendeleev could make little further progress because the Rutherford-Bohr model of the atom had not yet been formulated. Then in 1913, English physicist Henry Moseley, who worked with New Zealand-born British chemist Ernest Rutherford, showed that it is atomic number and not atomic mass, which is most fundamental to the chemical properties of any element. Moseley correctly predicted the existence of new elements based on atomic numbers. We know now that an element's chemistry is indeed determined by its atomic number and the way its electrons are arranged – its electronic configuration. The electronic configuration could explain why some elements are more reactive than others, why some elements are totally inert, and also why some elements are unstable. Slowly scientists were beginning to understand how chemistry works.

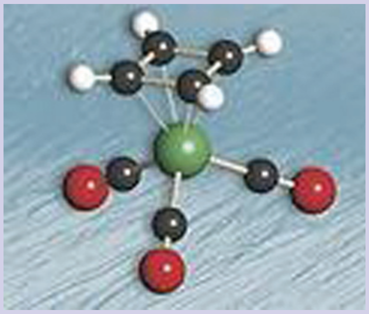
Fall of Vitalism

A major turning point in chemistry was the refutation of the long held 'vital force' theory to explain existence of organic compounds. Till the early 19th century, scientists commonly believed that there were two classes of chemical substances – those produced by non-living environment and those produced by living organisms.

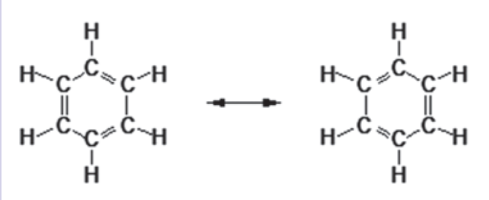
In 1807, Swedish chemist Jons Jacob Berzelius suggested that substances like olive oil or sugar, the characteristic products of living organisms, be called organic. Substances like water or salt, characteristic of the non-living environment, were inorganic. A significant observation that seemed to corroborate Berzelius's point of view was that organic



Robert Burns Woodward, who showed that natural products could be synthesised by careful applications of the principles of physical organic chemistry, and by meticulous planning



The resonant structures of benzene, as proposed by Kekulé



Chemistry is all about the nature of all matter around us – air, water, metals, plastics, drugs, everything – about how they behave, how they react, and how they change. It is about changing one kind of material into another.

substances could be easily converted, by heating or other harsh treatment, into inorganic substances. But no one knew of the reverse change – of an inorganic substance turning into an organic one.

Chemists who believed in vitalism predicted that organic materials could not be synthesised from inorganic components. It was commonly believed that organic substances required the vital force, found only in living beings. Chemists working with ordinary substances and techniques and without being able to manipulate a vital force in their test tubes could not bring about this conversion.

But this belief was overturned by a single experiment in1828, when German chemist Friedrich Wohler, who had been a pupil of Berzelius, accidentally converted the inorganic salt ammonium cyanate into a purely organic compound urea by simple heating. Actually Wohler was trying to synthesise ammonium cyanate by heating various combinations of cyanates of silver, lead and mercury, and ammonium salts. In the course of the heating, Wohler discovered formation of crystals resembling those of urea, a waste product eliminated in considerable quantity in the urine of many animals, including humans. Closer study showed the crystals were undoubtedly urea, which was, of course, clearly an organic compound. In the reaction ammonium cyanate appeared only as an intermediate before being transformed into urea. Remarkable as the finding was, this synthesis was a landmark in the history of science which disproved and undermined the vital force theory that held sway for centuries, by showing that organic compounds could be synthesised from inorganic materials.

Other similar successes followed Wohler's work. In 1847 German chemist Hermann Kolbe synthesised acetic acid from inorganic compounds for the first time. This reaction sequence consisted of chlorination of carbon disulfide to carbon tetrachloride, followed by pyrolysis to tetrachloroethylene and aqueous chlorination to trichloroacetic acid, which was subsequently electrolytically reduced to acetic acid.

Carrying matters further, the French chemist Pierre Eugene Marcelin Berthelot went about synthesising organic compounds systematically, turning them out in scores during the 1850s. These included such well-known compounds as methyl alcohol, ethyl alcohol, methane, benzene, and acetylene. With Berthelot, crossing the line from inorganic to organic ceased to be a thrilling intrusion upon the "forbidden", and became purely routine.

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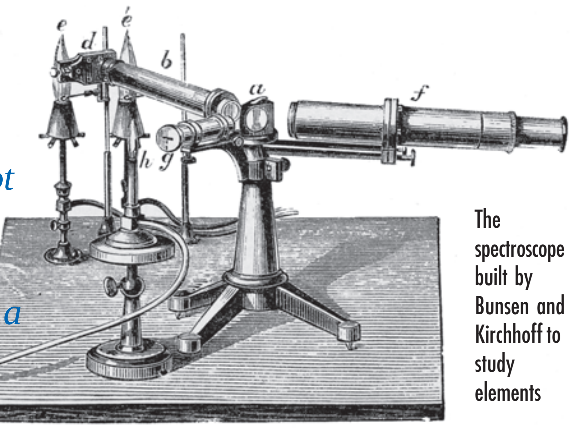

The spectroscope built by Bunsen and Kirchhoff to study elements

Kekule's Snake and Benzene Structure

The empirical formula for benzene was long known, but its highly polyunsaturated structure, with just one hydrogen atom for each carbon atom, presented a serious challenge for chemists. They could not think of any conventional structure that could account for all the carbon bonds in benzene. Then, in 1865, German chemist Friedrich August Kekulé brought in a revolution in structural chemistry by suggesting that the benzene structure contained a six-membered 'ring' of carbon atoms with alternating single and double bonds. (Kekule is said to have stumbled upon the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail!)

Kekulé was the principal formulator of the theory of chemical structure, which arose out the idea of atomic valence, especially the tetravalence of carbon (which Kekulé had announced late in 1857)

TABELLE II

REIHEN	GRUPPE I. — R^2O	GRUPPE II. — RO	GRUPPE III. — R^2O^3	GRUPPE IV. RH^4 RO^2	GRUPPE V. RH^3 R^2O^5	GRUPPE VI. RH^2 RO^3	GRUPPE VII. RH R^2O^7	GRUPPE VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev's 1872 periodic table. The spaces marked with blank lines represent elements that Mendeleev deduced existed but were unknown at the time, so he left places for them in the table. The symbols at the top of the columns are molecular formulas written in the style of the 19th century.

and the ability of carbon atoms to link to each other (announced in a paper published in May 1858). For organic chemists, the theory of structure provided a new clarity of understanding, and proved to be of immense help for both analytical and synthetic work. As a result of these developments, the field of organic chemistry developed rapidly from this point.

Tools of Chemistry

Development of analytical tools played a major role in the advancement of chemistry. In 1859 German chemists Robert Bunsen and Gustav Kirchhoff invented the spectroscope with which they discovered two alkali metals, caesium and rubidium. These discoveries ushered in a new era in the means used to find new elements. The first 50 elements discovered – beyond those known since ancient times – were either the products of chemical reactions or were released by electrolysis.

But following the invention of the spectroscope, the search was on for trace elements detectable only with the help of specialised instruments like the spectroscope. The spectroscope also made it possible for astronomers to learn about the composition of the Sun and the stars. In fact, the element helium was first detected on the Sun using spectroscopy long before it was discovered on Earth.

One of the most powerful tools for structure determination of complex molecules is X-ray diffraction, the brainchild of a young English physicist. In the autumn of 1912, William Lawrence Bragg, who was 22 years old, realised that X-rays could be used to detect the arrangement of individual atoms inside solid crystals. With his father's help he created a new science of X-ray crystallography. For his insight, Lawrence Bragg became the youngest ever Nobel Laureate in 1915.

X-ray crystallography opened up a whole new world of atoms and molecules. The technique led to a better understanding of chemical bonds and non-covalent interactions. The initial studies revealed the typical radii of atoms, and confirmed many theoretical models of chemical bonding, such as the tetrahedral bonding of carbon in the diamond structure. X-ray crystallographic studies have also led to the discovery of even more exotic types of bonding in inorganic chemistry, such as metal-metal double bonds, metal-metal quadruple bonds, and three-centre, two-electron bonds.

Since the 1920s, X-ray diffraction has been the principal method for determining the arrangement of atoms in not only large organic molecules but also minerals and metals. In 1953, it was through the study of X-ray diffraction patterns that American molecular biologist James Watson and English molecular biologist Francis Crick could unravel the molecular structure of DNA – the carrier of genetic information in all living beings – that ushered in the modern age of biotechnology and recombinant DNA technology. For this work Watson and Crick were jointly awarded the Nobel Prize for Physiology or Medicine for 1962.

Chemical Synthesis

One of the things that make chemistry unique among the sciences is chemical synthesis, which is actually the purposeful execution of chemical reactions to get a product, or several products. Using various techniques of chemical synthesis, chemists create things, new pharmaceuticals, food additives, materials, agricultural chemicals, coatings, adhesives, and all sorts of useful new molecules. They prepare them from simpler, more readily available starting materials.

The chemical synthesis of complex organic molecules is integral to many advances that enhance the quality of life, such as novel pharmaceuticals, agrochemicals without harmful environmental impact, and advanced materials for high-performance technology. In the total synthesis of a complex product it may take multiple steps to synthesise the product of interest, and inordinate amounts of time.

Skill in organic synthesis is prized among chemists and the synthesis of exceptionally valuable or difficult compounds has won chemists such as American organic chemist Robert Burns Woodward the Nobel Prize for Chemistry. Woodward is credited with synthesising many complex natural products including quinine, cholesterol, cortisone, strychnine, lysergic acid, reserpine, chlorophyll, cephalosporin, and colchicine. With these, Woodward opened up a new era of synthesis, sometimes called the 'Woodwardian era' in which he showed that natural products could be synthesised by careful applications of the principles of physical organic chemistry, and by meticulous planning.

Chemists who believed in vitalism predicted that organic materials could not be synthesised from inorganic components.

Despite the past achievements, there still remains a lot to explore and discover in chemistry. Novel molecules like fullerenes, graphene, and many others offer ample scope of research and development, which any talented student can take up as a challenge.

Why Learning Chemistry is Important

Apart from its multifarious involvement in our daily life, chemistry is so deeply ingrained in so many areas of business, government, industry, and environmental management that some background in the subject can be useful in fields as varied as product development, marketing, management, computer science, technical writing, and even law.

Everyone can and should understand basic chemistry, and it would be worthwhile to take a course in chemistry or even make a career out of it. It is important to understand chemistry if one is studying any of the sciences because all of the sciences involve matter and the interactions between types of matter. Apart from those wanting to become chemists, students wanting to become doctors, nurses, physicists, nutritionists, geologists, and pharmacists all need to study chemistry.

It is important to remember that the importance of chemistry would not be diminished over time; rather it will continue to remain a promising career prospect.

Mr Biman Basu was editor of *Science Reporter* for more than 30 years. Winner of the 1994 NCSTC National Award for best science and technology coverage in the mass media, Mr Basu has been involved in science communication through his popular science writings, radio talks and popular lectures for more than four decades. A prolific writer on a wide range of S&T topics, Mr Basu has to his credit more than 1,000 popular science articles and over 500 radio talks and features. He has also written about 30 popular science books, many of which have been reprinted several times.

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