# WHERE WOULD WE BE WITHOUT CHEMISTRY?*

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This year sees the world celebrating the International Year of Chemistry. The celebrations are wholly justified because chemistry is hugely important for all of us, wherever we live. If you were to strip away all the contributions of chemistry to the modern world, you would find yourself back in the stone age, life would be short and painful, you would be underfed, there would be little colour in the world, you would be dressed in skins and surrounded by few of the appliances that entertain us and ease our lives. I will admit from the outset that chemistry, like any great enterprise, does cause problems. It is used to make the explosives used in armaments. It creates poisons and the effluents of chemistry plants can ruin the environment. In some dreadful cases, accidents have killed and maimed thousands. The explosion at the Union Carbide Plant in Bhopal in India in 1984 blighted thousands of innocent lives and the terrible consequences are still with us today. Pollution of water and air has wrought havoc with our surroundings. These disadvantages and horrors have to be acknowledged — but all technological and scientific advances bring difficulties in their train. We should weigh them against the advantages. With some exceptions, the chemical industry is well aware of its obligations to humanity and environment and does what it can to avoid the potentially damaging effects of its activities. In this article, I shall concentrate on the positive contributions that chemistry makes to the modern world and leave you to judge whether the price is too high.

Chemistry is the science of matter and the changes that matter can undergo. In the broadest possible terms, chemists take one form of matter and conjure from it a different form. In some cases, they take raw material from the Earth, such as oil or ores, and produce materials directly from them, such as petroleum fuels and iron for steel. They might harvest the skies, taking the nitrogen of the atmosphere and converting it into fertiliser. In many cases, they take more sophisticated forms of matter and convert it into materials suitable for use as fabrics or as the substances needed for high technology.

## Communal Living is Possible:Thanks to Chemistry

Take water, for instance, the absolutely essential enabler of life. Chemistry has made communal living possible by purifying water and ridding it of

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pathogens. Chlorine is the principal agent enabling cities to exist: without it, disease would be rampant and urban living a gamble. Chemists have found ways of extracting this element from an abundant source: sodium chloride, common salt. Are there other ways, though? Can future chemists (of which you the reader might be one, or encouraging your students to pursue the study of chemistry) find ways of rendering urban life possible without the environmental disadvantages of using chlorine? Its replacement is highly desirable because chlorine is a dangerous and untrustworthy ally: although, through its potent chemical reactivity, it purifies water, that same reactivity means that it attacks other compounds and, for instance, enters the food chain as dioxins and related compounds. These compounds can attack the nervous system and accumulate in body fat. Chlorine and its compounds also rise high in the atmosphere where they contribute to the destruction of ozone and the formation of acid rain.

The application of a spray-applied membrane designed by BASF on the interior walls of a tunnel being built in the United Kingdom reduces the amount of concrete required, saving millions of euros in construction costs and reducing $CO_2$ emissions from cement-making

Chemists are at the forefront of the battle to obtain potable water from brackish water, from poisoned water in aquifers, such as the arsenic-laden water from deep aquifers in Bangladesh, and from that most abundant source of all, the oceans, by using water desalination plants. Chemists have contributed in direct ways to this crucial task by developing reverse osmosis, a process in which pressure is applied to brackish water to drive it through a filtering membrane, thereby rendering it potable. Chemists have also contributed in indirect ways by developing the membranes that contribute to the efficiency of the process by reducing its energy demands and increasing the lifetime and effectiveness of the membrane. It goes without saying that chemists' traditional skills of analysis — discovering what is present in it, what can be tolerated and what essential element should be removed to trigger the desired reaction — are crucial to this endeavour.

## How the Search for Explosives Spawned a Green Revolution

Then there is food. As the global population grows and the productive land area is eroded, so it becomes more and more important to coax crops into greater abundance. The traditional way to encourage abundance is to apply fertilisers. Here, chemists have contributed nobly by finding sources of nitrogen and phosphorus and ensuring that these can be assimilated by plants. Genetic engineering is another exciting way to proceed but remains controversial because of the fears of some as to the consequences of interfering with inheritable factors and the possibility of uncontrolled transfer into other species. Genetically modified food, though, can reduce the need for chemical pesticides, be resistant to viral infection and drought and can, like natural breeding, result in more abundant yields rich in desirable components. The introduction of golden rice, which includes genes from yellow daffodils to provide a high concentration of precursors of vitamin A, might help millions of people throughout Africa and Southeast Asia who suffer from vitamin A deficiency, responsible for millions of deaths and thousands of cases of irreversible blindness.

Nitrogen is astonishingly abundant, making up nearly three-quarters of the atmosphere, but it is there in a form that cannot be assimilated by most plants. One of chemistry's greatest achievements, made in the opening years of the twentieth century under the impetus not of a humane desire to feed but of an inhumane desire to kill, was to discover how to harvest nitrogen from the air and turn it into a form that could be absorbed by crops. The original impetus was the need to replace the natural source of nitrogen, nitrates mined in arid regions of Chile, by far more abundant and reliable supplies that at the time of the First World War (1914–1918) were needed for the manufacture of explosives. The development in Germany of an effective, economical process for converting non-reactive gaseous nitrogen into a reactive form by the German chemist Fritz Haber and his compatriot the chemical engineer Carl Bosch initially in 1909 and on an industrial scale in 1913 was a landmark achievement for the chemical industry, for as well as depending on the discovery of appropriate catalysts, the production of fertiliser required the development of an industrial plant that operated at temperatures and pressures never previously attained.

Rice farmer in China. The introduction of golden rice might help millions of people throughout Africa and Southeast Asia who suffer from vitamin A deficiency.

The discovery of reactive nitrogen revolutionised agriculture in the twentieth century by permitting more abundant yields. But the process remains energy-intensive. It would be wonderful if the processes known to occur in certain bacteria associated with the root systems of leguminous plants, such as clover, alfalfa and peanuts, could be emulated on an industrial scale to harvest nitrogen. In the natural process, nitrogen is released, in a usable form, when the plant dies and so becomes available to other plants. This is the basis for crop rotation in traditional farming practice and the emulation of traditional methods in organic farming. Chemists have invested decades of research into this possibility, dissecting in detail the enzymes that bacteria use in their quiet and energy-efficient, low-pressure, low-temperature way. There are glimmerings of success but if you want to go down in history as the chemist who cracked the problem of feeding the world, here is your opportunity.

## Recycling the Dead to Feed the Living

Phosphorus is abundant too, being the remains of prehistoric animals. Their bones of calcium phosphate and their special internal power source– the molecules of adenosine triphosphate (ATP) that powered everyone of their cells – lie in great compressed heaps below the oceans and the continents of the world. The most important use of phosphorus is for the production of fertilisers – derived from phosphate rock. Most of the world's phosphate rock reserves are concentrated in Morocco. Taken together, China and Morocco alone count 91 per cent of the world's reserves. Thus, by turning fossilised animals into fertiliser, chemists help to recycle the dead to feed the living.

In a scene imagined by palaeo-artist Peter Trusler, a dinosaur lies dying about 110 million years ago when the South Pole enjoyed a more clement climate. If the body of this Leaellynasaura amicagraphica is rapidly covered by sediments, it may fossilise, thereby trapping phosphorus in its bones in the form of phosphate rock

## Without Energy, Civilisations would Collapse

After water and food, we need energy. Nothing happens in the world without energy. Civilisations would collapse if it ceased to be available. Civilisations advance by deploying energy in ever greater abundance. Chemists contribute at all levels and to all aspects of developing both new sources and more efficient applications of current sources.

Petroleum is one of the legacies of the past, being the partially decomposed residue of organic matter, such as plankton and algae, that sank to the bottom of lakes and seas and was later subjected to heat and pressure. It is, of course, an extraordinarily convenient source of energy, as it can be transported easily, even in weight-sensitive aircraft. Chemists have long contributed to the refinement of the raw material squeezed and pumped from the ground. They have developed processes and catalysts that have taken the molecules provided by nature, cut them into more volatile fragments and reshaped them so that they burn more efficiently.

But burning nature's underground bounty might be seen by future generations as the wanton destruction of an invaluable resource. It is also finite and, although new sources of petroleum are forever being discovered, for the time being at least, they are proving hazardous and increasingly expensive. We have to accept that, although the empty Earth is decayed off, one day it will arrive. Chemists will need to contribute to the development of new sources of energy. Young people entering the profession today will find that they have great opportunities to make an impact on the future well-being of the world and its populations.

Where do chemists currently look for new sources? The Sun is an obvious source and the capture of its energy that nature has adopted, namely photosynthesis, an obvious model to try to emulate. Chemists have already developed moderately efficient photovoltaic materials and continue to improve their efficiency. Nature, with her four-billion year start on laboratory chemists, has already developed a highly efficient system based on chlorophyll. Although the principal features of the process are understood, a challenge for current chemists and perhaps future chemists like yourself will be to take nature's model and adapt it to an industrial scale. One route is to use sunlight to split water ($H_2O$) into its component elements and to pipe or pump the hydrogen to where it can be burned.

I say 'burned'. Chemists know that there are more subtle and efficient ways of using the energy that hydrogen and hydrocarbons represent than igniting them, capturing the energy released as heat and using that heat in a mechanical, inefficient engine or electrical generator. Electrochemistry, the use of chemical reactions to generate electricity and the use of electricity to bring about chemical change, is potentially of huge importance to the world. Chemists have already helped to produce the mobile sources, the batteries, that drive our small portable devices,

Solar panels on the roof of a sports stadium in the Spanish town of Baeza

such as lamps, music players, laptops, telephones, monitoring devices of all kinds and, increasingly, our cars.

Chemists are deeply involved in collaboration with engineers in the development of fuel cells on all scales, from driving laptops to powering entire homes and conceivably villages. In a fuel cell, electricity is generated by allowing chemical reactions to dump and extract electrons into and from conducting surfaces while fuel, either hydrogen or hydrocarbons, is supplied from outside. The viability of a fuel cell depends crucially on the nature of the surfaces where the reactions take place and the medium in which they are immersed. Here is another branch of chemistry where you, the reader, perhaps the aspiring chemist, could make a profound difference to the future of your country and the world.

Even nuclear power, both fission and one day fusion, the emulation on Earth of the Sun, depends on the skills of chemists. The construction of nuclear reactors for nuclear fission depends on the availability of new materials. The extraction of nuclear fuel in the form of uranium and its oxides from its ores involves chemistry.

Everyone knows that one fear holding back the development and public acceptance of nuclear energy, apart from political and economic concerns, is the problem of how to dispose off the radioactive spent fuel. Chemists contribute by finding ways to extract useful isotopes[1] from nuclear waste and by finding ways to ensure that it does not enter the environment and become a hazard for centuries to come. If you could collaborate with nuclear engineers to solve this problem, the world might take a more relaxed view about the perils of nuclear power and give a breathing space for the less hazardous nuclear fusion to be developed.

Nuclear fusion depends on smashing isotopes of hydrogen together and capturing the energy released as they merge to form helium, as happens on the Sun. The challenge is to achieve high temperatures because only then do the nuclei smash together with sufficient force to overcome their electrical repulsion – and to avoid the entire apparatus melting. The major nuclear fusion research effort taking place in France, known as the International Thermonuclear Experimental Reactor (ITER) project (*iter* is Latin for 'the way'), involves international collaboration on an unprecedented scale, involving countries representing half the world's population.

## Plastics from Oil

I have alluded to the seemingly wanton destruction of an invaluable resource when the complex organic mixture we know as oil is sucked from the ground where it has lain for millennia then casually burned. Of course, not all the oil goes through the exhausts of our cars, trucks, trains and aircraft. Much is extracted and used as the head of an awesome chain of reactions that chemists have developed which constitute the petrochemicals industry.

Look around you and identify what chemists have achieved by taking the black, viscous crude oil that emerges from the Earth, subjecting it the reactions that they have developed and passing on the products to the manufacturers of the artefacts of the modern world.

An assortment of everday household items. One urgent challenge chemists face is to reduce the time it takes for plastics, aluminium cans and the like to biodegrade

1. Each element has a given number of protons. Isotopes of an element share the same number of protons but the number of neutrons may change. Carbon 12, Carbon 13 and Carbon 14, for example, are three isotopes of carbon. The atomic number of the element always remains the same; in the case of carbon, it is six, as each carbon atom has six protons.

Perhaps, the greatest impact of these processes has been the development of plastics. A century ago, the everyday world was metallic, ceramic or natural, with objects built from wood, wool, cotton and silk. Today, an abundance of objects are built from synthetics derived from oil. Our fabrics have been spun from materials developed by chemists, we travel carting bags and cases formed from synthetics. Our electronic equipment like televisions, telephones and laptops are all moulded from synthetics. Our vehicles are increasingly fabricated from synthetics. Even the look and feel of the world is now different from what it was a hundred years ago: touch an object today and its texture will be typically that of a synthetic material. For this transformation, we are indebted to chemists. Even if you mourn the passing of many natural materials, you can still thank chemists for their preservation where they are still employed. Natural matter rots but chemists have developed materials that postpone decay. For instance, new wood preservatives, typically based on copper, have been developed to avoid problems with the old preservatives leaching into the soil and poisoning it with arsenic, copper and chromium.

## Lighter Cars, Molecular Computers and Intelligent Clothing

Plastics are but one face of the materials revolution that has characterised the last one hundred years and is continuing vigorously today. Chemists develop the ceramics that are beginning to replace the metals that we use in vehicles, lightening them and thereby increasing the efficiency of our transport systems. Ceramics are already used in the exhaust manifolds of some high performance cars and experiments have been conducted on replacing the entire engine block with ceramics. The car engine's cooling system has been simplified and its weight lessened because today's engines can withstand high temperatures. There remain problems with fabrication and crack-resistance, which you might be able to help to solve. Chemists are also responsible for developing the semiconductors that underlie the modern world of communications and computation. Indeed, one of the principal contributions of chemistry is currently the

Thai monk with a laptop. Chemists collaborate with engineers to develop the fuel cells that drive laptops

development of what could be regarded as the material infrastructure of the digital world. Chemists develop the semiconductors that lie at the heart of computation and the optical fibres that are increasingly replacing copper for the transmission of signals. The displays that act as interfaces with the human visual system are a result of the development of materials by chemists.

Currently, chemists are developing molecular computers, where switches and memories are based on changes in the shape of molecules. The successful development of such materials – with the optimism so typical of science, we can be confident that this endeavour will be successful – will result in an unprecedented increase in computational power and an astonishing compactness. If you are interested in the development of such smart materials, you can expect to contribute to a revolution in computation. There is also the prospect of the development of quantum computing. This will depend on chemists being able to develop appropriate new materials and result in a revolution in communication and computation that defies the imagination.

A model on the catwalk at a fashion show promoting Central Asian designs. Modern fabrics are heavily dependent on chemistry

Modern fabrics depend crucially on the contributions of chemistry. Take away those contributions and we are left almost naked, cold and drab. Even traditional dyes, such as those used in Javanese batik and Indian block-printing, are chemicals that have been extracted from plants and applied to fabrics. Modern fabrics include polyesters, nylon and polyamides. However, chemistry makes more subtle contributions than providing the material itself. It contributes to flame retardants by incorporating typically bromine compounds into the fabric. Modern developments include incorporating nanomaterials into fabrics to prolong their resistance to chafing, introducing resistance to bacteria and suppressing wrinkling. We are on the edge of even more exciting developments to which you might contribute: e-textiles (so called 'intelligent clothing') are being developed with embedded electronic capabilities, the ability to change colour, with swirling, changing, patterns (and advertisements!) that reflect our mood. Such textiles will be able to adjust their thermal properties to the ambient conditions and, let's hope, be self-cleaning.

This nineteenth century patient has been given nitrous oxide ($N_2O$) to dumb the pain of having a tooth extracted. Also known as laughing gas, nitrous oxide was identified as an anaesthetic in 1772 by the English Chemist Joseph Priestly

## Agents Against Disease: Pharmaceutical Companies

I have barely mentioned health. One of the great contributions of chemistry to human civilisation –and, it must be added, to the welfare of our herds – has been the development of pharmaceuticals. Chemists can be justly proud of their contribution to the development of agents against disease. Perhaps, their most welcome contribution has been the development of anaesthetics in the late nineteenth and early twentieth centuries and the consequent amelioration of the prospect of pain. Think of undergoing an amputation two hundred years ago, with only brandy and gritted teeth to sustain you! Some of the anaesthetics currently used, such as procaine, have been developed by chemists to avoid adverse side-effects, including addiction, that accompanied the use of materials derived from traditional medicine, such as cocaine obtained from Peruvian coca. Next in importance has been the development by chemists of antibiotics, often by observing nature closely. A century ago, bacterial infection was a deadly prospect; now it is curable. We have to hope that it remains that way but, we still need to prepare for the opposite.

The pharmaceutical companies often come under attack for what many regard as their profligate profits and exploitation but they deserve cautious sympathy. Their underlying motive is the admirable aim of reducing human suffering by developing drugs that combat disease. Chemists are at the heart of this endeavour. It is highly regrettable that drug development can be so expensive. Modern computational techniques are helping in the search for new lines of approach and to reduce reliance on animal testing. However, extraordinary care needs to be exercised when introducing foreign materials into living bodies and years of costly research can suddenly be trashed if, at the last stage of testing, unacceptable consequences are discovered. Your involvement in the industry one day might transform it in a manner we cannot yet foresee and you might become one of the proud chemists who have contributed to save millions of lives.

## How Biology Became Chemistry 50 Years Ago

Closely allied with the contribution of chemists to the alleviation of disease is their involvement at a molecular level, biology became chemistry just over 50 years ago when the double helix structure of DNA was discovered. Molecular biology, which in large measure has sprung from that discovery, is chemistry applied to organisms. Chemists, often disguised as molecular biologists, have opened the door to understand life and its principal characteristic, inheritance, at a most fundamental level and have thereby opened up great regions of the molecular world to rational investigation. They have also transformed forensic medicine, brought criminals to justice and transformed anthropology by tracing ethnic origins and ancestry.

The shift of chemistry's attention to the processes of life has come at a time when the traditional branches of chemistry – organic, inorganic and physical – have reached a stage of considerable maturity and are ready to tackle the awesomely complex network of processes going on inside organisms, human bodies in particular. The approach to treat disease – and more importantly to prevent it – has been put on a rational basis by the discoveries that chemists continue to make. If you plan to enter this field, genomics (the study of the genome of organisms) and proteomics (the study of the panoply of proteins that spring from the genome) will turn out to be of crucial importance to your work because they help to put the treatment of disease on a rational basis and relate it directly to the individual. This is truly a region of chemistry where you can feel confident about standing on the shoulders of the giants who have preceded you and know that you are attacking disease at its roots.

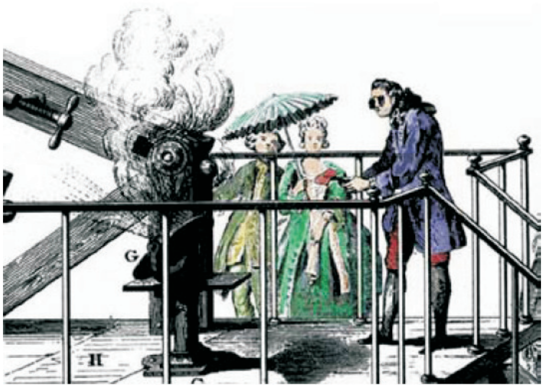
## Magicians of Matter

I have focussed on a few of the achievements of applied chemistry, for they are the tangible outcome of the labours of myriad working chemists over the ages and, it must be said with some caution, the Alchemists. Even though Alchemists were misguided in their efforts to turn base metals into gold, through their experiments they nevertheless acquired familiarity with matter and the transformations it can undergo.

Muhammad ibn Zakariya ar-Razi (865–925) was a Persian Alchemist, chemist, physician and philosopher. Many firsts are attributed to him, including that of writing the first book on paediatrics. He was also the first to discover sulphuric acid, after perfecting the methods of distillation and extraction, as well as numerous other chemicals and compounds, including kerosene, alcohol and ethanol

Professor Tebello Nyokong in her laboratory in the Department of Chemistry at Rhodes University of South Africa. One of the five L'OREAL–UNESCO laureates in 2009, she earned the award for her research on chemical compounds known as phthalocyanine dyes. These could be used to attack cancerous tissues in a procedure that would be less intrusive than chemotherapy. Activated by exposure to a red laser beam, the dyes are used to target cancerous tissues selectively. With her in the laboratory are Wu Xi, an exchange student from China, and Taofeek Ogunbayo, a South African Ph.D. student

There is, however, another aspect of chemistry that should not go unnoticed and which, for many, is its justification. Chemistry provides insight into matter and the workings of the material world. It is thus a deeply cultural pursuit: it is fitting that, in the light of UNESCO's support




Antoine Lavoisier (1743–1794) experimenting a combustion engine that focussed sunlight over flammable materials. The French chemist determined that water was composed of oxygen and hydrogen and that the air was a mixture of primarily nitrogen and oxygen. He was guillotined at the height of the French Revolution

of the International Year of Chemistry, chemistry should at the same time be educational, scientific and cultural. Chemistry opens our inner eye to the properties and behaviour of matter. Moreover, it is a truly transnational and transcultural activity, with advances built on contributions from almost every country in the world.

Chemists like Englishman John Dalton (1766–1844) brought the existence of atoms and molecules to our attention and their descendents have shown us how to relate those entities to what we observe. Although we can take pleasure from merely looking at the vibrant colour of a flower, through chemistry we can perceive the molecular origin of the colour and thus deepen our delight.

The early chemists began to understand why one substance reacted with another but not with something else. Their descendents have discovered the motive power of chemical change and have thereby opened our understanding of why anything happens in the world. We understand what drives the world forward, why crops grow, why we live and die and why anything happens at all.

Much remains to be done, of course. Although the fundamental principles of chemistry are now well-established, their application remains as challenging and vigorously pursued as ever. Chemistry lets us plumb the depths of matter, enabling chemists on Earth to fabricate subtle arrangements of atoms that might not exist anywhere else in the Universe and which possess properties that are exquisitely tuned for a hitherto unforeseen application. If you are or intend to become a chemist, then you will become a magician with matter, able to conjure unexpected or intended new forms from what surrounds us. But you will not be an actual magician: you will be a rational, understanding manipulator, an architect on the scale of molecules.

The International Year of Chemistry is rightly a celebration of the transformation of the world and the lives of its inhabitants. It rightly celebrates current achievements, the impact of chemistry on people everywhere and its advancement by collaboration throughout the world. It also rightly anticipates its putative contributions to the unforeseen new world yet to come.