Edited by Javier Garcia-Martinez
and Elena Serrano-Torregrosa

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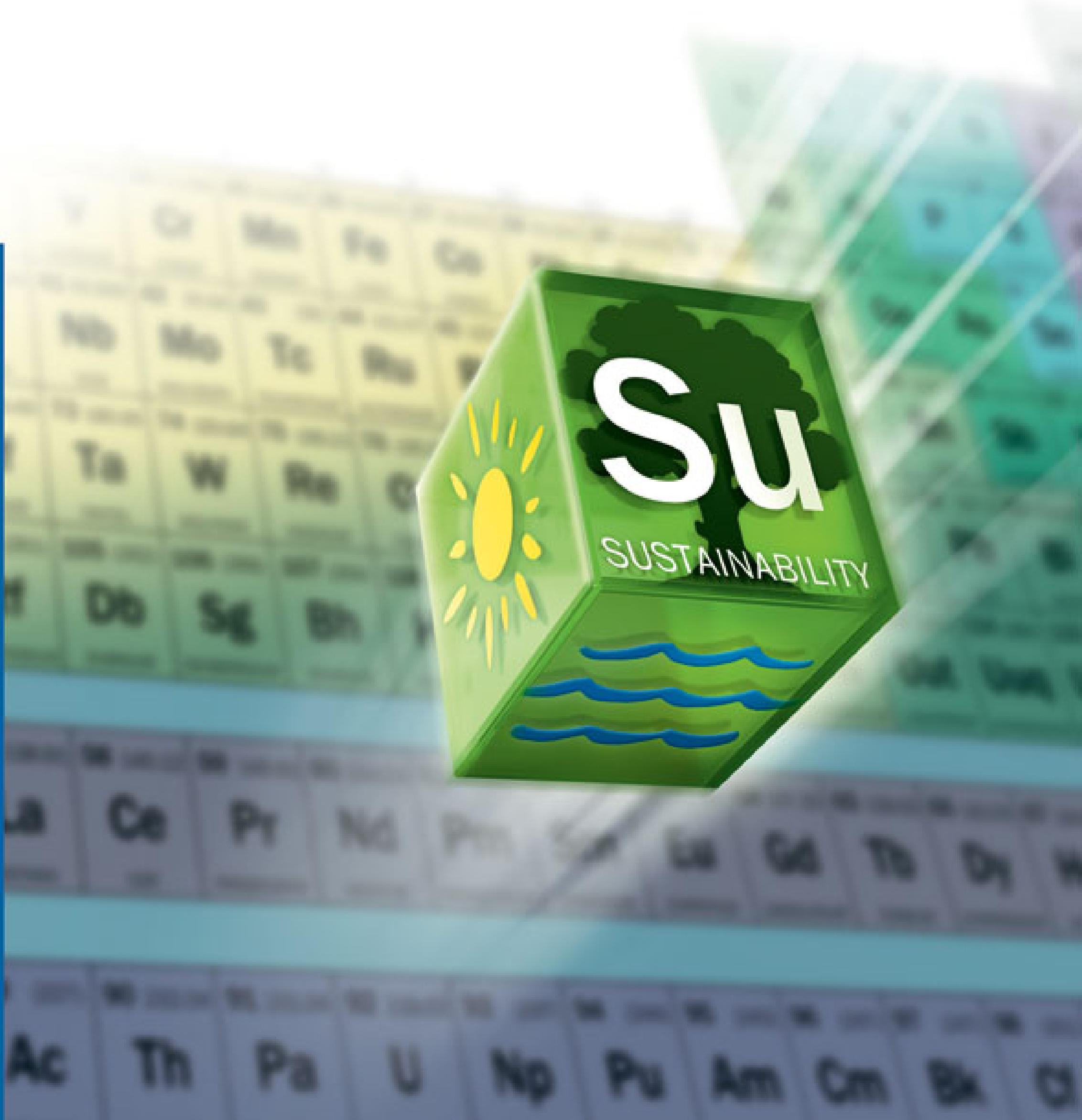
The Chemical Element

Chemistry's Contribution to Our Global Future



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The Chemical Element

Chemistry's Contribution to Our Global Future

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The Chemical Element: Chemistry's Contribution to Our Global Future

Every year several books are published dealing with chemistry, but this book is different and takes the reader far from the expected esoteric and academic chemistry to a chemistry that embraces our continuing existence on planet Earth. By placing chemistry at the centre of challenges and solutions for our planet, it provides a much-needed perspective on the role and importance of science for development and demonstrates the critical linkage between research in chemistry, policy, industry, education and concrete actions for sustainable development. The book is inspired by the United Nations declaration of 2011 as the International Year of Chemistry (IYC), and clearly spells out the role and importance of chemistry for meeting the United Nations Millennium Development Goals.

The International Union of Pure and Applied Chemistry (IUPAC) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO) were designated by the United Nations General Assembly as lead agencies for promoting and coordinating the IYC. The objectives of the Year are to:

- increase the public appreciation and understanding of chemistry in meeting world needs,
- encourage the interest of young people in chemistry,
- generate enthusiasm for the creative future of chemistry,
- celebrate the role of women in chemistry or major historical events in chemistry, including the centenaries of Mme. Curie's Nobel Prize and the founding of the International Association of Chemical Societies.

Through the Year, the world is celebrating the art and science of chemistry, and its essential contributions to knowledge, environmental protection, improvement of health and economic development. The critical over-arching need in this context is for the responsible and ethical use of chemical research, and its applications and innovations, for equitable sustainable development.

In January 2011, the official launch of the IYC took place at UNESCO Headquarters in Paris. This meeting set the themes for the Year by associating "chemistry" with the words "progress of civilization, solutions for global challenges, climate change, creating a sustainable future, nutrition, food production, water, health and disease, global health, energy solutions for the future, materials of tomorrow, economic and social aspects . . .". The chapters of this book mirror these themes and present the reader with a comprehensive view of what "chemistry" means for our lives and our futures.

This book is therefore to be highly recommended to a wide readership including individuals concerned for sustainable development, politicians, young people, scientists, teachers, and global strategists. It is a must for every chemist who can use it as a tool in teaching students or in informing non-scientists about the possibilities of this fundamental science. Most of all, we hope that this book will be used to show young people that "chemistry" is exciting and meaningful, and that many will be enticed and inspired to take up careers in this field of scientific endeavour.

We congratulate the editors and authors of this marvelous book, published specially as part of the celebration of the IYC.

Nicole Moreau
President, IUPAC

Julia Hasler
UNESCO Focal Point for IYC

Contents

Introduction

"*The future of humanity is uncertain, even in the most prosperous countries, and the quality of life deteriorates; and yet I believe that what is being discovered about the infinitely large and infinitely small is sufficient to absolve this end of the century and millennium*", wrote Primo Levi in his essay "News from the Sky". The challenge now is to apply all that knowledge to secure the future of humanity, improve our quality of life and tackle the challenges we have been facing for millennia.

With this aim, 192 heads of state and government joined in 2000 to agree on eight very specific and achievable goals, known as the Millennium Development Goals (MDG). *"Time is short. We must seize this historic moment to act responsibly and decisively for the common good"*, reminded United Nations Secretary-General Ban Ki-moon. Only four years before the deadline we gave ourselves to achieve these goals, the United Nations has declared 2011 as the International Year of Chemistry (IYC), which aims to "*overcome the challenges facing today's world, for example in helping to address the United Nations Millennium Goals*."

This book is a celebration of the many contributions of chemistry to our wellbeing, coinciding with the IYC, and also a roadmap of the tools we have at our finger tips to make a significant contribution to the lives of those who are not benefiting from the technological advances of our time. We try to provide at the same time a comprehensive review of the current status of some critical issues and a description of the technological possibilities we have today to overcome some of our most urgent needs. Our generation is the first one that has the financial resources and technological tools to significantly mitigate the suffering that many are sentenced to, from hunger to curable diseases, from unsafe water, and polluted air to poverty.

This book is divided into nine chapters that represent the biggest and most urgent challenges of our time in which chemistry can provide a significant contribution. Because of the scope and aim of this book, the authors are leaders in their fields and a broad representation of what chemistry is today. In general, each chapter covers one MDG by recognizing the present and future contributions of chemistry to this MDG. The chapters are excellent reviews of the current state of the subject, from the point of view of the world leaders in each field, but above all, a glimpse into the future.

Chapter 1, written by scientists of the International Organization for Chemical Sciences in Development (IOCD), summarizes the scope of the book by highlighting the possible state-of-the-art contributions of chemistry to human advancement through the classification of the MDG. Chemistry's contributions to human advancement include benefits in the health, agricultural and industrial sectors of developing countries, thereby improving the quality of life for the vast majority of people on the planet: food supply, medicines, construction materials, new jobs and clean water.

Chapters 2 and 3 are devoted to hunger and poverty, respectively. As mentioned in Chapter 1, the World Bank defines poverty in very crude terms: "*Poverty is hunger. Poverty is lack of shelter. Poverty is being sick and not being able to see a doctor. Poverty is not having access to school and not knowing how to read. Poverty is not having a job, is fear for the future, living one day at a time. Poverty is losing a child to illness brought about by unclean water. Poverty is powerlessness, lack of representation and freedom.*" These are major problems and chemistry can provide real solutions to every one of them, such as food even in poor soils using better fertilizers, shelters using more sustainable materials, new medicines for pandemic illnesses, and jobs and opportunities for many, as described in detail in these chapters.

Chemistry education's contribution to our global future, directly related to the second, seventh and eighth MDGs, is analyzed in Chapter 4. The central question of the chapter is focused on how scientists and citizens can do better in the decades following the IYC to answer the question: Has education about the nature and role of chemistry succeeded in creating the public climate needed to support the fundamental and applied research required to tackle these IYC global challenges?

The contribution of chemical science to health (fourth to sixth MDGs) is illustrated in Chapter 5. More specifically, the authors concentrate primarily on various aspects involved in drug discovery and development, as well as their research activities concerning the first commercial human synthetic vaccine against bacterial infections causing the death of more than half a million infants each year.

Chapter 6 is focused on green chemistry as a tool to integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources and reduce the biodiversity loss caused by the industries (seventh MDG).

Chapter 7, entitled Water: Foundation for a Sustainable Future, resumes the chemical contribution to water, as one of the principles of sustainable development ranging from poverty and health (Goals 1, 4–6) to environmental sustainability (Goal 7). Many of the MDGs are related to health and thus indirectly related to water and sanitation.

To quote Kofi Annan: *"For future scientific research to unleash the potential of life-changing technologies, the greatest challenge will be to provide clean and affordable energy to the poor"*. Chapter 8 provides a comprehensive and updated view of the many research activities for achieving energy security and sustainability and ending energy poverty. A significant burden on the shoulders of many nations is lack of enough energy to unleash their economic potential.

Chapter 9 deals with some of the most dramatic consequences of the bad applications of technologies that lead to ozone layer depletion and climate change. Whereas the former has been significantly mitigated by the use of alternative more benign solutions, climate change is one of the most serious threats to our well-being, safety and economic growth. Some of the solutions that are being investigated today to deal with CO_2 emissions, from reducing its production to its storage and reuse, are described by some of the leading experts in the field.

This book is intended to serve a very large audience interested in the roles of science and technology in global issues. For helping with new concepts, the book includes boxes with simple and concise explanations of key ideas and multiple examples, tables and figures.

What we managed to achieve so far is truly amazing, for example, turning air into bread by reacting nitrogen with hydrogen to produce ammonia and then fertilizers, which are responsible for the survival of 40% of our planet's human population. It is astonishing that approximately half of the nitrogen atoms in each human body have come at some point through the Haber–Bosch process. But there is much more waiting for us to be discovered. Only time will tell how human creativity and ingenuity will solve the problems we are facing. No doubt, this is an amazing endeavour worth taking.

Elena Serrano Torregrosa and Javier Garcia Martinez
Alicante (Spain), February 2011

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1
Chemistry for Development

Stephen A. Matlin and Berhanu M. Abegaz

1.1
Chemistry, Innovation and Impact

The foundations of modern chemistry were laid in the 18th and 19th centuries and further extended in the 20th century. They encompassed the development of a theoretical framework for understanding and explaining the physical and chemical properties of atoms and molecules, together with the invention of increasingly sophisticated techniques for interacting with these entities in order to study and influence their structures and behaviors. These developments have given humanity a degree of mastery over its physical environment that surpasses the sum of achievements over the entire previous period of human history.

Chemistry's contributions to human advancement need to be seen in terms of its own core role as a physical science, but also as a "platform science" in the context of its relationships within the group of "natural sciences" that includes physics and biology. Chemistry provides the basis for understanding the atomic and molecular aspects of these disciplines and, through its interfaces with a range of pure and applied sciences, underpins the dramatic advances seen in recent decades in such diverse fields as medicine, genetics, biotechnology, materials and energy. Hence, this discussion of the role of chemistry in the process of development is framed in the broader context of the roles of science, technology and innovation more generally.

Innovation, which may operate in both technological and social fields [1], encompasses not only the birth of an idea or a discovery, but its application in practice – taking the outputs of research and invention and using them to put new goods, services or processes into use. While innovation is sometimes represented as a straightforward linear system (Figure 1.1), in reality this is an over-simplified model and innovation needs to be treated as a complex, highly nonlinear ecosystem, full of interdependences and feedback loops.

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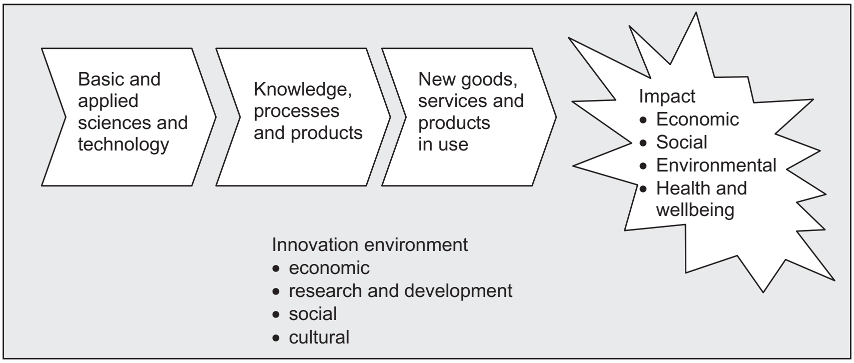

Figure 1.1 The chain of scientific innovation – from ideas to impact.

Chemistry may be involved not only in the initial stages of research (e.g., in areas such as agrochemicals and pharmaceuticals: chemical synthesis of new molecules for testing), but also in intermediate stages (e.g., product development, quality control) and in the evaluation of impact (e.g., health status assessment, environmental monitoring), thus contributing in key ways at every stage of the technological innovation chain.

Throughout the modern period of its development, chemistry has contributed enormously both to broad improvements in human wellbeing (including enhancements of health and quality of life) and to wealth creation for individuals and nations. Some landmark examples are summarized in Table 1.1. Early developments in electrochemistry and synergies with physics and engineering led to methods for producing electrical energy, which has impacted on virtually every aspect of human activity. Electrochemistry also provided the basis for the industrial transformation of many materials and, in particular, for the production of metals such as aluminum and important feedstocks such as caustic soda and chlorine. Industrial organic chemistry built on mid-19th century processes for manufacturing dyestuffs, but by the 20th century had expanded to include the synthesis of pharmaceuticals. In parallel with advances in public health (measures for reducing the spread of infectious diseases through improved water, sanitation and vaccination; and for improving health through ensuring optimal nutrition – in all of which areas chemistry has played a major role), pharmaceutical chemistry has contributed enormously to improving life expectancy and the quality of life through the treatment of infectious diseases and metabolic disorders and the control of pain. Chemistry has contributed to many of the advances in agriculture (e.g., fertilizers, plant growth regulators, pesticides) which have been characterized as a "green revolution" and which have helped to feed the world's population while it grew from about 1 billion to 6 billion during the 20th century. Moreover, chemistry has given the world a wide array of new materials, including polymers, plastics, semiconductors and superconductors, with applications from fabrics and structural materials to information and communications technologies and medical imaging.

Table 1.1 Landmark examples of chemistry breakthroughs contributing to health and wealth.

Date	Scientist	Breakthrough	Impact	Refs
		Industrial chemistry, electrochemistry, power and light		
1800	Alessandro Volta	Discovered that a continuous flow of electricity was generated when using certain fluids as conductors to promote a chemical reaction between the metals or electrodes.	Mass production of portable power sources enabled a vast range of applications– from automobiles to radios. The nickel–metal hydride battery, commercialized in 1990, provided a high energy density and absence of toxic metals. It has found numerous applications include mobile phones and laptop computers	[2]
1802	William Cruickshank	Designed the first electric battery capable of mass production.		
1839	William Grove	Invented the H_2/O_2 fuel cell.		
1859	Gaston Platé	Invented the first rechargeable battery, based on lead-acid chemistry.		
1806	Humphry Davy	Connected a very powerful electric battery to charcoal electrodes and produced "the most brilliant ascending arch of light ever seen".	Invention of the electric light bulb paved the way for replacement of polluting combustion processes for lighting and enabled mass lighting in homes, workplaces and public spaces.	[2]
1879	Thomas Edison	Discovered that a carbon filament in an oxygen-free bulb glowed but did not burn up.		
1820	André-Marie Ampère	Observed that wires carrying an electric current attracted or repelled one another.	Invention of the electric generator transformed life in industrialized countries, impacting on transport, work and leisure.	[2]
1831	Michael Faraday	Demonstrated that a copper disc was able to provide a constant flow of electricity when revolved in a strong magnetic field.		
1800	William Cruickshank	First description of electrolysis of brine	Electrolysis became an extremely important method of transforming materials and especially for the production of inorganic chemicals and compounds, either for use in their own right (e.g., see entry on aluminum below) as a source of feedstocks for the manufacture of other compounds, including organics. For example, the chlorine by-product from the electrolysis of brine was the starting point for the manufacture of organic compounds including solvents, pesticides and plastics	[2–4]
1833	Michael Faraday	Formulation of the laws that govern the electrolysis of aqueous solutions		
1861	Ernest Solvay (1838–1922)	Patented Solvay Process for manufacture of industrial soda using carbon dioxide, brine and ammonia. After the first commercial plant for the electrolysis of brine was built in 1891, caustic soda was increasingly produced directly by this method.		
1897	Herbert Dow	Dow persuaded a group of Cleveland investors to back him in building a chloralkali business in Midland, to be known as The Dow Chemical Co.		

Table 1.1 *Continued*

Date	Scientist	Breakthrough	Impact	Refs
1825	Hans Christian Oersted	Metallic aluminum first made by heating potassium amalgam with aluminum chloride.	Due to its low density, high thermal and electrical conductivity, non-magnetic character, high ductility and the capacity of the metal and its alloys to be cast, rolled, extruded, forged, drawn, and machined, aluminum became one of the most important and ubiquitous metals in the 20th century.	[5] [6]
1886	Charles Hall Paul Heroult	Electrolytic processes for the production of aluminum.		
1840s	August Hoffman	Discovery of aniline and process for its synthesis from benzene	Aniline dyes became the basis for the development of the dyestuffs industry in the 19th century, leading to major growth in chemical industries in the UK, France and Germany.	[7]
1856	William Perkin	Invention of mauve dye (aniline purple).		
		Medicinal chemistry and medicine		
1853	Charles Gerhardt	First synthesis of acetylsalicylic acid	Studies of microorganisms and the physiological effects of chemicals and work on the structural modification of natural products and synthetic chemicals in the 19th century laid the foundations for the pharmaceutical industry in the 20th century. Major classes of therapeutic agents soon emerged, including analgesics, anaesthetics, anti-infectives and anti-tumor agents.	[8–18]
1897	Felix Hoffmann	Investigated acetylsalicylic acid as a less-irritating replacement for salicylate medicines, e.g., for treating rheumatism.		
1860–1864	Louis Pasteur	Demonstrated that fermentation is caused by specific microorganisms and formulated the germ theory of disease – providing the basis for biotechnology and anti-microbial chemotherapy.	Growing understanding of the chemistry of metabolic processes and of the structures and functions of proteins and nucleic acids all contributed to the evolution of pharmacology and molecular biology as distinct sciences and to drug targeting and rational drug design.	
1909	Paul Ehrlich	Synthesis of anti-syphilis organo-arsenical drug, Salvarsan.		
1928 1940	Alexander Fleming Howard Florey Ernst Chain	Discovery of penicillin, the first of a family of β-lactam antibiotics, and development of large-scale process for its production		
1932	Gerhard Domagk	Began testing Prontosil, leading to development of the sulfonamide antibiotics	Understanding of the metabolic roles of vitamins and hormones paved the way for a range of drug therapies for metabolic disorders and for development of hormonal contraceptives.	

Table 1.1 *Continued*

Date	Scientist	Breakthrough	Impact	Refs
1865	Heinrich Lissauer	Used potassium arsenite to treat chronic myelogenous leukemia – the first instance of effective chemotherapy for malignant disease. The modern era of cancer chemotherapy began with the study of the cytotoxic effects of nitrogen mustards on lymphoid tissues by Alfred Gilman, Louis Goodman and coworkers in the 1940s.	The pharmaceutical industry now employs well over half a million people and generates global sales in excess of US$ 700 billion per year. In the UK alone, the industry provided employment for 67 000 workers in 2007.	
1912	Casimir Funk	Published the "vitamine theory", based on observations of the effects of depriving animals of small amounts of essential dietary chemicals. Paved the way for the modern understanding of vitamins and their roles as key biochemical catalysts.		
1901	Jokichi Takamine	First isolation of epinephrine.		
1915	Edward Kendall	First isolation in crystalline form of thyroxine from thyroid gland.		
1921–22	Frederick Banting John McLeod Charles Best	First isolation of insulin and demonstration of its capacity to treat diabetes.		
1951	Carl Djerassi	Synthesized norethindrone, the first effective oral contraceptive.		
1949	Linus Pauling, Harvey Itano, S. J. Singer, Ibert Wells	Publication of "Sickle Cell Anemia, a Molecular Disease" – the first proof of a human disease caused by an abnormal protein and the dawn of molecular genetics.		
1953	James Watson Francis Crick	Discovery of the double helix structure of DNA – the foundation of molecular biology.		
1955	Frederick Sanger	First determination of the complete amino acid sequence of a protein – insulin.		
1958	Max Perutz John Kendrew	First three-dimensional structures of proteins solved by X-ray crystallography – hemoglobin and myoglobin.		

Table 1.1 *Continued*

Date	Scientist	Breakthrough	Impact	Refs
		Dentistry		
1826	Auguste Taveau	First to use amalgam as a dental restorative material	The development of safe and effective materials for dental restoration and anesthesia transformed dentistry, which had hitherto been a crude and extremely painful procedure.	[19]
1844–1846	Horace Wells William Morton	First uses of nitrous oxide and ether as general anesthetics for dental extractions		
1901	Frederick McKay	Began investigating the cause of widespread brown staining of teeth in Colorado Springs, which he discovered was associated with a dramatic absence of dental caries. Work by chemists in the 1930s eventually traced the cause to fluoride in drinking water.	Water fluoridation and the development of fluoride-containing toothpastes have further contributed to a dramatic improvement in oral health in many countries.	
1905	Alfred Einhorn	First synthesis of procaine (novocaine), a synthetic analog of cocaine without its addictive properties and the first safe local anesthetic for dentistry.		
		Agrochemistry		
1909	Fritz Haber	Invented the Haber process for nitrogen fixation, later scaled up by Carl Bosch. Fixation of nitrogen as ammonia, which can then be oxidized to make nitrates and nitrites, made possible the industrial production of many classes of compounds including nitrate fertilizers and explosives.	The Haber process now produces 100 million tons of nitrogen fertilizer per year, consuming 3–5% of world natural gas production (ca. 1–2% of the world's annual energy supply) and generating fertilizer which is responsible for sustaining one-third of the Earth's population.	[20] [21] [22] [23] [24] [25]
1874	Othmar Zeidler	First synthesis of DDT.	The development of plant growth promoters, crop protection agents and agents promoting animal health contributed to an agrochemicals industry with global annual sales of over of US$ 100 billion and, together with advances in plant breeding and agronomy methods, produced the green revolution of the 1960s–1980s which has helped feed the burgeoning population of the planet.	
1939	Paul Müller	Insecticidal properties discovered. DDT became the first commercial organochlorine insecticide. Prior to its banning on environmental grounds, DDT was a major weapon in the fight to eliminate malaria.		
1951	Geigy Chemical Co.	Introduction of carbamate insecticides		
1960s	Michael Elliott	Development of synthetic pyrethroid insecticides.		

Table 1.1 *Continued*

Date	Scientist	Breakthrough	Impact	Refs
		Analytical chemistry		
1901	Michael Tswett	First use of an adsorption column for the separation of plant pigments marked the birth of chromatography – later to develop into a family of 2- and 3-dimensional techniques involving combinations of gas, liquid and solid phases, for analytical and preparative scale separation of compounds.	The pioneering studies by a range of scientists, including botanists, physicists and physical chemists, led to the development of extremely powerful sets of techniques for separating chemical species, identifying them and measuring their concentrations. The evolving and often intertwined fields of analytical and separation sciences have been of fundamental importance, not only to the advance of chemistry itself but also to a wide range of areas including clinical and environmental sciences.	[26] [27] [28] [29] [30] [31]
1800	William Herschel	Discovered infrared radiation.		
1854	August Beer	Extending earlier work by by Pierre Bouguer and Johann Lambert, published what became known as the Beer-Lambert Law, defining the relationship between the extent of absorption of light and the properties of the material through which it is traveling.		
1859	Robert Bunsen Gustav Kirchoff	Developed the first spectroscope.		
1895	Wilhelm Röntgen	First systematic studies of X-rays, which later became the basis of X-ray medical diagnosis and X-ray crystallography.		
1913	Joseph Thomson	Invented mass spectrometry.		
1938	Isidor Rabi	First described and measured nuclear magnetic resonance in molecular beams. NMR became the basis of techniques for molecular structure elucidation and also medical imaging.		

Table 1.1 *Continued*

Date	Scientist	Breakthrough	Impact	Refs
		Polymers and plastics		
1839	Charles Goodyear	Discovered the process of vulcanization of natural rubber by heating with sulfur	Materials based on synthetic plastics and polymers became ubiquitous in the 20th century, finding applications in clothing, products from containers and appliance casings to non-stick pans, thermal and electrical insulators, components of transport machinery, medical and surgical devices, in space exploration and in much else.	[32] [33] [34] [35] [36]
1855	Alexander Parkes	Created the first plastic by treating cellulose treated with nitric acid.		
1909	Leo Hendrik Baekeland	Bakelite, the first synthetic polymer plastic, made from phenol and formaldehyde.		
1934	Wallace Carothers	First synthesis of a synthetic fiber, nylon, by co-polymerization of hexamethylene diamine and adipic acid		
		Solid state chemistry		
1833	Michael Faraday	Described first semiconductor effect, noting that electrical conductivity in silver sulfide increased with increasing temperature	Semiconductors based on silicon became the basis of solid state electronic devices including computers and provided the foundation for the modern digital age.	[37]

The value added by these products of chemistry and related sciences has contributed to the rapid growth in world GDP [38], especially in the industrially advanced countries during the second half of the 20th century (Figure 1.2). Knowledge-intensive and technology-intensive industries are estimated [39] to have accounted for 30% of global economic output, or some US$15.7 trillion, in 2007.

1.2 Poverty and Disparities in Life Expectancy

The benefits from advances in chemistry and other sciences have not been evenly distributed globally. The least industrially/technologically advanced countries have remained the poorest and people in the low- and middle-income countries (LMICs) have often fared worse than those in high-income countries (HICs), as illustrated by the dramatic relationship between poverty and life expectancy: the poor die young. Life expectancies around the world have increased very markedly over the course of the last century, but as they have done so the disparities between populations have grown larger [40]. However, the relationship between life expectancy