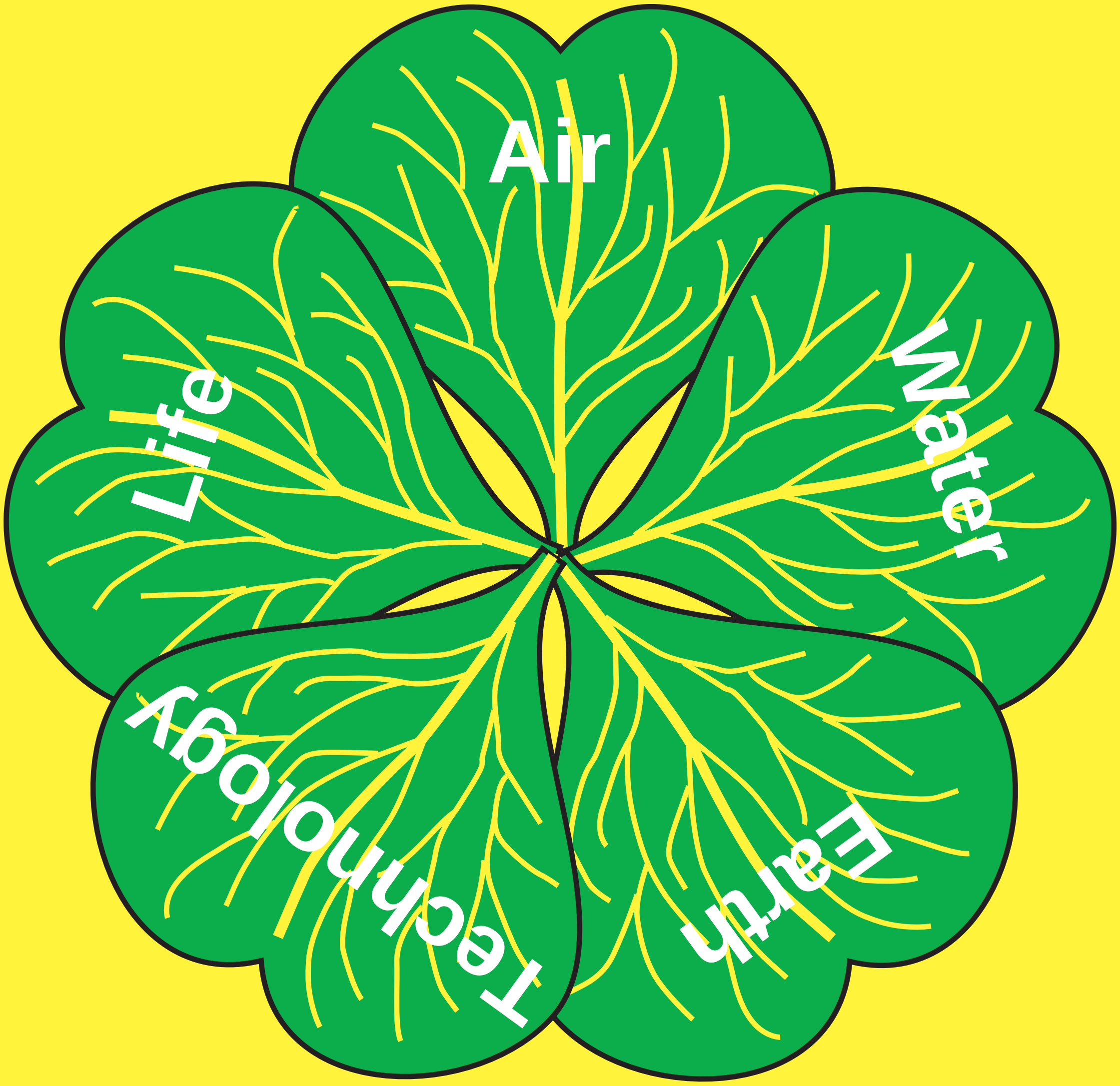
GREEN CHEMISTRY



AND THE TEN COMMANDMENTS OF SUSTAINABILITY

Stanley E. Manahan

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ChemChar Research, Inc.
2005

THE ELEMENTS

Atomic number	Name	Symbol	Atomic mass
1	Hydrogen	H	1.00794
2	Helium	He	4.0026
3	Lithium	Li	6.941
4	Beryllium	Be	9.01218
5	Boron	B	10.811
6	Carbon	C	12.011
7	Nitrogen	N	14.0067
8	Oxygen	O	15.9994
9	Fluorine	F	18.9984
10	Neon	Ne	20.1797
11	Sodium	Na	22.9898
12	Magnesium	Mg	24.305
13	Aluminum	Al	26.98154
14	Silicon	Si	28.0855
15	Phosphorus	P	30.973
16	Sulfur	S	32.066
17	Chlorine	Cl	35.4527
18	Argon	Ar	39.948
19	Potassium	K	39.0983
20	Calcium	Ca	40.078
21	Scandium	Sc	44.9559
22	Titanium	Ti	47.88
23	Vanadium	V	50.9415
24	Chromium	Cr	51.9961
25	Manganese	Mn	54.938
26	Iron	Fe	55.847
27	Cobalt	Co	58.9332
28	Nickel	Ni	58.6934
29	Copper	Cu	63.546
30	Zinc	Zn	65.39
31	Gallium	Ga	69.723
32	Germanium	Ge	72.61
33	Arsenic	As	74.9216
34	Selenium	Se	78.96
35	Bromine	Br	79.904
36	Krypton	Kr	83.8
37	Rubidium	Rb	85.4678
38	Strontium	Sr	87.62
39	Yttrium	Y	88.9056
40	Zirconium	Zr	91.224
41	Niobium	Nb	92.9064
42	Molybdenum	Mo	95.94
43	Technetium	Tc	98
44	Ruthenium	Ru	101.07
45	Rhodium	Rh	102.9055
46	Palladium	Pd	106.42
47	Silver	Ag	107.8682
48	Cadmium	Cd	112.411
49	Indium	In	114.82
50	Tin	Sn	118.710
51	Antimony	Sb	121.757
52	Tellurium	Te	127.60
53	Iodine	I	126.9045
54	Xenon	Xe	131.29
55	Cesium	Cs	132.9054
56	Barium	Ba	137.327
57	Lanthanum	La	138.9055
58	Cerium	Ce	140.115
59	Praseodymium	Pr	140.9077
60	Neodymium	Nd	144.24
61	Promethium	Pm	145
62	Samarium	Sm	150.36
63	Europium	Eu	151.965
64	Gadolinium	Gd	157.25
65	Terbium	Tb	158.925
66	Dysprosium	Dy	162.50
67	Holmium	Ho	164.9303
68	Erbium	Er	167.26
69	Thulium	Tm	168.9342
70	Ytterbium	Yb	173.04
71	Lutetium	Lu	174.967
72	Hafnium	Hf	178.49
73	Tantalum	Ta	180.9497
74	Tungsten	W	183.85
75	Rhenium	Re	186.207
76	Osmium	Os	190.2
77	Iridium	Ir	192.22
78	Platinum	Pt	195.08
79	Gold	Au	196.9665
80	Mercury	Hg	200.59
81	Thallium	Tl	204.383
82	Lead	Pb	207.2
83	Bismuth	Bi	208.98
84	Polonium	Po	209
85	Astatine	At	210
86	Radon	Rn	222
87	Francium	Fr	223
88	Radium	Ra	226.0254
89	Actinium	Ac	227.0278
90	Thorium	Th	232.038
91	Protactinium	Pa	231.0359
92	Uranium	U	238.0289
93	Neptunium	Np	237.048
94	Plutonium	Pu	244
95	Americium	Am	243
96	Curium	Cm	247
97	Berkelium	Bk	247
98	Californium	Cf	251
99	Einsteinium	Es	252
100	Fermium	Fm	257.1
101	Mendelevium	Md	258.1
102	Nobelium	No	255
103	Lawrencium	Lr	260
104	Rutherfordium	Rf	261.11
105	Dubnium	Db	262.11
106	Seaborgium	Sg	263.12
107	Bohrium	Bh	262.12
108	Hassium	Hs	265
109	Meitnerium	Mt	266

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[1] Elements above atomic number 92 have been made artificially.

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AND THE TEN COMMANDMENTS OF SUSTAINABILITY

2nd ed

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THE AUTHOR

Stanley E. Manahan is Professor of Chemistry at the University of Missouri-Columbia, where he has been on the faculty since 1965. He received his A.B. in chemistry from Emporia State University in 1960 and his Ph.D. in analytical chemistry from the University of Kansas in 1965. Since 1968 his primary research and professional activities have been in environmental chemistry, toxicological chemistry, and waste treatment. His classic textbook, *Environmental Chemistry*, 8th ed (CRC Press, Boca Raton, Florida, 2004) has been in print continuously in various editions since 1972 and is the longest standing title on this subject in the world. Other books that he has written are *Environmental Science and Technology*, 2nd ed., (Taylor & Francis, 2006), *Toxicological Chemistry and Biochemistry*, 3rd ed. (CRC Press/Lewis Publishers, 2001), *Fundamentals of Environmental Chemistry,* 2nd ed. (CRC Press/Lewis Publishers, 2001), *Industrial Ecology: Environmental Chemistry and Hazardous Waste* (CRC Press/Lewis Publishers, 1999), *Environmental Science and Technology* (CRC Press/Lewis Publishers, 1997), *Hazardous Waste Chemistry, Toxicology and Treatment* (Lewis Publishers, 1992), *Quantitative Chemical Analysis*, (Brooks/Cole, 1986), and *General Applied Chemistry*, 2nd ed. (Willard Grant Press, 1982). He has lectured on the topics of environmental chemistry, toxicological chemistry, waste treatment, and green chemistry throughout the U.S. as an American Chemical Society Local Section Tour Speaker, and has presented plenary lectures on these topics in international meetings in Puerto Rico; the University of the Andes in Mérida, Venezuela, Hokkaido University in Japan, the National Autonomous University in Mexico City, France, and Italy. He was the recipient of the Year 2000 Award of the Environmental Chemistry Division of the Italian Chemical Society. His research specialty is gasification of hazardous wastes.

PREFACE

Green Chemistry and the Ten Commandments of Sustainability, 2nd ed, was written to provide an overview of the emerging discipline of green chemistry along with the fundamental chemical principles needed to understand this science. The second edition follows the first edition published in 2004 under the title of *Green Chemistry: Fundamentals of Sustainable Chemical Science and Technology*, from which it differs by the inclusion of an additional chapter, Chapter 14, "The Ten Commandments of Sustainability." The year 2005 may well represent a "tipping point" with respect to sustainability. Extreme weather events, though not proof of global warming, are consistent with significant human effects upon global climate. Catastrophic events, such as Hurricane Katrina, which devastated the U.S. Gulf Coast and New Orleans, have shown the vulnerability of fragile modern infrastructures and may portend future disasters intensified by global climate change. The tremendous shrinkage of the Arctic ice cap evident during recent years provides an additional indication of global climate change. Sharp increases in petroleum and natural gas prices show that Earth is running out of these fossil fuel resources upon which modern economies are based.

It goes without saying that sustainability must be achieved if humankind is to survive with any sort of reasonable living standard on Planet Earth. Chemists and chemical science have an essential role to play in achieving sustainability. In the chemical sciences, green chemistry has developed since the 1990s as a key to sustainability. And it is crucial that nonchemists have an understanding of green chemistry and how it can be used to achieve sustainability, not just for humans, but for all life forms as well, on our fragile planet. Therefore, this book includes a basic introduction to the principles of chemistry for those readers who may have little or no prior knowledge of this subject.

Laudable as its goals and those who work to achieve them are, green chemistry has developed a somewhat narrow focus. For the most part, it has concentrated largely on chemical synthesis, more specifically organic synthesis. It needs to be more inclusive of other areas pertinent to the achievement of sustainability, such as environmental chemistry and the science of industrial ecology. This book attempts to integrate these and other pertinent disciplines into green chemistry. In so doing, it recognizes five overlapping and interacting environmental spheres. Four of these have long been recognized by practitioners of environmental science. They are (1) the biosphere, (2) the hydrosphere, (3) the geosphere, and (4) the atmosphere. But, to be realistic, a fifth sphere must be recognized and studied. This is the anthrosphere, which consists of all of the things that humans have made and the systems that they operate throughout the environment. Highways, buildings, airports, factories, cultivated land, and a huge variety of structures and systems produced by human activities are part of Earth as we know it and must be dealt with in any comprehensive view of the environment. A basic aspect of this book is to deal with the five environmental spheres and to discuss how — for better or worse — the anthrosphere is an integral part of this Earth system.

Chapters 1–4 of this book introduce the basic concepts of chemistry and green chemistry. Chapter 1, “Chemistry, Green Chemistry and Environmental Chemistry,” includes a brief “minicourse” in chemistry that introduces the reader to fundamental ideas of atoms, elements, compounds, chemical formulas, and chemical equations so that the reader can have the background to understand these aspects in later chapters. Chapter 2, “The Elements: Basic Building Blocks of Green Chemicals,” introduces the elements and fundamentals of atomic structure. It develops an abbreviated version of the periodic table consisting of the first 20 elements to give the reader an understanding of this important foundation of chemistry. It also points out the green aspects of these elements, such as elemental hydrogen as a means of energy storage and transport and fuel for nonpolluting fuel cells. Chapter 3, “Compounds: Safer Materials for a Safer World,” explains chemical bonding, chemical formulas, and the concept of the mole. It points out how some chemical compounds are greener than others, for example, those that are relatively more biodegradable compared to ones that tend to persist in the environment. With an understanding of chemical compounds, Chapter 4. “Chemical Reactions: Making Materials Safely Without Damaging The Environment,” discusses how compounds are made and changed and introduces the idea of stoichiometry. It develops some key ideas of green chemistry such as atom economy and illustrates what makes some chemical reactions more green than others.

It is impossible to consider green chemistry in a meaningful manner without consideration of organic chemistry. Furthermore, given the importance of biosynthesis and the biological effects of toxic substances, it is essential to have a basic understanding of biochemicals. These subjects are covered in Chapter 5, “The Wonderful World of Carbon: Organic Chemistry and Biochemicals.”

Chapter 6, “Energy Relationships,” discusses the crucial importance of energy in green chemistry. It explains how abundant, sustainable, environmentally friendly energy sources are a fundamental requirement in maintaining modern societies in a sustainable manner. Chapter 7, “Green Water,” discusses water resources and the environmental chemistry of water. The environmental chemistry of the atmosphere is covered in Chapter 8, “Air and The Atmosphere.” This chapter also explains how the atmosphere is a sustainable source of some important raw materials, such as nitrogen used to make nitrogen fertilizers. The biosphere is discussed in Chapter 9, “The Biosphere: How The Revolution in Biology Relates to Green Chemistry.” Obviously, protection of the biosphere is one of the most important goals of green chemistry. This chapter explains how the biosphere is a renewable source of some key raw materials. The geosphere is introduced in Chapter 10. “The Geosphere, Soil, And Food Production: The Second Green Revolution In Agriculture.” Soil and its role in producing food and raw materials are discussed in this chapter. The concepts of the anthrosphere and industrial ecology are covered in Chapter 11, “The Anthrosphere and Industrial Ecology.” Feedstocks, which are required to support the chemical industry are discussed in Chapter 12, “Feedstocks: Maximum Utilization of Renewable and Biological Materials.” Emphasis is placed on renewable feedstocks from biological sources in place of depletable petroleum feedstocks.

Terrorism has become a central problem of our time. A unique feature of this book is its coverage of this topic in Chapter 13, “Terrorism, Toxicity, and Vulnerability: Chemistry in Defense of Human Welfare.” Included are agents of terrorism such as military poisons, means of detecting terrorist threats, and measures that may be taken to reduce such threats. Because of the threats posed by toxic agents, toxicological chemistry is introduced and discussed in this chapter.

The book concludes with Chapter 14, “The Ten Commandments of Sustainability,” which distills the essence of sustainability into ten succinct principles. In so doing, the chapter places green chemistry within a framework of the sustainable society that must be developed if modern civilization is to survive with a reasonable standard of living for humankind.

Reader feedback is eagerly solicited. Questions and suggestions may be forwarded to the author at manahans@missouri.edu.

1 CHEMISTRY, GREEN CHEMISTRY, AND ENVIRONMENTAL CHEMISTRY

1.1. CHEMISTRY IS GOOD

Chemistry is the science of matter. Are you afraid of chemistry? Many people are and try to avoid it. But avoiding chemistry is impossible. That is because all matter, all things, the air around us, the water we must drink, and all living organisms are made of chemicals. People who try to avoid all things that they regard as chemical may fail to realize that chemical processes are continuously being carried out in their own bodies. These are processes that far surpass in complexity and variety those that occur in chemical manufacturing operations. So, even those people who want to do so cannot avoid chemistry. The best course of action with anything that cannot be avoided and that might have an important influence on our lives (one's chemistry professor may come to mind) is to try to understand it, to deal with it. To gain an understanding of chemistry is probably why you are reading this book.

Green Chemistry is written for a reader like you. It seeks to present a body of chemical knowledge from the most fundamental level within a framework of the relationship of chemical science to human beings, their surroundings, and their environment. Face it, the study of chemistry based upon facts about elements, atoms, compounds, molecules, chemical reactions, and other basic concepts needed to understand this science is found by many to be less than exciting. However, these concepts and many more are essential to a meaningful understanding of chemistry. Anyone interested in green chemistry clearly wants to know how chemistry influences people in the world around us. So this book discusses real-world chemistry, introducing chemical principles as needed.

During the approximately two centuries that chemical science has been practiced on an ever-increasing scale, it has enabled the production of a wide variety of goods that are valued by humans. These include such things as pharmaceuticals that have improved health and extended life, fertilizers that have greatly increased food productivity, and semiconductors that have made possible computers and other electronic devices. Without the persistent efforts of chemists and the enormous productivity of the chemical industry, nothing approaching the high standard of living enjoyed in modern industrialized societies would be possible.

But there can be no denying that in years past, and even at present, chemistry has been misused in many respects, such as the release of pollutants and toxic substances and the production of nonbiodegradable materials, resulting in harm to the environment and living things, including humans. It is now obvious that chemical science must be turned away from emphasis upon the exploitation of limited resources and the production of increasing amounts of products that ultimately end up as waste and toward the application of chemistry in ways that provide for human needs without damaging the Earth support system upon which all living things depend. Fortunately, the practice of chemical science and industry is moving steadily in the direction of environmental friendliness and resource sustainability. The practice of chemistry in a manner that maximizes its benefits while eliminating or at least greatly reducing its adverse impacts has come to be known as **green chemistry**, the topic of this book.

As will be seen in later chapters of this book, the practice of chemistry is divided into several major categories. Most elements other than carbon are involved with **inorganic chemistry**. Common examples of inorganic chemicals are water, salt (sodium chloride), air pollutant sulfur dioxide, and lime. Carbon occupies a special place in chemistry because it is so versatile in the kinds of chemical species (compounds) that it forms. Most of the more than 20 million known chemicals are substances based on carbon known as organic chemicals and addressed by the subject of **organic chemistry**. The unique chemistry of carbon is addressed specifically in Chapter 5, "The Wonderful World of Carbon: Organic Chemistry and Biochemicals." The underlying theory and physical phenomena that explain chemical processes are explained by **physical chemistry**. Living organisms carry out a vast variety of chemical processes that are important in green chemistry and environmental chemistry. The chemistry that living organisms perform is **biochemistry**, which is addressed in Chapters 5 and 9. It is always important to know the identities and quantities of various chemical species present in a system, including various environmental systems. Often, significant quantities of chemical species are very low, so sophisticated means must be available to detect and quantify such species. The branch of chemistry dealing with the determination of kinds and quantities of chemical species is **analytical chemistry**.

As the chemical industry developed and grew during the early and mid 1900s, most practitioners of chemistry remained unconcerned with and largely ignorant of the potential for harm — particularly damage to the outside environment — of their products and processes. Environmental chemistry was essentially unknown and certainly not practiced by most chemists. Incidents of pollution and environmental damage, which were many and severe, were commonly accepted as a cost of doing business or blamed upon the industrial or commercial sectors. The unfortunate attitude that prevailed is summarized in a quote from a standard book on industrial chemistry from 1954 (*American Chemical Industry—A History*, W. Haynes Van Nostrand Publishers, 1954): "By sensible definition any by-product of a chemical operation for which there is no profitable use is a waste. The most convenient, least expensive way of disposing of said waste — up the chimney or down the river — is best."

Despite their potential to cause harm, nobody is more qualified to accept responsibility for environmental damage from chemical products or processes than are chemists who have the knowledge to understand how such harmful effects came about. As the detrimental effects of chemical manufacture and use became more obvious and severe, chemists were forced, often reluctantly, to deal with them. At present, enlightened chemists and chemical engineers do not view the practice of environmentally beneficial chemistry and manufacturing as a burden, but rather as an opportunity that challenges human imagination and ingenuity.

1.2. THE ENVIRONMENT AND THE FIVE ENVIRONMENTAL SPHERES

Compared to the generally well defined processes that chemists study in the laboratory, those that occur in the environment are rather complex and must be viewed in terms of simplified models. A large part of this complexity is due to the fact that environmental chemistry must take into account five interacting and overlapping compartments or spheres of the environment, which affect each other and which undergo continual interchanges of matter and energy. Traditionally, environmental science has considered water, air, earth, and life — that is, the **hydrosphere**, the **atmosphere**, the **geosphere**, and the **biosphere**. When considered at all, human activities were generally viewed as undesirable perturbations on these other spheres, causing pollution and generally adverse effects. Such a view is too narrow, and we must include a fifth sphere, the **anthrosphere**, consisting of the things humans make and do. By regarding the anthrosphere as an integral part of the environment, humans can modify their anthrospheric activities to do minimal harm to the environment, or to even improve it.

Figure 1.1 shows the five spheres of the environment, including the anthrosphere, and some of the exchanges of material between them. Each of these spheres is described briefly below.

The atmosphere is a very thin layer compared to the size of Earth, with most atmospheric gases lying within a few kilometers of sea level. In addition to providing oxygen for living organisms, the atmosphere provides carbon dioxide required for plant photosynthesis, and nitrogen that organisms use to make proteins. The atmosphere serves a vital protective function in that it absorbs highly energetic ultraviolet radiation from the sun that would kill living organisms exposed to it. A particularly important part of the atmosphere in this respect is the stratospheric layer of ozone, an ultraviolet-absorbing form of elemental oxygen. Because of its ability to absorb infrared radiation by which Earth loses the energy that it absorbs from the sun, the atmosphere stabilizes Earth's surface temperature. The atmosphere also serves as the medium by which the solar energy that falls with greatest intensity in equatorial regions is redistributed away from the Equator. It is the medium in which water vapor evaporated from oceans as the first step in the hydrologic cycle is transported over land masses to fall as rain over land.

Earth's water is contained in the hydrosphere. Although frequent reports of torrential rainstorms and flooded rivers produced by massive storms might give the impression that a large fraction of Earth's water is fresh water, more than 97% of it is seawater in the oceans. Most of the remaining fresh water is present as ice in polar ice caps and glaciers. A small fraction of the total water is present as vapor in the atmosphere. The remaining liquid fresh water is that available for growing plants and other organisms and for industrial uses. This water may be present on the surface as lakes, reservoirs, and streams, or it may be underground as groundwater.

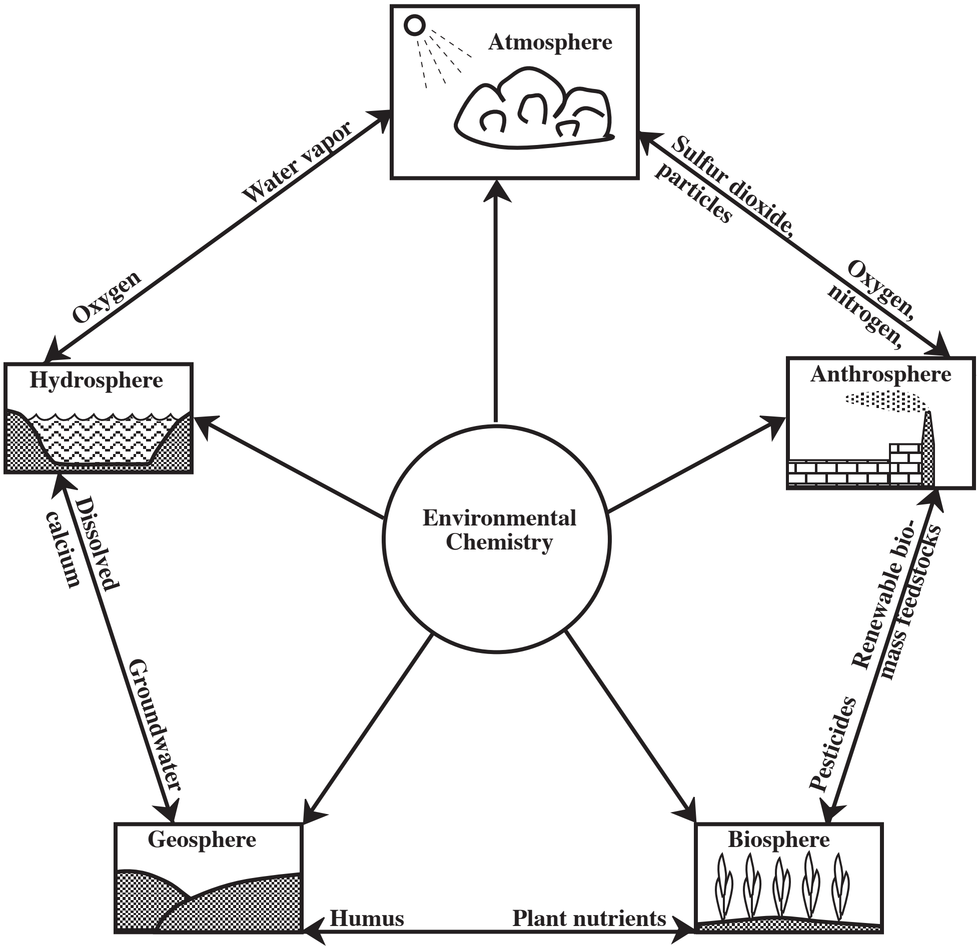


Figure 1.1. Illustration of the five major spheres of the environment. These spheres are closely tied together, interact with each other, and exchange materials and energy. A meaningful examination of environmental sciences must include all five of these spheres, including the anthrosphere.

The solid part of earth, the geosphere, includes all rocks and minerals. A particularly important part of the geosphere is soil, which supports plant growth, the basis of food for all living organisms. The **lithosphere** is a relatively thin solid layer extending from Earth's surface to depths of 50–100 km. The even thinner outer skin of the lithosphere known as the **crust** is composed of relatively lighter silicate-based minerals. It is the part of the geosphere that is available to interact with the other environmental spheres and that is accessible to humans.

The biosphere is composed of all living organisms. For the most part, these organisms live on the surface of the geosphere on soil, or just below the soil surface. The oceans and other bodies of water support high populations of organisms. Some life forms exist at considerable depths on ocean floors. In general, though, the biosphere is a very thin layer at the interface of the geosphere with the atmosphere. The biosphere is involved with the geosphere, hydrosphere, and atmosphere in **biogeochemical cycles** through which materials such as nitrogen and carbon are circulated.

Through human activities, the anthrosphere has developed strong interactions with the other environmental spheres. Many examples of these interactions could be cited. By cultivating large areas of soil for domestic crops, humans modify the geosphere and influence the kinds of organisms in the biosphere. Humans divert water from its natural flow, use it, sometimes contaminate it, then return it to the hydrosphere. Emissions of particles to the atmosphere by human activities affect visibility and other characteristics of the atmosphere. The emission of large quantities of carbon dioxide to the atmosphere by combustion of fossil fuels may be modifying the heat-absorbing characteristics of the atmosphere to the extent that global warming is almost certainly taking place. The anthrosphere perturbs various biogeochemical cycles.

The effect of the anthrosphere over the last two centuries in areas such as burning large quantities of fossil fuels is especially pronounced upon the atmosphere and has the potential to change the nature of Earth significantly. According to Nobel Laureate Paul J. Crutzen of the Max Planck Institute for Chemistry, Mainz, Germany, this impact is so great that it will lead to a new global epoch to replace the halocene epoch that has been in effect for the last 10,000 years since the last Ice Age. Dr. Crutzen has coined the term **anthropocene** (from anthropogenic) to describe the new epoch that is upon us.

1.3. WHAT IS ENVIRONMENTAL CHEMISTRY?

The practice of green chemistry must be based upon **environmental chemistry**. This important branch of chemical science is defined as *the study of the sources, reactions, transport, effects, and fates of chemical species in water, soil, air, and living environments and the effects of technology thereon*.[1] Figure 1.2 illustrates this definition of environmental chemistry with an important type of environmental chemical species. In this example, two of the ingredients required for the formation of photochemical smog — nitric oxide and hydrocarbons — are emitted to the atmosphere from vehicles and transported through the atmosphere by wind and air currents. In the atmosphere, energy from sunlight brings about photochemical reactions that convert nitric oxide and hydrocarbons to ozone, noxious organic compounds, and particulate matter, all characteristic of photochemical smog. Various harmful effects are manifested, such as visibility-obscuring particles in the atmosphere, or ozone, which is unhealthy when inhaled by humans, or toxic to plants. Finally, the smog products end up on soil, deposited on plant surfaces, or in bodies of water.

Figure 1.1 showing the five environmental spheres may provide an idea of the complexity of environmental chemistry as a discipline. Enormous quantities of materials and energies are continually exchanged among the five environmental spheres. In addition to variable flows of materials, there are variations in temperature, intensity of solar radiation, mixing, and other factors, all of which strongly influence chemical conditions and behavior.

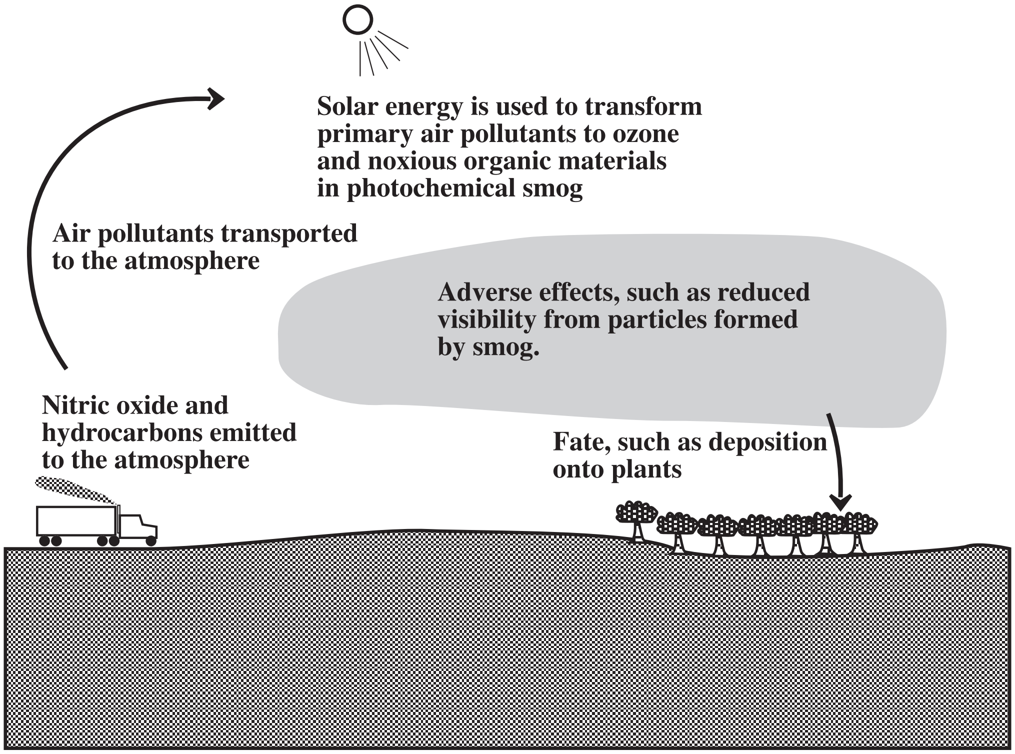


Figure 1.2. Illustration of the definition of environmental chemistry with a common environmental contaminant.

Throughout this book the role of environmental chemistry in the practice of green chemistry is emphasized. Green chemistry is practiced to minimize the impact of chemicals and chemical processes upon humans, other living organisms, and the environment as a whole. It is only within the framework of a knowledge of environmental chemistry that green chemistry can be successfully practiced.

There are several highly interconnected and overlapping categories of environmental chemistry. **Aquatic chemistry** deals with chemical phenomena and processes in water. Aquatic chemical processes are very strongly influenced by microorganisms in the water, so there is a strong connection between the hydrosphere and biosphere insofar as such processes are concerned. Aquatic chemical processes occur largely in “natural waters” consisting of water in oceans, bodies of fresh water, streams, and underground aquifers. These are places in which the hydrosphere can interact with the geosphere, biosphere, and atmosphere and is often subjected to anthrospheric influences. Aspects of aquatic chemistry are considered in various parts of this book and are addressed specifically in Chapter 7, “Green Water.”

Atmospheric chemistry is the branch of environmental chemistry that considers chemical phenomena in the atmosphere. Two things that make this chemistry unique are the extreme dilution of important atmospheric chemicals and the influence of photochemistry. Photochemistry occurs when molecules absorb photons of high-energy visible light or ultraviolet radiation, become energized ("excited"), and undergo reactions that lead to a variety of products, such as photochemical smog. In addition to reactions that occur in the gas phase, many important atmospheric chemical phenomena take place on the surfaces of very small solid particles suspended in the atmosphere and in droplets of liquid in the atmosphere. Although no significant atmospheric chemical reactions are mediated by organisms in the atmosphere, microorganisms play a strong role in determining species that get into the atmosphere. As examples, bacteria growing in the absence of oxygen, such as in cows' stomachs and under water in rice paddies, are the single greatest source of hydrocarbon in the atmosphere because of the large amounts of methane that they emit. The greatest source of organic sulfur compounds in the atmosphere consists of microorganisms in the oceans that emit dimethyl sulfide. Atmospheric chemistry is addressed specifically in Chapter 8, "Air and the Atmosphere."

Chemical processes that occur in the geosphere involving minerals and their interactions with water, air, and living organisms are addressed by the topic of geochemistry. A special branch of geochemistry, soil chemistry, deals with the chemical and biochemical processes that occur in soil. Aspects of geochemistry and soil chemistry are covered in Chapter 10 of this book, "The Geosphere, Soil, and Food Production: The Second Green Revolution in Agriculture."

Environmental biochemistry addresses biologically mediated processes that occur in the environment. Such processes include, as examples, the biodegradation of organic waste materials in soil or water and processes within biogeochemical cycles, such as denitrification, which returns chemically bound nitrogen to the atmosphere as nitrogen gas. The basics of biochemistry are presented in Chapter 5, "The Wonderful World of Carbon: Organic Chemistry and Biochemicals," and in Chapter 9, "The Biosphere: How the Revolution in Biology Relates to Green Chemistry." Chapter 12, "Feedstocks: Maximum Utilization of Renewable and Biological Materials," discusses how chemical processes carried out by organisms can produce material feedstocks needed for the practice of green chemistry. The toxic effects of chemicals are of utmost concern to chemists and the public. Chapter 13, "Terrorism, Toxicity, and Vulnerability: Chemistry in Defense of Human Welfare," deals with aspects of these toxic effects and discusses **toxicological chemistry**.

Although there is not a formally recognized area of chemistry known as "anthrospheric chemistry," most of chemical science and engineering developed to date deals with chemistry carried out in the anthrosphere. Included is industrial chemistry, which is very closely tied to the practice of green chemistry. A good way to view "anthrospheric chemistry" from a green chemistry perspective is within the context of **industrial ecology**. Industrial ecology considers industrial systems in a manner analogous to natural ecosystems. In a system of industrial ecology, various manufacturing and processing operations carry out "industrial metabolism" on materials. A successful industrial ecosystem is well balanced and diverse, with various enterprises that generate products for each other and use each other's products and potential wastes. A well-functioning industrial ecosystem recycles materials to the maximum extent possible and produces little — ideally no — wastes. Therefore, a good industrial ecosystem is a green chemical system.

1.4. ENVIRONMENTAL POLLUTION

Environmental chemistry has developed in response to problems and concerns regarding environmental pollution. Although awareness of chemical pollution had increased significantly in the two decades following World War II, the modern environmental movement dates from the 1962 publication of Rachel Carson's classic book *Silent Spring*. The main theme of this book was the concentration of DDT and other mostly pesticidal chemicals through the food chain, which caused birds at the end of the chain to produce eggs with soft shells that failed to produce viable baby birds. The implication was that substances harming bird populations might harm humans as well.

Around the time of the publication of Silent Spring another tragedy caused great concern regarding the potential effects of chemicals. This was the occurrence of approximately 10,000 births of children with badly deformed or missing limbs as a result of their mothers having taken the pharmaceutical thalidomide to alleviate the effects of morning sickness at an early stage of pregnancy.

The 1960s were a decade of high concern and significant legislative action in the environmental arena aimed particularly at the control of water and air pollutants. By around 1970, it had become evident that the improper disposal of chemicals to the geosphere was also a matter of significant concern. Although many incidents of such disposal were revealed, the one that really brought the problem into sharp focus was the Love Canal site in Niagara Falls, New York. This waste dump was constructed in an old abandoned canal in which large quantities of approximately 80 waste chemicals had been placed for about two decades starting in the 1930s. It had been sealed with a clay cap and given to the city. A school had been built on the site and housing constructed around it. By 1971 it became obvious that the discarded chemicals were leaking through the cap. This problem led eventually to the expenditure of many millions of dollars to remediate the site and to buy out and relocate approximately one thousand households. More than any other single incident the Love Canal problem was responsible for the passage of legislation in the U.S., including Superfund, to clean up hazardous waste sites and to prevent their production in the future.

By about 1970 it was generally recognized that air, water, and land pollution was reaching intolerable levels. As a result, various countries passed and implemented laws designed to reduce pollutants and to clean up waste chemical sites at a cost that has easily exceeded one trillion dollars globally. In many respects, this investment has been strikingly successful. Streams that had deteriorated to little more than stinking waste drainage ditches (the Cuyahoga River in Cleveland, Ohio, once caught on fire from petroleum waste floating on its surface) have been restored to a healthy and productive condition. Despite a much increased population, the air quality in smog-prone Southern California has improved markedly. A number of dangerous waste disposal sites have been cleaned up. Human exposure to toxic substances in the workplace, in the environment, and in consumer products has been greatly reduced. The measures taken and regulations put in place have prevented devastating environmental problems from occurring.

Initially, serious efforts to control pollution were based on a **command and control** approach, which specifies maximum concentration guideline levels of substances that can be allowed in the atmosphere or water and places limits on the amounts or concentrations of pollutants that can be discharged in waste streams. Command and control efforts to diminish pollution have resulted in implementation of various technologies to remove or neutralize pollutants in potential waste streams and stack gases. These are so-called end-of-pipe measures. As a result, numerous techniques, such as chemical precipitation of water pollutants, neutralization of acidic pollutants, stack gas scrubbing, and waste immobilization have been developed and refined to deal with pollutants after they are produced.

Release of chemicals to the environment is now tracked in the U.S. through the Toxics Release Inventory TRI, under requirements of the Emergency Planning and Community Right to Know Act, which requires that information be provided regarding the release of more than 300 chemicals. The release of approximately one billion kilograms of these chemicals is reported in the U.S. each year. Not surprisingly, the chemical industry produces the most such substances, followed by primary metals and paper manufacture. Significant amounts are emitted from transportation equipment, plastics, and fabricated metals, with smaller quantities from a variety of other enterprises. Although the quantities of chemicals released are high, they are decreasing, and the publicity resulting from the required publication of these releases has been a major factor in decreasing the amounts of chemicals released.

Although much maligned, various pollution control measures implemented in response to command and control regulation have reduced wastes and improved environmental quality. Regulation-based pollution control has clearly been a success and well worth the expense and effort. However, it is much better to prevent the production of pollutants rather than having to deal with them after they are made. This was recognized in United States with the passage of the 1990 Pollution Prevention Act. This act explicitly states that, wherever possible, wastes are not to be generated and their quantities are to be minimized. The means for accomplishing this objective can range from very simple measures, such as careful inventory control and reduction of solvent losses due to evaporation, to much more sophisticated and drastic approaches, such as complete redesign of manufacturing processes with waste minimization as a top priority. The means for preventing pollution are best implemented through the practice of green chemistry, which is discussed in detail in the following section.

1.5. WHAT IS GREEN CHEMISTRY?

The limitations of a command and control system for environmental protection have become more obvious even as the system has become more successful. In industrialized societies with good, well-enforced regulations, most of the easy and inexpensive measures that can be taken to reduce environmental pollution and exposure to harmful chemicals have been implemented. Therefore, small increases in environmental protection now require relatively large investments in money and effort. Is there a better way? There is, indeed. The better way is through the practice of green chemistry.

Green chemistry can be defined as the practice of chemical science and manufacturing in a manner that is sustainable, safe, and non-polluting and that consumes minimum amounts of materials and energy while producing little or no waste material. The practice of green chemistry begins with recognition that the production, processing, use, and eventual disposal of chemical products may cause harm when performed incorrectly. In accomplishing its objectives, green chemistry and green chemical engineering may modify or totally redesign chemical products and processes with the objective of minimizing wastes and the use or generation of particularly dangerous materials. Those who practice green chemistry recognize that they are responsible for any effects on the world that their chemicals or chemical processes may have. Far from being economically regressive and a drag on profits, green chemistry is about increasing profits and promoting innovation while protecting human health and the environment.

To a degree, we are still finding out what green chemistry is. That is because it is a rapidly evolving and developing subdiscipline in the field of chemistry. And it is a very exciting time for those who are practitioners of this developing science. Basically, green chemistry harnesses a vast body of chemical knowledge and applies it to the production, use, and ultimate disposal of chemicals in a way that minimizes consumption of materials, exposure of living organisms, including humans, to toxic substances, and damage to the environment. And it does so in a manner that is economically feasible and cost effective. In one sense, green chemistry is the most efficient possible practice of chemistry and the least costly when all of the costs of the practice of chemistry, including hazards and potential environmental damage are taken into account.

Green chemistry is sustainable chemistry. There are several important respects in which green chemistry is sustainable:

- Economic: At a high level of sophistication green chemistry normally costs less in strictly economic terms (to say nothing of environmental costs) than chemistry as it is normally practiced.
- Materials: By efficiently using materials, maximum recycling, and minimum use of virgin raw materials, green chemistry is sustainable with respect to materials.
- Waste: By reducing insofar as possible, or even totally eliminating their production, green chemistry is sustainable with respect to wastes.

1.6. GREEN CHEMISTRY AND SYNTHETIC CHEMISTRY

Synthetic chemistry is the branch of chemical science involved with developing means of making new chemicals and developing improved ways of synthesizing existing chemicals. A key aspect of green chemistry is the involvement of synthetic chemists in the practice of environmental chemistry. Synthetic chemists, whose major objective has always been to make new substances and to make them cheaper and better, have come relatively late to the practice of environmental chemistry. Other areas of chemistry have been involved much longer in pollution prevention and environmental protection. From the beginning, analytical chemistry has been a key to discovering and monitoring the severity of pollution problems. Physical chemistry has played a strong role in explaining and modeling environmental chemical phenomena. The application of physical chemistry to atmospheric photochemical reactions has been especially useful in explaining and preventing harmful atmospheric chemical effects including photochemical smog formation and stratospheric ozone depletion. Other branches of chemistry have been instrumental in studying various environmental chemical phenomena. Now the time has arrived for the synthetic chemists, those who make chemicals and whose activities drive chemical processes, to become intimately involved in making the manufacture, use, and ultimate disposal of chemicals as environmentally friendly as possible.

Before environmental and health and safety issues gained their current prominence, the economic aspects of chemical manufacture and distribution were relatively simple and straightforward. The economic factors involved included costs of feedstock, energy requirements, and marketability of product. Now, however, costs must include those arising from regulatory compliance, liability, end-of-pipe waste treatment, and costs of waste disposal. By eliminating or greatly reducing the use of toxic or hazardous feedstocks and catalysts and the generation of dangerous intermediates and byproducts, green chemistry eliminates or greatly reduces the additional costs that have come to be associated with meeting environmental and safety requirements of conventional chemical manufacture.

As illustrated in Figure 1.3, there are two general and often complemetary approaches to the implementation of green chemistry in chemical synthesis, both of which challenge the imaginations and ingenuity of chemists and chemical engineers. The first of these is to use existing feedstocks but make them by more environmentally benign, “greener,” processes. The second approach is to substitute other feedstocks that are made by environmentally benign approaches. In some cases, a combination of the two approaches is used.

Yield and Atom Economy

Traditionally, synthetic chemists have used **yield**, defined as a percentage of the degree to which a chemical reaction or synthesis goes to completion to measure the success of a chemical synthesis. For example, if a chemical reaction shows that 100 grams of product should be produced, but only 85 grams is produced, the yield is 85%. A synthesis with a high yield may still generate significant quantities of useless byproducts if the reaction does so as part of the synthesis process. Instead of yield, green chemistry emphasizes **atom economy**, the fraction of reactant material that actually ends up in final product. With 100 percent atom economy, all of the material that goes into the synthesis process is incorporated into the product. For efficient utilization of raw materials, a 100% atom economy process is most desirable. Figure 1.4 illustrates the concepts of yield and atom economy.

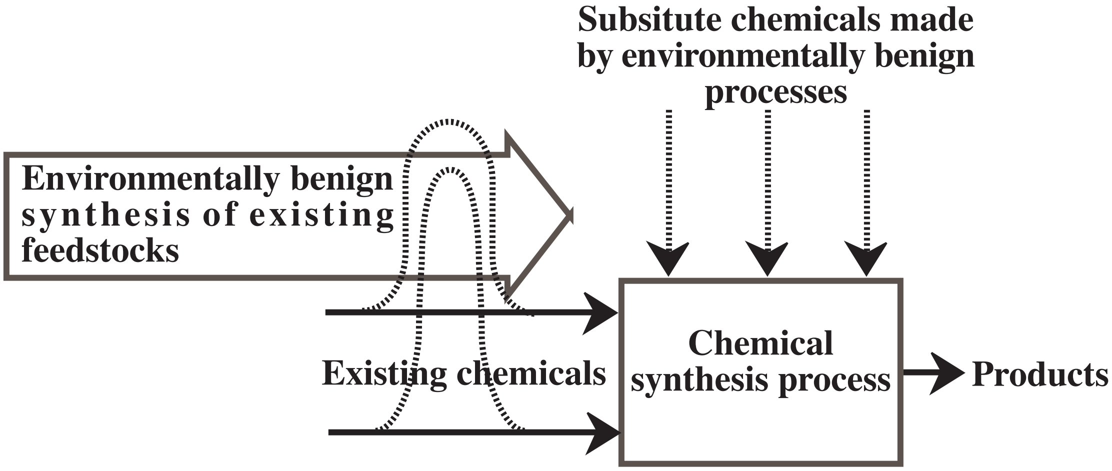


Figure 1.3. Two general approaches to the implementation of green chemistry. The dashed loops on the left represent alternative approaches to environmentally benign means of providing chemicals already used for chemical synthesis. A second approach, where applicable, is to substitute entirely different, environmentally safer raw materials.

1.7. REDUCTION OF RISK: HAZARD AND EXPOSURE

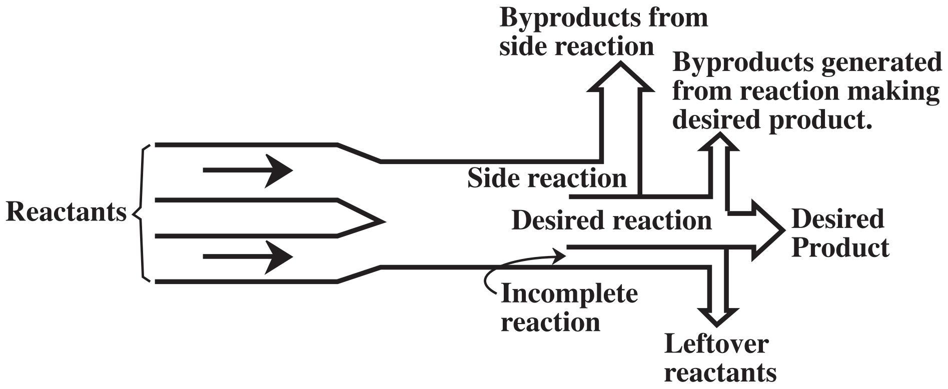
A major goal in the manufacture and use of commercial products, and, indeed, in practically all areas of human endeavor, is the reduction of risk. There are two major aspects of risk — the hazard presented by a product or process and exposure of humans or other potential targets to those hazards.

$$\text{Risk} = \text{F}\{\text{hazard} \times \text{exposure}\} \qquad (1.7.1)$$

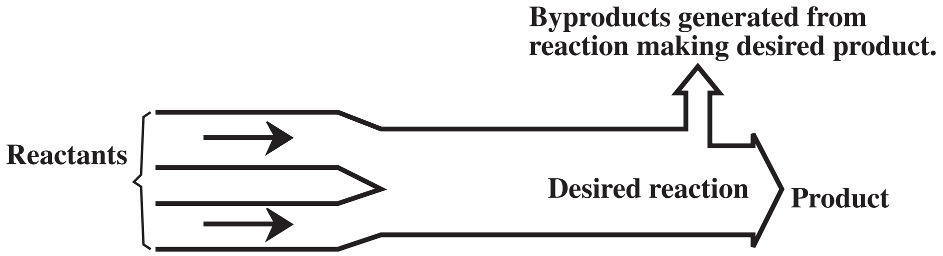
This relationship simply states that risk is a function of hazard times exposure. It shows that risk can be reduced by a reduction of hazard, a reduction of exposure, and various combinations of both.

The command and control approach to reducing risk has concentrated upon reduction of exposure. Such efforts have used various kinds of controls and protective measures to limit exposure. The most common example of such a measure in the academic chemistry laboratory is the wearing of goggles to protect the eyes. Goggles will not by themselves prevent acid from splashing into the face of a student, but they do prevent the acid from contacting fragile eye tissue. Explosion shields will not prevent explosions, but they do retain glass fragments that might harm the chemist or others in the vicinity.

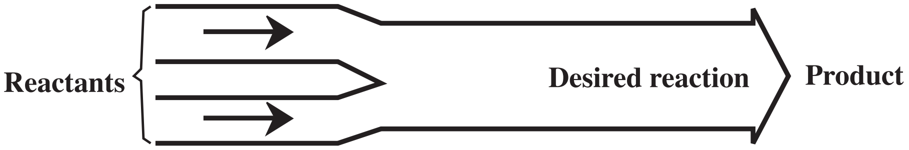
Reduction of exposure is unquestionably effective in preventing injury and harm. However, it does require constant vigilance and even nagging of personnel, as any laboratory instructor charged with making laboratory students wear their safety goggles at all times will attest. It does not protect the unprotected, such as a visitor who may walk bare-faced into a chemical laboratory ignoring the warnings for required eye protection. On a larger scale, protective measures may be very effective for workers in a chemical



(a) Typical reaction with less than 100% yield and with byproducts



(b) Reaction with 100% yield, but with byproducts inherent to the reaction



(c) Reaction with 100% atom economy, no leftover reactants, no byproducts

Figure 1.4. Illustration of percent yield and atom economy.

manufacturing operation but useless to those outside the area or the environment beyond the plant walls who do not have protection. Protective measures are most effective against acute effects, but less so against long-term chronic exposures that may cause toxic responses over many years period of time. Finally, protective equipment can fail and there is always the possibility that humans will not use it properly.

Where feasible, hazard reduction is a much more certain way of reducing risk than is exposure reduction. The human factors that play so prominently in successfully limiting exposure and that require a conscious, constant effort are much less crucial when hazards have been reduced. Compare, for example, the use of a volatile, flammable, somewhat toxic organic solvent used for cleaning and degreasing of machined metal parts with that of a water solution of a nontoxic cleaning agent used for the same purpose. To safely work around the solvent requires an unceasing effort and constant vigilance to avoid such hazards as formation of explosive mixtures with air, presence of ignition sources that could result in a fire, and excessive exposure by inhalation or absorption through skin that might cause peripheral neuropathy (a nerve disorder) in workers. Failure of protective measures can result in a bad accident or serious harm to worker health. The water-based cleaning solution, however, would not present any of these hazards so that failure of protective measures would not create a problem.

Normally, measures taken to reduce risk by reducing exposure have an economic cost that cannot be reclaimed in lower production costs or enhanced value of product. Of course, failure to reduce exposure can have direct, high economic costs in areas such as higher claims for worker compensation. In contrast, hazard reduction often has the potential to substantially reduce operating costs. Safer feedstocks are often less costly as raw materials. The elimination of costly control measures can lower costs overall. Again, to use the comparison of an organic solvent compared to a water-based cleaning solution, the organic solvent is almost certain to cost more than the aqueous solution containing relatively low concentrations of detergents and other additives. Whereas the organic solvent will at least require purification for recycle and perhaps even expensive disposal as a hazardous waste, the water solution may be purified by relatively simple processes, and perhaps even biological treatment, then safely discharged as wastewater to a municipal wastewater treatment facility. It should be kept in mind, however, that not all low-hazard materials are cheap, and may be significantly more expensive than their more hazardous alternatives. And, in some cases, nonhazardous alternatives simply do not exist.

1.8. THE RISKS OF NO RISKS

There are limits to the reduction in risk beyond which efforts to do so become counterproductive. As in other areas of endeavor, there are circumstances in which there is no choice but to work with hazardous substances. Some things that are inherently dangerous are rendered safe by rigorous training, constant attention to potential hazards, and understanding of hazards and the best way to deal with them. Consider the analogy of commercial flight. When a large passenger aircraft lands, 100 tons of aluminum, steel, flammable fuel, and fragile human flesh traveling at a speed of twice the legal interstate speed limits for automobiles come into sudden contact with an unforgiving concrete runway. That procedure is inherently dangerous! But it is carried out millions of times per year throughout the world with but few injuries and fatalities, a tribute to the generally superb design, construction, and maintenance of aircraft and the excellent skills and training of aircrew. The same principles that make commercial air flight generally safe also apply to the handling of hazardous chemicals by properly trained personnel under carefully controlled conditions.

So, although much of this book is about risk reduction as it relates to chemistry, we must always be mindful of the risks of not taking risks. If we become so timid in all of our enterprises that we refuse to take risks, scientific and economic progress will stagnate. The U.S. space program is an example of an area in which progress has been made only by a willingness to take risks. However, progress has probably been slowed because of risk aversion resulting from previous accidents, especially the 1987 Challenger space shuttle tragedy. If we get to the point that no chemical can be made if its synthesis involves the use of a potentially toxic or otherwise hazardous substance, the progress of chemical science and the development of such beneficial products as new life-saving drugs or innovative chemicals for treating water pollutants may be held back. It may be argued that thermonuclear fusion entails significant risks as an energy source and that research on controlled thermonuclear fusion must therefore be stopped. But when that potential risk is balanced against the virtually certain risk of continuing to use fossil fuels that produce greenhouse gases that cause global climate warming, and it seems sensible to at least continue research on controlled thermonuclear fusion energy sources. Another example is the use of thermal processes for treating hazardous wastes, somewhat risky because of the potential for the release of toxic substances or air pollutants, but still the best way to convert many kinds of hazardous wastes to innocuous materials.

1.9. WASTE PREVENTION

Waste prevention is better than having to treat or clean up wastes. In the earlier years of chemical manufacture the direct costs associated with producing large quantities of wastes were very low because such wastes were simply discarded into waterways, onto the ground, or in the air as stack emissions. With the passage and enforcement of environmental laws after about 1970, costs for waste treatment increased steadily. General Electric has agreed to spend tens of millions of dollars to remove PCBs from Hudson River deposits that were discarded to the river as wastes from the company's manufacture of electrical equipment. DuPont is paying up to $600 million as settlement for environmental damage caused by the production of Teflon and Gore-Tex. The cleanup of pollutants including asbestos, dioxins, pesticide manufacture residues, perchlorate and mercury are costing various concerns hundreds of millions of dollars. From a purely economic standpoint, therefore, a green chemistry approach that avoids these costs is very attractive, in addition to its large environmental benefits. By the year 2000 in the United States, costs of complying with environmental and occupational health regulations had grown to a magnitude similar to that of research and development for industry as a whole.

Although the costs of such things as engineering controls, regulatory compliance, personnel protection, wastewater treatment, and safe disposal of hazardous solid wastes have certainly been worthwhile for society and the environment, they have become a large fraction of the overall cost of doing business. Companies must now do **full cost accounting**, taking into full account the costs of emissions, waste disposal, cleanup, and protection of personnel and the environment, none of the proceeds of which go into the final product.

1.10. BASIC PRINCIPLES OF GREEN CHEMISTRY

From the preceding discussion, it should be obvious that there are certain basic principles of green chemistry. Some publications recognize "the twelve principles of green chemistry."[2] This section addresses the main ones of these.

As anyone who has ever spilled the contents of a food container onto the floor well knows, it is better to not make a mess than to clean it up once made. As applied to green chemistry, this basic rule means that *waste prevention is much better than waste cleanup*. Failure to follow this simple rule has resulted in most of the troublesome hazardous waste sites that are causing problems throughout the world today.

One of the most effective ways to prevent generation of wastes is to make sure that insofar as possible *all materials involved in making a product should be incorporated into the final product*. Therefore, the practice of green chemistry is largely about incorporation of all raw materials into the product, if at all possible. We would not likely favor a food recipe that generated a lot of inedible byproduct. The same idea applies to chemical processes. In that respect, the concept of atom economy discussed in Section 1.6 is a key component of green chemistry.

The use or generation of substances that pose hazards to humans and the environment should be avoided. Such substances include toxic chemicals that pose health hazards to workers. They include substances that are likely to become air or water pollutants and harm the environment or organisms in the environment. Here the connection between green chemistry and environmental chemistry is especially strong.

Chemical products should be as effective as possible for their designated purpose, but with minimum toxicity. The practice of green chemistry is making substantial progress in designing chemicals and new approaches to the use of chemicals such that effectiveness is retained and even enhanced while toxicity is reduced.

Chemical synthesis as well as many manufacturing operations make use of auxiliary substances that are not part of the final product. In chemical synthesis, such a substance consists of solvents in which chemical reactions are carried out. Another example consists of separating agents that enable separation of product from other materials. Since these kinds of materials may end up as wastes or (in the case of some toxic solvents) pose health hazards, *the use of auxiliary substances should be minimized and preferably totally avoided*.

Energy consumption poses economic and environmental costs in virtually all synthesis and manufacturing processes. In a broader sense, the extraction of energy, such as fossil fuels pumped from or dug out of the ground, has significant potential to damage the environment. Therefore, *energy requirements should be minimized*. One way in which this can be done is through the use of processes that occur near ambient conditions, rather than at elevated temperature or pressure. One successful approach to this has been the use of biological processes, which, because of the conditions under which organisms grow, must occur at moderate temperatures and in the absence of toxic substances. Such processes are discussed further in Chapter 12.

Raw materials extracted from earth are depleting in that there is a finite supply that cannot be replenished after they are used. So, wherever possible, *renewable raw* *materials should be used instead of depletable feedstocks*. As discussed further in Chapter 12, biomass feedstocks are highly favored in those applications for which they work. For depleting feedstocks, recycling should be practiced to the maximum extent possible.

In the synthesis of an organic compound (see Chapter 5), it is often necessary to modify or protect groups on the organic molecule during the course of the synthesis. This often results in the generation of byproducts not incorporated into the final product, such as occurs when a protecting group is bonded to a specific location on a molecule, then removed when protection of the group is no longer needed. Since these processes generate byproducts that may require disposal, *the use of protecting groups in synthesizing chemicals should be avoided insofar as possible*.

Reagents should be as selective as possible for their specific function. In chemical language, this is sometimes expressed as a preference for selective catalytic reagents over nonselective stoichiometric reagents.

Products that must be dispersed into the environment should be designed to break down rapidly into innocuous products. One of the oldest, but still one of the best, examples of this is the modification of the surfactant in household detergents 15 or 20 years after they were introduced for widespread consumption to yield a product that is biodegradable. The poorly biodegradable surfactant initially used caused severe problems of foaming in wastewater treatment plants and contamination of water supplies. Chemical modification to yield a biodegradable substitute solved the problem.

Exacting "real-time" control of chemical processes is essential for efficient, safe operation with minimum production of wastes. This goal has been made much more attainable by modern computerized controls. However, it requires accurate knowledge of the concentrations of materials in the system measured on a continuous basis. Therefore, *the successful practice of green chemistry requires real-time, in-process monitoring techniques coupled with process control.*

Accidents, such as spills, explosions, and fires, are a major hazard in the chemical industry. Not only are these incidents potentially dangerous in their own right, they tend to spread toxic substances into the environment and increase exposure of humans and other organisms to these substances. For this reason, it is best to *avoid the use or generation of substances that are likely to react violently, burn, build up excessive pressures, or otherwise cause unforeseen incidents in the manufacturing process*.

The principles outlined above are developed to a greater degree in the remainder of the book. They should be kept in mind in covering later sections.

1.11. SOME THINGS TO KNOW ABOUT CHEMISTRY BEFORE YOU EVEN START

Chapters 2-5 explain the basic principles of chemistry as they relate to green chemistry. However, at this point, it is useful to have a brief overview of chemistry, in a sense a minicourse in chemistry that provides the basic definitions and concepts of chemistry such as chemical compounds, chemical formulas, and chemical reactions before they are covered in detail in the later chapters.

All chemicals are composed of fewer than 100 naturally-occurring fundamental kinds of matter called elements. Humans have succeeded in making about 30 artificial elements since the late 1930s, but the amounts of these are insignificant compared to the total of known chemicals. Elements, in turn, are composed of very small entities called atoms. Atoms of the same element may differ a bit in their masses, but all atoms of the same element behave the same chemically. So we can logically begin the study of chemistry with the atoms that make up the elements of which all matter is composed.

Each atom of a particular element is chemically identical to every other atom. Each element is given an atomic number specific to the element, ranging from 1 to more than 100. The atomic number of an element is equal to the number of extremely small, positively charged protons contained in the nucleus located in the center of each atom of the element. Each electrically neutral atom has the same number of electrons as it has protons. The electrons are negatively charged and are in rapid motion around the nucleus, constituting a cloud of negative charge that makes up most of the volume of the atom. In addition to its atomic number, each element has a name and a chemical symbol, such as carbon, C; potassium, K (for its Latin name kalium); or cadmium, Cd. In addition to atomic number, name, and chemical symbol, each element has an atomic mass (atomic weight). The atomic mass of each element is the average mass of all atoms of the element, including the various isotopes of which it consists; therefore, it is not a whole number.

1.12. COMBINING ATOMS TO MAKE MOLECULES AND COMPOUNDS

About the only atoms that exist alone are those of the noble gases, a group of elements including helium, neon, argon, and radon located on the far right of the periodic table. Even the simple hydrogen atom in the elemental state is joined together with another hydrogen atom. Two or more uncharged atoms bonded together are called a **molecule**. As illustrated in Figure 1.5, the hydrogen molecule consists of 2 hydrogen atoms as denoted by the chemical formula of elemental hydrogen, H_2. This formula states that a molecule of elemental hydrogen consists of 2 atoms of hydrogen, shown by the subscript of 2. The atoms are joined together by a chemical bond. Recall from Figure 1.1 that the hydrogen atom has 1 electron. But, hydrogen atoms are more "content" with 2 electrons. So two hydrogen atoms share their two electrons constituting the chemical bond in the hydrogen molecule. A bond composed of shared electrons called a **covalent bond**.

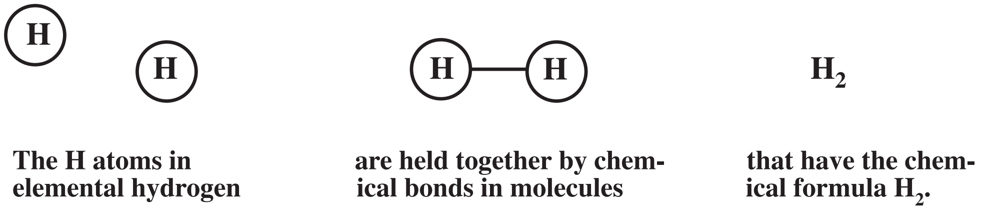
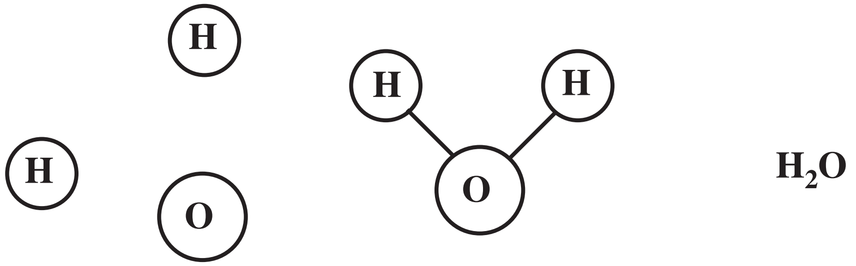


Figure 1.5. Molecule of H_2.

Chemical Compounds

The example just discussed was one in which atoms of the same element, hydrogen, join together to form a molecule. Most molecules consist of atoms of different elements joined together. An example of such a molecule is that of **water**, chemical formula H_2O. This formula states that the water molecule consists of *two* hydrogen atoms bonded to *one* oxygen atom, O, where the absence of a subscript number after the O indicates that there is 1 oxygen atom. The water molecule is shown in Figure 1.6. Each of the hydrogen atoms is held to the oxygen atom in the water molecule by two shared electrons in a covalent bond. A material such as water in which two or more elements are bonded together is called a **chemical compound**. It is because of the enormous number of combinations of two or more atoms of different elements that it is possible to make 20 million or more chemical compounds from fewer than 100 elements.



Hydrogen atoms and oxygen atoms bond together

To form molecules in which 2 H atoms are attached to 1 O atom.

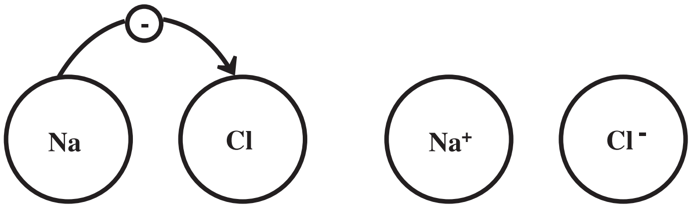
The chemical formula of the resulting compound, water, is H_2O.

Figure 1.6. A molecule of water, H_2O, formed from 2 H atoms and 1 O atom held together by chemical bonds.

Ionic Bonds

Two different molecules have just been discussed in which atoms are joined together by *covalent bonds* consisting of *shared* electrons. Another way in which atoms can be joined together is by *transfer* of electrons from one atom to another. Recall that a single *neutral* atom has an equal number of electrons and protons. But, if the atom loses one or more negatively charged electrons, it ends up with a net *positive* electrical charge and the atom becomes a positively charged **cation**. An atom that has gained one or more negatively charged electrons attains a net *negative* charge and is called an **anion**. Cations and anions are attracted together in an **ionic compound** because of their opposite electrical charges. The oppositely charged ions are joined by **ionic bonds** in a **crystalline lattice**.

Figure 1.7 shows the best known ionic compound, sodium chloride, NaCl (common table salt). The chemical formula implies that there is 1 Na for each Cl. In this case these consist of Na^+ cations and Cl^- anions. For ionic compounds such as NaCl, the first



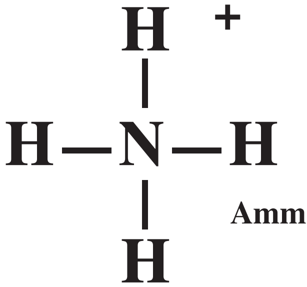
The transfer of a single negatively charged electron from a neutral sodium atom (Na) to a neutral chlorine atom (Cl)

produces a positively charged sodium cation and a negatively charged chloride anion.

Sodium cations held together with equal numbers of chloride anions by the attraction of their opposite charges (ionic bonds) constitute the ionic compound NaCl.

Figure 1.7. Ionic bonds are formed by the transfer of electrons and the mutual attraction of oppositely charged ions in a crystalline lattice.

part of the name is simply that of the metal forming the cation, in this case sodium. The second part of the name is based upon the anion, but has the ending *ide*. So the ionic compound of sodium and chlorine is magnesium chlor*ide*. As shown by the preceding example, ionic compounds may consist of ions composed of atoms that have lost electrons (producing positively charged cations) and other atoms that have gained electrons (producing negatively charged anions). However, ions may also consist of groups of several atoms with a net charge. Ammonium ion, NH_4^+, is such an ion. As shown below, the NH_4^+ cation consists of 4 H atoms covalently bonded (by 2 shared electrons) to a central N atom, with the group of 5 total atoms having a net electrical charge of +1.



$$\left[\begin{array}{c} H \\ | \\ H-N-H \\ | \\ H \end{array}\right]^+$$

Ammonium ion, NH_4^+

1.13. THE PROCESS OF MAKING AND BREAKING CHEMICAL BONDS: CHEMICAL REACTIONS

The preceding section has discussed chemical compounds and the two major kinds of bonds — covalent bonds and ionic bonds — that hold them together. Next is discussed the process of making and taking apart chemical compounds, **chemical reactions**. A chemical reaction occurs when chemical bonds are broken and formed and atoms are exchanged to produce chemically different species.

First consider two very simple chemical reactions involving only one element, oxygen. In the very thin air high in the stratosphere more than 10 kilometers above Earth's surface (above the altitudes where jet airliners normally cruise), high-energy ultraviolet radiation from the sun, represented by the symbol $h\nu$, splits apart molecules of elemental oxygen, O_2,

$$O_2 + h\nu \rightarrow 2O \tag{1.13.1}$$

to produce oxygen atoms. As with most single atoms, the O atoms are reactive and combine with oxygen molecules to produce ozone, O_3:

$$O + O_2 \rightarrow O_3 \tag{1.13.2}$$

Both of these processes are chemical reactions. In a chemical reaction, the substances on the left of the arrow (read as "yields") are the **reactants** and those on the right of the arrow are **products**. The first of these reactions states that the chemical bond holding together a molecule of O_2 *reactant* is split apart by the high energy of the ultraviolet radiation to produce two oxygen atom *products*. In the second reaction, an oxygen atom reactant, O, and an oxygen molecule reactant, O_2, form a chemical bond to yield an ozone product, O_3. Are these very simple chemical reactions important to us? Emphatically yes. They produce a shield of ozone molecules in the stratosphere which in turn absorb ultraviolet radiation that otherwise would reach Earth's surface, destroying life, causing skin cancer and other maladies that would make our existence on Earth impossible. As discussed in Chapter 8, the use of chlorofluorocarbon refrigerants (Freons) has seriously threatened the stratospheric ozone layer. It is a triumph of environmental chemistry that this threat was realized in time to do something about it and an accomplishment of green chemistry to develop relatively safe substitutes for ozone-threatening chemicals.

Many chemical reactions are discussed in this book. At this point a very common chemical reaction can be considered, that of elemental hydrogen with elemental oxygen to produce water. A first approach to writing this reaction is

$$H_2 + O_2 \rightarrow H_2O \tag{1.13.3}$$

stating that elemental hydrogen and elemental oxygen react together to produce water. This is not yet a proper *chemical equation* because it is not balanced. A **balanced chemical equation** has the same number of each kind of atom on both sides of the equation. As shown above, there are 2 H atoms in the single H_2 molecule on the left and 2 H atoms in the single molecule H_2O product. That balances hydrogen, but leaves 2 O atoms in the O_2 molecule on the left with only 1 O atom in the single H_2O molecule product. But, writing the reaction as

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1.13.4}$$

gives a balanced chemical equation with a total of 4 H atoms in 2 H_2 molecules on the left, 4 H atoms in 2 H_2O molecules on the right, and a total of 2 O atoms in the 2 H_2O molecules on the right, which balances the 2 O atoms in the O_2 molecule on the left. So the equation as now written is *balanced*. A **balanced** chemical equation always has the same number of each kind of atom on both sides of the equation.

1.14. THE NATURE OF MATTER AND STATES OF MATTER

We are familiar with matter in different forms. We live in an atmosphere of gas that is mostly N_2 with about 1/4 as much oxygen, O_2, by volume. We only become aware of this gas when something is wrong with it, such as contamination by irritating air pollutants. A person stepping into an atmosphere of pure N_2 would not notice anything wrong immediately, but would die within a few minutes, not because N_2 is toxic, but because the atmosphere lacks life-giving oxygen. The same atmosphere that we breathe contains water in the gas form as water vapor. And we are also familiar, of course, with liquid water and with solid ice.

The air that we breathe, like most substances, is a **mixture** consisting of two or more substances. Air is a **homogeneous mixture** meaning that the molecules of air are mixed together at a molecular level. There is no way that we can take air apart by simple mechanical means, such as looking at it under a magnifying glass and picking out its individual constituents. Another common substance that is a homogeneous mixture is drinking water, which is mostly H_2O molecules, but which also contains dissolved O_2 and N_2 from air, dissolved calcium ions (Ca^{2+}), chlorine added for disinfection, and other materials.

A **heterogeneous mixture** is one that contains discernable and distinct particles that, in principle at least, can be taken apart mechanically. Concrete is a heterogeneous mixture. Careful examination of a piece of broken concrete shows that it contains particles of sand and rock embedded in solidified Portland cement.

A material that consists of only one kind of substance is known as a **pure substance**. Absolutely pure substances are almost impossible to attain. Hyperpure water involved in semiconductor manufacturing operations approaches absolute purity. Another example is 99.9995% pure helium gas used in a combination gas chromatograph/mass spectrometer instrument employed for the chemical analysis of air and water pollutants.

Mixtures are very important in the practice of green chemistry. Among other reasons why this is so is that separation of impurities from mixtures in the processing of raw materials and in recycling materials is often one of the most troublesome and expensive aspects of materials utilization. Impurities may make mixtures toxic. For example, toxic arsenic, which is directly below phosphorus in the periodic table and has chemical properties similar to phosphorus, occurs as an impurity in the phosphate ores from which elemental phosphorus is extracted. This is not a problem for phosphorus used as fertilizer because the small amount of arsenic added to the soil is negligible compared to the arsenic naturally present in the soil. But, if the phosphorus is to be made into phosphoric acid and phosphate salts to be added to soft drinks or to food, impurity arsenic cannot be tolerated because of its toxicity requiring removal of this element at considerable expense.

Many byproducts of manufacturing operations are mixtures. For example, organochlorine solvents used to clean and degrease machined parts are mixtures that contain grease and other impurities. As part of the process for recycling these solvents, the impurities must be removed by expensive processes such as distillation. The separation of mixture constituents is often one of the most expensive aspects of the recycling of materials.

States of Matter

The three common states of matter are gases, liquids, and solids. These are readily illustrated by water, the most familiar form of which is liquid water. Ice is a solid and water vapor in the atmosphere or in a steam line is a gas.

Gases, such as those composing the air around us, are composed mostly of empty space through which molecules of the matter composing the gas move constantly, bouncing off each other or the container walls millions of times per second. A quantity of gas expands to fill the container in which it is placed. Because they are mostly empty space, gases can be significantly **compressed**; squeeze a gas and it responds with a decreased volume. Gas **temperature** is basically an expression of the tendency of the gas molecules to move more rapidly; higher temperatures mean faster molecular movement and more molecules bounding off each other or container walls per second. The constant impact of gas molecules on container walls is the cause of gas **pressure**. Because of the free movement of molecules relative to each other and the presence of mostly empty space, a quantity of gas takes on the volume and shape of the container in which it is placed. The physical behavior of gases is described by several gas laws relating volumes of gas to quantities of the gas, pressure, and temperature. Calculations involving these laws are covered at the beginning of Chapter 8.

Molecules of **liquids** can move relative to each other, but cannot be squeezed together to a significant extent, so liquids are not compressible. Liquids do take on the shape of the part of a container that they occupy. Molecules of **solids** occupy fixed positions relative to each other. Therefore, solids cannot be significantly compressed and retain their shapes regardless of the container in which they are placed.

LITERATURE CITED

1. Manahan, Stanley E., *Environmental Chemistry*, 8th ed., CRC Press/Lewis Publishers, Boca Raton, FL, 2004.

2. Anastas, Paul T., and John C. Warner, *Green Chemistry Theory and Practice*, Oxford University Press, 1998.

QUESTIONS AND PROBLEMS

1. What is chemistry? Why is it impossible to avoid chemistry?
2. What is green chemistry?
3. Match the following pertaining to major areas of chemistry:

A. Analytical chemistry	1. Occurs in living organisms
B. Organic chemistry	2. Underlying theory and physical phenomena
C. Biochemistry	3. Chemistry of most elements other than carbon
D. Physical chemistry	4. Chemistry of most carbon-containing compounds
E. Inorganic Chemistry	5. Measurement of kinds and quantities of chemicals

4. What are the five environmental spheres? Which of these did not exist before humans evolved on Earth?
5. Discuss why you think the very thin “skin” of Earth ranging from perhaps two or three kilometers in depth to several kilometers (several miles) in altitude has particular environmental importance.
6. What is environmental chemistry?
7. Which event may be regarded as the beginning of the modern environmental movement?
8. What is the command and control approach to pollution control?
9. What is the Toxics Release Inventory, TRI. How does it reduce pollution?
10. Why is the command and control approach to pollution control much less effective now than it was when pollution control laws were first enacted and enforced?
11. What is the special relationship of green chemistry to synthetic chemistry?
12. What does Figure 1.1 show?
13. In which important respects is green chemistry sustainable chemistry?
14. With respect to raw materials, what are two general and often complementary approaches to the practice of green chemistry?
15. What is the distinction between yield and atom economy?
16. What is shown by Figure 1.4?
17. What are two factors that go into assessing risk?

18. What are the risks of no risks?
19. What are the major basic principles of green chemistry?
20. What is shown by the formula O_3? What about H_2O_2?
21. How does a covalent bond differ from an ionic bond?
22. What is the name given to a material in which two or more different elements are bonded together?
23. Considering the compound shown in Figure 1.7, what is the name of Na_2O?
24. Summarize the information given by $3H_2 + O_3 \rightarrow 3H_2O$.
25. In addition to showing the correct reactants and products, a correct chemical equation must be ____.
26. Name three kinds of matter based upon purity. Which of these is extremely rare?
27. In terms of molecules, how are gases, liquids, and solids distinguished?
28. Describe gas pressure and temperature in terms of molecular motion.

14 THE TEN COMMANDMENTS OF SUSTAINABILITY

14.1. WE CANNOT GO ON LIKE THIS

In 1968 the Stanford University biologist Paul Ehrlich published a book entitled *The Population Bomb*,[1] a pessimistic work that warned Earth had reached its population carrying capacity sometime in the past and that catastrophe loomed. Ehrlich predicted rapid resource depletion, species extinction, grinding poverty, starvation, and a massive dying of human populations in the relatively near future. "Not so," retorted Julian Simon (deceased) a University of Maryland economist writing in a number of books, the most recent of which is titled *Hoodwinking the Nation*.[2] Ehrlich hedged his views by stating that he might be wrong and that "some miraculous change in human behavior" or a "totally unanticipated miracle" might "save the day." Simon expressed the view that Ehrlich's doom and gloom views were nonsense and that human ingenuity would overcome the problems foreseen by him.

The debate between Ehrlich and Simon led to a famous wager by Simon in 1980 that $200 worth of each of five raw materials chosen by Ehrlich — copper, chromium, nickel, tin and tungsten — would actually decrease in price over the next 10 years in 1980 dollars. Each did in fact decrease in price and Ehrlich paid. Simon then offered to raise the ante to $20,000, a proposition that Ehrlich declined. This incident is often cited by anti-environmentalists as evidence that we will never run out of essential resources and that a way will always be found to overcome shortages.

However, common sense dictates that Earth's resources are finite. Whereas unexpected discoveries, ingenious methods for extracting resources, and uses of substitute materials will certainly extend resources, a point will inevitably be reached at which no more remains and modern civilization will be in real trouble.

Unfortunately, the conventional economic view of resources often fails to consider the environmental harm done in exploiting additional resources. Fossil fuels provide an excellent example. As of 2005, there was ample evidence that world petroleum resources were strained as prices for petroleum reached painfully high levels. This has resulted in a flurry of exploration activities including even drilling in some cemeteries! Natural gas supplies have been extended by measures such as tapping coal seams for their gas content, often requiring pumping of large quantities of alkaline water from the seams and release of the polluted water to surface waters. There is no doubt that liquid and gaseous fossil fuel supplies could be extended by decades using coal liquefaction and gasification and extraction of liquid hydrocarbons from oil shale. But these measures would cause major environmental disruption from coal mining and processing, production of salt-laden oil shale ash, and release of greenhouse gases.

The sad fact is that on its present course humankind will deplete Earth's resources and damage its environment to an extent that conditions for human existence on the planet will be seriously compromised or even become impossible. There is ample evidence that in the past civilizations have declined and entire populations have died out because key environmental support systems were degraded.[3] A commonly cited example is that of the Easter Islands where civilizations once thrived and the people erected massive stone statues that stand today. The populations of these islands vanished and it is surmised that the cause was the denuding of once abundant forests required to sustain human life on the islands. A similar thing happened to pre-Columbian Viking civilizations in Greenland, where 3 centuries of unusually cold weather and the Vikings' refusal to adopt the ways of their resourceful Inuit neighbors were contributing factors to their demise. Iceland almost suffered a similar fate, but the people learned to preserve their support systems so that Iceland is now a viable country.

Fortunately, modern civilizations have the capacity to avoid the fates of the ancient Easter Islanders and Greenland Vikings — if they can muster the will and the institutional framework to do so. The key is **sustainability**, which simply means living in ways that do not deplete Earth's vital support systems. The great challenges to sustainability are (1) population growth beyond Earth's carrying capacity, (2) potentially disruptive changes in global climate, (3) provision of adequate food, (4) depletion of Earth's resources, (5) supply of adequate energy, and (6) contamination of Earth's environment with toxic and persistent substances. It won't be easy to overcome these challenges and achieve sustainability and it is by no means certain that humankind will ultimately succeed or even survive on Earth. But we have to try; the alternative of a world population reduced to just a few million people surviving in poverty and misery on a sadly depleted planet under conditions hostile to higher life forms is too grim to contemplate.

The achievement of sustainability will require adherence to some important principles. These can be condensed into **ten commandments of sustainability**, which are listed below:

1. Human welfare must be measured in terms of quality of life, not just acquisition of material possessions, which demands that economics, governmental systems, creeds, and personal life-styles must consider environment and sustainability.

2. Since the burden upon Earth's support system is given by the relationship

Burden = (number of people)×(demand per person)

it is essential to address both numbers of people on Earth and the demand that each puts on Earth's resources.

3. Given that even at the risk of global catastrophe, *technology will be used* in attempts to meet human needs, it is essential to acknowledge the anthrosphere as one of the five basic spheres of the environment and to design and operate it with a goal of zero environmental impact and maximum sustainability.
4. Given that energy is a key to sustainability, the development of efficiently-used, abundant sources of energy that have little or no environmental impact is essential.
5. Climate conducive to life on Earth must be maintained and acceptable means must be found to deal with climate changes that inevitably occur.
6. Earth's capacity for biological and food productivity must be maintained and enhanced, considering all five environmental spheres.
7. Material demand must be drastically reduced; materials must come from renewable sources, be recyclable and, if discarded to the environment, be degradable
8. The production and use of toxic, dangerous, persistent substances should be minimized and such substances should not be released to the environment; any wastes disposed to disposal sites should be converted to nonhazardous forms.
9. It must be acknowledged that there are risks in taking no risks.
10. Education in sustainability is essential; it must extend to all ages and strata of society, it must be promulgated through all media, and it is the responsibility of all who have expertise in sustainability.

Each of the ten commandments of sustainability is discussed in the remaining sections of this Chapter.

14.2. THE FIRST COMMANDMENT: HUMAN WELFARE MUST BE MEASURED IN TERMS OF QUALITY OF LIFE, NOT JUST ACQUISITION OF MATERIAL POSSESSIONS, WHICH DEMANDS THAT ECONOMICS, GOVERNMENTAL SYSTEMS, CREEDS, AND PERSONAL LIFE-STYLES MUST CONSIDER ENVIRONMENT AND SUSTAINABILITY.

This commandment goes to the core question of, "What is happiness?" Many people have come to measure their happiness in terms of material possessions—the larger sport utility vehicle, the bigger house on a more spacious lot farther from the city, more and richer food. But such measures of human welfare based upon the accumulation of more stuff has come at a high cost to Earth as a whole and even to the people who acquire the most stuff. The sport utility vehicle guzzles fuel from steadily decreasing petroleum supplies, commodious houses require more energy to heat and cool, large lots remove increasingly scarce farm land from food production, dwellings far from the workplace mean long commutes that consume time and fuel, and too many of the current generation of humans have consumed food to a state of unhealthy obesity.

The things that really count for happiness — good health, good nutrition, physical comfort, satisfying jobs, good interpersonal relations, interesting cultural activities — can be had with much less consumption of materials and energy than is now the case in wealthier societies. In order for sustainability to be achieved, it is essential for societies to recognize that happiness and well-being are possible with much less consumption of materials and energy.

Environmental and Sustainability Economics

Conventional neoclassical (Newtonian) market economics have not adequately considered resource and environmental factors in the overall scheme of economics. Since about 1970, however, environmental and natural resource economics has developed as a viable discipline.[4] This discipline, commonly called **environmental economics** addresses the failure of a strictly market economy to deal with scarcity and to address environmental problems. Much more complex than neoclassical economics, environmental economics addresses sustainability issues, resource economics, pollution costs, costs and benefits of pollution control, and the value of natural capital. Economic instruments can be powerful influences in reducing pollution and extending resources. The conventional market economy does act to extend resources. For example, as petroleum prices increase to painfully high levels, the rate at which consumption increases is diminished. Artificial market intervention can act to thwart such a desirable income. For example, U.S. government subsidies of biomass-based ethanol and biodiesel fuels contribute to increased stress on agricultural resources requiring increased amounts of fertilizers and fuel to grow the extra grain required to produce grain-based fuels.

Economic measures can be used to reduce pollution and demand on resources. Carbon and energy taxes can be imposed to reduce emissions of greenhouse gas carbon. Pollution trading has evolved as an effective pollution control measure. In the case of greenhouse gas carbon dioxide, for example, a utility installing a new coal-fired power plant may pay another concern to do reforestation projects that take an equivalent amount of carbon dioxide from the atmosphere.

More difficult to quantify, but no less real, are environmental amenities. There are certainly costs associated with impaired air quality in terms of increased respiratory disease and damage to buildings. In principle, such costs are quantifiable. Much more difficult to quantify are the value of a beautiful scenic view or the costs of eyesore billboard clutter.

A major issue with environmental economics is that of expenditures in the public sector versus those in the private sector. Free market capitalism is a powerful force in providing goods and services and in promoting innovation. Dismal past failures of planned economies and subsequent growth of these economies after they were converted to free market systems — China is probably the most striking example — illustrate the power of market forces. However, much of what is needed for sustainable development requires investment in the public sector, especially in infrastructure. The central challenge for economic systems in the future will be to integrate essential development in the public sector with free market forces. Both are essential in order for sustainable economic systems to flourish.

The Role of Governments

Sustainability will require the strong involvement of governments at all levels and extending across international boundaries. At local levels ordinances and regulations that promote sustainability are essential. For example, there are many cases in which local governments have set up recycling programs for paper, plastic, glass, and metals to reduce the need to dispose of solid wastes. In many cases only national governments have the power and authority to undertake massive projects and to promote changes required for sustainability. Since sustainability is a global concern, ways must be found to enable governmental action and cooperation among nations.

An essential part of the role of government in sustainability is the quality of government and the people involved in it as well as the public perception of government. "Government bashing" is fashionable in many circles, and in some cases is even richly deserved. However, in order for sustainability to succeed, the finest minds that societies have must be willing to enter government service and their contributions must be respected by the public.

Personal Life Styles and Value Systems

The achievement of sustainability will require an unprecedented commitment from individuals. This may well be the most difficult of all objectives to achieve. Many people seem to have an insatiable appetite for possessions and activities that consume large amounts of materials and energy. Nothing illustrates this better than the private automobile; most teenagers find the wait to get their driver's licenses excruciatingly long and senior citizens dread the day when they are no longer able to drive.

Although people in developed countries are commonly accused of being too materialistic, populations in less developed countries have the same desires for material possessions. Some of the greatest environmental and resource impacts occur when the economies of less developed nations improve to the point that large numbers of their citizens can afford more of the things and services that prosperity, conventionally defined, offers. For example, as of 2005, the fastest growing market for automobiles was in China as its economy grew.

The achievement of sustainability will require that individuals adopt sustainability as part of their belief systems. Indeed, it would be very helpful if environmental protection and the preservation of Mother Earth and her limited resources were to become virtually a religion or to be incorporated into existing religions. In this respect, some of the more primitive of Earth's tribes had belief systems that were much more consistent with sustainability than the predominant religions of today. In some pre-Columbian Native American cultures, Earth and nature were worshipped, a belief system that could well serve as an example to current denizens of the globe. There is some evidence that modern religions are beginning to consider sustainability as a moral issue. One example is the movement, "What would Jesus drive?," that preaches that pollution from vehicles significantly impacts human health, peace and security are threatened by reliance on imported oil from politically unstable regions, and, therefore, Jesus would not likely drive a fuel guzzling sport utility vehicle!

14.3. THE SECOND COMMANDMENT: GIVEN THAT THE BURDEN UPON EARTH'S SUPPORT SYSTEM IS THE PRODUCT OF NUMBER OF PEOPLE TIMES DEMAND PER PERSON, IT IS ESSENTIAL TO ADDRESS BOTH NUMBERS OF PEOPLE ON EARTH AND THE DEMAND THAT EACH PUTS ON EARTH'S RESOURCES.

The burden placed upon Earth's support systems can be expressed by the equation

$$\text{Burden} = (\text{Number of people}) \times (\text{Demand per person}) \qquad (14.3.1)$$

This equation shows that both the number of people and the demand that each puts on Earth's resources must be considered in reducing the impact of humans on Earth. Both must be addressed to achieve sustainability.

As of 2005, Earth's human population stood at approximately 6.5 billion people and that of the U.S. at approximately 295 million people. These are staggering numbers to be sure. However, the good news is that these numbers are not nearly so high as those from projections made 40 or 50 years earlier. Even in developing countries, birth rates have fallen to much lower levels than expected earlier. Particularly in Italy, Spain, France, and other nations in Europe, birth rates have fallen to much below the replacement level and there is concern over depopulation and the social and economic impacts of depleted, aging populations. Even in the U.S., the birth rate has fallen below replacement levels and population growth that is taking place is the result of immigration. The increase in world population that has occurred over the last half century has been more due to decreasing death rates than to increasing birth rates. One U.N. official opined that, "It is not so much that people started reproducing like rabbits that they stopped dying like flies!" Although these trends do not provide room for complacency — explosive population growth could resume — they are encouraging and give hope that the first factor in Equation 14.3.1 may be controlled.

The second factor in the above equation, demand per person, may prove to be more intractable. A reasonable indicator of demand is reflected in the amount of carbon emitted per person each year, which reflects fossil fuel consumption as shown for several major countries in Figure 14.1. This figure shows that the more industrially developed countries emit the most per capita. However, the two countries with the largest populations, China and India, have much lower carbon emissions per person. As the economies of these two giants grow, demand for material goods and energy-consuming services will grow as well. For example, if the living standard of the citizens of China were to reach the average of those of Mexico, a country with a minimal living standard, world petroleum consumption would have to double under conventional economic systems. Were the average person in China to live like the average person in the U.S., an impossible burden

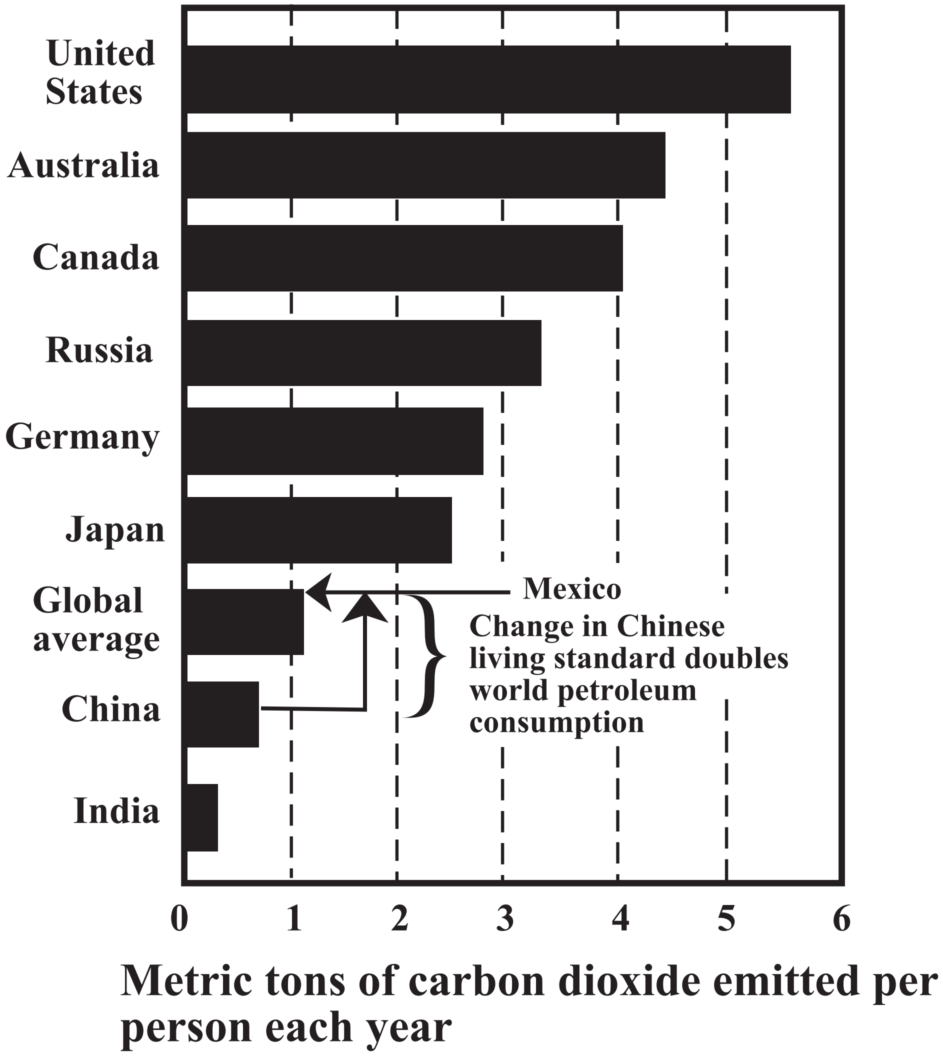


Figure 14.1. Per capita emissions of carbon dioxide per year in some major countries. The data shown are from 2004.

would be placed on Earth's carrying capacity. Obviously, ways must be found to meet the basic resource demands per person in more developed countries and means found to deliver a high quality of life to residents of less developed countries without placing unsupportable demands on Earth's resources.

Figure 14.1 illustrates another point regarding the relationship of population and consumption per capita, that the addition of population to more developed countries has a much greater impact on resources than it does to less developed nations. Taking per capita carbon emissions as a measure of impact, it can be seen that the addition of one person to the U.S. population has *at least 10 times* the impact as adding one person to India's population. It may be inferred that immigration into the U.S. and other developed countries from less highly developed nations has an inordinate impact upon resources as the immigrants attain the living standards of their new countries.

14.4. THE THIRD COMMANDMENT: GIVEN THAT EVEN AT THE RISK OF GLOBAL CATASTROPHE, *TECHNOLOGY WILL BE USED* IN ATTEMPTS TO MEET HUMAN NEEDS, IT IS ESSENTIAL TO ACKNOWLEDGE THE ANTHROSPHERE AS ONE OF THE FIVE BASIC SPHERES OF THE ENVIRONMENT AND TO DESIGN AND OPERATE IT WITH A GOAL OF ZERO ENVIRONMENTAL IMPACT AND MAXIMUM SUSTAINABILITY.

One of the most counterproductive attitudes of some environmentalists is a hostility to technology and to technological solutions to environmental problems. Humans are simply not going to go back to living in caves and teepees. Technology is here to stay. And even recognizing that the misuse of technology could result in catastrophe, *it will be used* to attempt to fulfill human needs. To deny that is unrealistic and foolish.

So a challenge for modern humankind is to use technology in ways that do not irreparably damage the environment and deplete Earth's resources. In so doing it is essential to recognize the anthrosphere — structures and systems in the environment designed, constructed, and modified by humans — as one of the five main spheres of the environment. Some of the major parts of the anthrosphere are shown in Figure 14.2.

A key to sustainability is reorientation of the anthrosphere so that (1) it does not detract from sustainability and (2) it makes a contribution to sustainability. There is enormous potential for improvement in both of these areas.

Much is already known about designing and operating the anthrosphere so that it does not detract from sustainability. This goal can be accomplished through applications of the principles of industrial ecology discussed in Chapter 11. Basically, the anthrosphere must be operated so that maximum recycling of materials occurs, the least possible amount of wastes are generated, the environment is not polluted, and energy is used most efficiently. Furthermore, to the maximum extent possible, materials and energy must come from renewable sources.

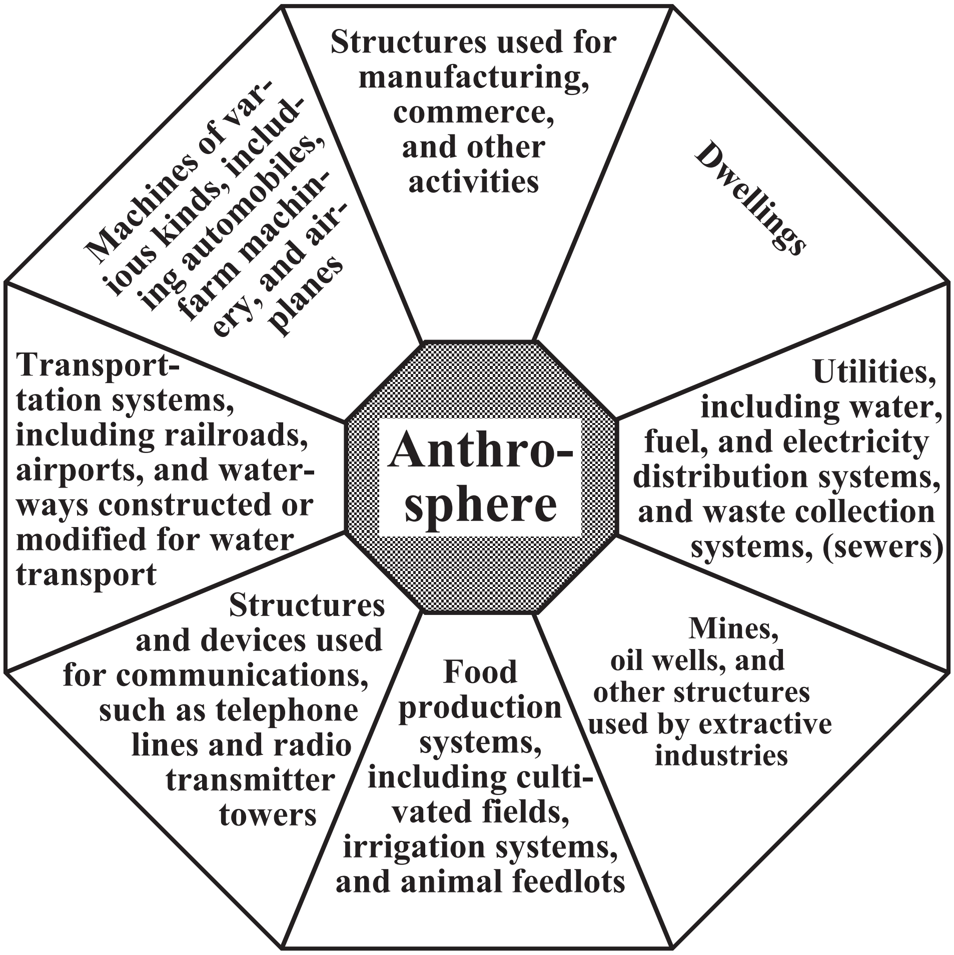


Figure 14.2. The anthrosphere is a multifaceted system designed and constructed by humans.

The anthrosphere can be designed and operated in a positive way to improve and enhance the other environmental spheres. For example, modern earth-moving equipment with its capacity to move enormous amounts of material, though largely used in the past in ways that harmed the environment, can be employed positively to modify the geosphere surface in ways that will enhance the biosphere. Some specific examples of things that can be done are the following:

- Restoration of topsoil in areas depleted of this resource by poor farming practices or by contamination by wastes and pollutants
- Construction of wetlands that can serve to restore wastewater to a quality enabling its release to the environment
- Terracing land to prevent water erosion of soil
- Pumping water underground to restore depleted aquifers

- Construction of impoundments for water
- Addition of “meanders” to streams, some of which have been unwisely straightened in the past, to reduce erosion and flooding
- Dredging of sediments from bodies of water and sediments to restore conditions conducive to aquatic life
- Construction and operation of reverse osmosis plants to remove excess salt from irrigation waters
- Construction of electrified railroads to replace inefficient, resource intensive, environmentally damaging truck transport

14.5. THE FOURTH COMMANDMENT: GIVEN THAT ENERGY IS A KEY TO SUSTAINABILITY, THE DEVELOPMENT OF EFFICIENTLY-USED, ABUNDANT SOURCES OF ENERGY THAT HAVE LITTLE OR NO ENVIRONMENTAL IMPACT IS ESSENTIAL.

With enough energy almost anything is possible. Toxic organic matter in hazardous waste substances can be totally destroyed and any remaining elements can be reclaimed or put into a form in which they cannot pose any hazards. Wastewater from sewage can be purified to a form in which it can be reused as drinking water. Pollutants can be removed from stack gas. Essential infrastructure can be constructed.

The accomplishment of sustainability is impossible without the development of efficient, sustainable, nonpolluting sources of energy. Here lies the greatest challenge to sustainability because the major energy sources used today and based on fossil fuels are inefficient, unsustainable, and, because of the threat to world climate from greenhouse gases, threaten Earth with a devastating form of pollution. Alternatives must be developed.

Fortunately, alternatives are available to fossil fuels, given the will to develop them. Most renewable energy sources are powered ultimately by the sun. The most direct use of solar energy is solar heating. Solar heating of buildings and of water has been practiced increasingly in recent decades and should be employed wherever possible. The conversion of solar energy to electrical energy with photovoltaic cells is feasible and also practiced on an increasing scale. At present, electricity from this source is more expensive than that from fossil fuel sources, but solar electricity is gradually coming down in price and is already competitive in some remote locations far from power distribution grids. A tantalizing possibility is direct solar conversion of water to hydrogen and oxygen gases. Hydrogen can be used in fuel cells and oxygen has many applications, such as in gasification of biomass discussed below.

Wind energy has emerged as a somewhat surprising alternative to fossil fuels and is now competitive in price in many areas. There are numerous geographical locations that are suitable for installation of large aerogenerators, which are to be found increasingly in

Europe, particularly in Denmark and Germany. In the U.S., areas of California, Kansas, and West Texas are particularly well adapted to the installation of wind generating facilities. Some people regard the tall, graceful aerogenerators as ugly, but they are certainly not as ugly as the landscape will become if massive climate warming occurs.

There is one big problem common to solar and wind energy: their intermittent nature. Solar energy works poorly when the sun does not shine and wind energy fails when the wind does not blow (although modern aerogenerators function at remarkably low wind speeds). Therefore, it is necessary to have reliable means of energy storage to provide for an even energy flow. For small installations, the means of energy storage is the lead storage battery, but these would be impractical on the large scale of an entire power grid. Pumped water storage is a known technology in which electrically-powered pumps drive water to an elevated reservoir when electricity is available, then use it to run through turbines hooked to generators when electricity is not being generated from the source. Energy can also be stored in the momentum of large flywheels spinning at extremely high speeds on virtually friction-free air-lubricated bearings. Another means of getting steady supplies of energy from intermittent sources is to use electricity to electrolyze water to elemental hydrogen and oxygen as noted in the discussion of photovoltaic electricity above.

Vast amounts of energy can be harvested from moving water. Hydroelectric installations throughout the world provide significant fractions of total electricity. Water power harvested from the hydrologic cycle is actually another means of utilizing solar energy because the water is pumped through the cycle by energy from the sun (see Figure 7.3). Although conventional hydroenergy is a significant contributor to world energy supplies, it probably cannot be developed further without causing unacceptable environmental effects, particularly from dam construction on free-flowing rivers. Indeed, because of their adverse environmental effects, many hydroelectric installations should be dismantled allowing the rivers on which they are located to flow freely again.

Another source of energy from moving water is that from tides, changing levels of sea water resulting from the gravitational pull of the sun and moon. Tidal energy is feasible as demonstrated by the 240 megawatt tidal power station that has operated reliably in the Rance estuary region of France since it was constructed in 1966. This facility has about 1/4 the capacity of a standard 1,000 MW coal-fired or nuclear plant. Several other small installations have been built including an 18 MW experimental unit at Annapolis Royal, Canada. Tidal electricity generating stations suffer from the disadvantage that sufficient water flows to generate electricity only about 10 hours per day. Nevertheless, the amount of energy potentially available from tides is enormous and it is completely renewable.

Nuclear energy is a source of continuous power that does not contribute to greenhouse warming. It has the advantage of being a proven technology that has contributed substantial amounts of electricity in some nations for several decades. Many U.S. Navy submarines and ships are powered by nuclear reactors, some of which are scheduled to serve for 28 years before requiring refueling! None of the reactors in the U.S. fleet has ever suffered a malfunction that harmed personnel or released significant amounts of radioactivity. Resources of fissionable uranium are abundant enough to sustain nuclear energy worldwide for several centuries. Latest design nuclear reactors have passive safety features that make a Chernobyl-type of catastrophe impossible and can prevent almost any type of accident that would result in release of significant radioactivity.

The most cited problem with nuclear energy is the waste disposal problem. As of 2006, use of the U.S. nuclear waste repository at Yucca Mountain in Nevada has been delayed because of concerns over its safety, largely of a political nature. In the meantime, spent fuel rods from years of nuclear power generation are stored in pools at power plant sites. This option is not as bad as it sounds because the activity of spent fuel decreases most rapidly during the years immediately following removal from a reactor. The only way that nuclear energy can become an acceptable long-time energy option is for spent fuel to be reprocessed. This reclaims the uranium which can be enriched in the fissionable uranium-235 isotope and put back into nuclear fuel rods. Fission products can be separated and put into waste disposal sites, where after about 600 years they will have only about the same activities as the original uranium ore from which they were extracted. The longer-lived actinides including fissionable plutonium formed by non-fission neutron capture by uranium nuclei can be separated and put back into nuclear fuel where they will be "burned" during reactor operation.

All of the energy alternatives discussed above deal with the generation of electrical energy. Electrification of railroads would enable electricity to be used for a significant fraction of transportation demand. However, energy sources are needed to power automobiles, buses, trucks, and ships that cannot be tethered to an electrical power grid. Elemental hydrogen using fuel cells is often cited as "the fuel of the future." However, to date, no satisfactory way has been found to carry enough of this gas, which is a liquid (and a hazardous one at that) only at very low temperatures under pressure for vehicles that may have to run for relatively long times before refueling. Such vehicles will have to be powered by liquid fuels, which are now petroleum based and in short supply and which all release greenhouse gas carbon dioxide.

The best sustainable alternative for producing liquid fuels is to make them from biomass. Such fuels are greenhouse-gas-neutral, that is, the carbon in the carbon dioxide released by their combustion came originally from the atmosphere by photosynthesis (as did the carbon in fossil fuels, but over a vastly longer time frame). Biomass is now used for liquid fuels in the form of ethanol made from the fermentation of grain or sugar from sugarcane and diesel fuel made by esterifying plant oils, particularly soybean oil. But these sources require a high-value raw material that is in demand for food and are economic only because of substantial government subsidies. Efforts to extract sugars for fermentation to alcohol from wood and crop byproduct sources including stalks, leaves, and straw have proven difficult and uneconomical.

The best alternative for preparing liquid fuels from biomass sources is thermochemical gasification, which produces a synthesis gas consisting of a mixture of carbon monoxide, CO, and elemental hydrogen, H_2. The proportion of H_2 can be increased by reacting CO with steam (H_2O). The CO and H_2 can be combined in various proportions to produce a wide range of fuels including methane, gasoline, jet fuel, and diesel fuel. The technology for accomplishing these objectives is well known and long-established; for example, it was practiced on a large scale in Germany during World War II and more recently by the Sasol, South Africa, installation.

14.6. THE FIFTH COMMANDMENT: CLIMATE CONDUCIVE TO LIFE ON EARTH MUST BE MAINTAINED AND ACCEPTABLE MEANS MUST BE FOUND TO DEAL WITH CLIMATE CHANGES THAT INEVITABLY OCCUR.

The most plausible way that humans can ruin the global environment is by modifying the atmosphere such that global warming on a massive scale occurs. The most likely cause of such a greenhouse effect is release of carbon dioxide into the atmosphere from fossil fuel combustion as discussed in Section 4.9. Human activities are definitely increasing atmospheric carbon dioxide levels and there is credible scientific evidence that global warming is taking place. These phenomena and the climate changes that will result pose perhaps the greatest challenge for human existence, at least in a reasonably comfortable state, on the planet.

The Fifth Commandment is very much connected with the Fourth Commandment because so much of the increased atmospheric carbon dioxide levels are tied with energy and fossil fuel use. Other factors are involved as well. Destruction of forests (see the Sixth Commandment below) removes the carbon dioxide-fixing capacity of trees, and the decay of biomass residues from forests releases additional carbon dioxide to the atmosphere. Methane is also a greenhouse gas. It is released to the atmosphere by flatulent emissions of ruminant animals (cows, sheep, moose), from the digestive tracts of termites attacking wood, and from anoxic bacteria growing in flooded rice paddies. Some synthetic gases, particularly virtually indestructible fluorocarbons, are potent greenhouse gases as well. The achievement of sustainability requires minimization of those practices that result in greenhouse gas emissions, particularly the burning of fossil fuels.

Unfortunately, if predictions of greenhouse gas warming of Earth’s climate are accurate, some climate change inevitably will occur. Therefore, it will be necessary to adapt to warming and the climate variations that it will cause. Some of the measures that will have to be taken are listed below:

- Relocation of agricultural production from drought-plagued areas to those made more hospitable to crops by global warming (in the Northern Hemisphere agricultural areas will shift northward)
- Massive irrigation projects to compensate for drought
- Development of heat-resistant, drought-resistant crops
- Relocation of populations from low-lying coastal areas flooded by rising sea levels caused by melted ice and expansion due to warming of ocean water
- Construction of sea walls and other structures to compensate for rising sea levels
- Water desalination plants to compensate for reduced precipitation in some areas

14.7. THE SIXTH COMMANDMENT: EARTH'S CAPACITY FOR BIOLOGICAL AND FOOD PRODUCTIVITY MUST BE MAINTAINED AND ENHANCED, CONSIDERING ALL FIVE ENVIRONMENTAL SPHERES.

The loss of Earth's biological productivity would certainly adversely affect sustainability and, in the worst case, could lead to massive starvation of human populations. A number of human activities have been tending to adversely affect biological productivity, but these effects have been largely masked by remarkable advances in agriculture such as by increased use of fertilizer, development of highly productive hybrid crops, and widespread irrigation. Some of the factors reducing productivity are the following:

- Loss of topsoil through destructive agricultural practices
- Urbanization of land and paving of large amounts of land area
- Desertification in which once productive land is degraded to desert
- Deforestation
- Air pollution that adversely affects plant growth

Biological productivity is far more than a matter of proper soil conditions. In order to preserve and enhance biological productivity, all five environmental spheres must be considered. Obviously, in the geosphere, topsoil must be preserved; once it is lost, the capacity of land to produce biomass is almost impossible to restore. Deforestation must be reversed and reforestation of areas no longer suitable for crop production promoted. (This is happening in parts of New England where rocky, hilly farmland is no longer economical to use for crop production.) In more arid regions where trees grow poorly, prairie lands should be preserved, desertification from overgrazing and other abuse prevented, and marginal crop lands restored to grass.

The hydrosphere may be managed in a way to enhance biological productivity. Measures such as terracing of land to minimize destructive rapid runoff of rainfall and to maximize water infiltration into groundwater aquifers may be taken. Watersheds, areas of land that collect rainwater and which may be areas of high biological productivity should be preserved and enhanced.

Management of the biosphere, itself, may enhance biological productivity. This has long been done with highly productive crops. The production of wood and wood pulp on forest lands can be increased — sometimes dramatically — with high-yielding trees, such as some hybrid poplars. Hybrid poplars from the same genus as cottonwoods or aspen trees grow faster than any other tree variety in northern temperate regions, so much so that for some applications they may be harvested annually. They have the additional advantage of spontaneous regrowth from stumps left from harvesting, which can be an important factor in conserving soil. Furthermore, it may be possible to genetically engineer these trees to produce a variety of useful products in addition to wood, wood pulp, and cellulose.

Proper management of the anthrosphere is essential to maintaining biological productivity. The practice of paving large areas of productive land should be checked. Factories in the anthrosphere can be used to produce fertilizers for increased biological productivity.

14.8. THE SEVENTH COMMANDMENT: MATERIAL DEMAND MUST BE DRASTICALLY REDUCED; MATERIALS MUST COME FROM RENEWABLE SOURCES, BE RECYCLABLE AND, IF DISCARDED TO THE ENVIRONMENT, BE DEGRADABLE

Reduced material demand, particularly that from nonrenewable sources, is essential to sustainability. Fortunately, much is being done to reduce material demand and the potential exists for much greater reductions. Nowhere is this more obvious than in the communications and electronics industries. Old photos of rail lines from the early 1900s show them lined with poles holding 10 or 20 heavy copper wires, each for carrying telephone and telegraph communications. Now far more information can be carried by a single thread-sized strand of fiber optic material. The circuitry of a bulky 1948-vintage radio with its heavy transformers and glowing vacuum tubes has been replaced by circuit chips smaller than a fingernail. These are examples of **dematerialization** and also illustrate **material substitution**. For example, fiber optic cables are made from silica extracted from limitless supplies of sand whereas the conducting wires that they replace are made from scarce copper.

Wherever possible, materials should come from renewable sources. This favors wood, for example, over petroleum-based plastics for material. Wood and other biomass sources can be converted to plastics and other materials. From a materials sustainability viewpoint natural rubber is superior to petroleum-based synthetic rubber, and it is entirely possible that advances in genetic engineering will enable growth of rubber-producing plants in areas where natural rubber cannot now be produced.

Materials should be recyclable insofar as possible. Much of the recyclability of materials has to do with how they are used. For example, binding metal components strongly to plastics makes it relatively more difficult to recycle metals. Therefore, it is useful to design apparatus, such as automobiles or electronic devices, in a manner that facilitates disassembly and recycling.

Some materials, by the nature of their uses, have to be discarded to the environment. An example of such a material is household detergent, which ends up in wastewater. Such materials should be readily degradable, usually by the action of micoorganisms. Detergents provide an excellent example of a success story with respect to degradability. The household detergents that came into widespread use after World War II contained ABS surfactant (which makes the water “wetter”) that was poorly biodegradable such that sewage treatment plants and receiving waters were plagued with huge beds of foam. The ABS surfactant was replaced by LAS surfactant which is readily attacked by bacteria and the problem with undegradable surfactant in water was solved.

14.9. THE EIGHTH COMMANDMENT: THE PRODUCTION AND USE OF TOXIC, DANGEROUS, PERSISTENT SUBSTANCES SHOULD BE MINIMIZED AND SUCH SUBSTANCES SHOULD NOT BE RELEASED TO THE ENVIRONMENT; ANY WASTES DISPOSED TO DISPOSAL SITES SHOULD BE CONVERTED TO NONHAZARDOUS FORMS.

The most fundamental tenet of green chemistry is to avoid the production and use of toxic, dangerous, persistent substances and to prevent their release to the environment. With the caveat that it is not always possible to totally avoid such substances (see the Ninth Commandment below) significant progress has been made in this aspect of green chemistry. Much research is ongoing in the field of chemical synthesis to minimize toxic and dangerous substances. In cases where such substances must be used because no substitutes are available, it is often possible to make minimum amounts of the materials on demand so that large stocks of dangerous materials need not be maintained.

Many of the environmental problems of recent decades have been the result of improperly disposed hazardous wastes. Current practice calls for placing hazardous waste materials in secure chemical landfills. There are two problems with this approach. One is that, without inordinate expenditures, landfills are not truly "secure" and the second is that, unlike radioactive materials that do eventually decay to nonradioactive substances, some refractory chemical wastes never truly degrade to nonhazardous substances. Part of the solution is to install monitoring facilities around hazardous waste disposal facilities and watch for leakage and emissions. But problems may show up hundreds of years later, not a good legacy to leave to future generations.

Therefore, any wastes that are disposed should first be converted to nonhazardous forms. This means destruction of organics and conversion of any hazardous elements to forms that will not leach into water or evaporate. A good approach toward this goal is to cofire hazardous wastes with fuel in cement kilns; the organics are destroyed and the alkaline cement sequesters acid gas emissions and heavy metals. Ideally, hazardous elements, such as lead, can be reclaimed and recycled for useful purposes. Conversion of hazardous wastes to nonhazardous forms may require expenditure of large amounts of energy (see the fourth commandment, above).

14.10. THE NINTH COMMANDMENT: IT MUST BE ACKNOWLEDGED THAT THERE ARE RISKS IN TAKING NO RISKS.

Some things for which there are no suitable substitutes are inherently dangerous. We must avoid becoming so risk adverse that we do not allow dangerous, but necessary activities (some would put sex in this category) to occur. A prime example is nuclear energy. The idea of using a "controlled atom bomb" to generate energy is a very serious one. But the alternative of continuing to burn large amounts of greenhouse-gas-generating fossil fuels, with the climate changes that almost certainly will result, or of severely curtailing energy use, with the poverty and other ill effects that would almost certainly ensue, indicates that the nuclear option is the best approach.

So it is necessary to manage risk and to use risky technologies in a safe way. As discussed above, with proper design and operation, nuclear power plants can be operated safely. Modern technology and applications of computers can be powerful tools in reducing risks. Computerized design of devices and systems can enable designers to foresee risks and plan safer alternatives. Computerized control can enable safe operation of processes such as those in chemical manufacture. Redundancy can be built into computerized systems to compensate for failures that may occur. The attention of computers does not wander, they do not do drugs, become psychotic, or do malicious things (although people who use them are not so sure). Furthermore, as computerized robotics advance, it is increasingly possible for expendable robots to do dangerous things in dangerous areas where in the past humans would have been called upon to take risks.

Although the goal of risk avoidance in green chemistry and green technology as a whole is a laudable one, it should be kept in mind that without a willingness to take some risks, many useful things would never get done. Without risk-takers in the early days of aviation, we would not have the generally safe and reliable commercial aviation systems that exist today. Without the risks involved in testing experimental pharmaceuticals, many life-saving drugs would never make it to the market. Although they must be taken judiciously, a total unwillingness to take risks will result in stagnation and a lack of progress in important areas required for sustainability.

14.11. THE TENTH COMMANDMENT: EDUCATION IN SUSTAINABILITY IS ESSENTIAL; IT MUST EXTEND TO ALL AGES AND STRATA OF SOCIETY, IT MUST BE PROMULGATED THROUGH ALL MEDIA, AND IT IS THE RESPONSIBILITY OF ALL WHO HAVE EXPERTISE IN SUSTAINABILITY.

Although the achievement of sustainability is the central challenge facing humanity, most people know pathetically little about it. The reader of this chapter belongs to a small fraction of the populace who have been exposed to the idea of sustainability. If asked, a distressingly large number of people would probably say that they had never heard of the concept of sustainability. Therefore, education is essential and a key to achieving sustainability.

Education in sustainability must begin early with children in primary school and should be integrated into curricula from kindergarten through graduate school. By providing containers for recyclables in grade schools, there is some small benefit from the waste paper, plastics, and aluminum cans collected, but a much greater benefit in the lessons of sustainability that those containers illustrate. Green chemistry should be part of the background of every student graduating with a university degree in chemistry and the principles of green engineering should be part of the knowledge base of every engineering graduate. But of equal — often greater — importance is the education of people in nontechnical areas in the principles of sustainability. Lawyers, political scientists, economists, and medical professionals should all graduate with education in sustainability.

A particular challenge is that of informing the general public of the principles of sustainability and of its importance. The general public has more choice in its sources of information than does the captive audience of a student body, so the challenge of informing them about sustainability is greater. In this respect the media and the internet have key roles to play. Unfortunately, relative to the large amounts of time devoted in the media to the salacious antics of some fool — matters that have virtually no relevance to the lives of everyday citizens — almost no air time is devoted to sustainability, which is highly relevant to the lives of all. Therefore, those who have an interest in, and knowledge of sustainability have an obligation to get the message out through the media and the internet.

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QUESTIONS AND PROBLEMS

1. The U.S. Geological Survey posts prices in metals corrected for inflation from 1959 through 1998 at http://minerals.usgs.gov/minerals/pubs/metal_prices/. Other internet sources give current prices of metals. Using these resources, look up past and current prices of copper, chromium, nickel, tin and tungsten, the metals in the historic Ehrlich/Simon wager to see how the wager would have turned out in recent years. Explain your observations and suggest future trends.
2. At the beginning of the chapter were stated six "great challenges to sustainability." Using a diagram, if appropriate, suggest how these challenges are very much interrelated.
3. Much of Earth's population is dependent upon seafood for its protein. Suggest how provision of adequate food by this route might be affected by the challenges

of adequate energy supply as related to contamination of Earth's environment with toxic and persistent substances.

4. Suggest scenarios by which the people of your country might be adversely affected and its population might even decline because of declines in key environmental support systems. Suggest how these problems might be avoided in the future by actions taken now.
5. Look up telecommuting on the internet and explain how it might fit with the ten commandments of sustainability.
6. In a quote attributed to the British sociologist Martin Albrow, sociospheres consist of "distinct patterns of social activities belonging to networks of social relations of very different intensity, spanning widely different territorial extents, from a few to many thousands of miles." Suggest how sociospheres relate to the anthrosphere. What is your sociosphere? How might sociospheres be important in sustainability.
7. It has been estimated that U.S. coal resources can provide for up to three centuries of U.S. energy needs and could provide energy for much of the world. Is this a sustainable source of energy? Explain.
8. Explain how unsustainability may be the result of depletion of resources, environmental pollution, or a combination. Give an example in which environmental pollution reduces resource availability.
9. From news events of the last five years, cite evidence that global climate change is in fact occurring. Cite evidence to the contrary.
10. Currently, population growth tends to occur in coastal areas. Suggest how global warming might reverse that trend, especially in light of the 2005 U.S. Gulf Coast hurricanes.
11. Prior to European settlement, vast areas of the U.S. Great Plains supported huge herds of bison that provided the base for a viable Native American population. Given the erratic climate of that region, depleted groundwater for irrigation, and the aversion of many people to dwell on the "lone prairie," some authorities have suggested that these areas revert to a bison-based system, sometimes called the "buffalo commons." Suggest how such a system might be viable and sustainable and give arguments against it.
12. Is the term "secure chemical landfill" an oxymoron? What are the alternatives to such landfills?