The Basic Science Needed to Understand the Relation of Energy to Economics

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The fundamental cause of the trouble is that in the modern world the stupid are cocksure while the intelligent are full of doubt. (Bertrand Russell).

This chapter is designed to provide, in a very basic way, enough science so that it is possible for the reader who has not had an extensive background in science, or who simply wants a review focused on the science associated with understanding real economic systems, to do so relatively easily. The contents of this chapter are divided into five main sections: understanding nature, the scientific method, the physical world, the biological world, and is economics science?

15.1 Understanding Nature

15.1.1 What Is Nature?

We start by considering what is nature and the natural world. In the most common view, nature is all of the world that is not explicitly human or human-dominated. In the lovely Rocky Mountain rural environment where this is being written, it seems obvious what nature is: go to one of the National Parks, get on a hiking trail, and hike until there seems to be little human influence. Nature clearly is the rocks, streams, clouds, and animals. But here too, it may be difficult to find pure nature, as there is usually a trail under your feet maintained by other human hikers and the Park Service; many of the plants, including lovely flowers, are introduced pest species; all of the plants are growing in an environment influenced by carbon dioxide increased by human activity; the glaciers we may look at are shrinking; and the rainbow and brown or brook trout you may see or catch were stocked from original populations in British Columbia, Europe, or the Eastern United States. On the other hand, humans are products of natural selection in natural environments, are animals just as much as deer or trout, and are limited in as many ways by their own genetic and physiological capacities as are the wild plants and animals. Humans, like other animals, can die from too much heat or cold, and they need water nearly daily and food regularly—or they die. But humans are different from most other animals in that they can modify their environment significantly. In addition, humans can adapt rapidly through cultural evolution. For the purposes of this book, we do not get very concerned about the nuances and usually say that while humans are derived from, and still part of, nature, *culture* is that which is human-dominated and *nature* is that which is not, including land, oceans, rivers and lakes, soils, rocks and mineral deposits, the natural plants and animals, and microbes of all of these places at scales from the subatomic to the universe and possibly beyond. Nature is also the natural forces that constrain all these things and allow them to operate. Humans of course have always sought to, indeed needed to, exploit nature for their own survival and, often, for the production of wealth. In order to do this, it was necessary to understand nature to some degree. So how have humans gone about understanding nature?

15.1.2 Human Explanation of Nature

Human existence has always been fraught with uncertainty and with great difficulty in being able to understand and predict events. This has been especially true with respect to our economic lives. Early humans understood nature well enough to gather the plants and hunt the animals that were necessary for them to eat and to predict usual seasonal patterns of plant growth and animal migrations, and early farmers certainly understood a lot about plants, soils, water, manure, and so on. But humans have always sought more cosmic or at least comprehensive explanations for the natural events around them and for more power in predicting or influencing whether a particular venture would be successful or not. Early Greeks and Romans, and indeed most prescientific peoples, believed that a god or whole series of gods controlled the day-to-day events in their lives, including the weather, how well their crops grew, and so on. Very often, the ancients would make some sort of a sacrifice—frequently human—as an investment to please the gods and to help insure the success of a planting, a military campaign, or whatever. Similar practices seemed to be characteristic of many other cultures around the world. These practices give humans a sense that there is something they can do to influence important events in their life. But how do we know whether these various approaches, or any others, work at a rate any better than random? In other words, nearly any human endeavor will always have some chance of succeeding and some chance of failing, independent of any divine, governmental or policy intervention, or even, perhaps, whether the endeavor itself is a particularly good idea. How can we increase our odds of getting something right? The answer is to use the *scientific method.* But first, we need to think a little more about why prediction can be so difficult, even with the scientific method.

Most of us have had both good and bad things happen to us, and frequently these have been beyond our control. Why should the events of life be such a mixed bag of successes and failures? Is it just the random or at least unpredictable nature of the universe? Perhaps it is because natural selection itself *must* be based on both failures and successes occurring. In other words, evolution must have both successes to move genes forward in time and failures to help generate the most fit. This was obvious to Charles Darwin [1]. But how can we determine when something good happened that was a result of our good decisions or actions vs. by chance alone? This is where science comes in, for it can help us to determine whether something really works or not, or works just by chance alone. Certainly science cannot resolve all issues, for example, science may have little to say about what values should be pursued by a person or a nation (although it can help in understanding the effects of implementing certain values), but we do believe that the domain of science can and should be expanded, and this includes into economics and indeed the general understanding of our lives.

15.1.3 Cause and Effect

Normally in science we seek *cause* and an *effect* and reasons for their linkages. So if we observe an effect, such as an apple falling from a tree, we ask, as did the great early physicist Isaac Newton, “why”? Newton determined that it was the attraction of the Earth to the apple, and the apple to the Earth, that caused this to happen and expressed this idea in beautiful and elegantly simple mathematics: the force between two objects was proportional to the product of their masses divided by the square of the distance between them. This simple law, which works equally for molecules and for the sun and planets in our solar system, has been verified again and again by others. We say that the force is the *independent* variable, that is, it exists whether the apple falls or not, and the falling of the apple is the *dependent* variable, that it occurs when the force is applied in the right direction and at the right distance. Likewise, in economies a dependent event (say the production of some corn) will occur only if the independent variable takes place, that is, the farmer plants the seeds. Of course, the corn production will take place only if other things occur too: the sun must shine to provide energy, rain needs to fall or irrigation water provided, there must be sufficient fertilizing elements in or applied to the soil, and so on. In this case, we would say that the production of the corn is a multiparameter issue, that is, the dependent variable occurs as a result of many independent variables. The various independent variables in turn may be a consequence of other independent variables, such as climate change or a farmer’s economic ability to provide fertilizer or willingness to work hard. These factors operating together form a *system*, that is, a series of interconnected causes and effects. Thus, unraveling economic cause and effect is not always easy. This is why we advocate in later chapters a *systems approach* to understanding real energy and economic issues. This may seem impossibly complex to the reader now, but in fact with proper training is quite manageable.

The degree to which energy studies should be based in science has rarely been questioned, as energy analysis in many respects forms the basis of science. In addition, most aspects of energy seem to follow known scientific laws. An important question, however, one to which we have no easy answer, is to what degree *economics* should be a science. While economics is usually identified as a social science, the degree to which its basic assumptions are given using, and subjected to, the scientific method is not quite so clear. Introductory economics books don’t put forth their fundamental economic principles as hypotheses to be tested but as truisms to be learned. In addition, there is usually no particular effort to ask, as we do here, whether or to what degree economic principles are consistent with the basic scientific laws. The reason that these issues are important in economics is that real economic systems must operate in the real material world where the laws of science always apply, regardless of whether we or some economist might wish them not to.

15.2 The Scientific Method

15.2.1 Formalizing Our Search for Truth Amidst Uncertainty

How do humans get to know things? How can we know things for sure? The answer is partly that there is no way that we can know anything absolutely for sure, and a common aphorism is that those people who know little often know it with certitude, while those who know a great deal tend to approach that knowledge with great uncertainty and humility. Thus, it is true that we cannot trust finally and forever even those things derived from good science, for there may be special cases or new information that causes us to change our mind or at least to understand how what we thought was true had some limitations. For example, we once thought that matter could not be created or destroyed, although could be changed in form. But the great physicist Albert Einstein found that under special conditions, matter could be transformed to energy according to his famous equation $E = mc^2$. In this case, the advance of science told us that the earlier law of conservation of energy worked under usual conditions but that there are exceptions. This perspective enriches our understanding of the law of conservation of matter, which is now considered the law of the conservation of matter and energy. Angier [2] has written a useful book that summarizes much of what we have learned from the scientific method, and how we have learned it, in a very accessible style.

We believe very strongly that—even if there are many important exceptions to the power of science—if there is any knowledge we can trust, it must be derived from, or at least be consistent with, science and the scientific method. We believe that because the economy must operate in the real world, it cannot operate as if it were a perpetual motion machine, which in fact is the most common way of representing economic systems in introductory economics textbooks. More generally, there is a great deal of information derived in the natural science disciplines that could be of great value for understanding actual economies but that this information is rarely if ever put into economic textbooks. In addition, as we stated in the introduction, we do not believe that the education of our young people should be compartmentalized so that one learns natural sciences only in chemistry, physics, geology, or biology classes or, on the other hand, that you never hear about science in an economics course.

But what is science? How does "scientific truth" agree with or differ from other kinds of truths, including logical truths, economic truths, religious truths, and so on. Before we give more economics, we will focus on more science, going beyond the basic energy needed to understand economics by developing some basic science needed to understand both energy and economics.

15.2.2 The Need for Science to Understand How Economies Work

The more we can increase our scientific understanding of the world, the better we should be able to understand what good economics is and should be. This follows in the same way that our ability to do medicine is improved as we understand better the human body, the environment of humans, the technology of disease prevention and control, and the social interactions between health-care providers and sick people. In other words, we believe in a comprehensive systems approach for all but the simplest problems. Our list of the most important things you need to learn about science includes especially the scientific method and the most basic concepts pertaining to nature including matter, energy, life, and the fundamental interactions of all of these within the biosphere. Economics, if it is to be a real science, *must* be consistent with, and constrained by, these scientific principles, for we know of no exceptions to them. Humans can *want* to do many things, but they are *able* to do only what is possible within the laws of nature and the resources actually available, and if these concepts are not understood, human endeavors are apt to backfire (some might say continue to backfire).

15.2.3 Steps in the Scientific Method

The scientific method is usually taught to undergraduates as a series of experiments, with hypotheses, tests, and controls that a scientist follows in the process of gaining new knowledge. The formalized procedures of the scientific method usually includes observation of phenomena, the formation of hypotheses that are thought to explain those phenomenon, and the rejection of those hypotheses that are not supported by appropriate experimentation. Usually, the procedure requires a "test" and a "control," identical in all respects except for the one factor that is being tested. Thus, to test the hypothesis that phosphorus is needed for plant growth, one might grow two plants in pots with the soil in the pots being identical except that one contains phosphorus and one does not. The use of a control is usually critically important to identify the causative agent.

In fact, the process of science tends to be much more complex and messy, with many different pathways to new scientific understanding. Neither Isaac Newton nor Charles Darwin, probably the two most important and creative scientists that ever lived, particularly followed the scientific method as mentioned above. Rather, they were extremely astute observers and thinkers about what might be behind what they observed. Today, the fundamental criteria by which science is judged are that the mechanisms are consistent with known science and also that the results generated by the science *works*, "works" being defined as generating predictable results that are repeatable by others. For example, when we sent men to the moon, we were able to aim the space capsule based simply on Newton's laws of motion, laws that worked so well that not even small midcourse corrections were necessary—even though we had never tested them previously outside of the Earth's local environment. Surely, we would like to have such predictive power in economics! A problem, however, as any good economist or scientist will tell you, is that it is difficult to make predictions in a multiparameter world, that is, in a situation where many factors in addition to the one you are interested in or have control over might influence the results. Since real economies have many inputs and many outputs, determining which factor or factors may be most important can be quite difficult (but see the next chapter where we show how this can be done well, if not perfectly).

This is a problem faced by much of the rest of science too, and often it has been overcome with the help of statistical analysis designed for that purpose. But first, we need to think more basically about how we seek and sometimes find truth using science. As defined by the scientific methodologist Glymore [3], "science" is that field of intellectual inquiry that is amenable to the scientific method. Exactly what constitutes the scientific method is certainly debatable. Most practicing scientists would agree that most good scientists, natural and social, strive for *rigor*. Generally, rigor means intellectually defensible while using conceptual models that capture both reality itself and the mechanisms that determine the relation between cause and effect. It is often assumed that mathematical rigor means scientific rigor, but as we shall see, this is often not the case.

Within the natural sciences rigor generally means, at a minimum, that the concept, descriptor, or model used (1) is explicitly and unambiguously defined, (2) is consistent with *first principles* (i.e., things we know to always hold—at least so far!), (3) has been tested with adequate controls using some form of the scientific method (where that is possible) and has survived that testing, (4) explains an appropriate and nontrivial set of observed phenomena well, and, perhaps most important, (5) is repeatable by others who also follow the above rules. If *all* of these criteria, and as appropriate others, are *not* met, then we have to consider the theory or approach in question as a theory, or a hypothesis, or a myth, or something else but not yet in any sense a scientific law or even a scientifically supported concept or theory. *Probably the strongest criterion that marks something as science is that the observation and/or experiment is repeatable by others who follow the appropriate directions of the person promoting the hypothesis (and who usually are trying to get it to fail).* While it is very hard to say something is unequivocally correct using the scientific method, and some philosophers of science (most notably Karl Popper [4]) make the point that we can only fail to falsify a hypothesis, the true power of science comes from a theory's ability to withstand very explicit attempts to falsify it and to predict nontrivial outcomes.

Many very exciting new concepts in natural science have fallen when they have failed to satisfy all the points given above. On the other hand, there are some extremely powerful scientific theories, such as plate tectonics and natural selection, that explain a great many observations but that are amenable to experimentation in only a limited way. So it is not always required to meet all of the criteria listed above, but if they do not, then we have some very careful explaining to do. For example, Charles Darwin thought that we would never see natural selection in action, or be able to test it explicitly, because he thought the timescales were far too long and the experimental manipulation extremely difficult, in part due to the complex, multiparameter reality of nature. Nevertheless all other information—such as the fossil record—was so convincing that nearly all biologists came to accept Darwin's theory even without experimental verification. Recently, however, biologists such as Peter and Rosemary and Grant [5] and Dolph Schluter [6] have devised very clever observations and even experiments that have allowed us to observe and even manipulate natural selection, and it works essentially exactly as Darwin had hypothesized. So with very careful attention to scientific methodology and to the system in question, it is possible to undertake experiments to test our hypotheses even when people originally thought it impossible. An amazing thing is that as we learn much more about the mechanisms of how life works with all of our new molecular biology, we confirm that in fact nature behaves very much according to the basic principles that Darwin put down 150 years ago.

We next look at some fundamental physical and biological laws and principles that have been derived by using the scientific method that we believe are most solid and also most important for a good understanding of real economies and of biophysical economics. Most fundamentally, we ask "how does it work?" Whatever our answer, it must be consistent with science and derived by the scientific method; otherwise, we cannot accept its validity.

15.3 The Physical World

The two fundamental divisions of the physical world are energy and materials. Thus, we start our tour of scientific knowledge with a look at energy. Then we will look at materials.

15.3.1 Energy Sources

The principal sources of energy for the Earth are the sun, the movements of the sun and the moon relative to the Earth, and the radioactive decay within the Earth. The movements of the sun and the moon cause tides, and possibly some large-scale movements of portions of the solid Earth. The decay of radioactive elements within the Earth (plus residual heat from early Earth history) causes the interior of the Earth to be warmer than the surface. These factors also cause volcanoes and continental drift. Essentially all other energy, including wind, oil, gas and coal, our food, and that of all nature, comes directly or indirectly from the sun, which is an enormous thermonuclear furnace fed by hydrogen being converted to helium. We do not know exactly what the energy is that comes from the sun, but the effects are obvious. Scientists have more or less settled on calling sunlight "photon flux" and the amount of it "photon flux density." Sunlight tends to be of relatively short wavelength (Fig. 15.1) and because of this has very high energy and can do a great deal of work. The solar

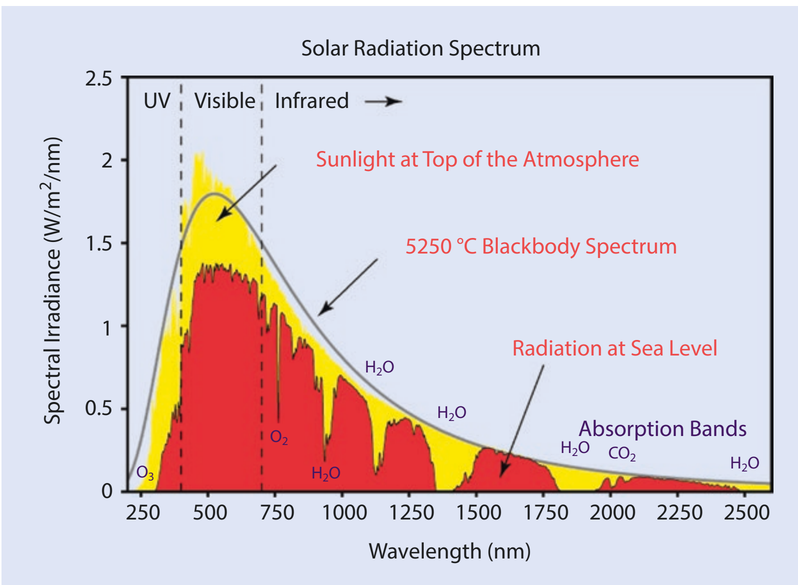

Fig. 15.1 Distribution of sunlight as a function of wavelength. **a** at top of atmosphere and **b** on the Earth's surface. (Source: Wikimedia Commons)

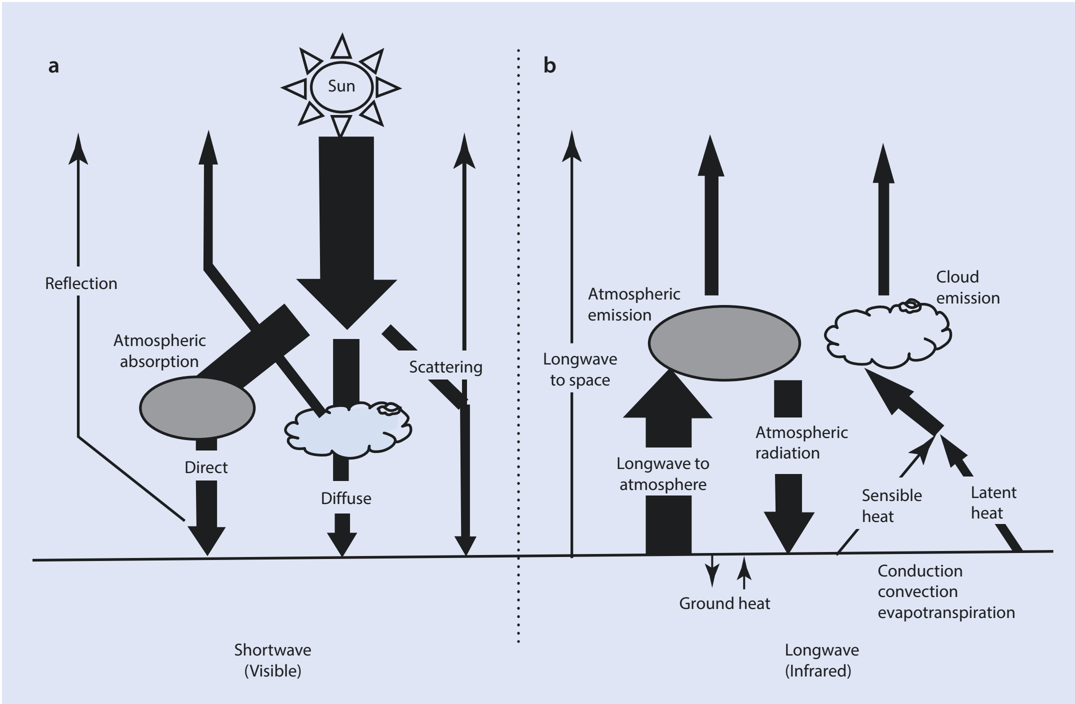

Fig. 15.2 Disposition of incoming solar radiation. Short wave radiation is high energy incoming photons and long wave radiation is outgoing (Source: Amy Chen)

constant, that is, the amount of sunlight received from the sun at the top of the atmosphere, is about 1367 Watts per meter squared perpendicular to the sun, equal to 4.9 KJ per square meter per hour. About one-quarter of this, on average, gets transferred through the atmosphere to the Earth's surface. Figure 15.2 gives the disposition of this incoming solar energy. Some of it is immediately reradiated to space, some evaporates water, and the majority is turned into longer wavelength, less energetic waves that we call sensible (i.e., we can sense it) heat. This transformation is very obvious when you walk barefoot on a black surface when the sun is bright. Sunlight has a broad spectral distribution, meaning that when separated by a prism, it has many different colors. Plants absorb and use for photosynthesis red and blue light but not green and hence reflect green. The sky is blue because the small particles suspended in the atmosphere are at roughly the same size as the blue wavelength, so the other colors go straight through the atmosphere, while some of the blue light is reflected (scattered) from the atmosphere to your eyes.

When the solar energy strikes the Earth's surface, the portion that is not reflected does considerable work. We can feel the effects in the heating of dark surfaces. The largest amount of work that sunlight does on Earth is to evaporate water. Wind and more generally weather is caused by the uneven heating of the Earth's surface by the sun. This operates the great heat engine of atmospheric circulation. Most importantly, the sun heats the Earth more at the equator than toward the poles because the land is perpendicular to the photon flux. This in turn causes the air over the equator to rise. As this air rises, it cools, and the associated loss of energy means that the atmosphere can hold fewer water molecules—which over time fall out as rain. Thus, the equator is a very wet region, and it is here that tropical rain forests are found. The exact place of the greatest rain changes north and south with the seasons, but it is always directly "under" the sun, i.e., at the location where the sun's rays are most nearly perpendicular. The rising air is eventually constrained by gravity and accumulates at about 5–10 miles high over the equator. This causes a

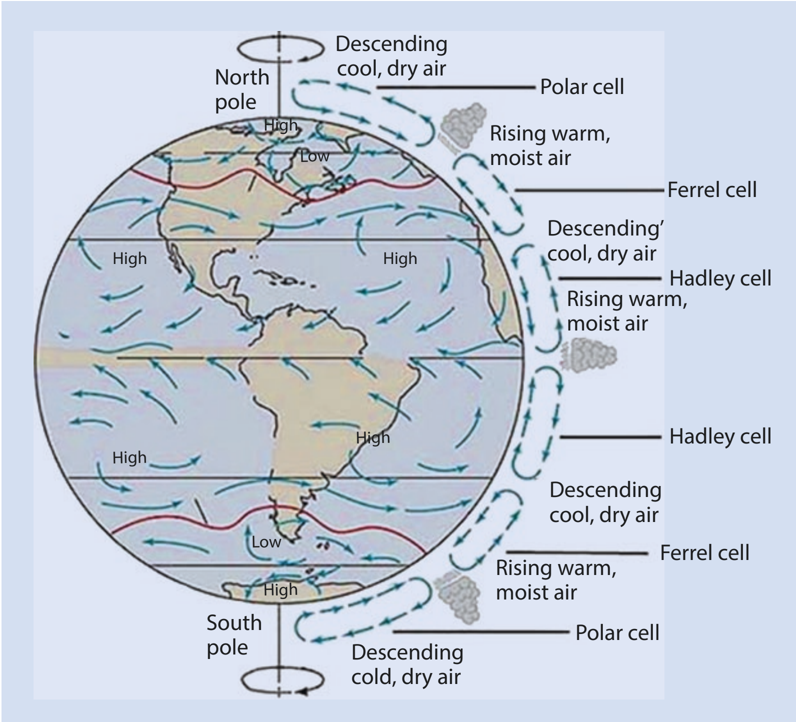

Fig. 15.3 The basic heat engine of the Earth. Electromagnetic radiation, usually considered as traveling in "packets" called photons, enters the Earth's atmosphere after traveling from the sun. Since the Earth's surface is more nearly perpendicular to their entrance path near the equator, they tend to be more concentrated there and subsequently heat the Earth's surface especially well at the equator. This causes warm air masses to rise at the equator and then disperse north and south as described in the text. As the air masses rise they cool, and as cooler air has less energy to keep the water molecules suspended, it rains a lot on the (thermal) equator, which moves north in summer and south in winter. The rising air masses create high pressure above the equator, pushing air masses north and south until they descend at 30° (Source: Kaufmann & Cleveland, 2008)

high-pressure zone there and, because the air masses have been moved upward, a low-pressure zone on the surface at the equator. This high pressure at altitude pushes the air north and south until it cools enough to descend at about 30° north and south. As the air descends, it warms again and hence has the energy to hold more and more water, so that when it comes in contact with the Earth's surface, it literally sucks the moisture out of the soil and vegetation, generating the Earth's great deserts. It also generates another high-pressure area there (at the Earth's surface at 30° north and south) which pushes air back toward the low-pressure air on the equator while being bent to the right in the Northern Hemisphere and left in the Southern Hemisphere by the Earth's rotation (the Coriolis force). This causes the steady *trade winds* characteristic of the tropics which become increasingly moisture-laden as they approach the equator. The high pressures at about 30° also push air masses poleward, and these winds as effected by the Coriolis force cause our familiar westerly winds in the temperate zones of the Northern hemisphere. These are familiar to those living in the temperate regions as they watch storm systems move across the land from west to east (Fig. 15.3). The net result is the very steady trade winds of the tropics.

British meteorologist George Hadley figured out the first (equatorial) cell in 1735 which bears his name. What he did was to explain the wind patterns that savvy ship captains had known since the time of Columbus: use the aptly named trade winds for moving from Europe to the Americas and the westerlies further north to go from the Americas to Europe, while avoiding, where possible, the doldrums on the equator and the horse latitudes at 30° where air masses move vertically rather than horizontally. This is an early example of where scientific knowledge was of great assistance to the economic situation of those who understood it.

15.3.2 Basic Thermodynamics

The basic laws of thermodynamics were given in the previous chapter. Their importance includes the concept that while material can be recycled energy cannot. Once we have used energy, it is, essentially, gone forever as a useful resource. This has enormous implications as civilization plows through its remaining resources of fossil fuels.

15.3.3 Entropy and Its Relation to Human Economies

When we think about energy, it is normally from the perspective of our own personal ability to get something done, go somewhere, or keep warm in winter or cool in summer. But the reach and importance of energy is far, far more pervasive principally because of *entropy*, which we have covered in the previous chapter. The things bought and sold in economies, cars, houses, and food, are bits of *negentropy*, or negative entropy, that is something highly organized or specialized structures, something extremely unlikely by itself. A nation, civilization, or economy must constantly invest money and energy into maintenance; otherwise buildings, bridges, and even entire civilizations will collapse. In addition, if there is to be growth, then that requires additional energy.

A simple example will help to think about entropy. A tuna sandwich, your own self, and an automobile are extremely unlikely, nonrandom structures that have been developed by taking the elements and materials of nature, initially scattered more or less at random over the surface of the Earth, and using energy to concentrate these elements and their compounds into very specific structures. Once the structure is made (i.e., wheat, the tuna fish, yourself, a bridge, a city), energy must be continuously invested or the materials of which it is composed will tend to go back on their own toward entropy—i.e., a more random assemblage, and the structure will fall apart. If that sandwich is put into a refrigerator, a device that uses energy to maintain the structure of its contents, the integrity of the sandwich will be maintained for some time. Pull the plug and the sandwich goes into a more random assemblage, first smelly organic residues and then, eventually, carbon dioxide and simple nitrogen compounds. Likewise, yourself, a car, or a modern city cannot run for long without the energy required for its repair, something sometimes called “fighting entropy.” If and as high-quality energy becomes less available, then we may have to choose between maintaining our infrastructure, building more, or other consumption such as driving a car. While this may sound far-fetched as of 2017, the majority of states in the United States are facing severe debt and budget (and hence energy) shortfalls and are having to make painful decisions about which programs and infrastructures to maintain.

Most civilizations that have lost their main energy supplies have collapsed, as Tainter [7] and Diamond [8] have elegantly examined. Mexico is still rich in oil even as its main fields decline and uses much of it to maintain the 20 million people concentrated in Mexico City. The need for a continual input of energy to that city was once made clear to us when we were caught in a 10 mile long traffic jam of bumper to bumper enormous trucks that bring food and fuel into Mexico City every night. Mexico is filled with the ruins of enormous earlier cities and civilizations that, by some accounts, grew beyond their capacity to provide the energy resources that their large populations needed. Will the same fate befall modern Mexico City when oil becomes less abundant, as inevitably it will and which has already begun?

15.3.4 A Little Geology of Importance to Economics

We now shift our focus to materials. Economics is about goods and services. All goods are derived in some way from nature (including minerals, the soil, and the atmosphere), so it is useful to have information about where they came from. Services too are generally derived from nature, for example, the fuel that runs a transportation service or the metals in a bus. Most of the materials that we use in our economic life come from either plants, i.e., agriculture (food or chemical feedstocks), or forests (paper, lumber), or from the ground (rock; sand; cement; minerals such as iron, copper, and aluminum; fossil fuels including coal, natural gas, and oil). Most plastics are derived from fossil fuels, especially natural gas. The conditions under which these materials are found are normally considered the province of geology, agronomy, or forestry.

The first important geological fact about the Earth is that it is very old, roughly 4.5 billion years old. Over this very long time period, mountains were thrown up by volcanic or tectonic activity, continents drifted across the ocean and life evolved, and in the process changed the Earth itself. Some kind of simple life has existed for about half to three-quarters of that time, but fishes, for example, and primitive life on land have existed for only about 500 million years. Land plants evolved and changed the atmosphere from reducing to oxidizing [9]. Humans as a recognizable species have been around for about 1 million years, less than one-thousandth of the time that the Earth has had life. It is thought that very large asteroids from outer space hit the Earth every few hundred million years and change things very much, for example, by eliminating dinosaurs and opening up the environment for the evolution of mammals.

There are three basic types of rocks, igneous (formed by volcanic activity), sedimentary (formed by deposition of sand, silt, or marine skeletons on the bottom of the sea or large lakes), and metamorphic, which are either of the former that have been transformed by crustal movements and pressures. Sedimentary rocks are further divided into sandstones, shales, and limestone, formed specifically from sand, silt, and marine organisms. In areas once covered by the ocean, such as Central New York State, there are often alternating layers of sandstone and shale, representing successive geological eras. Why is there sometimes shale and sometimes sandstone and sometime limestone, sometimes in alternating bands? It is because in the past different types of sediments were found at differing distances from the source materials on the continental shelves. Since sand drops out of moving water relatively rapidly the presence of sandstone implies that the source of the sediments was originally not very far or that ocean currents were strong. The finer silt that constitutes the shales could travel much further from their continental origin before falling out, and limestone represents the remains of active populations of animals that made their shells out of calcium carbonate. Each of these materials can contain a certain amount of organic material (i.e., leftover plant and animal material) that can be the basis of the formation of fossil fuels.

The earth is a very dynamic place if you think in terms of geological time, with large crustal plates moving about its surface. For example, South America is separating increasingly from Africa to which it was once joined. Centers of activity where one plate smashes into another such as along the Andes of South America are characterized by mountain chains, volcanoes, and frequent earthquakes. The continents move about in response to geologic energies (deep "hot spots") that sometimes come up in the middle of the oceans, often causing volcanoes (as in Iceland and Hawaii) and continental drift. These hot spots generate island chains such as Hawaii, where a plate drifting over a single hot spot formed the islands from volcanic activity that is still continuing on the southern tip of the southernmost Island. At other locations, the Earth pulls apart, causing rift valleys. Good examples are found in East Africa, where there are a series of large lakes formed in basins where the land is being pulled apart. Eventually the edges will move far enough apart so that the sea will tumble in and the lakes will become inland seas. This has already happened in the Red Sea where Egypt is separating from the Arabian Peninsula and where Madagascar has separated from Africa. Another example is where Scotland has drifted away from Norway. As we shall see below, these rift areas are very important for the formation of oil.

15.3.5 Concentration, Depletion, and the "Best First" Principle

The most important geological issue relating to economics is that the materials that economies are based on, whether those of antiquity or of today, are not found distributed randomly (as we might expect from our discussion of entropy) about the Earth but rather in various concentrations of widely different purity and quality, the most concentrated are called ores or deposits. This is because past geologic energies, includ-

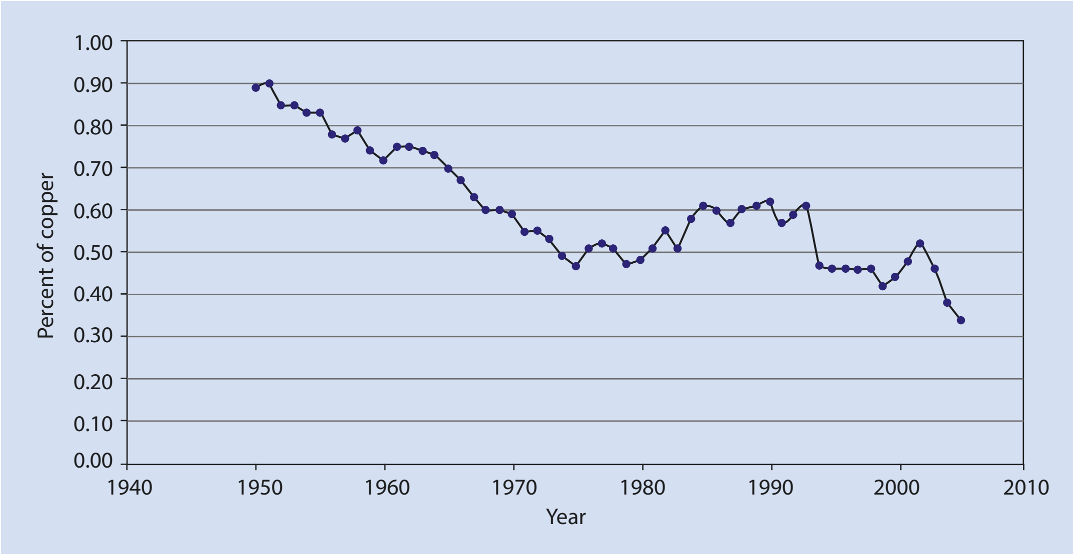

Fig. 15.4 Average grade of copper mined in the United States (Source U.S. Bureau of Mines and the U.S. Geological Survey)

ing volcanism, tectonic actions, river transport, microbial actions, or other processes, have tended to concentrate the different elements (and certain compounds) in particular locations where they may be orders of magnitude (i.e., factors of 10) more abundant than the general background "crustal average". Such differences have been obvious for millennia to humans who have tended to exploit, and deplete, the highest grade materials first. The initial copper and tin deposits in Crete, one place humans began the process of mining and smelting metals, were initially at such high concentrations that the metals abundantly flowed in a pure stream out of fireside rocks. When these rocks were all depleted, then humans had to invent mining and much more complex metallurgy to supply the metals. Today, the Earth is a very well-explored place—and with a few exceptions there have been relatively few large discoveries of very important materials for many decades. Now, rich mines are only a memory, and we get most of our metals either from recycling (roughly half) or from huge, relatively low-grade deposits that require enormous machines and very large quantities of energy to extract the metals from the ores.

A good example is for copper in the United States. Over time, the best grades of copper were mined first because it takes less energy (and labor and equipment and hence money) to process these materials into forms that society finds useful. For example, if you go to the end of Main Street in Butte Montana, you will look into a hole several miles across and nearly half a mile deep. This was once a hill, and it had been called the "richest hill on earth." The hill contained copper ore that was up to 50% copper, and once the proper machinery was in place, it was relatively easy and very profitable to mine that hill. Some 20 billion pounds of copper, plus gold, silver, zinc, and other minerals, were taken out of that hill. Some ancient geological processes, we are not sure exactly what but it appears to have involved cooling of mineral rich magma-heated water intrusions, concentrated copper there, where it had lain until the miners dug it up. Now, that rich copper ore is gone, and the huge hole has been slowly filling up with water which has turned to sulfuric acid because of the sulfur deposits that were associated with the copper. It is so acidic that if migrating waterfowl land on the lake in that hole they immediately die.

Today, the average grade of copper ore extracted from US copper mines contains about 0.4% copper [10], in other words, only about 1% of what they were getting out of Butte at the turn of the last century (Fig. 15.4). Consequently, some 100 times more ore has to be dug up, crushed, and processed per kg of copper delivered to society than back then. Thus, an important geological issue that effects economics is that, over time, the best deposits tend to be used first, so that the energy, dollar, and often environmental cost of getting a purified product tends to increase. Of course, technologies tend to improve over time, reducing costs and often energy use. Technology is in a race with depletion, sometimes one "winning," sometimes the other. In the case of copper, it appears that at first, the energy cost of getting a kilogram of pure copper decreased and subsequently it increased [10]. For most materials, it appears that energy costs are increasing, but a much better case-by-case review is needed. It is possible that the depletion of copper could limit the development of solar PV energy [11].

This *"best first" principle* is rarely mentioned in the economic literature (although it seems consistent with the law of diminishing returns). The concept also applies to many other aspects of human and indeed other organismal behavior. This principle has enormous economic implications as we deplete so many resources upon which we depend, especially as we can no longer count on more energy being available to mine ever lower-grade resources.

15.3.6 The Formation of Fossil Fuels

Because oil and gas are so important to our economic life and because there is so much controversy about how much is left to exploit, it is important to consider in some detail the very special circumstances that were required for their formation. Oil and gas are organic materials, that is, they are plant and animal remains composed of mostly carbon (and hydrogen) as is all life. (The word "organic" technically means carbon based; organic chemistry is about the chemistry of carbon and has little to do with the popular use of the term to denote low use of agrochemicals.) As life evolved, a great deal of organic material was formed, most of which was oxidized relatively soon and turned back to carbon dioxide in the atmosphere, becoming available for new plant growth. But some of this organic material found its way to *anaerobic* (meaning without oxygen) basins. For example, coal was formed in great freshwater swamps in what is now Pennsylvania, Ohio, and Wyoming.

Oil was formed in two principle places: rift basins such as once existed between Scotland and Norway or Saudi Arabia, and river deltas such as off the Mississippi or Niger River. Rift basins are formed when the land on one or both sides moves apart (as is the case today with East African lakes), generating deep basins called grabens, often with lakes or invading marine waters within (Fig. 15.5). Phytoplankton, tiny marine or freshwater plants would grow in the water and fall to the bottom of some of the deep rift basins where there was no oxygen and hence little decomposition. This process is greatly assisted when the water cannot mix deeply, i.e., is *stratified* by temperature, a phenomenon familiar to many of you who have dived deeply into a summer lake. Hence, a general requirement is that the oil-forming basins were located in the tropics and/or were active during periods of climate warming. Warm surface water can be mixed with deep water only with great difficulty (such as by a fierce wind). In the tropics, both lakes and the ocean tend to be strongly stratified all year around, so that very often the deeper parts use up all of their oxygen and remain anaerobic.

Under extremely rare circumstances, often related to a warming climate with lots of evaporation, the sinking phytoplankton were protected from oxidation in the deep, non-mixing anaerobic bottom waters for long periods of time, thousands to many millions of years. As time went on and if the climate happened to change from dry to wet, sediments would wash down from the surrounding hills, covering the organic material with layers of sand and silt which, over time, became rock (Fig. 15.5b). If enough sedimentary rock (say 3–5 thousand meters) covered the basin, the pressure would heat up the organic material, and over millions of years, the ancient phytoplankton would be "pressure cooked" at about the temperature of boiling water, breaking the long plant molecules of typically hundreds of carbons tied together into shorter ones, thus forming oil and gas. The familiar word "octane" refers to oil with eight carbon atoms arranged in a ring which is the best formulation for gasoline as it does not combust too easily and hence cause preignition or knocking. Natural gas is what remains when the chains have been broken to lengths of only one or two carbon atoms.

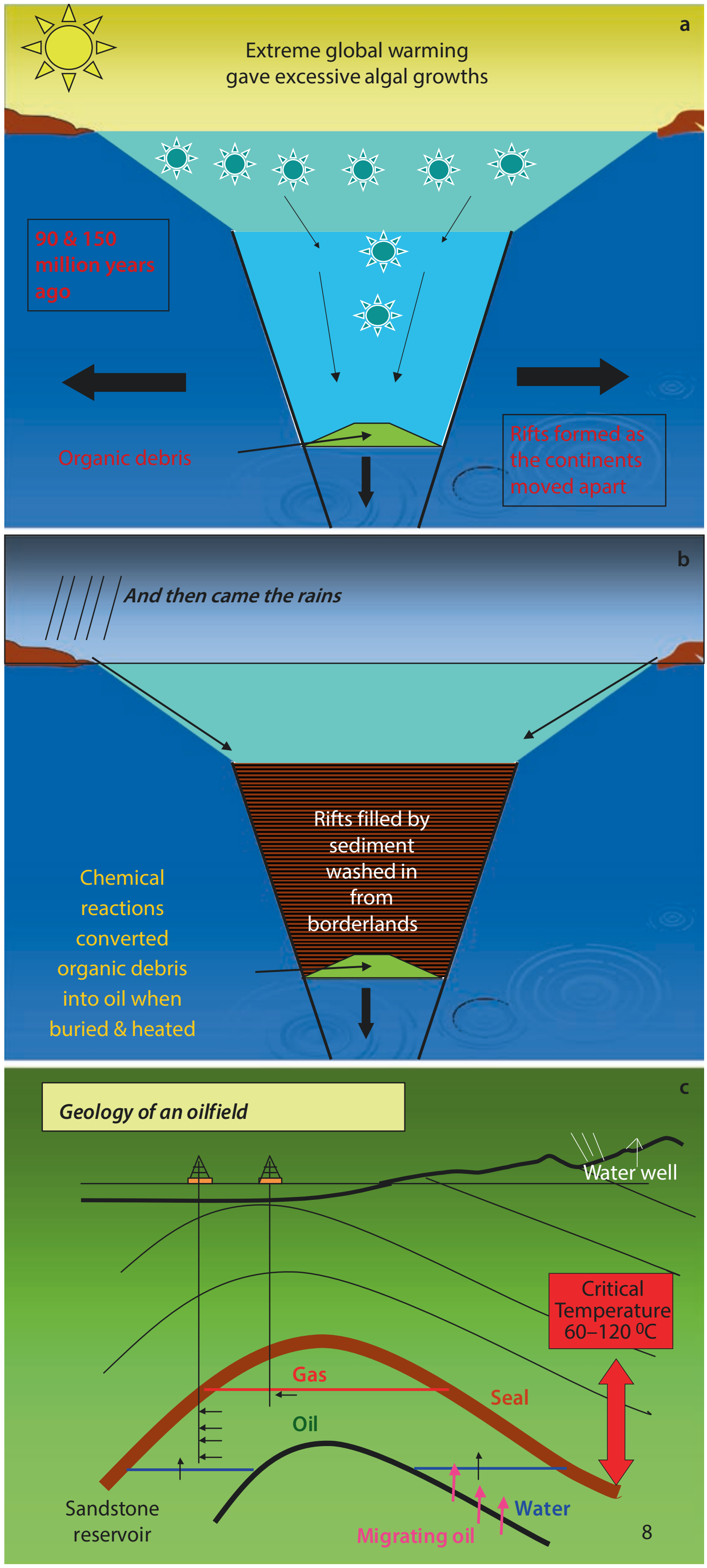

Fig. 15.5 The typical formation of oil. Oil is not formed often or in very many places and requires very special conditions for formation. It was formed on the Earth in only two general geological times, about 90 and about 150 million years ago. In order for oil to form a series of steps must occur in sequence (Source: Colin Campbell): **a** First a very deep lake or marine trench must be formed, such as when the crust moves apart forming a graben, during a period of climate warming. Phytoplankton, whose growth is encouraged by the warm conditions, sinks into the deep anaerobic waters. **b** Then it is necessary to have an extensive period of rains that wash sediments into the basin, covering the organic materials with thousands of meters of sediments. Then the organic material is pressure cooked for many tens of millions of years, breaking down ("cracking") the complex molecules into simpler ones. **c** The relatively light hydrocarbons end up moving upward from the source rocks. Most of it escapes to the atmosphere, but some small part is caught by impervious "trap rocks." This forms the oil and gas deposits we exploit

These very rare and special rocks are known in petroleum geology as *source rocks*. The oil and gas thus formed would then tend to rise upward over geological time as they are less dense than the Earth's sediments within which are found. Some small proportion, perhaps 1%, of the oil and gas migrating upward from the source rocks find their way to particular rock formations impervious to their movement, such as salt domes or sandstone, where they are trapped. These rocks, which may be far above the source rocks, are known as *trap rocks* and are normally the locations that humans exploit (◘ Fig. 15.5c). A good example of where all this took place was the rift valley where Scotland and England left Norway some 100–200 million years ago. The oil that we now exploit from the North Sea was created as a series of grabens were formed and flooded with water. Large phytoplankton growth in the productive water settled into deep basins and eventually were covered by thick layers of sediments. Some of these layers, particularly those made of limestone but sometimes sandstones, formed both reservoirs and traps.

Similar burial of phytoplankton or other organic matter sometimes has taken place within, and off of, river deltas where highly productive estuarine systems such as those associated with the Mississippi, Niger, and Orinoco rivers generate a lot of organic material and where periodic sediment deposits covered over anaerobic basins. The general lesson from these descriptions is that the special conditions required for the creation of exploitable oil and gas fields have been quite rare in the geologic past (occurring mostly some 90 and 150 million years ago in very special and limited environments) and that the time to make oil and gas is extremely long. As a consequence, significant commercially exploitable oil and gas are found in a relatively few regions of the Earth's surface. Coal, requiring similar but far less stringent conditions for its production, is much more common. Gas too is widely dispersed, but the main reservoirs were relatively rare. On the other hand, gas is found widely at low concentrations in "tight" shales and sandstones. Exploitation of these diffuse resources is becoming increasingly important as the large true gas fields found earlier face serious depletion. Whether or not these newer "unconventional" fields can maintain US gas production at the present level for very long is unknown at this time.

As with copper (◘ Fig. 15.4) and another example of the "best first" principle, humans have tended to exploit the large, high-quality and easy oil deposits first. They have exploited deeper, and deeper offshore regions, mainly off the Mississippi River, where there are more than 4000 very expensive offshore platforms that are responsible for much of the United States' remaining oil and gas production. As this was being written, there was considerable excitement about finding the new, possibly large Tiber oil field in the Gulf of Mexico. But the field is 35,000 ft (6 miles) under the Gulf of Mexico and would be extremely, perhaps prohibitively, energy intensive to develop. On the other hand, the high pressures there may force the oil to the surface without expensive pumping or pressurizing. For the United states, we found the most oil in the 1930s and for the world the most in the 1960s (◘ Fig. 8.3). All of these factors have very important implications for EROI (► Chap. 18).

15.3.7 A Little Chemistry of Importance to Economics

The world and everything in it, including yourself and your surroundings, is composed of chemicals. Economies generally mine or otherwise obtain source materials for chemicals (called *feedstocks*), refine or transform them, often times combining them with other chemicals, and using or selling the products. The most fundamental chemicals, incapable of being transformed to other chemicals, are called elements; these include such familiar chemicals as hydrogen, oxygen, and carbon. When two or more elements combine, they generate *compounds*, which include most of the common materials of everyday life: hydrogen and oxygen combine to make water, hydrogen and carbon to natural to make gas or oil. The chemistry of the world and of our economy is extremely complicated, but usually it is based mostly on only about 20 or 30 elements and their compounds.

15.3.8 Conservation of Matter: Supplies of Inputs

Perhaps the most important aspect of chemicals, or more generally all materials, for economics is the *law of the conservation of matter*. This law says that while matter (also called mass) can be transformed in many ways, it can be neither created nor destroyed. Again there is the exception that under very special conditions (nuclear reactions) matter can be transformed to energy. There are two reasons that this law is of critical importance to economics. The first has to do with the supply of the materials required by the economy, and the second relates to the disposal of waste materials. In other words, the goods that interest us as consumers or economists are derived from elements "borrowed" from nature. Cars are made from iron, copper, sand (for glass), natural gas (for plastics), and many other things; fish come from the sea; many houses, books, and newspapers come from trees; clothes from plants, animals or, increasingly, petroleum; computers are made from plastics, copper, aluminum, gold, and silicon, and so on. Essentially every good starts as some material extracted from nature somewhere. Energy is required to do step to make the final product.

Take for example plastics, a suite of materials made from hydrocarbons. Plastics are ubiquitous and very useful, they can be formed into many shapes, and they are cheap. A common ketchup bottle may have seven layers of different kinds of plastics to protect the ketchup inside. Chemists have learned to be very clever at manipulating elements and molecules, but the carbon and hydrogen atoms in the plastic still have to start with raw materials from feedstocks, usually natural gas, or sometimes oil or coal. Increasingly plastics are recycled, but they may pollute the environment for 1000 years. As fossil fuels become more expensive, the molecules can come from biomass such as from trees or crop residues.

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15.3.9 Carbon Chemistry

Most of our food, fuels, plastics, and many other things are carbon based. Carbon can take many extraordinarily different forms and can be transformed from one form to another relatively easily. Carbon may be found as carbon dioxide gas in the atmosphere; pure carbon in a pencil "lead" or a diamond; combined with hydrogen in *hydrocarbons* such as coal, gas, and oil; with hydrogen and oxygen in *carbohydrates* that includes most of the fuels that we eat; with the element calcium in limestone (from which we make cement), and so on. In general (as stated in ► Chap. 14), compounds with lots of hydrogen and little or no oxygen, such as hydrocarbons, are called *reduced* and serve as excellent fuels, and compounds that have a great deal of oxygen (such as CO_2) are called *oxidized* and are poor fuels. Carbohydrates are mostly reduced but slightly oxidized and hence do not make quite as good a fuel per gram as hydrocarbons. Combining oxygen with a hydrocarbon or carbohydrate releases energy that can be used to propel an athlete, an automobile, a chemical reaction, or a manufacturing operation.

You are made of principally carbon, with quite a bit of hydrogen, some oxygen, and more than a little nitrogen. Natural selection has chosen carbon as the basic skeleton for life because it has the possibility of combining with other atoms in four directions (i.e., it has four electrons in its outer or active ring), allowing the construction of the quite complex compounds that life requires, such as carbohydrates and fats. Because the element carbon is so closely associated with life, the chemistry of carbon, living or not, is called *organic* chemistry. Carbohydrates, fats, and protein are the basic biological compounds and also the basic food groups. Nitrogen too is an element of special importance, with five electrons in its outer shell and room for three bonds, and is also able to make very complex compounds that are often proteins. In its elemental form N_2 nitrogen forms about 78% of the atmosphere. In this state it is very inert, meaning that it does not react with most other elements except under very special conditions. But nitrogen can also be found combined with oxygen and with hydrogen, and in these states (nitrates and ammonia), it is extremely important for life because organisms can take the nitrogen from these compounds and (with carbon) make proteins. Proteins are important because they allow very great specificity, that is, very exact kinds of molecules. Nitrogen is critical for economies because it is the most important fertilizer used in agriculture, because plants need it to make their own proteins, and agriculture is usually one of the, or the, most important sectors in the economies of most nations.

15.3.10 Nitrogen Chemistry and the Haber-Bosch process

Although nitrogen is one of the most abundant elements on the Earth's surface (as N_2 in the air), it is relatively rare in its "fixed" form, that is, combined with hydrogen or oxygen. Fixing is uncommon in nature because it takes a great deal of energy to break the three chemical bonds holding the two nitrogen atoms of N_2 together. This occurs only when great energy is applied to the atmosphere (as in a lightning bolt) or when special organisms (only certain bacteria and blue green algae) invest a lot of their own photosynthetically derived energy into deliberately splitting the two nitrogen atoms apart so that they can get nitrogen for their own purposes, principally to make proteins. Until 1909, the major source of nitrogen for agricultural plants was from manure, and the first author's father remembers spending much of his childhood, as many did in 1920, hauling cow manure from the barn to the fields. Many of the readers of this book would be doing that too except for one great chemical discovery.

Ammonia (NH_3) is an extremely valuable chemical because of its long use in the dye industry and because it was the basis for explosives and fertilizer. Until 1908, however, ammonia was made only by natural process from certain bacteria and blue green algae or from lightning in the atmosphere. As such, its supply was limited. Although the principle by which synthetic ammonia might be made was simple and known for about 100 years, the actual process had eluded many important chemists. The equation is simply:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The N_2 is readily available as the major component of the atmosphere, although extraordinarily unreactive, and the hydrogen was readily available from coal or natural gas. After failing in several earlier attempts in 1909, the German chemist Fritz Haber discovered how to split the nitrogen molecules of the air industrially by adding a great deal of energy to N_2. He did this by heating a cylinder that was injected with air (the source of nitrogen) and natural gas (the source of hydrogen) while compressing the gases and using a special catalyst (initially osmium) [11]. The result was an output flow of ammonia (NH_3), a chemical very useful to plants and to industrial chemistry. None of Haber's university colleagues understood why he was so excitedly running around the campus shouting that he had done what no other person had done—to create "fixed" nitrogen from atmospheric nitrogen. Nor did they understand, as Haber did, why this was so important.

Haber had been assisted in this by a contract with the German industrial firm BASF, which quickly scaled up Haber's mechanism to commercial scale and under the leadership of Carl Bosch soon built enormous factories. These factories required enormous amounts of energy to run the process. While the early attempts produced some spectacular explosions, it also, once perfected, generated enormous amounts of commercial ammonia which has insured, at least potentially, enough food for all and freed most of us from carrying manure to the fields. It also had some rather different results, as industrially derived ammonium nitrate was and is the basis for gunpowder and other explosives. In 1914, at the start of the First World War, the Germans had only 6 months of gunpowder, derived from Chilean guano (bird dung). Without the industrially produced gunpowder of the Haber-Bosch process, the war would have ended quickly [12]. Thus, the Haber-Bosch industrial fixation of gunpowder is credited with making First World War last for 4 additional miserable years, and, one might add, allowing the second World War to be as devastating as it was. Even terrorists today blow up markets in Baghdad and buildings in Oklahoma City using ammonium nitrate explosives.

15.3.11 Phosphorus

Plants need more than nitrogen fertilizer to survive and grow. Phosphorous and potassium, and in smaller quantities, sulfur, molybdenum, and perhaps a dozen other chemicals are all essential plant nutrients. When the nuclear scientists Goeller and Weinberg [13] examined the entire periodic table, they found that for all elements necessary to civilization at that time, there was a substitute: aluminum wires could substitute for copper, energy could in effect substitute for nitrogen through the Haber process, and so on. But they found one exception: phosphorus. Phosphorus was completely necessary for plant growth and life in general, and there was no substitute. In the approximate words of geochemist Edward Deevey [14] some five decades ago, "there is something peculiar about the geochemistry of the Earth today that life is so dependent upon phosphorus, but it is now in such short supply." In other words, it might seemed that life evolved when phosphorus was more abundant. Today, most phosphorus comes from mines in Florida and Morocco, and much of it goes in a one-way trip from mine to crops to animals to humans to toilets to waterways to the ocean. Thus, the chemistry of phosphorus is of critical concern to modern economies because of its critical importance and non-substitutability for plant growth and because its main sources (in Florida and Morocco) are increasingly depleted. Thus, more energy is required for fertilizer production, and because as a waste product, it causes very undesirable growths of algae in our water bodies.

15.3.12 Conservation of Matter: Wastes

A second implication of the law of conservation of matter beyond the continual need for new supplies is that all of the elements in all of the materials that are ripped out of the Earth and brought into an economy must end up somewhere: as products or by-products, as recycled matter, or as wastes dumped into the environment. So if we manufacture a product, say a cleaning chemical, that material, or at least its elements, will be around indefinitely in some form or another. In the past, and still in many situations, whatever was left over after humans had used something was simply dumped—into the river, into a landfill, into the environment. Additionally, each step in the use of a chemical implies losses at each step, in mining, concentrating, processing, manufacturing, transport, use, and disposal. At each one of these steps, some part, large or small, of the original product is lost to the general environment. When the economies of humans were based mostly on the products of nature directly, their wastes (e.g., food wastes, logging wastes) were normally simply the routine wastes that were part of ecosystems and could be processed like any others—for which billions of years of natural selection had generated the dung beetles, bacteria, and so on to take advantage of these resources (to them) and in so doing keep things "cleaned up." Over the past several hundred years, humans greatly increased the scale of things—of agriculture, of mining, of economies, and of themselves—in cities and, eventually, through industrial and scientific processes. Humans also generated thousands of new chemicals that organisms had no previous experience with and for which there were often few organisms able to process. The net effect was to overload many ecosystems that had previously been able to adapt to humans. For example, the synthetic fertilizers that were generated from the Haber process and from mining phosphorus and potassium tended to be much more abundant in some locations than the natural quantities and hence wash into rivers and lakes, where they often caused serious pollution even though these elements had always been part of nature. While phosphorus and nitrogen are essential requirements for all plant life, an excess amount in waterways caused this once rare element to become abundant in many places, especially in the surface waters of the Earth where it generates undesirable algae growth and low oxygen conditions, a condition known as *eutrophication*.

Over time, nature tends to process human-made chemicals into more innocuous forms, but there is often very serious production of pollution along the way. Humans have become much better at recycling materials in recent years, and this recycling often has reduced greatly the amount of waste materials entering the environment. But recycling does not always reduce environmental impact as much as one might think, and again we need to think using a systems approach. For example, it would seem to be unequivocally good for the environment to recycle newspapers, that is, to make new newspapers from old. But if newspapers are to be recycled first, they need to be deinked, and then the fibers separated from the other materials. When all is said and done, it takes *more* energy to make a ton of newspaper from recycled materials compared to virgin materials, and more wastes are produced, mostly from the old ink. This is a good example where understanding the law of conservation of mass (the materials in the ink) helps us to understand the implications of what might seem initially to be an unequivocally good policy. It may still make sense to recycle newspapers, for example, to save space in landfills, and there are soy inks that are much easier to process, but it is not easy to make that judgment without undertaking a quite complex systems study. Probably the thing that makes the most sense is to reduce our use of paper, for example, a very large component of its use is for advertisements that people do not even look at or that even if they do are for products that may be really quite unnecessary and that also generate pollutants in their manufacture. In fact this is happening now as the internet increasingly does the function once done by newspapers, but one cost of this is that the revenue to newspapers declines so it is harder for them to maintain their staff of investigative reporters, in our view a critical part of society.

Thus, chemistry is extremely important to economies with respect to both our growing dependence upon the use of chemicals and also as pollutants. The natural world is full of complex chemical compounds, most of which are relatively innocuous but some of which are very toxic. In fact many natural compounds are designed to be very toxic. All plant materials represent a potential food resource for a whole plethora of viruses, bacteria, and insects, not to mention grazers such as deer. One response has been for plants to develop over time various chemical defenses to make themselves unpalatable or even to kill their potential consumers. Familiar examples include mustard oils, caffeine, turpentine, and, to some, the alkaloid *Tetrahydrocannabis*. While small amounts of these materials may make interesting dietary supplements, a diet composed of only one or more of them would kill us. That is a problem the insects face when they alight on, say, a mustard plant. Eat up and die! Well, not surprisingly, most insects choose to go somewhere else for lunch and the plant is protected. Animals in turn have developed kidneys and livers to detoxify many of these chemicals, so that they can eat some of the material. Thus, over evolutionary time, there is a sort of cat-and-mouse game of defense and offense, with few clear winners but many clear losers—given that maybe 99.9 or so percent of all former species have gone extinct!

Humans have changed the world around them in many ways through the rapid understanding and application of industrial chemistry. One of the most important examples is DDT, the first synthetic pesticide. DDT, developed in the second world war, was considered a godsend to our soldiers, for it was cheap and nontoxic to humans and eliminated many harmful and irritating pests, such as body lice with a single, simple dusting. Soon it was used on agricultural crops with similar spectacular results in reducing the losses to insects. It seemed to be too good to be true, and it was. Rachel Carson, a marine biologist and gifted writer, wrote one of the most important books of all time *Silent Spring* [15], which documented the very large impact that DDT had on bird reproduction. This book helped launch the environmental movement and for the first time suspicion that not all new inventions, nor progress itself, were necessarily desirable. DDT was especially a problem because it did not break down in nature—put it in the environment and it stays there, cycling through food chains and becoming concentrated as one organism ate another. The case against DDT was made further when it was discovered that the insects had become not only resistant to DDT but that some even required it for their survival! Natural selection can be that powerful and that fast! Chemists have responded to these problems by developing new pesticides that, while often more toxic directly to humans, break down to relatively harmless compounds in a matter of weeks so that it appears that the long-term toxicity problems are solved—as long as the good chemicals are used! But the pests still evolve to them and over time the pesticides lose their effectiveness. Agronomist David Pimentel argues that even as we use far more pesticides that we still loose about the same proportion of our food to pests that we did in the past, before pesticides.

Probably the most important, quantitatively, pollutants worldwide, other than the pathogens that kill humans outright, are the various carbonaceous waste products, including especially the fecal wastes of humans and domestic animals, especially when they are dumped into water bodies. This is a natural process and has happened naturally long before humans. But humans and their cities have completely changed the scale. Most natural bodies of water can handle moderate amounts of carbonaceous wastes through oxidation, changing the carbon materials into relatively harmless compounds such as water and CO_2. The problem occurs when too much polluting material is added. Then, the oxidizing capacity of the water bodies are overwhelmed and all or most of the oxygen is used up, resulting in bad smells, fish deaths, and a generally degraded water body. As developed above, a somewhat similar process happens when too much phosphorus is added to water bodies. Phosphorous compounds are the basis of very effective detergents, but they also encourage the excessive growth of aquatic plants, which then die and use up the oxygen in a process called eutrophication. Fortunately, these problems can be ameliorated or eliminated by relatively modest public expenditures in sewage treatment plants and by using other chemicals in detergents. Such successes in reducing environmental impacts are good examples as to how it is possible to successfully resolve serious externalities through good chemistry, good engineering, good economics, and especially good public policy implementation. But at the same time, treating sewage uses a considerable amount of energy and the total impact of growing human populations, and their growing use of materials leads to increased pollution of the Earth as a whole.

15.3.13 Chemistry and Physics

While chemistry is usually considered independent from physics, in fact, the two interact in many, many ways. Here are a few simple examples:

1. Essentially any chemical reaction is accelerated by *increasing the temperature*. For example, getting food particles to become unstuck from dishes requires work that occurs because you add physical energy by your scrubbing actions and by the chemical reactions in which you emulsify the food particles in a soap or detergent. Using hot water to clean the dishes adds additional energy to the process and accelerates the cleaning. Or leaving the dishes in the sink overnight after first filling them with clean water allows you to use the chemical energy of clean water (the molecules of water have positively and negatively charge ends that attract the materials stuck to your plate) to do work that you would otherwise have to do yourself! Polluted water has less energy to do that as the charged ends are already occupied. Thus, clean water is economically much more valuable than soiled water because it can do more work, such as cleaning work, in industrial or other economic processes.
2. Chemical reactions are usually greatly accelerated by *increasing the surface to volume ratio*, which is usually done by making the reactive particles smaller. This is familiar to most of us when we build a campfire: we must start with small dry twigs or even paper, with a very high surface to volume ratio and hence exposure to oxygen in the air, and then feed in progressively large twigs and the logs once we have a good hot bed of coals. In the process of industrial combustion, some hydrocarbon (such as oil or coal) is combined with oxygen to produce energy that is then used in, say, some economic process. The efficiency with which oxygen combines with the carbon and hydrogen in the fuel depends upon how closely each oxygen molecule comes into contact with each fuel molecule. Humans have been burning coal for a long time, and most of you are familiar with old pictures of factories or locomotives belching black smoke into the air. That black smoke, and the soot and other pollutants that are in it, are a product of incomplete combustion. We have learned to pulverize coal before we burn it, so that the carbon is nearly completely oxidized, providing more energy and less pollution—although even this does not decrease the quantity of CO_2 produced. On a more personal level, it is obvious that if you want to cool your food in a cooler for camping rapidly and completely, then you use crushed ice, but if you want to keep your food reasonably cool for a long time, you want to use a block of ice. All of these examples are related to issues of *surface to volume ratios*, that is, the surface of the material upon which the reaction (cooling or combustion) takes place compared to the total volume of the material. Of course, good engineers learn these and many more basic scientific principles early on, and from them they are able to use resources in a more intelligent and efficient way. What these concepts mean to economics is that there are many ways that simple science can be used to generate more efficient, less polluting economic activities, even when sometimes that costs more.

15.3.14 Climate and the Hydrological Cycle

A basic point of this book is that the basic inputs to the economy are not simply labor and investments but also natural resources, especially energy, and a proper working environment. Of the latter, the most important are soil and water as well as a proper temperature and other attributes of climate. Climate refers to the average temperature, rainfall, humidity, cloudiness, and so on that characterizes a spot or region of the Earth's surface, including the normal variations one might expect. Every species has its own ideal temperatures and humans are no exception. Probably you do not think of it too often but a proper temperature is critical for all of us. Just watch what happens if a classroom deviates very much from the range of about 68–78° Fahrenheit. Students will add or remove clothes, open windows, turn the thermostat or otherwise *thermoregulate*. We don't think about it very much, in part because it seems so natural (it is) and also because we live in a climate-controlled world where often sophisticated clothing and an enormous amount of fossil energy is used routinely to manipulate climates of the spaces that we occupy. If, however, the temperature gets very far from our preferred temperature, people will respond strongly, becoming agitated, work less effectively, become very unhappy, and greatly increase their efforts to try to get comfortable. At the extreme they will die, as happened to many older persons in Chicago and France in the hot summers of the early part of this century. Similarly other plants and animals have a rather restricted range of temperatures and often other environmental conditions they can withstand. There is a rather well-developed science within the discipline of ecology that has undertaken considerable analysis of the response of organisms to *gradients* (i.e., ranges) of temperature and other factors. Figure 15.6, for example, shows the production of coffee and bananas in Costa Rica as a response to local variations in climate. What this means for economics is that each species of cultivated plant has an optimal place to grow in a country, and once these areas are planted, it is much more difficult to make a good profit on the suboptimal lands. What this means in terms of economics is that the areas of the world in which it is possible to make a good profit from an agricultural crop are far more restricted than all the area that a crop might grow. The take home lesson here is that the physical environment can affect economies in many ways (Fig. 15.6).

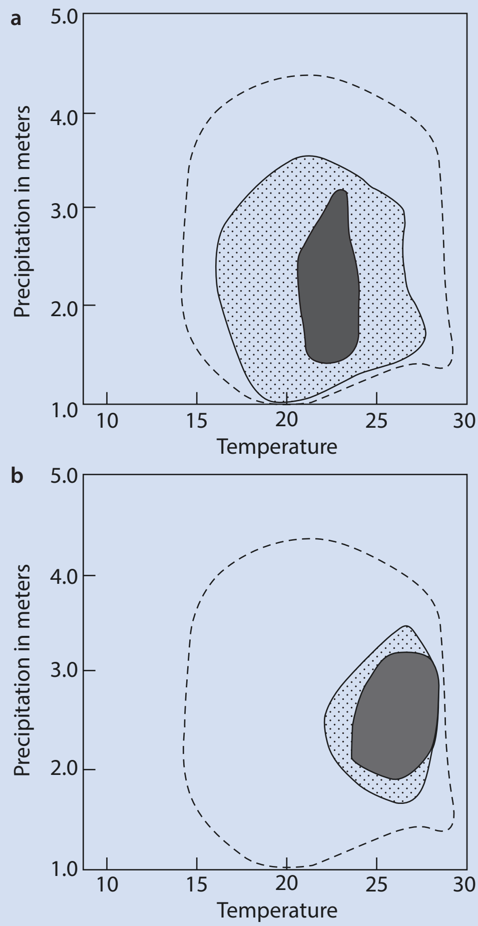

Fig. 15.6 The production of coffee and bananas in Costa Rica as a response to local variations in climate. The vertical axis is precipitation, the horizontal is temperature. While coffee and bananas can grow essentially anywhere in Costa Rica, sufficient yields of coffee **a**, to make it economic are found only in the central circle and likewise for bananas **b** (Source: Hall 2000)

The climate of the Earth is extremely varied, something that might not be quite so apparent to those who have not traveled far or simply hop from one air conditioned airport or resort to another. Most obviously the tropics and subtropics are warmer, or at least they are at low elevations. More importantly, for life, the temperatures there vary less over the year, and most of these areas do not freeze, a critical issue for many plant species. Less obviously there are many areas in the tropics that are very cold. These are at high elevations, and since there are many mountains in the tropics or subtropics (including the Andes, the Himalayas, and many other high mountains), there are large areas of the tropics that are far from warm. For example, Mount Kenya and Kilimanjaro are nearly on the equator, but they have, at least for now, permanent glaciers. Although the tropics at any one location tend to have very little temperature variation over the year, they tend to have much greater rainfall variation, especially in the subtropics (Fig. 15.7). Temperate areas often have much more regular rainfall but greater extremes over the year in temperature. As you go toward the poles, obviously, it gets colder yet and the sea-

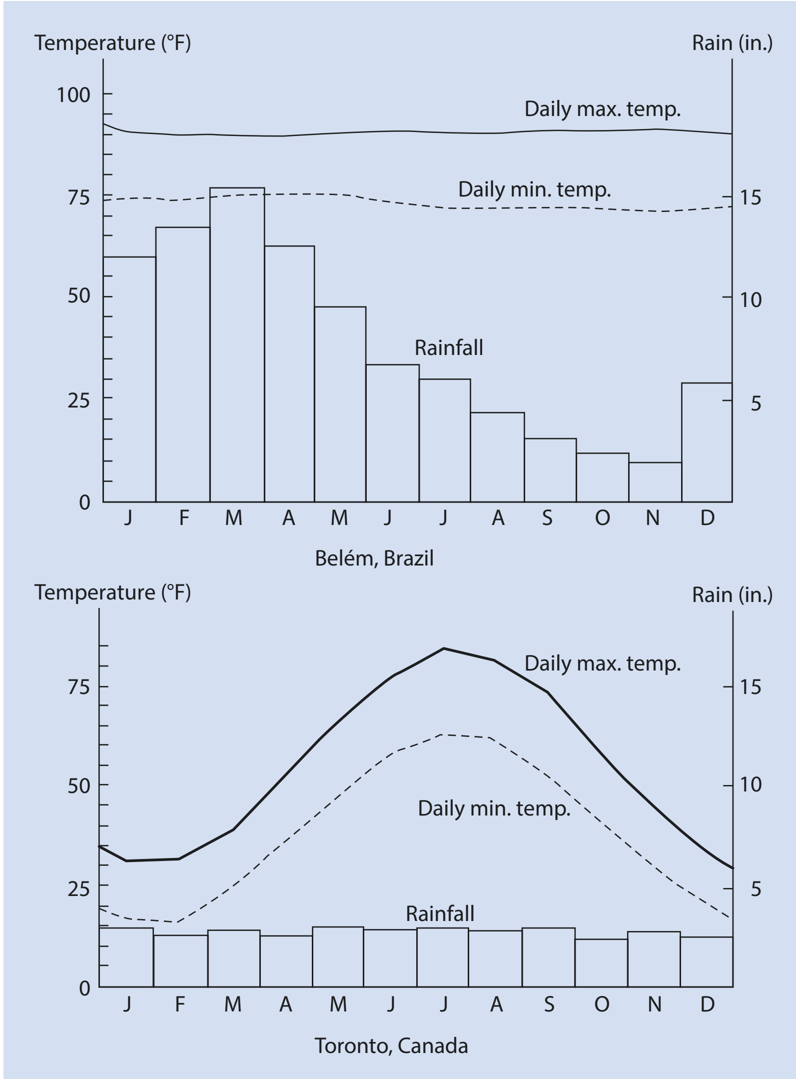

Fig. 15.7 Variability of temperature and rainfall in a typical tropical location (Belem, Brazil) and temperate location (Toronto, Canada) (Source: MacArthur, 1972)

sonal variation in temperature more extreme. Water in general and oceans in particular are much harder to heat than land. We say that water has a very large *thermal mass*. Land areas that are far from oceans or great lakes tend to have *continental* climates, that is, they get warmer in summer and colder in winter than land areas near the water which have what we call *maritime* climates. The West coast of the United States has less temperature variation than the East coast because the winds tend to blow from the west, bringing oceanic influences onto the land. Likewise areas downwind from or close to large lakes have less temperature extremes so that, for example, many wineries are associated with large lakes.

15.3.15 The Hydrologic Cycle

The hydrological or water cycle is closely related to the climate and it, like most things on this planet, depends upon the sun. Solar energy enters our atmosphere and about half of it reaches the Earth's surface where most of it is converted eventually to thermal energy. But first, it does a great deal of work, the most important or at least largest component

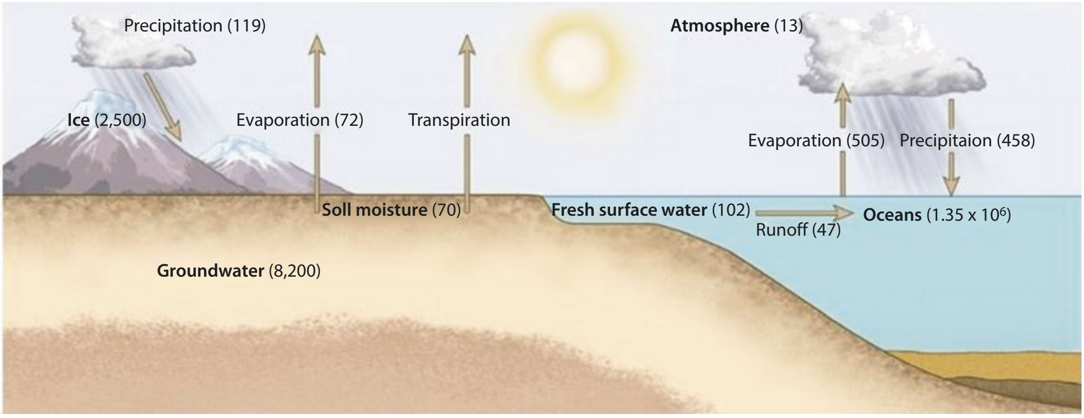

Fig. 15.8 The hydrological cycle. Water is evaporated from the land and (especially) the sea by solar energy, carried to land areas by winds where, if temperatures decline, it is deposited on land. From there, it is evaporated or runs to the sea in river (Source: Kaufmann & Cleveland 2008)

of which is evaporating water. As we will return to from time to time, the proper functioning of the hydrological cycle is probably the most important component of the economy, although it is hardly mentioned in most economic analyses. This issue is increasingly of more than academic interest as water quality and water quantity are increasingly changed and diminished through human activity such as groundwater depletion, deforestation, pollution, and global climate change.

The freshwater cycle starts in the ocean where most of the planet's water resides and most of the planet's evaporation takes place (Fig. 15.8). Evaporation is a truly amazing process that purifies water (since salt and pollutants essentially do not evaporate) and lifts the water into the atmosphere, often higher than the highest mountains. This very pure water then falls onto the Earth's surface, especially over land and most importantly over mountains, providing soils, rivers, lakes, ecosystems, and people with clean water. All of this is very energy-intense work, and it is done completely by energy from the sun. The reader can get some idea as to how much work nature does for us through the hydrological cycle by considering what people living in New York City would have to do to get their clean water were it not done for them by the sun. They would have to go to the Atlantic Ocean, say at Jones Beach, dip out two pails of water and somehow remove the salt. Probably the easiest way would be to build a fire and boil the water, collecting and condensing the steam that would be given off. Then that purified water would have to be put back into the buckets, and you would have to start hiking to, and then up to the top of, the Catskill Mountains, where you would empty your buckets into the streams there. Even if all of the people that lived in New York City did this, it would be but a trickle compared to what comes out of the actual rivers. Nature does a great deal of work for us and for our economy, and we must respect that. This work, however, rarely enters into the economist's calculations because there is no money involved.

The fundamentals of the water cycle can be seen in Fig. 15.8. Water evaporates principally from the sea, travels about the Earth as clouds and also invisibly in the atmosphere, propelled by winds, then falls onto the earth where it is held in the soil and then, if it does not evaporate, travels underground to rivers, and returns to the sea. Rain is more abundant near oceans, especially downwind from them, and at higher elevations due to the *orographic* effect. When air masses are lifted up a mountain, or more usually pushed up by winds, the air cools (Fig. 15.9). Cool air has less energy and so can do less work, including the work of keeping water molecules in suspension. The net result is that more water falls from the atmosphere in mountains, especially tall mountains. As the air masses move over the mountains and descend the other side, they warm and can hold more water, especially as most of the water that once was in the air masses was lost on the

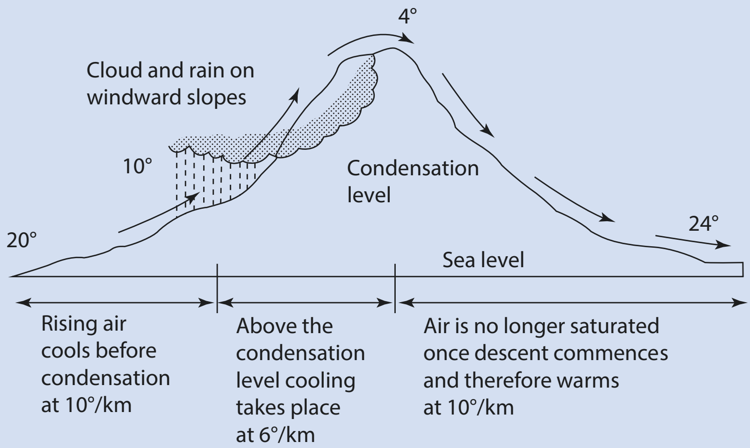

Fig. 15.9 The orographic effect. As air masses are pushed up mountains the air cools and loses energy so that it can no longer keep water molecules in suspensions, and rain occurs. As the air descends on the leeward side of mountains, deserts are created by the dry air (Source: MacArthur, 1972)

windward side. Thus, there tends to be a *rain shadow* downwind from mountains. Most of the rain, both in the mountains and elsewhere, falls onto the ground and filters slowly downhill underground. In general, all of the soil under our feet contains water which is mostly flowing very slowly toward the sea. Some soils can hold considerable water because there are considerable spaces between the soil particles. Gravel and sand hold water much better than silt or clay. Any water-holding belowground substance is called an *aquifer*. The depth below which the soil contains water is called the *water table*, and if you dig a hole to a little below that depth you can have a *well*. Where water flows naturally from where the ground level intercepts an aquifer, we call it a *spring*. More generally where the surface of the ground is below the water table, we find a *river*. Where rivers are dammed by some natural process, such as glacial debris, volcanic flow, or a beaver, we have a *pond* or *lake*. When this blockage is by human activity we call it a *reservoir*.

Rivers do a great deal of work. Since moving water has considerable energy, it can erode and hold in suspension many particles. Very fast water can move boulders, fast water can move gravel, and medium-velocity water can move sand, but slowly moving water moves only silt. Rivers erode landscapes, making valleys and depositing particles alongside the rivers when there are floods and some of the river water slows down outside the river channel. When something is moved by a river, it is called *alluvial*, and the general word for areas next to a river is called *riparian*. Steep upland areas are called *erosional* areas because the action of the river erodes away the rocks there. Where the river slows down in flatter sections, usually downstream, we find *depositional* environments. Hence, riparian or streamside soil tends to be especially fertile for both natural vegetation and for agriculture because new soils are made frequently from floods, and they are also especially important areas for wildlife and even a source of food for many fish. The rain drives the levels of rivers, and the rain varies a great deal. Consequently, the level, width, and volume of flow of rivers vary enormously. Small floods occur yearly, moderate ones at decadal levels, and large ones less frequently. A relatively small flood is a once in a decade flood, a larger one a once in a hundred year flood. A once in a thousand year flood is possible next year, but very unlikely, with a probability of 0.001. A once in 10 million year flood can help to seal off an oil-forming deposit of organic material. Rivers travel through *flood plains*, which are obvious when you look at a topographical map or a river from the right place. Rivers meander back and forth across the flood plain over time, and often shift their position entirely. Much of our societal infrastructure is destroyed each year because people do not respect that eventually rivers will flood floodplains. Misguided Federal flood insurance has encouraged people to live where they should not. An interesting, comprehensive plan for reconsidering how we manage the floodplains of the Mississippi River is given in Mitsch et al. [16].

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The economic value of the various parts of the hydrologic cycle is immense—even incalculable. Most importantly, it provides rain for our agriculture and rivers to bring water to cities, to industries, and to irrigation. Most of the things that we make require very large amounts of water. Rivers also build soil when they flood in the spring, and the reduced energy of slower flow allows suspended particles to fall out on *floodplains*. It is no accident that human agriculture first started in such fertile riparian regions as the Tigris-Euphrates rivers of present-day Iraq, the Indus river of India, the Yangtze river of China, and the Nile river of Egypt. Another particular advantage of riparian soils, both in the past and also today, is that while most soils over time tend to wear out through erosion and nutrient depletion, the yearly flooding of most natural rivers builds new, fertile soil each year. When rivers are dammed, there are many obvious gains (hydroelectricity, water for irrigation) but also many costs. The costs include the burying of fertile soils under the reservoir and the cessation of the soil-regenerating processes below the dam because the particles tend to sink into the still, low-energy waters of the reservoir and hence are lost from the river.

Natural ecosystems, such as the forests that cover the Catskill Mountain watersheds that are the water supplies for New York City, also do work for the human economy because they clean and purify water as well as regulate stream flow, reducing the flooding potential. Forests and grassland soils and aquifers absorb some of the excess of a heavy rainstorm and then release it slowly over time. Where forests are cut, the water cycles tend to be disrupted and humans must use more energy and more money to correct for these problems, as is also true with river pollution. Rivers will always eventually go where the forces of nature dictate. Humans invest huge amounts of money and energy trying to keep rivers where they want them, but it will always be temporary. Smart economists and smart people more generally will understand what nature will do eventually and will build accordingly. Arrogant ones build many houses where they should not be. If you want to live on the edge of a river or the sea that is your business, but remember there may be a price. The US Federal Government recognizes this and is wisely removing flood insurance from places where human structures do not belong.

Humans have tended to exploit, and often overexploit, whatever water supplies they can find. When there are few people in a region, water is taken from streams or a well, but if over time, more humans move in often the river becomes polluted or the well is pumped dry. Later, people have to go after more expensive water. The city of Los Angeles is a great example. The early explorer John Fremont said of Southern California that it was a lovely spot, but there never would be very many European-Americans living there because it was simply too dry (although many Native Americans were doing just fine there using the relatively small natural rivers). That was changed, however, when the larger rivers in Northern California were diverted through canals all the way to Southern California, allowing the great city of Los Angeles to be developed in a near desert. Water also was diverted from the Owens River far to the East in California and eventually even the Colorado River, several states away. All of this water allowed not only the existence of Los Angeles but also much productive agriculture in Southern California. What is less talked about, however, is the costs of diverting that water, for example, destroying the once very large salmon fisheries of Northern California, causing San Francisco Bay to become much more saline with many adverse effects and completely drying up the Colorado River so it never makes it to the ocean. How do we weigh the costs and the benefits? We will talk about that later. What is clear is that often different people get the benefits and get the costs.

Humans have continued to exploit, develop, manage, pollute, and otherwise influence the natural water supply. Presently, water is an extremely serious issue for much of the world's population. Two especially difficult issues are that human population growth is often greatest where water is least available (such as in the Middle East) and the potentially disastrous effects of climate change. In general, these extremely important issues, or indeed the economic benefits that are a consequence of a well-functioning hydrologic cycle, are not included very well, or often at all, in economic analyses. This is because we do not pay in our markets for the work of nature, but rather just for our cost of exploiting nature. Water is often considered a "free good" and for those who measure the value of things by their price as having little value.

15.3.16 Climate Change

These climatic issues have very large implications for economies, including the crops that can be grown or not grown and the rate of production of those that can be, the amount of energy needed to keep people comfortable, the availability of water over the year, and so on. Of increasing concern is the degree to which climate is changing or may change. So the first question might be: will the climate change? That answer is easy, yes, certainly, for it has always changed! But although climates have always changed, and presumably always will due to natural causes, natural selection has prepared both humans and their important plants and animals for only a relatively small range from within the possible temperatures, soil moistures, water levels, and so on that exist or might exist on the Earth in the future. The reader may have been exposed to various points of view as to whether the climate is changing and what the effects might be. So our second question is: is the Earth warming? Again here there is little disagreement among most environmental scientists: the Earth is indeed getting warmer, glaciers are melting as the first author has seen again and again with his own eyes, the polar ice is probably shrinking, the temperature of the sea and probably the land is warming, and many areas seem to be getting drier.

Our third question is much more difficult: is the present climate change a function of human activities such as putting more and more carbon dioxide into the atmosphere? The answer is probably, and in the minds of very many scientists most certainly. In particular, many of the changes mentioned above are credited to the "greenhouse" effect, the idea that the increase in atmospheric CO_2 caused by the burning of carbonaceous fossil fuels is causing an increase in CO_2 in the atmosphere. What is the greenhouse effect? This is the process where atmospheric gases, principally water vapor and carbon dioxide (CO_2), but also methane, nitrous oxides, and other gases, act as a one way "blanket," allowing high energy, shortwave radiation (i.e., photons from the sun) to penetrate the Earth's atmosphere to a greater degree than lower energy, longwave heat can leave. When the photons strike the Earth's surface, they are transformed to heat (according to the second law of thermodynamics). Since this heat is trapped to some degree by the greenhouse effect, the Earth warms.

The initial lines of argument that said that the Earth was likely to be heating due to human economic activity were theoretical and went back to the great Swedish Chemist Svante Arrhenius who noted the property of CO_2 to absorb thermal energy in the laboratory in the 1880s. He reasoned that since the burning of fossil fuel generated CO_2 that it would inevitably lead to a warming of the Earth's surface. Further logical evidence came from planetary scientists who found that the temperature of the Earth was about 30 degrees centigrade warmer than it "should" be as determined by the position of the Earth relative to Venus and Mars. In other words, the Earth was a little too far away from the sun to be as warm as we are (based on our neighbor planets).

There are at least four main lines of empirical argument that show that the climate is changing: (1) the surface of the Earth is getting warmer, as revealed by thermometers; satellite surveys of, for example, temperatures and polar icecaps; and most critically the temperatures of both deep wells and of the ocean itself (which are very hard to heat!), (2) glaciers and tundra are melting all around the world, (3) many plants and animals are moving poleward and plants and rocks are appearing on the South Pole land mass that have never been previously observed by humans, and (4) the upper atmosphere, robbed of some of its heat from the Earth's surface, is cooling, something that was predicted by climate models before it was observed. Initially, real measurements of temperature change were difficult to interpret, and in the 1960s, temperatures actually seemed to decline! What we understand now is that industrial fuel processes do at least two things to the atmosphere: they increase the CO_2 *and* they release dust, especially sulfate particles, which reflect sunlight and cause a cooling. But the dust settles out in roughly 2 weeks, while the CO_2 is cumulative, that is, once it goes into the air, it stays for a very long time. By the 1980s, the CO_2 effect (in both models and reality) became more powerful than the dust cooling effect, so that the temperatures of the Earth have continued to set new records, more or less year after year and decade after decade. A majority of climate scientists attribute these signs of a warming Earth to the heat-trapping effects of the CO_2 (and water vapor) in our atmosphere. Starting in about the 1970s, computers began to be large and fast enough to run global climate models, and these showed again and again that if we kept increasing CO_2 that temperatures would rise. Many difficulties remain, such as understanding how water vapor and clouds might change, but the trends are clear.

The majority of scientists who work on this problem believe that it is the human-caused release of CO_2 and other "greenhouse gases" that is responsible for the global warming that we have observed. But because the Earth warmed considerably 12,000 years ago as we came out of the last ice age (with no help from human release of CO_2), there are some who say that the warming we are seeing today is just a continuation of that process. Perhaps, the Earth is still responding to whatever caused those changes. Important drivers in this long-term glacial cycling process are thought to be Milankovitch cycles, relating to the distance and tilt of the Earth to the sun, which tend to be repetitive on three very long timescales, changes in solar output (associated with sunspot activity), or something else. The arguments between these two groups are often extremely acrimonious. Thus, we come down on the side that the observed climate change is caused by industrial activity but acknowledge that the case is not quite as air tight as many would like it to be.

15.3.17 How Climate Change Can Affect Human Economies

If in fact global warming continues, the impacts will not all be bad, for example, the movement of many fish species northward in the Northern Hemisphere benefits, for example, Alaskan salmon fishermen at the expense of Oregon salmon fishermen. But overall the effects are expected to be overwhelmingly negative for most economies around the world. For example, Rind [17] predicts that huge areas of the tropics will suffer from serious drying of soils. Considerable information exists that suggests that many tropical and warm-climate diseases and pests are moving Northward in the United States. The Atlantic Ocean is measurably warming, and, because the heat in oceans is the source of energy that fuels hurricanes, the warmer the ocean (probably), the more powerful and possibly frequent the hurricanes and the stronger the hurricanes, the greater the damage to many coastal economies. Bark beetles are moving north in the Rocky Mountains with devastating results on forests because the winters are no longer severe, many birds and ocean fish are moving northward, and Australia and Africa are seeing prolonged and unusual droughts. There are ways that this climate change can enormously impact entire regions and countries: entire cities and island nations, such as the Seychelles, and the Maldives may disappear under the waves as the sea level rises with glacial melt and thermal expansion of oceans. This would displace millions of people inland to regions already stressed by excess populations. Many of the world's great cities in South America and Asia are completely dependent upon the summer melt of glaciers to supply water during that part of the year, and glaciers and sometimes their flows are declining. For example, the glacier that supplied warm-weather water to the city of La Paz, Bolivia, finally disappeared in 2009. These various impacts are clearly occurring now, with some severe economic impacts at this time. The economics of stopping or reversing global warming is overwhelmingly huge, but the consequences of not dealing with it are potentially more serious [18]. If the majority view is correct, then we must make enormous investments into replacing carbonaceous fuels with solar or nuclear power or suffer the consequences. If, on the other hand, the minority opinion is correct or, to further complicate matters, if there were a great increase in the number and severity of volcanoes that throw dust into the stratosphere or a reduction of solar output, the climate could become cooler. The likelihood of this occurring is very small, but the impact is potentially very important. Then it would be a poor use of our resources to change so quickly to expensive and intermittent solar energy sources. What a dilemma! Clearly climate is a very complex and important issue!

Our view is also that making our new energy investments in solar rather than fossil fuel is probably justified for other reasons too, including long-term energy availability, economic and national security issues, making jobs at home rather than abroad, making communities more self-reliant, and protecting the ocean from acidification and the land from the mercury that is released by burning coal. But we also believe that a conversion to mostly renewable resources would be extraordinarily difficult, would require a large proportion of our remaining fossil fuels, and would possibly greatly reduce societies' EROI. The full accounting has yet to be done, and this is a critical area for the application of biophysical economics (see ► Chap. 23).

15.4 The Biological World

15.4.1 Natural Selection and Evolution

We now turn in our quest for the basic science needed to understand economics from the physical world to the biological world. We start with a further consideration of natural selection and evolution. All of life is the product of relentless natural selection operating on our ancestors for millions and even billions of years. This evolution has been a complex process that has resulted in the immense diversity of life as we know it and also our own genetic makeup. It has large elements of chance: will a meteor's path, set by some cosmic forces perhaps a million or billion years ago and light years away, intercept the Earth's orbit or not? Is that meteor large enough to cause a tsunami that wipes out half of Tokyo or an even larger one that might extinguish major components of life? This almost certainly happened some 55 million years ago when, apparently, a huge asteroid struck the Earth, probably near Yucatan, and a large number of species went extinct. These elements of chance have operated in many, many ways and often under what seems to be quite peculiar circumstances. The opposable thumb with which I carried the computer to the table and the stereoscopic vision I am reading the words on the screen are almost certainly an artifact of our ancestor's arboreal existence extending perhaps some 4–20 million years ago.

But evolution is nonrandom as well, for we know that a process called *adaptive convergence* generates similar-appearing and similarly adapted plant and animal species in, for example, the different deserts of the world even when starting from completely different raw genetic materials. In each environment of the Earth, there are problems that have to be solved, and only so many ways (thick cuticles, spiny defense of water reserves, and so on for deserts) in which that can be done well. Thus, many different species "converge" in the ways that they solve the problems imposed by a particular environment. For example, the similar-appearing desert plants in Southern Africa and Southern America were derived from very different genetic stocks, Euphorbs and Cactaceae, respectively.

This similarity in life form and function in similar environments is the case in part because the material building blocks available nearly anywhere in nature tend to be the same: the element carbon is especially useful because its valence structure leaves four locations on its outer shell where other atoms can be hooked. Only silica of the abundant elements has this possibility. Carbon has been selected by organisms because it is abundant, lighter, and hence less energy intensive to use as a basic structural material. Nitrogen is also extremely abundant, making up some 70% of the atmosphere and roughly 3–7% of most life excepting water. Its abundance and special properties have been exploited by organisms through evolutionary time for the construction of proteins. Proteins are especially important for life because of their specificity, meaning that the available locations on their outer electron allow for the construction of many complex and very specific compounds. But there is a hitch: atmospheric nitrogen occurs as N_2, and N_2 is characterized by three chemical bonds holding the two atoms together. (Carbon dioxide, e.g., does not have this characteristic.) Thus, there are only a very few groups of organism, essentially the "nitrogen fixers," found only within the "primitive" groups bacteria and blue green algae, that have evolved the energy-intensive means to split the triple bonds and make the nitrogen available for use by these organisms. All other organisms, each of which needs relatively large quantities of nitrogen, get it indirectly from the activities of these two groups. Thus, part of the reason for evolutionary convergence is the relatively limited raw materials from which it makes sense to use for construction and partly because the problems that all life must solve are similar for similar environments.

For example, all around the world, trees must stand up, be anchored, exploit mineral resources form soil, and fix carbon through photosynthesis. This leads to the observation that all around the world trees look basically the same: they have trunks, roots, and leaves to solve the above problems. Where water is rarer, the approach of grass-like organisms works better, and so on. So although evolution is unpredictable, due to the importance of random environmental events and random mutations, to some degree, it is comforting to the experienced biologist that there are many common problems that life in different, or even the same, environment face, and many common ways to solve these problems.

A large component of the randomness that occurs within evolution occurs because of the randomness of environmental change, at least it is random from the perspective of the organisms that are affected. The Earth, which seems more or less stable from the time and space consideration of several human generations, is actually an extremely dynamic and unpredictable place if you wait long enough, with frequent climatic excursions that put very difficult stresses on the organisms that are adapted for the previously normal conditions at each location on the planet. So-called Milankovitch cycles that result from the eccentricities and wobbles of the Earth's orbit relative to the sun are but one of the main forcing functions. The point is that the ecological "theatre," that is, the environmental milieu within which the evolutionary "play" takes place, is a dynamic and changing place, requiring organisms to adapt to those changes, migrate, or die.

15.4.2 How Does Natural Selection Work? The Ecological Theatre and the Evolutionary Play

Charles Darwin made the fundamental observation that populations of reproducing organisms tended to generate many, many more offspring than were necessary to replace the parents. There are three properties of the world that, if true, would necessarily lead to a world in which natural selection must operate. These three properties are first, that there is variation among the genome of a given species (you can see that this is true for our own species simply by riding a bus or teaching a class, especially in any metropolitan area in the United States); second, that these variations are to at least some degree passed from one generation to another (you can see that is true by simply observing that human children tend to look reasonably, but not perfectly, like their genetic parents); and third, that this variation leads to differential survival and reproduction, that is, that from among the variability, some properties of organisms will be more likely, however slightly, to lead to organisms that are more successful at reproducing. The latter is far more difficult to observe today because there is relatively little mortality among children today, especially when compared to, say, one or more hundred years ago when the majority of children would die. Nevertheless it is obvious that a faulty immune system or a less robust physique or physiology can certainly work against the survival and eventual reproduction of people even today, and it would be much more important if medical interventions were not so prevalent and generally successful. It certainly is operational to a great degree for wild plants and animals.

We will examine some additional evidence for this third proposition below. But the logic of this argument is overwhelming: if these three properties of the world are true, then natural selection *must* occur. To our minds and that of most biologists, the evidence is overwhelming and accumulates every year as we find more and more "missing links" in the fossil record, as we watch natural selection work before our eyes as agricultural pests and human pathogens acquire resistance to our once-trusted tools of pesticides and antibiotics in a way that is straightforwardly explained by simple Darwinian selection, and as scientists who study the design and behavior of organisms operating in nature see that those designs and behaviors consistently fit Darwinian predictions. The net result of natural selection has been evolution of life over time and the natural world as we observe it today, including ourselves. If there is a deity that has been in some way responsible for all of this (and science by itself is not equipped to make a judgment on that one way or another), then it is clear that that deity both operates at least most of the time through or in concert with natural selection or that he or she has gone to an enormous amount of trouble to lay down the fossil record, adjust radiocarbon dates, and so on to make it appear that evolution according to Darwinian principles has occurred. If that is the case, one then wonders why. For ourselves and most scientists, it makes far more sense to simply accept the Darwinian explanation. But we recognize that a large portion of our potential readership and many of our friends are strongly religious, and we do not want them to close the book now. Although we personally are not particularly religious, at least in the conventional European-American way, there is nothing inconsistent to us with religious faith and the scientific explanation of the universe. In fact the outline of the creation of the world given in Genesis is pretty close to that as we understand it from science—if we assume that God has long days, and why not? It is time that those arguments are put to rest and we get on with the tremendous problems facing the world.

Natural selection operates on three characteristics of an organism, its morphology (shape), physiology (function, chemical, and otherwise), and behavior. Characteristics of each of these are determined by the genetic plan donated by the organism's parents and by the environmental conditions (e.g., intense exercise will make muscles larger and stronger). But the expression of genes is not perfectly straightforward, for, as Mendel showed, the expression of any characteristic may depend upon how genes from the mother and the father come together, including many issues related to dominance and recessiveness, and because many genes can determine any particular characteristic such as eye or skin color or, at the extreme, personality. We call the genetic makeup of an organism its *genotype* and its actual expression its *phenotype*. Phenotype, that genetic makeup that is outwardly expressed, is what we observe and what natural selection operates on. Thus, an important issue is that natural selection cannot operate simply and directly on genes but only more indirectly through their collective and environmentally contingent phenotypic expression. An important new discovery in biology is that we are finding that traits are not simply determined by genes for that trait but also by other "regulator" genes that turn particular "expression" genes on and off. These genes are also subject to natural selection but the net effect is to make the possibility for more rapid evolution than we had previously thought.

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Throughout evolutionary time, evolution has finely tuned organisms to their environment by eliminating those genes that do not contribute to fitness, that is, survival and reproduction. But what is fit is not a constant, for natural selection is chasing a moving target. For example, Jim Brown [19] and his students have unraveled the interaction of climate and the size of pack rats in Colorado and Nevada and found that the size of the rats increased during cooler geological periods and decreased during the warmer periods as the climate cycled over long time periods. While it is clear why it should be advantageous to be large (e.g., in competitive trials for mates), it is not so clear why it should be advantageous to be smaller. These investigators found that during warm periods a large surface to volume ratio, characteristic of smaller organisms, was important for dissipating heat, so large rats would get too warm when the climate was warm. This might not kill the rat directly but would, for example, make it more difficult to forage and hence to get enough food. Without a food energy surplus, females would have a much harder time getting enough energy to reproduce and provide lactation for their young.

15.4.3 Adaptation to Biotic Agents

Probably the biotic components of the environment, including predators, pathogens, and perhaps competitors, are even more important than the biophysical components such as climate in determining the natural selection forces on an organism. These too are related to energy cost. The ultimate example is of course loss to predation, which represents a complete loss of all energy reserves. Other interactions are more subtle, and there is a cat-and-mouse game of energy losses and investments among different species throughout evolutionary time. Trees, for example, are great food for many insects. Since most trees are apparent in the landscape, they can hardly hide from the insects that want to eat them, which of course would rob them of their energy reserves and of their ability to generate an energy profit that would allow for reproduction. The evolutionary response of trees has been to generate what are called secondary compounds, for example, tannins in oak leaves, that defend the trees against most insects. But there is an energetic cost for the tree to make most of these secondary compounds, so through evolutionary time, there has been a trade-off of more vs. less natural pesticides. For oak trees, the "correct" amount of tannins seems to be about 20% of the dry matter of the leaf.

Pathogens too impose an energy loss on organisms even when they do not kill them. A particularly nice study was done by Moret and Schmid-Hempel [20] who trained bumblebees to feed on small glass spheres, which the bees mistook for pollen. When the bees were fed this diet, they would die from lack of energy in about

5 days. When the investigators infected the bees with a bumblebee pathogen, the bumblebees would survive if they had real food but would die in only 3 days when fed the glass spheres. This shows that when challenged with the pathogens, the bumblebees need to use their own energy reserves to fight them.

Finally, competitors decrease the energy flow and sequestration in organisms either by forcing the organism to invest energy or lose exploitable resources in response to a toxic material (butternut trees do this). More commonly, they reduce the light, nutrients, or food available to the competitor or increase the energy cost of sequestering it. Examples are common in any forest. For one example, it is easy to see where evergreen trees grow next to a path or clearing that branches that are shaded die (or are thrown off) sooner than branches that are not shaded. If a branch does not pay the energy cost of its maintenance metabolism through sufficient photosynthesis, it is sloughed off.

15.4.4 Ghosts of Natural Selection Past

Within each species, there is a trade-off between being well adapted to today's particular conditions and maintaining contingencies for more extreme but rarer events. An example is all around those who live in the more Northerly latitudes. The trees that live in these locations obviously must be well adapted to the conditions that exist there today. Each year each adult tree produces on average hundreds to thousands of offspring of which far fewer than one can survive. Those many young will tend to have some genetic variation among themselves, and if the region is a bit drier or wetter, warmer, or colder, subject to more or less impact from a certain herbivore, then some genetic properties are likely to be a little more frequent in future years. In any case, there is genetic selection for the tree to send well-equipped seeds into the world, for a young tree with large food reserves (think of an acorn or a beech nut) would, other things being equal, be more likely to "make it" in the world. But there is a cost too—heavy seeds tend not to travel far.

But at the same time, all of these trees "remember" the ice age, when only those trees with long-range migratory capacity (e.g., smaller seeds that could travel better on the wind, or at least fall further from the parent in a heavy wind) were able to migrate and hence survive better. This ability to migrate is well represented in present day trees in New England, for the region was entirely under ice 12,000 years ago and no trees were found within thousands of miles. And since there were at least five major ice ages, then there was a strong premium against those genetic groups that "forgot" how to migrate. Thus, there may be less selective pressure on organisms to be able to disperse their seeds widely today, but many trees retain that capacity, for once it was extremely valuable. For another example, the common salt marsh grass, *Spartina alterniflora*, is found along most seacoasts in the temperate regions. Each fall, this plant produces millions of seeds at great energy expense. Nevertheless the plant rarely reproduces through these seeds, but rather through the use of underground stems or rhizomes. Why then should the plant produce seeds? The answer is that the seeds are necessary to colonize new areas, and new areas were constantly being formed as the sea rose against the land following the cessation of the past glacial period. Thus, those *Spartina* plants that did not produce seeds were drowned out as the sea level rose, and those that did were able to colonize new areas as they occurred. With climate change again increasing the level of seas, those "migratory" genes are likely to again be advantageous.

15.4.5 The Units of Selection

Natural selection works most obviously on individuals, for individuals survive or not and those that live are obviously the only ones that contribute to future generations. Perhaps it is more accurate to say that organisms that survive and leave the most surviving offspring are the ones that are more likely to be represented in the future. Organisms are selected to do whatever it takes to propel their genes into the future. But the situation is a bit more complicated, for we have found increasingly that evolution works in complex ways. At one extreme, Richard Dawkins [21] talks of *The selfish gene* that what survives or not over a longer period of time is not the species (for after all most species that have been on this Earth are extinct) but rather genes. To Dawkins, the genes are "selfish" in that they "use" organisms and species as their temporary receptacle to carry them forward in evolutionary time. Again it is not that they are deliberately doing this through some kind of cognitive process but that there will be selection for the patterns that cause this to occur. Perhaps it is more accurate to say that from this perspective genes are molecules capable of reproducing, and they exist in populations to the degree that they are successful in doing that.

At the other extreme, there are many who argue that the units of selection are larger than the organism. The simplest and clearest example is that parents will often risk their lives for their offspring: this is obviously a behavior that has been strongly selected for. The late William D. Hamilton argued that there has been selection for organisms to look after relatives not their offspring, cousins, for example, because whereas an offspring has half the genes from a particular parent, a cousin has one quarter and so on. According to Hamilton, an organism should be willing to take on average half the risk to help a nephew or niece that it would for its own offspring other things being equal. The idea is that this is completely consistent with a Darwinian perspective of propelling one's genes into the future. A more complex situation has been argued by Robert Trivers [22]. Reciprocal altruism is the situation where an organism will do something that appears to cost it something (hence reducing its own fitness) in order to assist an unrelated organism—but with the expectation that the one being helped will return the favor at some future time. A clear example of this is a herd ungulate defending the young of another unrelated animal from a predator. Again this seems to have a clear Darwinian genetic basis with direct recompense to the genes of the organism doing the activity, and in fact all may benefit with relatively small costs.

It gets more complex with interspecies interactions, but these are very common and are generally called coevolution. The idea is that a close interspecies interaction often benefits both species. The most common example is honeybees and apple trees: the bee gets its food, and the apple tree gets pollination services. More complex examples exist where the role of a predator in regulating the numbers of a prey can keep the prey from overexploiting its food resources. The more we look, the more of these we find, but an important point is that this does not occur through pure altruism on the part of an organism but apparently only via a tit for tat where the interaction, no matter how complex, is always of direct (or occasionally indirect) benefit to the organism engaging in the activity.

Finally, the most complex issue is to what degree does coevolution occur at the level of an entire ecosystem. Anyone studying ecosystems is impressed with the apparent "harmony" of the system: although there may be important fluctuations in populations or overall structure, one gets the sense that year after year the system continues to "keep itself together," adapt to, and bounce back from incoming stressors such as variable climates or storms while maintaining and even incrementing its basic structure. Herbivores tend to keep plants in check, but not cause their extinction, dead material is degraded into soil increasing its utility for other species, nutrients are maintained within the system, predators and prey increase and decrease but not to the extremes they might be capable of, and so on. To what extent is this "balance of nature" a case of many, complex coevolutions vs. simply "every organism for itself?"

Or, perhaps, are ecosystems regulated by the principle of Le Chatelier:

$$(A + B \longleftrightarrow B + C)$$

This principle, derived in chemistry, says simply that as a chemical (or other) reaction goes forward, it will tend to be limited eventually by the depletion of the source materials that allowed it to occur in the first place or the accumulation of products. For example, plant biomass grows and grows until it has used up the nutrient inventory, and then further growth must await the death, decay, and mineralization of earlier plants. We cannot answer this question of regulation at the level of an ecosystem very well at this time, but one thing is clear: a natural ecosystem is a wonderful and mostly self-regulating thing, whatever the mechanisms that control it might be. They run themselves for free off the energy of the sun. Human-dominated ecosystems, such as agriculture, require our constant intervention and management to be maintained in the form we wish.

15.4.6 Energy and All Biology

Take a look at most wild or domestic animals. What are they doing? Most of the time they are simply eating, if they are able to, or they are trying to position themselves to eat. If they are not eating, they tend to be resting, when they must use energy for their own maintenance metabolism to fight entropy—at least when it is not the breeding season when, obviously, things get more complicated. In other words, animals tend to be either trying to gain energy while using it for necessary maintenance while trying to diminish its loss or to use past energy surpluses to breed. Plants too are spending most of their time dealing with energy: for example, they are photosynthesizing any time the sun is shining and it is warm enough, and at night, they must use some of their energy reserves for maintenance metabolism. Thus, all organisms on this planet are very much about energy every minute of every day. Humans are a bit different because food energy is (at this time in our history) so abundant and also because our energy requirements for the more usual sedentary lifestyle of today are only about half of what they were when we were more active.

15.4.7 Ecology

Both ecology and economics are derived from the Greek word *oikos*, which means pertaining to the household. This is quite appropriate, for conceptually in this book, we are talking about managing both our immediate and also our larger household, and we believe that proper management makes both ecological and economic good sense in the long run. *Ecology* refers most specifically to an academic discipline "the study of interactions among plants, animals and their physical environment within the natural or human-dominated environment" or "the study of environmental systems" [23]. The suffix "-logy" is derived from the Greek *logos* referring to a discourse. This definition is a very different from the popular or newspaper definition of ecology that emphasizes the normative or value-laden "protect the environment" or "concerns for human health" perspective and includes the perspective of values. While most professional ecologists certainly do not mind the word ecology being used to refer to environmentalist issues, and they may in fact be focused professionally on protecting the environment, most would agree that the word "environmentalist" or "environmental" is probably a better word to use than "ecologist" or "ecological" for the activist or protectionist or other values-associated perspective. This retains "ecology" for the more academic or technical one. Finally, the words *environmental scientist* refers to many different people, hydrologists, atmospheric scientists, ecologists, economists, activists, and others, who study the environment from many perspectives using the scientific method. It may refer to a person that is a pure scientist or one oriented towards advocacy or policy. We believe it very important that all people involved in studying the environment and making policy judgments based on such studies use regularly and explicitly, or at least be very aware of, the scientific method for we find that many people have very strong opinions about the environment that are not, in fact, supportable by research to date.

We love the concept of ecology as a basis for thinking about economics because ecology is about interactions among the many physical and biotic components of a section of the Earth's surface, often natural but also including all systems with varying degrees of human influence, up to and including cities. Additionally, real ecosystems are constrained by the laws of nature and the energy inputs and material circumstances of their environment, as are, ultimately, economic systems. We believe that academic ecology has suffered somewhat by being taught too often as principally a biological science with a focus almost entirely on natural plants and animals and with humans too often ignored except as a provider of insults to natural ecosystems. More accurately ecology is about the science of all environmental relations and interactions, both biotic and abiotic, including, when appropriate, humans as part of those systems. It is about *how environmental systems work*, principally natural systems but also cities, counties, and other human-dominated ones. Economic systems are very similar to natural systems in that energy must be used to exploit resources from the Earth and atmosphere and to move and recycle materials through the systems to build structures and to provide energy for maintenance metabolism to fight entropy and to reproduce individuals, cities, and all systems. Humans are dependent upon complicated interactions among many natural and economic energy and material flows.

The important ecological concepts that an economist needs to know to be a good economist are quite extensive and beyond the short coverage that we provide. But there are a few important issues that we can summarize. First, ecologists have tended to study ecology at many levels, at the level of the *individual* organism, or of a *population* of individuals, or of a *community* of different populations (i.e., of all of the species) and finally of *ecosystems*, which includes all of the living and nonliving components of a landscape or a waterscape whether natural or human-influenced. The ecosystem perspective is most useful for understanding economics. Within any of these levels ecologists tend to study the *structure* and the *function* and the *controls* of ecosystems. Structure might include the physical nature of the ecosystems (i.e., size of individual plants), the abundance of different species (or kinds of plants and animals) (collectively known as the *diversity*), the number of individuals of a species (e.g., number of white tail deer per square mile), or biomass, meaning the total living weight of a species, or of all species, again usually expressed per unit area. Function can mean the rate of energy capture from the sun, the use of energy by various components, the transfer of energy from one group to another, the decomposition rate, the way nutrients are recycled, and so on. The controls can include external or climatic controls (temperature, rainfall, catastrophic events, and so on) and internal controls (self-regulating population control, nutrient limitations etc.). Ecologists have tended to focus on these four levels in studying their discipline.

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Thus, an ecologist interested in *individual organisms* may look at how individual organisms interact with their local environment, for example, at the effect of temperatures, sunlight, or plant nutrients on the growth of individual plants. Thus, we find that each species tends to do more or less well (i.e., grow, be abundant, or some other factor) along *gradients* of conditions [24] (see ◘ Fig. 15.6). As we have discussed, this climate dependence has very large implications in limiting the types of organisms that can or cannot live in different regions, for example, different agricultural crops can be grown with a good profit only where climatic conditions are rather favorable for them. Another consequence is that each general region of the Earth has only a relatively few species (at least as a proportion of all species) that can live there. One practical consequence is that as various parts of the world are destroyed for economic gain often times many species are lost because they are found nowhere else.

An ecologist using the second approach (called *population dynamics*) might look at how populations change over time and what the controls might be. There have been long and acrimonious arguments about the relative importance of *density dependent* (i.e., influenced by the density of the population being considered, i.e., self-regulation) and *density independent* (i.e., influenced principally by external factors) throughout the history of ecology, a debate that continues today. Ecologists interested in *community* ecology might examine the interactions among all the different species and populations of an ecosystem. The community approach often asks what determines the number of species collectively in a given location, and how these different species control how that ecosystem operates. Finally, ecologists interested in the *ecosystem* approach often focus on energy flow or *trophic* (i.e., food) relations. We can, for example, follow the flow of energy from the sun through the food chain of an ecosystem. Primary producers (mostly green plants) are able to capture solar energy and use that to turn CO_2 and water (with a little help from mineral fertilizing elements) into biomass. *Herbivores* (such as deer or grasshoppers) eat plant material. *Carnivores*, such as wolves or an insect-eating bird, eat other animals, and top carnivores, such as a tiger, eat other animals including carnivores. Detritus is dead plant or animal material, and *detritivores* eat, well, detritus, meaning dead organic material and the microbes within it. That concept may sound disgusting to you, but remember every time you are eating bread, cheese, most crackers, pepperoni, or beer or wine (i.e., every time you have a party), you are, essentially, a detritivore! Because ecosystems science tends to be more focused on energy than other approaches, we will go into it a little deeper here. An energy-based approach is conceptually very useful to think about evolution from a systems perspective [25, 26].

At each transfer of energy from one trophic level to another, about 80 or 90% of the energy is lost as heat, mostly for the energy that is required to support the living organisms and the growth of each trophic level. Tuna fish may require at least seven trophic levels to concentrate the energy of tiny phytoplankton into packages such as sardines or flying fish large enough to be food for a tuna. The low efficiency of transfer from one trophic level to the next (10% or so) is usually considered a manifestation of the second law of thermodynamics, although it also reflects the need for maintenance metabolism at each trophic level. Omnivores are animals such as bears and humans that eat both plant and animal material. The implications of this for economics is principally related to food chain length. Where human population densities are relatively small or agricultural production is high relative to the number or people, then people can afford to eat meat at every meal. Where people are crowded, poor and/or agricultural production is low then people must eat only plants. So, for example, although rich people in India or China may have a considerable amount of meat in their diet, the many poor people there and in many other countries must eat principally rice or other plant materials. There would not be enough plant material to afford the 80 or 90% that would be lost as heat if the food were transformed into another trophic level. Energy is also often the basis for understanding more fully evolutionary issues, as it appears that essentially all aspects of natural selection are at least in part about energy costs and gains [24, 25].

Ecologists are often called upon to help understand and mitigate particular environmental problems by studying important environmental relations among the parts of an ecosystem, including those of one species to others or of the movement of different chemicals, such as nitrogen or phosphorus, through ecosystems. These have become important issues economically in many different ways. For example, as developed above, too much phosphorus (from fertilizers or laundry detergent) tends to make many water bodies *eutrophic*, meaning excessively rich. Probably most readers are familiar with water bodies that should be blue and inviting but are instead green and stinky. Intense algae blooms are often associated with human activities and remain a large and important and often very expensive issue economically. Acid rain is another important issue related to economics. Since most of the energy to run economies comes from fossil fuel, and many fossil fuels are roughly 1% sulfur, the burning of fossil fuels creates sulfuric acid, and this then creates a condition called acid rain that has killed many plants and fish. Acid rain can also be generated from nitrogen from air when air is used to provide oxygen for combustion. Sometimes the issues bring up serious regional issues. For example, acid rain produced in power plants in Ohio has been implicated in fish kills, and economic losses associated with loss of tourism, etc. in the Adirondack mountains of New York State, and the same problem relates cause in England and effect in Sweden, where there has been a huge loss of crayfish, a very popular item in the traditional Swedish diet. In other words, the ecological and economic cost of the activity falls on others who do not take part in the economic gain from burning the fuel. This is called an *externality*, that is, a cost that is not included in the price. Fortunately, it has been shown possible to stabilize and even reduce acid rain, but again it is an expensive process. Because acid rain itself creates many environmental costs, we can say that there are large costs to not mitigating acid rain. Because we have been fairly successful in reducing acid rain, at least in the United States and Europe, we can say that this is a fairly successful example of internalizing an externality.

An important applied area of ecology that we cover here is that of biodiversity losses and more generally what is called *conservation biology*. Almost all human economic activity destroys at least some natural ecosystems, and often the organisms and even species that live therein. In about 1980, a varied group of ecologists, conservationists, and naturalists came together and pooled their different approaches to what they viewed as a global crisis: the global loss of very many species or of what they called biodiversity. There has been a great deal of effort since that has put into attempting to understand and reducing this loss. Since many species are very important for humans (e.g., for food, for pollination of plants, for the many different medicines that come from tropical rain forests, and for regulatory aspects of many ecosystems), there have been many studies of the economic importance of these issues.

15.4.8 Ecological Stability

We end our discussion of ecology with a less precise but extremely important aspect of ecology, that of stability and control. Undisturbed natural ecosystems tend to be broadly the same from year to year. When they are subjected to enormous impacts from changing weather, landslides, invasions, and human impacts, they tend to have within them a tremendous resilience or ability to spring back once the impacts are relaxed. When we study the vegetation on the slopes of Mount St. Helens, Oregon, which was eliminated when the volcano exploded in 1980, we find that the forests are being reconstructed relatively rapidly. Likewise when humans cut tropical rain forests, new forests will form within years or decades if given a chance (if the soil is not destroyed). Again, and again, we find a certain stability to many ecosystems even as they are impacted by natural or human-directed processes. We might think of nature as having a great deal of resilience. This is sometimes called the "balance of nature," although "balance" is not exactly right as there are many fluctuations. But the fluctuations tend to be, within broad limits, within certain ranges, and ecosystems tend to return their base conditions if they are left alone, at least on the scale of human lifetimes. One exception to this can be when new species are introduced that are very different from the original species, such as brown snakes on Guam or starlings on Hawaii. Because the original species have not encountered anything like these species, the ecosystems can be heavily impacted.

In contrast, human societies appear much less resilient, and as Tainter [7] and Diamond [8] point out the historical and prehistorical record is full of the collapse of once proud and dominant cultures and economies. How are these different from the much more stable natural ecological systems? A great deal of this resilience, at least compared to human systems, is that the energy sources (mostly the sun but also inputs from other ecosystems) tend to be constant and predictable in natural systems. So if and as the species change, the amount of primary productivity tends to be limited by the amount of sun and the climate, both of which tend to change little from 1 year or decade or even century to the next. Nutrients are potential limiters to plant growth, but since they are tightly recycled in undisturbed ecosystems, they rarely limit a natural ecosystem. Even floods and droughts tend to come and go within long-term ranges to which the ecosystems are adapted. Humans, through technology and their own too-clever minds, tend to exploit and then overexploit the basic energy and other resources upon which they are dependent. Of course, this leads to the great question facing humanity today: are we exploiting the Earth at a level beyond what the Earth can provide, and if so, do we have the ability to be as resilient as natural systems tend to be?

While this consideration of ecology, like the other sections in this chapter on science, has been very brief, we think it will help the reader understand many contemporary economic issues and, we hope, the need for an ecological basis for understanding economics. There is much more to be learned, and we encourage you to take additional courses in ecology and indeed in science in general, not simply to train yourself for your professional understanding but also, like art or music, to enrich your life by helping you to understand the world around you.

15.5 Is Economics Science?

This chapter has been a review of what we think are the basics of natural science and the scientific principles that we believe are important for understanding real economic systems. A question that must be in the mind of many readers is "to what degree does existing economics follow these rules of science?" We address this issue in the following chapters.

Questions

1. How have humans explained and tried to predict events traditionally?
2. Are humans part of nature?
3. Explain the difference between an independent and a dependent variable.
4. What does multiparametered mean? Can you give an example?
5. Would you, or how would you, reformulate the question: "The scientific method leads to truth?"
6. Give the steps of the scientific method.
7. How do we know when science "works"?
8. What does scientific rigor mean? Can you give five characteristics of scientific rigor?
9. Is it possible to test the theory of natural selection?
10. What are the energy sources for the Earth?

11. What work does solar energy do on Earth?
12. What is a Hadley cell? How does it work?
13. What is continental drift? Where is it occurring?
14. What is the "best first" principle?
15. What, technically, does "organic" mean?
16. Can you give the geological steps usually associated with the formation of oil?
17. What is the difference between source rocks and trap rocks?
18. What are the characteristics of the oil deposits that we have tended to find and exploit first?
19. What is the law of the "conservation of matter"?
20. What does "reduced" mean? How is that different from something that is called "oxidized"?
21. Why is it so difficult for plants to get nitrogen?
22. Who was Fritz Haber and what did he do?
23. Why is phosphorus important?
24. Explain eutrophication.
25. What is pollution?
26. Discuss some characteristics of an environment that increase the reaction rate of a chemical.
27. Why does the West coast of the United States have a more regular temperature than the East coast?
28. Draw the basics of the hydrological cycle
29. Define and explain the reason for the orographic effect and rain shadow.
30. Give an example of how natural ecosystems provide services to cities?
31. Will the climate change? Why or why not?
32. Give four observations consistent with the idea that the world is getting warmer. What are some other processes that might cause the Earth to get cooler?
33. What are three observations that, if true, must lead to organic evolution? Do you think these apply to humans?
34. What are the three general characteristics of organisms that natural selection effects?
35. Discuss the units of selection.
36. What is the principle of Le Chatelier and how might it effect ecosystems?
37. What is the difference between the usual public use and the academic meaning of the word "ecology"?
38. Why does ecology make a good basis for thinking about economics? Why might it not?
39. Discuss structure, function, and control with respect to an ecosystem.
40. What does the word trophic mean?
41. What is an externality? Can you give several examples?

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