Chapter 1

Introduction

People are currently paying much attention to the ability of present and future human populations to influence Earth’s climate through the emission of greenhouse gases (GHGs) such as carbon dioxide. According to some, such a self-induced change in our physical environment qualifies humans for the distinction of a “superspecies” that has passed a threshold of biological evolution. Some 2 to 3 billion years ago, another organism changed the environment in a very pronounced way: a primitive unicellular organism called cyanobacteria (blue-green algae). These cyanobacteria “discovered” a new energy source that enabled them to develop a photosynthetic apparatus that assimilates carbon dioxide through conversion of solar energy to chemical energy. In the process, a “useless” waste product, oxygen, began to accumulate and gradually changed the composition of the atmosphere. As a result, new, more complex oxygen-consuming forms of life evolved, eventually leading to humans. The algae that started it all, while still flourishing, then became the first link in a very elaborate food chain. (I will return to algae as a source of biofuel in Chapter 11).

Billions of years later, starting with the Industrial Revolution of the 18th century, humans learned to exploit a new source of energy: fossil fuels. The fossil fuels became the driving force for the 20th century’s technical revolutions that now have the potential to impact today’s atmosphere and our future climate. But unlike the cyanobacteria, we can make choices about how these developments will affect our environment. These choices (including the choice to do nothing) require collective action that can only be implemented through the political process. Collective action requires shared knowledge of some basic information relevant to environmental issues. This book presents the fundamental issues through examination of the data on global warming. Selected data, in the form of graphs or tables, are chosen not to emphasize or “prove” a point of view but to lay a foundation for interpretation. Many different stories can be derived by emphasizing different aspects of the data, but we must all refer to the same frame of reference. This book will present the case that the synergism between global anthropogenic (man-made) climatic changes, energy policy, and resource allocation on every level makes a holistic approach the most productive one. The data consist of energy use, population, and various wealth indicators. Chapter notes at the end of the book provide a summary of the databases that I use as sources. These sources are also marked wherever data are used. The
data on these issues are constantly changing. Fact-checking in this context is not equivalent
to checking exact numbers. In Chapter 2, I will try to quantify the delicate balance between
accuracy and transparency (Box 2.5). Thus trends and ideas should be accurately represented;
database-derived numbers should agree within an order of magnitude (with exceptions). If a
reader is double-checking the databases (Great!) and finds disagreements that result in the
repudiation of my conclusions, then I will be the first one to cheer.

We start with four key findings (Chapter 2):

- Average global temperature trends over the last 100 years
- Carbon dioxide emissions over the same periods
- Measures of our standard of living in the form of gross domestic product per capita
  versus our energy use per capita
- An examination of how and if carbon dioxide sources match nature’s carbon dioxide
  sinks and how this relates to changes in atmospheric chemistry

I will describe how the information is collected, explore the underlying science, and uncover
the assumptions embedded in projected scenarios.

Time scales are fundamental to the presentation. In the first four chapters I will present
data on temperature variations over the last 100 years as compared to those of the last 700,000
years. Further, I will explore the use of geological tools such as isotopic content and fossil
identification, as well as the environmental archeology of land, ice, sea, rock formations, and
minerals, which allow us to read history on a geological time scale. The emphasis here will be
on paleoclimatology, the geological history of Earth’s climate. My purpose is to distinguish
between man-independent natural cycles and anthropogenic contributions. I will follow with
a detailed discussion of the carbon cycle and the timing of movements and mixing that deter-
mine equilibration times for areas with high and low concentrations of carbon dioxide. This
is germane for questions such as how long it will take for the enormous amount of carbon
dioxide stored in rocks (primarily limestone) and oceans to equilibrate with the atmosphere
and how to estimate the consequences of disturbing the equilibrium between air and oceans.

Chapters 5 and 6 will lay the foundation for the basic scientific issues involved in the over-
all balance of energy use and climate change. I will start with the physics of temperature and
radiation, describing Earth’s energy balance with a simple demonstration of how to calculate
Earth’s average temperature. I then describe how certain transparent thermal shields can shift
this balance and change the equilibrium temperature. I will follow with descriptions of atmo-
spheric substances that act as thermal shields, such as GHGs, and of atmospheric compo-
nents, such as aerosols and ash, that act in the opposite manner and will include a discussion
of the thermal shields’ mechanisms. I will continue with more complex feedback mechanisms,
many of which are not yet fully understood, and discuss their possible effects on the successful prediction of climatic changes. This will lead into a discussion of the mix of possible energy sources and the correlations between energy mixes and the anthropogenic discharge of GHGs. The key figure in Chapter 10 will be the ever-changing estimate of our recoverable oil reserves. I will present the argument that we must decide on how the energy mix will look after we exhaust recoverable oil reserves.

Choices that we make today are based on predictions about tomorrow. The principal tools that we use to predict the future involve simulations. In Chapter 8 I will explore present, state-of-the-art climate simulations, emphasizing possible scenarios and their implications. I will compare present results with past simulations and analyze the differences in predictions.

The most important choice concerning resource allocation that we have to make with respect to the energy-climate mix involves the postoil energy mix. The economic issues (Chapter 12) of these choices are discussed in the context of their effects on standard of living and how the choices are manifested in terms of the price of energy products and the allocation of research and development (R&D) dollars to various alternative technologies. Reallocation of resources requires political debate on a global scale. The status and history of the Kyoto Protocol (Chapter 13), as well as global population dynamics, portray the dynamics of this debate. Chapters 14 and 15 describe early manifestations of global warming not necessarily anthropogenic in nature—namely, the physical manifestation of temperature increases and their economic consequences and some proposed first steps in the process to influence global energy use. A prerequisite to such an effort is to learn how to perform our own energy audit. The book ends with some personal conclusions about our collective difficulties accepting predictions about the catastrophic consequences of inaction.

The general structure of the book has a dual presentation. The key data and the corresponding descriptions are presented continuously without resorting to “tutorials” about the prerequisite science. Instead, boxes present the prerequisite science and other scientific issues. These inserts will be trivial to some and very demanding to others, but they provide the foundation to the story.

Thomas Friedman wrote it best in an op-ed in the New York Times, by quoting Rob Watson: “As the environmentalist Rob Watson likes to say: ‘Mother Nature is just chemistry, biology and physics. That’s all she is.’ You cannot sweet-talk her. You cannot spin her. You cannot tell her that the oil companies say climate change is a hoax. No, Mother Nature is going to do whatever chemistry, biology and physics dictate, and ‘Mother Nature always bats last, and she always bats 1.000,’ says Watson. Do not mess with Mother Nature. But that is just what we’re doing.”

In democratic societies, the decision-making process to address such an existential issue is in our collective hand, and yet most of us can use some help with the fundamental science in order to think about it in a rational way.
Before we proceed I must address two important issues. The first focuses on the available mechanisms for acceptance or rejection of information. The second aims to establish a common language for discussion, specifically in regard to a quantitative description of physical data.

**Whom to Believe?**

Many of the issues raised in the book have become intensely contested political topics. Chances are these issues will remain at the center of the public debate well into the foreseeable future. As we will see, the numbers support that observation. In countries where the political process is determined through the vote, the question is raised as to whether the general public can make informed, educated decisions about these issues. And the question applies not only to the knowledge base of the voting public but also to that of the political leadership responsible for making decisions that impact so many others.

One could pose the question as to what makes us, the nonspecialist general public, believe in something that requires in-depth understanding of highly specialized technical knowledge. In the face of conflicting opinions, how do we know what the “truth” is? There are a few established methods that help us determine the truth. The first, and probably the most popular method, is to rely on authority. If we have a single authority that dictates our lives, such as in the case of religious beliefs, then we have no problem in terms of our decision-making ability. If we have more than one authority, each providing conflicting information, then we need to make a choice. The second method was adopted by the legal system: this is the advocacy system. We choose lawyers to represent different points of view, and an impartial judge decides which lawyer makes a better case. We can shop for an epistemological lawyer who will advise us how to make these decisions, but how do we choose these lawyers?

If we choose to assume individual responsibility for our interactions with the physical environment, then we need to use the same language that scientists use to describe the physical environment. The language and reasoning associated with the physical environment are summarized in what is known as the scientific method. In spite of the fact that the scientific method is taught as part of science education and philosophy courses, any random assemblage of scientists who presumably practice the method will come up with a different rendition that represents more their personal experience than the philosophical underpinnings of the method. Since I am going to base most of my arguments on the method, it is appropriate that I clarify what I mean by the scientific method. The basic elements are presented in Figure 1.1. One starts with observations, followed by analysis of the data, which might include fitting the data to a mathematical formula, statistical analysis, and so on. The next stage is to formulate a hypothesis that places the data in the context of other data and offers some explanation of the observations, as well as predictions for further
Figure 1.1. Schematic description of the scientific method

observations. The next step is to try to connect various hypotheses into an axiomatic structured theory that models parts of reality in terms of some fundamental concepts. So far there is really no difference between perceptions of reality based on religious belief and ones based on science. The fundamental difference rests in what follows—and here I will lean on Karl Popper's idea that the only difference is that the scientific method requires that the hypothesis and the theory are refutable. Objections to this requirement arise based on the argument that it is often as difficult to refute a theory as it is to prove it. We can see in Figure 1.1 that the Popperian interpretation is cyclical—namely, that there is a constant testing of the hypothesis and the theory. It took 2000 years for Nicolaus Copernicus to suggest that the Aristotelian hypothesis that Earth is the center of the universe around which the planets and the stars revolve should be replaced by the hypothesis that the sun is at the center and that Earth is just another planet that revolves around the sun. It took about 200 more years for Isaac Newton to formulate the law of gravity, to describe the connection between
motion and force, and to formulate a general theory of gravity that would describe the motions of planetary bodies in terms of laws that could be tested and refuted on a laboratory bench top. It took an additional 200 years for Albert Einstein to show that when objects move at a speed approaching the speed of light, the fundamental Newtonian concept that reality is expressed in terms of fixed, independent coordinates of time and space must be revised. The Newtonian description of reality was replaced by an axiom in which the speed of light is constant and time and distance change with the relative velocity of the observer and the event observed. New observations will constantly challenge the accepted view, and thus an increase in knowledge is accomplished through continuous inquiry and, when needed, reformulation of theories.

One of the arguments against practicing the scientific method is that there is a distinction between experimental sciences such as physics, chemistry, and to a lesser degree, biology, in which one can perform controlled experiments designed to refute a hypothesis, and observational sciences such as astronomy (including astrophysics), most of geology, and most of the social sciences, in which one cannot make such controlled experiments. I do not share this view. The refutability (and testability) of observational sciences rests not in the ability to perform experiments that test a hypothesis but in the ability to look for observations that might refute the hypothesis. The two key ingredients in Figure 1.1 are the two gray circles—the observations and the theory. The whole scheme is anchored to the observations. All the testing of the various theoretical scenarios is done through observations. The reliance is such that David Deutsch—in his fascinating book *The Fabric of Reality* on the “parallel universes” picture of nonintuitive reality within the Popperian interpretation of the scientific method—presents the nonobservation part of the theory as a “story.” This is shown schematically in Figure 1.2, where I have replaced

![Figure 1.2. Simplified description of the scientific method](image-url)
the circles that designate the theory, model, and hypothesis with one circle labeled “story.” The “story” might be a very good story—but it never reaches the status of absolute truth. Absolute truth, by this interpretation, does not exist in science. This does not mean that scientific knowledge is a cultural construct. The laws of science are universal laws that describe reality in the best way that we know how. It only means that there is intrinsic asymmetry between validation of a theory and refutation of a theory. One can never absolutely validate a theory, but one critical experiment that can stand scrutiny can refute a theory. The more entrenched the theory, the more scrutiny the experiments to refute it will receive, but once the observations pass reliability and reproducibility tests, the theory is discarded. A new theory must be developed.

Let us take an example of such a story from the mythology of ancient civilizations. The story that Earth is supported by a living creature runs through most civilizations. In Hindu myth, the turtle Chukwa supports the elephant Maha-Pudma, which in turn supports Earth. The Iroquois believed that Earth was created out of growing mud on the back of a giant turtle. It all sounds primitive today; we “know” that Earth does not sit on the back of an elephant or a turtle. We know because we have satellites that take photographs of Earth, and Earth just floats in space held in orbit around the sun by the gravitational force. The ancient Hindu and the Iroquois did not have satellites. Their range was measured by their walking distance. Nothing around them just floated in empty space. Based on their observations, the best story for Earth was that it was supported by something—a giant turtle was as good as anything else. What supports the turtle was a different issue that they did not address—this situation is not that much different from our present best story to explain the creation of the universe, the big bang theory. What happened “before” the big bang is a subject of mostly silence because time and space were created at the big bang. Nevertheless, the ignorance is the same. The ancient mythologies are refutable because, in principle, one can walk to the edge of Earth or acquire the technology to build a satellite that will fly above Earth and observe whether one can see the turtle. Up to here the story follows all the rules of the Popperian scientific method. Suppose that we walk to the edge of Earth or launch the satellite and do not observe the giant turtle. Then we have refuted the theory and need to come up with a different theory that fits the observations. But the story may say that not seeing the giant turtle is not because it is not there but because it is invisible. Now, in a single stroke, we have converted the “scientific” theory into an irrefutable religious theory and the arguments stop.

An interesting observation I made on a New York City subway ride to work succinctly demonstrates the importance of raw data. The aforementioned ride was in one of the newest subway cars, in which a public address system, in the form of a very pleasant female voice, announced each station. I was dozing, and in my half conscious state, I suddenly heard the name of stations way outside my route. I immediately woke up and looked out the window to see what stations we were passing. It became immediately clear that I was on the right train
and that the public address system was malfunctioning. I was able to look at the raw data and immediately realize that my first interpretation (that I was on the wrong train) was incorrect. A similar experience in Japan might have ended differently. A few years ago the subway in Osaka had similar subway cars. The public address system in the subway cars in Osaka was announcing names of stations in both Japanese and English; however, at that time, the names of the stations were written only in Japanese (now they are written in both languages). A Westerner such as myself who does not read Japanese relies exclusively on the public address system. I would have had to step out of the train, find myself an epistemological lawyer (somebody who can read Japanese and speak English), and establish whether I was on the right train or not. The original data were not available to me.

**Learning from Experience**

A common way of figuring out what to do in particular situations is to learn from experience: either from our own experience or from the experience of others. On the issues that concern us here we do not have that luxury. Everything that marks human existence in relation to the outside environment is dominated by unique events. We cannot, with certainty, make the statement that life on our planet is unique in the universe. Personally, I believe that there is a possibility that some advanced form of self-reproducing species might exist (present, past, or future) somewhere in the universe. There are billions of stars in our galaxy and there are billions of galaxies in the universe and a billion is a very large number. Many of these stars probably have planets that circle them, and some of these planets might have an average surface temperature suitable for liquid water. Given enough time, a series of complex chemical processes might lead to the evolution of self-reproducing adapting species similar to what we have on our own planet. There are a lot of strongly conditional sentences in this paragraph. The reason is that we have no idea if any of this is true because the distances are so large that communication is impractical. In our own solar system, we are unique. It is possible that on a planet such as Mars one might find traces of microscopic living organisms—the search is continuing and seasonal announcements that follow with counterarguments are in abundance. However, we cannot “learn” from microscopic organisms. The nearest star to our solar system is the bright double star Alpha Centauri and its small neighbor Proxima Centauri. They are about 4 light-years away from us. A light-year sounds like a unit of time, but it is really a unit of distance that astronomers use to describe distances of celestial objects. A light-year is the distance that a beam of light travels in 1 year. According to Einstein’s theory of special relativity, the speed of light is the fastest speed that can be attained. The value of the speed of light is approximately 300,000 km/sec, so the distance to our nearest neighbor stars is
about 40,000 billion (40 trillion) km. The speed of light is also the fastest rate that information can travel. Thus everything that we are presently able to observe in the neighborhood of Alpha Centauri happened there 4 years ago, and it would take 8 years for a message to get there and back. We have not yet found any planets orbiting Alpha Centauri. The closest one that has been observed outside our solar system orbits a star called Epsilon Eridani about 10 light-years away. These planets are much larger and more massive than Earth. They resemble Jupiter and Saturn in our solar system. Like Jupiter and Saturn and the rest of the universe, the main chemical element in these planets is hydrogen. Planets outside our solar system are called exoplanets. We are constantly looking for new one (as of July 2010, the count is around 300). As far as we know these are not conditions suitable for the development of complex life. The conclusion from all this is that although there are billions and billions of stars that in principle might host planetary systems suitable for the development of complex life-forms, we are presently still searching for planets, and it is unreasonable to assume that we will find extra-terrestrial civilizations that will be able to share their experiences with us about the secrets of maintaining equilibrium with the environment and the consequences of not succeeding.

What about learning from past civilizations on our own planet? If we count the beginning of agriculture (i.e., the domestication of plants and animals and the beginning of collective governance in terms of the first urban settlements) as the onset of human civilization, then archeological evidence can establish a timeline that starts around 10,000 years ago. Figure 3.2 in Chapter 3 shows that this is halfway through the present warming period that took us out of the most recent ice age. Human civilization did not yet have time to develop through even a single global climatic cycle, so predictions based on past experience are impossible. This does not mean that storms, floods, droughts, fires, and volcanic eruptions do not affect civilizations. They do today and they did throughout history. We can learn from the experience of past civilizations and we can learn from each other how best to handle such experiences. However, all these natural disasters are local both in terms of geography and in terms of duration.

From this analysis we can conclude that learning from either our own experience or that of others about interactions between global climatic changes and civilizations is impossible. We must find another way to gain knowledge of the possible consequences of our interactions with the global environment. To a limited degree this can be done through scientific modeling of the global system—modeling that includes the human race as an important contributor to the system and an important inheritor of the consequences. We are starting to do that mainly through the initiatives of the United Nations. This effort is discussed in Chapter 8.
THE FERMI PARADOX

The search for extraterrestrial life captures our collective imagination. A recent book by Paul Davies, titled *Eerie Silence*, beautifully and critically summarizes the efforts to make a contact with a technologically advanced (i.e., capable of sending and receiving radio messages) life-form. The effort to communicate with extraterrestrial life through observations (as opposed to visit them) is known as Search for Extra Terrestrial Intelligence (SETI). The probability of the existence of such life-forms was estimated by Frank Drake in 1960 and summarized in Davies’s book. It involves two kinds of terms: cosmological terms and “biological” terms. The cosmological terms calculate the probability that a planet exists in our galaxy (in other galaxies it becomes really too far to make any useful contact) that can support biological systems consisting of large bodies of liquid water and that can be stable long enough to allow for evolution to the degree of complexity that will enable setting and interpreting radio telescope observations. The two “biological” terms are as follows: one for converting a nonliving mixture of essential chemicals into a living organism (defined in terms of its ability for independent reproduction by using environmental resources) and the other for building and interpreting observations from a radio telescope when such life-forms reach the complexity and life-span required to send signals. What is of great interest to us here is the last issue. Davies points out that since we are the only intelligent life-form that we know about, the best place to start the search for these two conditions is here on Earth. He gives some suggestions for the first but is silent on the second. The search for such intelligence became very famous (at least among physicists) by a lunch remark made by Enrico Fermi while working at the Los Alamos National Laboratory in 1950. Fermi was one of the most respected productive physicists at that time, and when he spoke people listened. His remarks came as a response to the perceived commonality of extraterrestrial life (mainly in the form of unidentified flying objects, or UFOs) and the time that the extraterrestrials had to develop “galactic” technical capabilities. But Fermi asked, _where are they?_ By now, extraterrestrials should have had enough time to explore the galaxy and contact us. This “dilemma” became known as the Fermi paradox.

The beginning of our technological intelligence can be traced to the middle of the previous century (computers, rockets, lasers, etc.). The time scale that the scientists at SETI are talking about is about a million years. Even if we are a bit more modest and choose a time scale of only 1000 years to develop technology to reach habitable planets in case Earth becomes inhospitable, we cannot control most cosmological events that might lead to the destruction of life on Earth. We can, however, control some of our local collective behavior and monitor the planet to assure survival.
**Quantitative Description of Data: Units**

We often hear that we cannot compare apples to oranges or, as my math teacher used to say, you cannot add doors and windows. Actually, you can add apples and oranges if you generalize them to “fruits,” thus describing them in terms of common “units.” To describe quantities in the physical world, we usually need both numbers and units. Thirty miles is different from 30 hours—this is the equivalent of comparing doors and windows. Even when we describe a single physical quantity, such as distance, we need to specify the units—miles, kilometers, centimeters, and so forth.

It would be lovely if each physical quantity came with a unique set of units with appropriate subdivisions to describe various denominations—similar to describing the monetary values of items. However, when we describe the monetary value of an item in the United States versus one in England, we use different currencies. When we travel abroad we need to change our currency for the local currency. What would happen in a world with a single currency? Such a world would require a central bank that would set the same interest rate all over the world and thus eliminate the ability of local governments to use monetary policy to adjust for local imbalances. Nevertheless, in January 2002 most countries in the European Union substituted their local currencies with the euro. Can we do the same with units of other physical quantities?

The reasons that we have different sets of units that describe the same physical quantity stem from decision processes based partially on ignorance and partially on geographic isolation. The physical quantity that I will use the most in this book is energy, and there is no better example for describing the origin of the diversity of units. The background for the use of energy units is described in Box 1.1. The practice adopted by most books and articles is to adopt a set of units (e.g., the British thermal unit, or Btu) and convert all other given energy units to match. This minimizes effort for the reader. In some cases I chose not to follow this practice; in these cases I feel that the presented data should reflect the data source. So oil supply will usually be presented in barrels of oil (or millions or billions of them), natural gas will be represented in cubic feet, electrical consumption in kilowatt-hours, and so forth. The purpose is not to confuse the issues but to keep the anchor at the data sources. The data that we work with are constantly changing, and we should be able to refer to the sources at any time and decide if the conclusions that we outline here are consistent with the data—this is the only valid yardstick.

Fortunately, in the Internet age we have easy access to what are often called “unit conversion” calculators into which we can plug the numbers in one set of units and easily convert them to another unit of the same quantity that we want (we still cannot convert doors to windows by using a calculator). A summary of the units that we use in this book, and examples of unit conversion, is provided in Appendix 1.
Box 1.1 includes a description of another set of units—those of quantities of matter or mass. Everyday practice describes the quantity of matter in units such as pounds (lb) or kilograms (kg). Many aspects of the science of the physical environment require expressing quantities of matter in terms of the number of molecules. The following box will make the connection between the two presentations.

**Box 1.1**

**UNITS: ENERGY AND MASS**

**Energy**

When we pay our heating bill in the United States, the units we use are Btus for oil, cubic feet for natural gas, and kilowatt-hours for electricity. If we want to convert from one fuel to another fuel and calculate the relative cost, then we have a problem. If we were to move to continental Europe, we would suddenly be faced with whole new sets of units for energy such as the joule (J). At the same time, when we eat a big New York–style bagel, the package tells us that the bagel contains 300 food calories. If we want to get rid of these calories by running up and down the stairs, our exercise book will help us to calculate how much work we are doing, often providing the results in joules.

One of the main reasons for the multiplicity of energy units is that until some key experiments were conducted in the 19th century, mainly by English physicist James Prescott Joule (1818–1889), the prevailing thinking was that heat energy and mechanical work were largely unrelated quantities, thus deserving different sets of units. So Calories are defined in terms of heat production, whereas joules are used to measure work. Calories are units of heat based on the metric system, which is mainly used in Europe, and uses meters (km, cm, mm, etc.) to measure length, kilograms (mg, g, metric tons, etc.) to measure mass, seconds (minutes, hours, etc.) to measure time, and degrees Celsius to measure temperature.

What is known as the English system of units uses feet (miles, yards, etc.) to measure distance, pounds to measure weight, and degrees Fahrenheit to measure temperature. Mercifully, the units for time are the same in both systems of units. The units for energy derive from this set of basic units, so that one Calorie (= 1 food calorie) is the amount of heat that it takes to raise the temperature of 1 kg of water (1 L) by 1°C, whereas one Btu is the amount of energy that it takes to raise the temperature of 1 lb of water by 1°F.
Mass

There is a unit of mass not widely used outside schools and science, and this will require a short plunge into chemistry. The unit is the gram-molecular weight (otherwise known as the mole). It is the amount of a substance in which the weight, in grams, is numerically equal to the molecular weight of that substance. For example, 1 mole of molecular oxygen, O₂ (molecular weight approximately 32), is 32 g, and 1 mole of water, H₂O (molecular weight approximately 18), is 18 g. The molecular weight may be calculated from the molecular formula of the substance; it is the sum of the atomic weights of the atoms making up the molecule. For example, water has the molecular formula H₂O, indicating that a molecule of water has two atoms of hydrogen and one atom of oxygen. In chemistry, a formula is an expression showing the chemical composition of a compound. Chemical compounds are combinations with fixed proportions of chemical elements. The list of known elements is given in the periodic table of the elements (see Appendix 2). The smallest unit of an element is the atom. The atom consists of a central, positively charged core, the nucleus, and negatively charged particles called electrons located in orbits around the nucleus. Atomic nuclei are composed of two types of particles, protons and neutrons, which are collectively known as nucleons. The sum of the number of protons and neutrons in an atomic nucleus of an atom of an element is the atomic weight of this element. The molecular formula of water is H₂O—two atoms of hydrogen (atomic weight approximately 1) and one atom of oxygen (atomic weight approximately 16). This makes the molecular weight of water approximately 18, and 1 mole of water thus weighs 18 g. A mole of a compound contains a fixed number of molecules. This number, called Avogadro’s number, is very large. It is equal to 6 × 10²³ molecules or 600 sextillion molecules. When we deal with global issues, we often must use very large numbers. We can try to remember the names such as million, billion, trillion, quadrillion, sextillion, and so forth, but we find that even for these names, we have different conventions in England and in the United States. An alternative is to use scientific notation that is a decimal number between 1 and 10 multiplied by 10 to the power of an exponent.