Chapter 2
Scientific Principles

Abstract An introduction is given to scientific principles including the laws of thermodynamics and the differences between natural laws, hypotheses, and theories. The concept of geologic time is introduced with examples given of the age of the Earth, the time it takes for climate to change, and examples from the geologic record. Scientific notation is described with examples from very large and very small numbers. Some of the jargon used by climate change scientists is defined. Some early scientists are named from Pliny the Elder to Karl Popper along with their main contributions. Chaos theory is introduced as is the "butterfly effect." The concept of multiple working hypotheses is explained.

Keywords Heat • Thermodynamics • Philosophy • Adiabatic • Feedback • Forcing • Orbital • Tectonic • Entropy • Internet • Climate • Change • Energy • Misinformation • Disinformation • Climategate • Hothouse • Icehouse • Deduction • Induction • Heliocentrism • Hypotheses • Theories • Logarithms • Geologic

Things to Know

The following is a list of things to know from this chapter. It is intended to serve as a guide of emphasis for the student to keep in mind while reading this chapter. It is not intended to be a complete list of "things" in this chapter or on this subject and your instructor may introduce additional topics. Before finishing with this

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_2,

chapter, each of the "Things to Know" should be understood and can be used for review purposes. This list may not include all of the topics and concepts required by your instructor.

Things to Know	
Aristotle	Conservation of Energy
Isaac Newton	W/m^2
Global Warming	Adiabatic Process
Earth's Energy Imbalance	Richard Feynman
Climate Change	Greenhouse Effect
Joule	Enhanced Greenhouse Effect
Climate Forcing	Climate Feedback
Geologic Time	Watt
Geologic Time Scales	Orbital Events and their Time Span
Tectonic Events	Glacial-Deglacial Events
Historical Events	Age of the Earth
Empiricism	Francis Bacon
Karl Popper	Induction
Deduction	Models and Simulations
T. C. Chamberlin	Laws of Thermodynamics
Natural Science	Scientific Notation
Calculus	Heliocentrism

2.1 Introduction

Scientific principles are those principles that scientists use to conduct scientific work and participate in advancing the knowledge base of humankind. It is not possible to cover all of the principles of science in this volume so only those important to climate change science will be considered here. However, some scientific principles are comprehensive and apply to all scientific studies and these will be briefly considered.

Scientific principles are quite varied. It often depends upon the science as to what principles apply, but there are general principles that all scientists use and those are the ones discussed in these beginning sections of Part I. Without an understanding of the principles of scientific work it is difficult to appreciate what science is all about and the contributions that scientists have made to our way of life and understanding of the world around us.

The concept of the expanse of geologic time is basic to the science of climate change and is presented in this introduction as are the durations of certain climate shifts in the fairly recent and geologic past. The age of the Earth is given as is reference to the geologic time scale. The geologic time scale is shown graphically in an appendix (Appendix I).

The philosophy of science is introduced early in this text beginning with the ancient Greeks and the origin of empirical approaches to science. Major advances in climate and Earth science are introduced with those scientists who first presented them; a few of the individual scientists who made important contributions to learning and to climate science are briefly discussed.

The scientific method is reviewed and examples given as are uses of scientific notation, the difference between hypothesis and theory, and a synopsis of the way science is conducted in the real world. An introduction to global warming and some of the evidence for it is given along with examples.

Denialism is introduced and some of the reasons for it are discussed. Denialism is the tendency to ignore facts when presented with an abundance of them. Denialism in climate science and global warming shares much in common with other proven facts of science, such as the denying of organic evolution.

While there are multiple causes of climate change, the majority of the global warming of the past 50 plus years has been and is being caused by humans burning fossil fuels and cutting down trees and changing the natural landscape. As the reader progresses in this text it will become apparent what the current drivers are that cause the Earth's surface, ocean, and atmosphere to warm, what the causes are, the data supporting them, and what can and should be done about them.

2.2 Internet Searches

A search of the Internet by one of the available search engines such as Google for "scientific principles" will provide one with a list of a variety of subjects. A dictionary of scientific principles, such as the aptly named "*Dictionary of Scientific Principles*" by Stephen Marvin lists over 3,000 principles from mathematics, physics, astronomy, and other subjects including some non-scientific subjects such as philosophy. Only a small number of scientific principles are discussed in this current volume; the scientific principles necessary to lay the foundation for the study of climate change science.

2.3 The Warming Earth: Heat and the Principles of Thermodynamics

As climate is about energy and its transfer throughout the Earth system and heat is energy, the laws of thermodynamics apply. Thermodynamics deals with heat, pressure, work, and volume and these can be applied to gases and the atmosphere is made up mainly of gases. As a matter of fact, the principles of thermodynamics grew out of the development of the steam engine and the principle that pressure is inversely proportional to volume. As pressure increases, volume decreases. When heated, gases expand.

There are three main laws of thermodynamics which were defined first and a fourth law or principle called the Zeroth Law that was defined later. The names First, Second, and Third laws were kept.

The four laws of thermodynamics are discussed in the following sections.

2.3.1 The Zeroth Law of Thermodynamics

The zeroth law states that if two systems are in thermal equilibrium with a third system, they are also in thermal equilibrium with each other.

Although the concept of thermodynamic equilibrium is fundamental to thermodynamics, the need to state it explicitly as a law was not widely perceived until it was stated in the 1930s, long after the first, second, and third laws were already widely understood and recognized. Hence it was numbered the zeroth law. The importance of the law as a foundation to the first through third laws is that it allows the definition of temperature in a non-circular way without reference to entropy.

Entropy is defined by the second law of thermodynamics and has to do with the buildup of energy as work is accomplished. Additional information on entropy may be found at the following web site: http://www.entropylaw.com/entropyenergy.html.

The Zeroth Law is often stated as follows: "If A and C are each in thermal equilibrium with B, A is also in equilibrium with C." If A, B, and C are in thermal equilibrium, then there is no net change of energy. If two objects of different temperature are brought into physical contact, they will eventually reach thermal equilibrium and this is also true for a third object.

There are some thermodynamic processes in which there is no heat transfer. Climate scientists call this type of process an adiabatic process and there are simple equations which relate the pressure and temperature of a gas for an adiabatic process. An adiabatic climatic process involves no heat exchange.

2.3.2 The First Law of Thermodynamics

The first law of thermodynamics distinguishes between two kinds of physical processes, namely energy transfer as work, and energy transfer as heat. Heat is important to climate change science. Energy can be changed from one form to another, but it cannot be created or destroyed. It tells how this shows the existence of a mathematical quantity called the internal energy of a system. The internal energy obeys the principle of conservation of energy but work and heat are not defined as separately conserved quantities. The first law is sometimes called the "conservation of energy law" and can be applied to the Earth's radiation budget.

The energy entering, reflected, absorbed, and emitted by the Earth system are the components of the Earth's radiation budget. Based on the principle of conservation of energy, this radiation budget represents the accounting of the balance between incoming radiation, which is almost entirely solar radiation, and outgoing radiation, which is partly reflected solar radiation and partly radiation emitted from the Earth system, including the atmosphere. A budget that's out of balance can cause the temperature of the atmosphere to increase or decrease and eventually affect Earth's climate. The units of energy employed in measuring this incoming and outgoing radiation are Watts per square meter (W/m^2).

The first law of thermodynamics states that the total amount of energy in the universe is constant. This means that all of the energy has to end up somewhere, either in the original form or in a different from. We can use this knowledge to determine the amount of energy in a system, the amount lost as waste heat, and the efficiency of the system.

2.3.3 The Second Law of Thermodynamics

The second law of thermodynamics distinguishes between reversible and irreversible physical processes. It is sometimes referred to as the "law of entropy." It tells how this shows the existence of a mathematical quantity called the entropy of a system, and thus it expresses the irreversibility of actual physical processes by the statement that the entropy of an isolated macroscopic system never decreases.

The second law of thermodynamics has been stated in many ways. Rudolf Clausius, one of the principal founders of the field of thermodynamics, perhaps said it best, as follows:

> Heat generally cannot flow spontaneously from a material at lower temperature to a material at higher temperature.

The climate change or global warming skeptic tells us that, because the air including greenhouse gases is cooler than the surface of the Earth, it cannot warm the Earth. If it did, that means heat would have to flow from cold to hot, in apparent violation of the second law of thermodynamics.

So have climate scientists made an elementary mistake? No! The skeptic is ignoring the fact that the Earth is being warmed by the Sun, which makes all the difference. Consider the analogy of a blanket covering a human body. The blanket does not produce heat so it is cold when placed against a human body. With time, however, the blanket causes the body to warm because it traps heat given off by the human body. This is similar to the "blanket" provided by the greenhouse gases in the atmosphere holding in heat from the Earth. The heat warms the Earth which has been warmed by the Sun. The greenhouse gases in the atmosphere do re-radiate some heat back to the Earth but the primary heat source is the Sun.

The second law of thermodynamics states that the disorder in the universe always increases. As the disorder in the universe increases, the energy is transformed into less usable forms. Thus, the efficiency of any process will always be less than 100%.

2.3.4 The Third Law of Thermodynamics

The third law of thermodynamics concerns the entropy of a perfect crystal at absolute zero temperature, and implies that it is impossible to cool a system to exactly absolute zero.

The third law of thermodynamics tells us that all molecular movement stops at a temperature we call absolute zero, or 0 K (−273°C). Since temperature is a measure of molecular movement, there can be no temperature lower than absolute zero. At this temperature, a perfect crystal has no disorder.

These laws state that a concentrated energy supply must be used to accomplish useful work. But these four laws are just four of many laws used by scientists to try to understand how the world and the Universe work.

2.4 Climate Scientists

Climate scientists, or climate change scientists, those that we are concerned with here, are those scientists that deal with climate that has changed in the past, is changing today, and will undoubtedly change in the future. Climate change scientists are not the same as climatologists, although some may be climatologists by training, but are scientists that study climate changes over time scales not normally studied by those who have a classical training in climatology. Climate change scientists study climates that have evolved over thousands, millions, tens and hundreds of millions, and billions of years. Climate change scientists may have started their careers as physicists, biologists, geologists, chemists, oceanographers, or one of the other specialties of science. Rarely do they begin their professional careers outside one of the scientific disciplines.

Wikipedia defines climatology as follows:

> Climatology (from Greek κλ μα, *klima*, "place, zone"; and -λογ α, *-logia*) is the study of climate, scientifically defined as weather conditions averaged over a period of time, and is a branch of the atmospheric sciences. Basic knowledge of climate can be used within shorter term weather forecasting using analog techniques such as the El Niño – Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), the North Atlantic Oscillation (NAO), the Northern Annular Mode (NAM), the Arctic oscillation (AO), the Northern Pacific (NP) Index, the Pacific Decadal Oscillation (PDO), and the Interdecadal Pacific Oscillation (IPO). Climate models are used for a variety of purposes from study of the dynamics of the weather and climate system to projections of future climate.

Skeptics and deniers of climate change (usually not scientists) are often quoted as stating that climate has changed in the past and is always changing, so the current changes and global warming are natural and mankind has had little to do with it. Hence, nothing can be done about climate change; it's part of a natural cycle. As will be seen in this text, recent and current global warming is not natural and is not part of a natural cycle although natural climate change has happened in the past. There are undeniable human fingerprints on the current warming of the Earth. The most recent warming is being caused largely by the burning of fossil fuels and the process of deforestation, as we will see going forward in this text.

Individual climate scientists, chosen for their major contributions, will be discussed later in this text. Climate change scientists are also climate scientists and their major field of study is climatology. However, in order to understand current climate change and trends and perhaps to be able to forecast the future of climate on Earth, climate change scientists must know more than climatologists have had to know in the past, for new tools have recently become available to them and their interpretation requires knowledge not available to climatologists trained prior to the 1970s.

2.4.1 Scientific Laws and Climate Scientists

Scientific laws or principles that are of interest in this text are those that climate change scientists use to conduct scientific studies, including experiments; to be able to start out right to end up right, to carefully gather data in a prescribed manner, to logically interpret these data, draw valid conclusions, formulate explanatory hypotheses and theories, conduct valid tests and experiments, document and publish the results, and produce new knowledge. Science is all about producing new knowledge.

Non-scientists often see scientists as discovering new things step by step and proceeding or plodding along in a straight line until all the problems of the Universe are solved. It is true that knowledge is cumulative. We know much more about the atom now than we used to know and within the past 100 years or so new subatomic particles have been discovered one after another. But most science does not proceed in a straight line. Often, many new things are discovered at once and some may be totally unexpected. It is the unexpected that makes science so interesting; the "Eureka!" or "Aha!" moment, suddenly realizing one has an entirely new species of fossil or living fish, or equation that nobody has ever seen before. It needs a name and you can name it, thus living forever in the annals of science. This is one of the least important aspects of science but it is difficult to overestimate the thrill of discovery.

The world of science is no different from the world of anything else. It is the same world, with the same problems, the same solutions, the same engineering. It is only mysterious because only relatively few people truly understand it. And this is largely the fault of scientists, those who practice doing science. Mostly scientists have been content to pursue their research and have not been either willing or able to inform the public of its importance or of its methods and successes. As a result, many have a Frankensteinian view of science; of the "mad scientist" in his laboratory with lightning striking all around.

Scientists are beginning to understand that they must communicate more often, more effectively, and with more foresight with the media and the public than in the past and this is especially true for climate change scientists.

Climate is familiar to everyone as weather. Climate has been described as weather over a long period of time usually taken to mean at least 30 years. But it is more than weather. Weather is forecast days and weeks in advance. Climate deals with decades, years, millennia, and millions and billions of years in the past as well as projections of climate into the future.

Although climate change science has established that the Earth is undergoing a warming trend; it is becoming warmer and the number of supporting published scientific papers is growing exponentially, news about this strengthening evidence for global warming is tending to only trickle out to the public in bits and pieces. The individuals representing the news media (radio, television, the blogosphere, newspapers, and magazines) have shown an amazing lack of leadership in reporting the truth about global warming. It's as if there is an attempt by them to present the two sides equally when they are anything but equal. Approximately 97% of climate scientists recognize that the Earth is warming and that global warming is real. There are not two equal sides to the science of climate change just as there are not two equal sides to the sciences of plate tectonics or evolution.

The Earth's climate is changing and the world's population must get the proper information to be able to deal with it. The press and other media must extract the facts concerning global warming and report these to the public; but it is also the climate change scientist that must communicate these changes to the media and the media, in addition to the scientist, must communicate these changes to the public.

In order to understand climate science or any science it is necessary to first understand some basic principles, and these are not difficult. There is no grand mystery about science or scientists. The basic principles of science are those with which most people are familiar; such as logical and critical thought, organization, documentation, the ability to write complete sentences, persistence, patience, and the ability to communicate the results of their science to each other, the media, and the public.

Individual scientists don't work 24 hours a day in a lonely laboratory with a subservient assistant who brings him or her coffee or tea. Scientists today usually work as a team of individuals, some with different backgrounds. For example, a computer programmer may need a piece of information from a chemist in order to write a formula for the climate program that the group is using. Often geologists need information from a physicist or an oceanographer to complete a theory or hypothesis.

Scientists are also humans and go to their homes after the work day and play with their video games, spouses, children, and grandchildren. Most can be said to be "normal" individuals. They participate in their communities, go to sporting events, go camping, help their children and their friends with their school work, judge science fairs, travel to conferences, and in general attempt to enjoy life.

2.5 Scientific Jargon

It is true that each science has its own set of jargon, as does medicine, but once past the jargon almost anyone can become a scientist with the proper education and set of personal values. Most of the jargon of climate science is found in the Glossary that is at the end of the text but like any science there are a few basic terms that must be defined here for the purpose of getting started. A partial list of these terms is given below.

The following definitions are important and necessary when beginning a discussion of climate change science:

- **Joule** – A unit of energy that is defined as the work required to produce one Watt of power for one second, or one "Watt second" (W·s).

- **Watt** – The unit, defined as one joule per second, measures the rate of energy conversion or transfer. In climate science, energy is measured as Watts per square meters (W/m^2).
- **Global climate change** – A forcing of the Earth's climate system to change. The changes are worldwide, not regional or local, and may include a warming or cooling.
- **Global warming** – A heating up of the Earth system either by forcing or by feedbacks, usually in combination. This is occurring worldwide but there may be exceptions locally and regionally.
- **Radiation** – The Sun radiates energy in all directions and that energy striking Earth warms the atmosphere, land, and oceans as shortwave or ultraviolet radiation. Some of the energy that impacts Earth is re-radiated back to space as longwave radiation. Not all of this energy escapes to space and some of it is trapped in the atmosphere by greenhouses gases (GHGs) that re-radiate energy back toward Earth.
- **Ultraviolet (UV) radiation** – Sunlight received by the Earth's atmosphere is in the form of shortwave ultraviolet radiation, visible light, and some other wavelengths.
- **Infrared (IR) radiation** – Heat given off by the Earth is in the form of longwave infrared radiation.
- **Greenhouse effect** – Warming of the lower atmosphere by greenhouse gases that trap energy and re-radiate it back to Earth. Carbon dioxide (CO_2) and water vapor are two of these greenhouse gases. Carbon dioxide consists of one carbon atom with an oxygen atom bonded to each side. When its atoms are bonded tightly together, the carbon dioxide molecule can absorb infrared radiation and the molecule starts to vibrate. The vibrating molecule will emit the radiation again and it is likely to be absorbed by another greenhouse gas molecule, or radiated to outer space, or back to Earth's surface. This absorption-emission-absorption cycle serves to keep heat near the Earth's surface, effectively insulating the surface. The greenhouse effect is that which allows living forms to exist on Earth. A portion of the Sun's radiant energy is reflected back to space by the top of the atmosphere (TOA). The Sun's rays are UV radiation. Some UV radiation is absorbed by the atmosphere, the land, and the ocean. The land and ocean, warmed by the Sun re-radiate heat energy as IR radiation. Without the greenhouse effect, Earth's surface temperature would average at least −15°C based on its size, constitution, and distance from the Sun.
- **Enhanced greenhouse effect** – Increased greenhouse effect causing further warming of the Earth because of the addition of greenhouse gases to the atmosphere by the burning of fossil fuels (coal, petroleum, natural gas) and deforestation. We are now living on an Earth that is experiencing an enhanced greenhouse effect due to human (anthropogenic) activities.
- **Earth system** – The solid Earth, the oceans, the Earth's interior, the gases making up the atmosphere, the Solar System, and any other influences which may affect the Earth. The Earth system includes the whole Earth; past, present and future.

- **Climate forcing** – A natural or anthropogenic (man-made) cause for climate to change. A force that causes climate change. An example of forcing is the amount of radiation given off by the Sun; if the Sun is more active, radiation increases that strikes the Earth, the planet warms; if the Sun's radiation output decreases, the Earth cools. A forcing causes the planet's climate system to build up or lose heat and this is what caused the climate to change.
- **Climate feedback** – A response to a forcing causing an amplification or reduction of the forced climate change. A climate feedback can either be positive or negative. A positive feedback causes a forcing to increase; a negative feedback stops or slows a forcing from increasing; a negative feedback could also cause a forcing to be reversed.

2.6 Communication Between Scientists and the Public

The communication between scientists and the public, especially via the media, is a problem that has proven difficult for scientists in most areas of science.

Most scientists are content to just do science and let others do the communicating. Many large organizations that employ scientists, such as the U.S. National Laboratories and large private companies (e.g., tobacco, chemical, or energy companies) have a public relations department or an organization within the organization that deals with the public. This organizational group usually does not have scientists on its staff and often basic scientific facts and concepts are lost in the communication between the scientist and the public relations group, or between the public relations group and the media, or between the media and the public. The result is miscommunication and the loss of, or the distortion of, basic scientific knowledge. The public is often misinformed.

Misinformation, unintentionally false, may be passed along to the public. And this is unfortunate but is oftentimes corrected. If a journalist makes a mistake, the honest journalist is usually quick to correct it. However, most of the mistaken information passed to the public is disinformation (intentionally false) due to vested interests or ignorance or both. And disinformation is not corrected because it is intentional.

Another situation that has occurred recently (2009 and 2011) is exemplified by emails stolen from a group of climate scientists and selectively edited and forwarded to global warming skeptics and deniers on the Internet. This came to be known as "Climategate." The news media picked up the story and it made headlines all over the world. At least nine independent investigations have been conducted (including one by the U.S. Congress and another by the U.K. House of Commons). Even though all of these investigations determined that the emails didn't change the science that global warming was occurring, the news media largely ignored the facts resulting from the investigations. The corrections were no longer news and many citizens in the general public continue to be misinformed.

2.7 The Concept of Time

Climate change science deals with scientific principles and it also deals with climate change over time. Climate change occurs over decades, years, millennia, and millions of years. Time is something we all experience but it is not something that is easily defined. For our purposes, one way to look at time is to divide time into the past, present, and future. The following are statements that refer to time:

- The U.S. Civil War began in 1865;
- John Q. was born at 5:14 am, November 2, 2000;
- The War of 1812 was fought between the Revolutionary War and World War I;
- The Earth was formed about 4.54 billion years ago;
- Warren C. completed the Boston Marathon in 5 h and 32.5 min;
- Martin's fastball has been clocked at 95.3 miles per hour.
- A Russian satellite will enter Earth's atmosphere on June 10, 2050.

From the above statements it can be seen that some references to time are in absolute time, such as the birth of John Q. and the age of the Earth. Others are in reference to an interval of time, such as Martin's fastball travelling at 95.3 miles per hour. Another statement of time is by reference to other events, such as the War of 1812.

Such statements may be interesting to some but none tells us what time is. A dictionary definition of time is as follows:

> A part of the measuring system used to sequence events, to compare the durations of events and the intervals between them, and to quantify rates of change such as the motion of objects (from Wikipedia, the Free Encyclopedia).

So time is a system devised by humans to measure events, such as the start, duration, prediction, or end of an event or sequence of events.

In order to measure something, one must have a scale, such as a clock or reference point, like the start to a race or the beginning of an event; a week, month, or a year measured on a calendar; or a birth date. It can be stated in a relative sense, such as the U.S. Civil War occurred after the Revolutionary War and before World War One. Or it might be stated as an event beginning on a certain date, hour, minute and second of time. Time may be measured on a relative scale or stated as an absolute time.

Geologic and climatic events take place over a variety of time scales: decades, years, hundreds, thousands, and millions of years. Geologic time is usually expressed in the thousands, millions, or billions of years. The diagram below (Fig. 2.1) shows timelines for historical and climatic events.

The events representing geological time (Fig. 2.2) take place over millions of years (such as tectonic or mountain building episodes), thousands of years (orbital, glacial, interglacial episodes), and human events take place over minutes, hours, days, weeks, decades, centuries, and possibly a couple of thousands of years (such as historical events, like year 01–2012 AD).

Geologic time is measured on a scale that is divided into major events, like the first appearance in the fossil record of trilobites (Cambrian), or the first

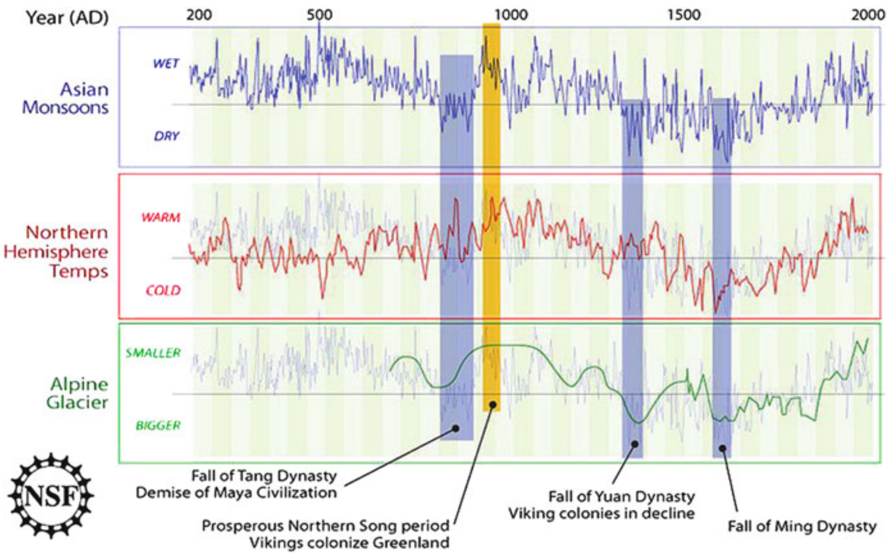

Fig. 2.1 Time scales for different climatic and historic events for the past 2,000 years. *Blue* – Asian monsoons; *Red* – Northern Hemisphere temperatures; *Green* – Alpine glaciers (U.S. National Science Foundation, Public Domain)

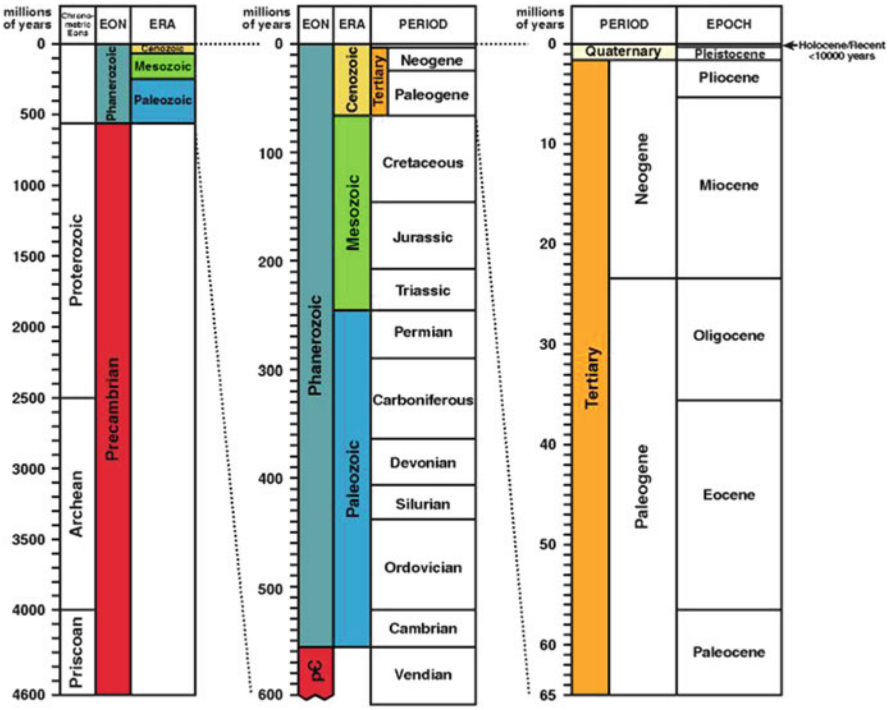

Fig. 2.2 The major divisions of geologic time (From Copyright © 1996–1997 by Andrew MacRae, University of Calgary, Alberta, Canada)

human-like fossils (4.4 million years ago), the extinction of the dinosaurs (the Cretaceous-Tertiary boundary 65.5 million years ago), or the first signs of life in the fossil record (3.5 billion years ago). The geologic time scale is shown diagrammatically in Fig. 2.2 and Appendix I, and it is important that one be familiar with the major subdivisions of geologic time, such as periods and epochs shown in Appendix I as soon as possible. The geologic time scale is used throughout this text and events are given in either absolute time or relative time, or both.

Tectonic (mountain building) events take place over millions of years; orbital events, changes in Earth's orbit, take place over hundreds of thousands of years; glacial-interglacial events take place over thousands of years; and historical events take place over hundreds or thousands of years.

How is time expressed? In a preceding paragraph, Cambrian, 4.4 million, 3.5 billion, and the Cretaceous-Tertiary boundary are all used to express time, either as years ago or by using geologic names such as Cambrian, Cretaceous, and Tertiary. From the geologic column in Fig. 2.2 and Appendix I, it is possible to put both of these means of expressing time into a geological perspective; it is possible to place the above events into a timeframe of geologic time.

Earth is about 4.54 billion years old; this means the Earth originated 4.54 billion years ago or 4,540,000,000 years ago, or 4.54×10^9 years ago. The first 4,000,000,000 (4 billion) years of Earth history, as interpreted by the rocks that were formed during that length of time, does not tell us very much about the events that occurred during that interval. The rocks representing that time interval are just too complex and reworked to reveal much about the time represented. Geologists refer to that length of time as the "Precambrian" or Precambrian time. The Precambrian is not a formal name but refers to a geologic time interval which preceded the Cambrian Period (Fig. 2.2).

Five hundred and forty million years ago or 540,000,000 (540 million) years ago, or 5.4×10^8 years ago, something happened that allowed organisms living then to be able to extract calcium carbonate and silica from sea water to make hard parts. These hard parts are today preserved in rocks of the Earth and allow geologists (and paleontologists) to interpret events surrounding these organisms; how they lived, where they lived, how they died, and how they evolved.

The Earth's climate began to cool about 35 million years ago, 35,000,000 years ago, or 3.5×10^7 years ago and the continent of Antarctica began to ice over (glaciers began to form on the continent). The Earth continued to cool and the planet experienced several ice ages; then it warmed and cooled again and again in cycles.

The last continental glacial advance on Earth reached its maximum extent about 18,000 or 1.8×10^4 years ago and glaciers have been retreating ever since, for the last 18,000 years, with relatively short periods of stoppage and then expansion.

In the last 260 plus years, since the Industrial Revolution, the retreat of Earth's glacial ice has increased due primarily to carbon dioxide emissions and other greenhouse gases from the anthropogenic (humankind's) burning of fossil fuels (coal, petroleum, and natural gas); and it is now happening so rapidly that it has become a problem of global proportions and concern.

2.8 From Hothouse to Icehouse

Climate change has been happening throughout much of Earth's history on scales of decades, hundreds, thousands, millions and billions of years. Temperatures on Earth have gone from "hothouse" to "icehouse" and back again in cycles throughout Earth's history. But the climate changes of the distant past are natural; they have had natural causes that scientists can identify. The most recent climate changes beginning about 10,000 years ago, and especially the last 260 or so years, have been the result of the activities of humankind and their impact on the Earth's climate.

There is abundant evidence that humans are living in a period of Earth history that is unique because of these effects of humankind on the planet. Because of this, the current time is being referred to as the Anthropocene Epoch. The Anthropocene began approximately 8,000 years ago with the advent of agriculture, when humans began to grow food for more and more people; the end of the hunter-gatherer stage of human existence. The impact of agriculture on the atmosphere is, of course, continuing today with agriculture, the burning of fossil fuels, and deforestation and these impacts will continue well into the future. These different impacts that humans are having and have had on Planet Earth will be discussed in later sections of this text.

2.9 Earth's Energy Imbalance

When the amount of energy entering a system equals the energy released by a system, the system is said to be in equilibrium. On planet Earth, if the amount of energy going out of the system equaled the amount of energy that was coming into the system, the system would be in a state of energy equilibrium. Earth currently does not have a condition of energy equilibrium because more energy is coming into the climate system than is being released into space. This energy imbalance is what is causing the Earth to warm.

The amount of energy coming into the Earth's climate system is measured precisely at the top of the atmosphere by satellites. Satellites also precisely measure the amount of energy escaping back into space. The latter is less than the former and this has been measured since the late 1970s when satellites capable of measuring the Earth's energy were placed into Earth orbit.

Earth's energy imbalance is discussed in more detail later in this text.

2.10 An Introduction to Science

Science is the use of natural laws and principles to further the advance of human knowledge. In this respect, science is distinguished from non-science by using natural laws to solve problems and gain understanding. Scientific research and empiricism are basic to expanding human knowledge.

Most of western thought can be traced back to the ancient Greeks where we see the beginnings of attempts to understand the natural world. This period of human history marks the end of the exclusive practice of mysticism to explain natural laws and events.

Modern science is generally traced back to the early modern period during what is known as the Scientific Revolution of the sixteenth and seventeenth centuries. The Scientific Revolution was marked by a new way of studying the natural world, by methodical experimentation and observation aimed at defining "laws of nature."

Examples of the basic sciences are astronomy, biology, chemistry, physics, and geology. Each of these sciences has areas of specialization, such as biology (ecology, genetics), chemistry (organic, inorganic, and analytical), Earth Science (climatology, oceanography), physics (experimental, theoretical), and geology (petrology, mineralogy, paleontology). Each of the sciences is experimental and observational with human knowledge advancing greatly by each one of them. There are also interdisciplinary sciences such as geophysics, biochemistry, etc.

Breakthroughs in biology are such things as mapping the human genome and discovering the structure of DNA. Breakthroughs in chemistry are all around us with new organic compounds and medicines. Breakthroughs in physics are greater understanding of the cosmos and the atom. Breakthroughs in geology have been the concept of plate tectonics and continental drift, and breakthroughs in Earth science are in the areas of climatology and climate change science.

2.10.1 Reasons to Study Science

There are many reasons to study science but perhaps the main one, at least for Earth scientists, is curiosity about the natural world. The answers to questions such as how did the Earth get to where it is today, why are hills and valleys where they are today, how did they get to be that way, where did humans come from? Why do humans exist? All of these questions have answers and scientists are the ones to provide them.

Curiosity drives science and scientific endeavors, or research. Richard Feynman, a physicist and one of the most respected scientists of the twentieth century and one of the scientists at Los Alamos Natural Laboratory who worked on development of the atomic bomb during WWII, described science to his students as follows:

> The principle of science, the definition, almost, is the following: The test of all knowledge is experiment. Experiment is the sole judge of scientific 'truth.' But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess.

Feynman also observed, "…there is an expanding frontier of ignorance…things must be learned only to be unlearned again or, more likely, to be corrected."

2.10.2 The Philosophy of Science

The philosophy of science is simply for one to strive to understand and to hopefully make the world a better place. This is also the philosophy of scientists. Making the Earth a better place to live is not easy and cannot be left only to chance because humans are having an adverse influence on our planet and have been having this kind of influence since at least the beginning of the Industrial Revolution in the mid-eighteenth century. If we accept the concept of the Anthropocene (*anthros*, "human"; *cene*, "new") as a legitimate interval of time, humans have been adversely affecting the planet for the past 10,000 years or before, since the first tree was chopped down or the first man-made fire was started.

Science has caused civilization to advance in many ways and some scientists have become well-known as a result: Galileo (the Earth's place in space relative to the Sun), Albert Einstein (relativity, $E=MC^2$), Charles Darwin (evolution and natural selection), Watson and Crick (DNA), Isaac Newton (basic laws of modern physics), Carl Sagan (astronomy), etc. Earth science has seen some of its scientists become well-known also, such as James Hutton (Uniformitarianism), Harry Hess (seafloor spreading), Michael Mann (the "hockey stick"), Phil Jones (CRU and stolen emails), Richard Alley (Earth: The Operator's Manual), etc. But scientists don't practice science to become well-known, famous, rich, or even notorious. They become scientists to advance knowledge of the world around them; to experiment, to test, and thereby expand the knowledge of the world around us.

Science usually advances in somewhat mysterious ways. A major breakthrough is most often announced to the press or someone wins a Nobel Prize, or someone invents a new device such as the cell phone or a new personal computer, electronic tablet or smart phone. Science advances in fits and starts. But it has made life on the planet much better in many ways. Advances in medical science are usually well publicized as they affect people directly; but so does climate change, even more so than medicine. Global climate change affects everyone on Earth and global climate change may eventually lead to the "four horsemen of the Apocalypse; famine, death, pestilence, and war," and will affect every living creature on Earth that is supported by the atmosphere; but then again it may not.

The second decade of the twenty-first century (2010–2019) is on pace to be the hottest decade ever recorded after the first decade (2000–2009) was the warmest ever recorded even though its rate of temperature rise has tailed off a bit. Introductory science students need to understand that the planet is getting hotter and know what is happening, why, and something about what needs to be and can be done about it, if anything.

Why do we study science and how do we study it? Why is science important? Let's next take a look at what some of the great thinkers of the past have taught us about why science and the acquisition of knowledge are important to mankind.

The basic philosophy of science can be traced from Aristotle through medieval times (500–1450 AD) to the present by discussing some of the different philosophers of science and how their ideas have evolved over time, especially those related to science in general and climate science in particular.

Philosophers of science have mainly been mathematicians due to their perception of the purity of mathematics (e.g., Descartes, Russell). Bacon, Newton, Popper and others, and their ideas, are briefly discussed in the following sections. The “black swan” metaphor is used in discussing empiricism.

The philosophy of science is as old as science itself. Philosophy has been described as “the love of wisdom” and it is difficult to distinguish from science. Science is also the love of wisdom or at least the love of knowing how to obtain the answers to problems. And solving problems and obtaining answers provide wisdom.

As the ancestors of modern man began to wonder about the things around him he began to ask the questions “what” and “why.” And he found the answers to them slowly as he became more and more aware of his world as time passed.

The philosophy of science is classified as a subject in philosophy, not in science. Those who practice it for the most part are not scientists, but they have made contributions to how the world views science and scientists so it is pertinent to introduce it here, although others might disagree. “Philosophy of science is about as useful to scientists as ornithology is to birds,” according to physicist Richard Feynman. In response to Feynman’s quip, some philosophers have pointed out that it is likely that ornithological knowledge would be of great benefit to birds, were it possible for them to possess it.

Most ideas and the beginnings of western thought began with the ancient Greeks. Many ideas can be traced back in time to Aristotle, especially ideas about how knowledge is acquired.

2.10.3 Early History of Science

Science began when humans began to wonder about the world around them. Early humans were most likely terrified by natural events such as high winds, earthquakes, and lightning. Violent storms are today still frightening natural events and may be deadly when they spawn floods, tornadoes, and cyclones. Volcanic eruptions are still awe-inspiring and the early human inhabitants living near them were frightened of them and wondered what was causing them. Their early explanations were fantasy and superstition. They concocted gods and devils to explain the unknown and this may be witnessed today in modern society.

Humankind’s curiosity is one of the most basic of human attributes. The need to know how something works and why it works is a basic part of human nature and curiosity fuels the need for humans to try and understand natural systems, such as the climate system. And the climate system is indeed complex and fluid and difficult to understand. But that is reason enough for climate scientists to work at understanding and specialists, such as oceanographers and glaciologists, to try to unravel bits and pieces of it. And climate change scientists use empiricism, induction, and deduction from which to draw their conclusions and to build their models.

Early scientists of note were Greek and Roman; such names as Aristotle, Pliny the Elder, etc. These were supplanted by English, German, and other European scholars after the Dark Ages and the Renaissance, such as Bacon and Newton, and then by more modern scientists.

2.10.4 Aristotle (384–322 BC)

Aristotle was a Greek philosopher whose writings included physics as well as many other subjects (e.g., metaphysics, linguistics, politics, biology, etc.) and is considered one of the founding fathers of Western philosophy. His views went a long way in shaping medieval scholarship and extended into the Renaissance and even today. His scientific views, both in the physical and biological sciences, and his explanation of logic form the basis for much of the later scientific and mathematical works in those fields.

Aristotle's views on logic and religion continue to be read. It is estimated that only about 1/3 of his works have survived but those that have are still being studied. He believed that knowledge was gained by empirical observation and experience.

Our attempt to justify our beliefs logically by giving reasons results in the "regress of reasons." Since any reason can be further challenged, the regress of reasons threatens to be an infinite regress. However, since this is impossible, there must be reasons for which there do not need to be further reasons, i.e., reasons which do not need to be proven. By definition, these are "first principles." The "Problem of First Principles" arises when we ask why such reasons would not need to be proven. Aristotle's answer was that first principles do not need to be proven because they are self-evident, i.e., they are known to be true simply by understanding them and understanding results from observation and experience.

Aristotle's empiricism was that knowledge begins with experience. We get to first principles through induction. But there is no certainty to the generalizations of induction. The "Problem of Induction" is the question 'How do we know when we have examined enough individual cases to make an inductive generalization.' Usually we can't know. Thus, to get from the uncertainty of inductive generalizations to the certainty of self-evident first principles, there must be an intuitive "leap," through what Aristotle calls "Mind." This ties the system together. A deductive system from first principles (like Euclidean geometry) is then what Aristotle calls "knowledge" ("*epistemê*" in Greek or "*scientia"* in Latin).

Aristotle's influence lasted longer in the Roman Catholic Church than it did in the philosophy of science. In the physical sciences, Aristotle's scientific views were supplanted by Newtonian physics.

2.11 Early Scientists

It is difficult to tell who the very first scientist was and it greatly depends on one's definition of scientist. We know that Aristotle's writings show that he used empiricism and deduction. He reasoned very much as scientists do today. But perhaps, and almost certainly, there were intelligent naturalists who reasoned from things that they saw around them and drew conclusions from those observations.

It is most likely that among our very early ancestors there were those that used their minds in a scientific way so it is unimportant to identify the first scientist even if we could; just as it is unimportant to identify the very first human ancestor. Physical anthropologists and human paleontologists might disagree but for our purposes we just need to trace the earlier interests in the natural world and climate change to be able to put our current ideas about climate change in historical perspective.

2.11.1 Pliny the Elder (23 AD–79 AD)

Pliny the Elder was a Roman scholar and naturalist who lost his life in the 79 AD eruption of the volcano Vesuvius, located in the Bay of Naples, Italy, which destroyed the cities of Pompeii and Herculaneum. Pliny was the leading naturalist of his day and wrote numerous volumes on what was then called natural history, including geology, botany, and zoology. He is referred to as Pliny the Elder because his nephew and adopted son, who wrote articles about his life and death, is referred to as Pliny the Younger (63–113 AD).

Pliny the Elder was the author of at least 75 published books, not to mention another 160 volumes of unpublished notebooks. His books included volumes on cavalry tactics, biography, a history of Rome, a study of the Roman campaigns in Germany (20 books), grammar, rhetoric, contemporary history (31 books), and his most famous work, his one surviving book, *Historia Naturalis* (Natural History), published in AD 77. Natural History consists of 37 books including all that the Romans knew about the natural world in the fields of cosmology, astronomy, geography, zoology, botany, mineralogy, medicine, metallurgy, and agriculture.

Pliny the Elder was on a ship in the Bay of Naples when the 79 AD eruption of Vesuvius began and, according to one story, he received a message from a friend who was in the vicinity of the volcano and asked to be rescued. Pliny took a fast boat to shore to rescue his friend and either died naturally on shore or was killed by the toxic gases issuing from the volcanic eruption. Additional information on the life and accomplishments of Pliny the Elder can be found at the following web site: http://www.livius.org/pi-pm/pliny/pliny_e2.html.

2.11.2 Claudius Ptolemy (c. AD 90–c. AD 168)

Claudius Ptolemy (c. AD 90–c. AD 168), was a Roman citizen of Egypt who wrote in Greek. He was a mathematician, astronomer, geographer, astrologer, and poet. He is credited with having written the only surviving comprehensive ancient treatise on astronomy in which he considered the known universe to be geocentric with everything revolving around the Earth. This model became known as the Ptolemaic Hypothesis or Ptolemaic model of the Solar System; that the Sun, Moon, and all the planets revolved around the Earth.

2.11.3 Nicolaus Copernicus (1473–1543)

Nicolaus Copernicus (1473–1543) was a Renaissance astronomer who first proposed that the Earth was not the center of the Universe or the Solar System. He proposed that the Sun was the center of the Solar System and the Earth revolved around it. Such a scheme is called a heliocentric cosmology or heliocentric theory. This concept radically changed the way humankind viewed the Earth and led to the beginning of modern astronomy. The concept began what is sometimes called the Copernican Revolution.

It is impossible to know exactly why Copernicus began to espouse the heliocentric cosmology as his reasons are lost to history. Despite his importance in the history of philosophy, there is a paucity of primary sources on Copernicus. His astronomical writings were few. Therefore, many of the answers to the most interesting questions about Copernicus's ideas and works have been the result of conjecture and inference, and we can only guess why Copernicus adopted the heliocentric system.

2.11.4 Galileo Galilei (1564–1642)

Galileo Galilei (1564–1642) was born in Pisa, Italy but spent most of his life near Florence. He was trained as a mathematician and taught mathematics at the University of Pisa and the University of Padua.

Galileo began to make telescopes after hearing of a similar magnifying device from the Dutch. He ground his own lenses and turned his telescopes to the night sky. It is said that in 2 months (in December and January, 1609), Galileo made more discoveries that changed the world than anyone has ever made before or since. He saw what he believed to be mountains on the Moon, to have proved that the Milky Way was made up of stars, and to have seen four small bodies orbiting Jupiter.

Galileo's observations resulted in his conclusion that the Earth and Moon revolved around the Sun, as Copernicus had theorized before him; that the Earth was in daily motion about its axis and in yearly motion around a stationary Sun. Galileo also discovered Sunspots and reported on these in 1612.

At the time Galileo began his work the Bible was interpreted literally by the Catholic Church and it was believed that the Earth was the center of the Universe. The theory of Claudius Ptolemy (85–165), a Greek astronomer and geographer, was that the Earth was at the center and all heavenly bodies revolved around it. In 1632, Galileo published *Dialogue Concerning the Two Chief Systems of the World – Ptolemaic* *and Copernican*, which favored the Copernican view. Until this publication, Galileo had received little notice from the Church. After its publication, the Inquisition banned its sale and distribution and ordered Galileo to appear before it in Rome. By this time, Galileo was in ill health and could not travel to Rome. He was found guilty in absentia and was condemned to lifelong imprisonment. The sentence in actuality amounted to house arrest and not imprisonment and Galileo continued to write and to have contact with his colleagues.

Galileo used observations (empiricism) to develop his support for the Copernican theory that the Earth revolved around the Sun and not vice versa, and Galileo is given credit for finally proving the Copernican theory.

2.11.5 Francis Bacon (1561–1626)

Francis Bacon (1561–1626) was an English philosopher and scientist and has been called the "father of empiricism" although, as we've seen, that title should be reserved for Aristotle. He established inductive methodologies for scientific work, called the Baconian method (or simply the scientific method). His pre-planned approach to the study of natural science forms the basis for the scientific method used today. To take the place of the established tradition that was in existence during his early life (which has been described as a combination of Scholasticism, humanism, and magic), he proposed an entirely new system based on empirical and inductive principles and the active development of new arts and inventions, a system whose ultimate goal would be the production of practical knowledge for "the use and benefit of men." Bacon spent a great deal of his professional years in politics and rose to become the Lord Chancellor of England. Unfortunately, his political career ended in disgrace in 1621 and he spent the last few years of his life writing about science and philosophy.

2.11.6 Johannes Kepler and Tycho Brahe

Johannes Kepler (1571–1630) was a German mathematician and astronomer and a major figure in the scientific revolution in the seventeenth century. His work and formulation of planetary motion formed the basis for Newton's theory of universal gravitation.

Kepler was familiar with both the Ptolemaic and the Copernican hypotheses of the Earth and Sun and became a strong advocate of the ideas of Copernicus.

He is best known for his laws of planetary motion. His work provided the foundation of Isaac Newton's universal laws of gravitation. Kepler was a student of the Danish nobleman Tycho Brahe (1546–1601). Brahe compiled extensive data on the planet Mars, which would later prove crucial to Kepler in his formulation of the laws of planetary motion because it would be sufficiently precise to demonstrate that the orbit of Mars was not a circle but an ellipse. Brahe was apparently suspicious of Kepler's intellect, fearing that Kepler would outshine him as a scientist, and therefore kept a large portion of his work from Kepler.

2.11.7 Isaac Newton

Isaac Newton (1642–1727) was an English physicist, mathematician, and astronomer who laid the foundation for classical mechanics, the three laws of motion, and universal gravitation. He is considered by many to be "the greatest and most influential scientist who ever lived." He removed the last doubts of heliocentrism and went a long way to advance the Scientific Revolution of the seventeenth century. He built the first reflecting telescope. Newton shares with Gottfried Leibniz the credit for developing differential and integral calculus. We will come back to Isaac Newton again in the following chapter in discussing the laws of motion.

2.12 Empiricism

Empiricism is the idea that knowledge can be derived by careful observation and formulating hypotheses or laws from these observations. The origins of empiricism lie with Aristotle. Aristotle would consult all of the experts and written texts of the time, document and catalog their ideas, observe as much as he could, then derive principles and laws based on all the information he had seen or read. Medicine in ancient Greece was based on Aristotelian empiricism which has had an influence on medicine and science to the present day.

Empiricism emphasizes experience and evidence in the formulation of principles and laws. It is fundamental to the philosophy of science and the scientific method that all hypotheses and theories be tested against observations in the natural world or in the laboratory. Thus, scientific methodology is largely empirical.

There are problems with empiricism that are intuitive. How does one know when enough evidence is acquired to form a conclusion? If one counts all the swans in one area and they are all white, the conclusion based on empiricism is that all swans are white. Then one observes a black swan in another or the same area and the conclusion is shown to be wrong (the "black swan metaphor"). It is often impossible to know all the evidence for a particular conclusion, so scientists resort to statistical analyses and probability theory with large sets of data.

2.13 Inductive Logic

Inductive logic is contrasted with deductive logic. Inductive logic tells one that if a generalization is true, then a conclusion based on the generalization is also true.

In the process of induction, one begins with some facts or observations, and then determines what general conclusion can logically be derived from those facts. One determines what hypothesis or theories could explain the data.

One example often given to illustrate inductive logic is the following: the scientist or philosopher notes the probability of becoming schizophrenic is greatly increased if at least one parent is schizophrenic and from that concludes that schizophrenia is inherited. This is certainly a reasonable hypothesis given the data. However, the induction does not prove that the hypothesis is correct. There are alternate hypotheses that are supported by the data. For example, the behavior of the schizophrenic parent may cause the child to be schizophrenic, not the genetic makeup. What is important in induction is that the hypothesis does offer a logical explanation of the data. To conclude that the parent has no effect on the schizophrenia of the child is not supported given the data and would, therefore, not be a logical conclusion. This leads us to the idea of multiple working hypotheses.

2.14 Multiple Working Hypotheses

Scientists use inductive logic often in research keeping in mind that there may be alternate hypotheses to explain the facts. They must always keep in mind that their main hypothesis may be wrong. As a matter of fact, there is a way of conducting scientific work called the method of multiple working hypotheses first formalized by the geologist T. C. Chamberlin in 1889–1890. As a way of conducting scientific investigations, this is usually the way scientists progress through a research project; always keeping in mind all the possible hypotheses that may explain the data, i.e., multiple working hypotheses.

An example of the use of multiple working hypotheses is given by the problem of the sedimentary rock breccia. Breccia is composed of angular fragments of other rocks, which may be of any kind, naturally cemented together. Breccia may be the result of landslides or avalanches; it may be formed along faults; it may result from the impact of meteorites. When one finds a sample of breccia in the field, all of these possible origins come to mind and they become multiple working hypotheses as to the origin of that particular breccia. The geologist is then ready to seek further information to find the answer to the rock's origin.

Karl Popper (1902–1994), an Austrian-British philosopher of science, rejected the classical empiricism of science and the classical observationalist-inductivist method of science that had grown out of empiricism. His view of theories was that a theory should be considered scientific if and only if it is falsifiable. A search of the Internet will lead to much more information on Karl Popper's ideas on science. Popper is considered one of the most influential of the twentieth century's philosophers of science, but his rejection of empiricism leaves him as not a favorite son of most scientists.

Additional information and examples of inductive logic can be found at the following website: http://plato.stanford.edu/entries/logic-inductive/.

2.15 Deductive Logic

Deductive logic is that used most often in science. Deductive logic begins with a statement, called a *premise*, that is assumed to be true, than determines what else would be true if the premise is true. Using deductive logic, one can provide absolute proof of a conclusion given that the premise is correct. The premise remains unproven and must be accepted on faith for the purpose of exploration or experimentation.

Deduction and induction by themselves are not adequate for a scientific approach. While deduction gives absolute proof, it never makes contact with reality; there is no place for observation or experimentation of the premise, no way to test the validity of the premises. And, while induction is driven by observation, it never approaches actual proof of a theory. The development of the scientific method, over time, has involved a gradual synthesis of these two logical approaches.

Induction is used to formulate an idea or hypothesis which results in the collection of data. After or during the data collection, deduction leads to a conclusion. Either the original idea is right or it is wrong. If the collected data support the original idea, more data are collected or a hypothesis or theory is developed to explain the data. If the data do not support the idea or hypothesis, a new hypothesis is formulated. Many have described the scientific method as being "trial and error." The main intent and hopefully the result of using the scientific method is to minimize the latter (error) and maximize the former (trial).

2.16 Models and Simulations

Models in the context of science are simulations or scaled up or down examples of an actual entity, situation, or perception. One would not build a car, airplane, or spaceship, or even a theory without building a model, if only a mental one. However, in the case of a car, airplane, or spaceship, one would not attempt to build a real one without first building a scale model; and certainly a person would not want to get in it and make it go without having confidence that a model had been used before final construction and all the parts had been checked. Children and some adults have models of cars, trucks, airplanes, helicopters, teddy bears, action figures, etc. and they provide an indication of what the real thing will look like or do.

Models using computers that simulate real-world situations are used often in science, especially in climate change science. Models are used to draw conclusions by scientists every day and they allow scientists to project what may happen well into the future. In climate change science, computer programs that include basic equations of physics and chemistry are used in the process of modeling the climate, which allow climate change scientists to project climate changes into the future and to vary the input and study various scenarios of what might happen in the future.

Models are not only used in science, society, and industry. They are also used in the military. For example, if a general wants his troops to go into battle, it is best to run a model of the terrain and conditions (e.g., weather) expected to be found in the area where the battle is to take place. If the general does not have a model, then the troops may be sent into battle and may be slaughtered. The general would soon be out of troops to die for their country or cause and the battle would be lost, and possibly the war.

Before the advent of computers and computer models, climate scientists and generals ran models in their heads or drew them in their heads or on a chart or table or in the soil. They imagined or drew what the conditions would be like in the future for climate or on the field of battle and relied on these images to decide when to take action and to send troops onto the battlefield. This sometimes worked but often it did not. Although the human brain can run numerous simulations, it can't run millions in a few seconds like a high speed computer. However, models are only as good as the computer programmer and the scientist or general can make them.

Climate models that are used to simulate climate change and project that change into the future are treated in greater detail later in the text.

2.17 The Nature of Science

The early practitioners of science were referred to as natural philosophers and their field of expertise was considered to be natural science. The designation of natural science can be seen today in names such as "Natural Science Museum" and may be used to distinguish the "natural sciences" from the social sciences and "formal sciences" such as mathematics and logic, although the latter are rarely considered sciences. Natural science also includes natural history as in the American Museum of Natural History in New York, NY or the National Museum of Natural History, a part of the Smithsonian complex in Washington, D. C., both in the U.S.

Natural sciences include astronomy, chemistry, physics, geology, Earth science, biology, meteorology, oceanography, materials science, and branches thereof. Climatology and climate change science are also considered natural sciences. The nature of science also deals with the science of nature.

2.18 The Science of Nature

All natural sciences are sciences that study nature. Natural scientists try to determine how the Universe and everything in it works. Astronomers are trying to see farther and farther into the Universe and to explain what is seen there, and this is natural; chemists are performing experiments to try to determine how different substances react with each other and what new substances are produced, many of which are found in nature; physicists are studying the motions of things from subatomic particles to objects in space and the physics and laws of nature; geologists are attempting to decipher all the events of Earth history as can be determined from Earth materials and are also studying rocks, minerals, and gases from other planets, comets and asteroids; Earth scientists are studying all aspects of the Earth; biologists are trying to learn all there is about life; meteorologists are trying to understand and predict weather; oceanographers are unraveling the secrets of the seas; and materials scientists are doing all kinds of things with new and exciting materials, all dealing with the science of nature.

A great many natural events seem to occur without rhyme or reason, as in storms or earthquakes. Many natural systems appear to be in a state of chaos; but what is chaos?

2.19 Chaos Theory

Chaos theory is a branch of mathematics. It is a sub-discipline of mathematics that deals with systems that exhibit chaos but can be made sense of and analyzed mathematically. Some of the complex systems that chaos theory helps us understand are weather, water boiling on a stove, migratory patterns of birds, and how vegetation spreads across a new piece of land. Chaos theory is really about finding the underlying order in apparently random data. Something described as chaotic has numerous variables or moving parts, such as weather or traffic patterns in a large city such as Washington, D.C., London, England, Rome, Italy, or Paris, France.

Chaos theory was introduced by an experiment done in the early 1960s by Edward Lorenz, an American mathematician and meteorologist. In 1960, he was working on the problem of weather prediction. He had a computer set up, with a set of 12 equations to model the weather. It didn't predict the weather itself. However this computer program did theoretically predict what the weather might be. One day in 1961, he wanted to see a particular sequence again. To save time, he started in the middle of the sequence, instead of the beginning. He entered the number off his printout and left to let it run.

When he came back an hour later, the sequence had evolved differently. Instead of the same pattern as before, it diverged from the pattern, ending up wildly different from the original.

Eventually he figured out what had happened. The computer stored the numbers to six decimal places in its memory. To save paper, he only had it print out three decimal places. In the original sequence, the number was .506127, and he had only typed the first three digits, .506.

By all conventional ideas of the time, it should have worked. He should have gotten a sequence very close to the original sequence. A scientist considers him- or herself lucky if (s)he can get measurements with accuracy to three decimal places. Surely the fourth and fifth, impossible to measure using reasonable methods, can't have a huge effect on the outcome of the experiment. Lorenz proved this idea was wrong.

This effect came to be known as the butterfly effect. The amount of difference in the starting points of the two curves is so small that it is comparable to a butterfly flapping its wings and the effects that may ensue.

> The flapping of a single butterfly's wing today produces a tiny change in the state of the atmosphere. Over a period of time, what the atmosphere actually does diverges from what it would have done. So, in a month's time, a tornado that would have devastated the Indonesian coast doesn't happen. Or maybe one that wasn't going to happen does. (From Ian Stewart, *Does God Play Dice? The Mathematics of Chaos*, pg. 141)

This phenomenon, common to chaos theory, is also known as "sensitive dependence on initial conditions." Just a small change in the initial conditions can drastically change the long-term behavior of a system. Such a small amount of difference in a measurement might be considered experimental noise, background noise, or an inaccuracy of the equipment. Such things are impossible to avoid in even the most isolated lab. With a starting number of 2, the final result can be entirely different from the same system with a starting value of 2.000001. It is simply impossible to achieve this level of accuracy – just try and measure something to the nearest one millionth of an inch!

In dealing with very small and very large numbers and a great number of variables, digital computers are essential because they can make extremely fast calculations. This is the reason that chaos theory didn't come about until the advent of the digital computer age and the calculating capabilities of the 1960s.

Additional information on chaos theory may be found at the following web site: http://www.abarim-publications.com/ChaosTheoryIntroduction.html#.TtVP2GMk6nA.

Scientists deal with very large (astronomical) and very small (microns) numbers and they have special ways of managing, using, and referring to them.

2.20 Scientific Notation

Scientific notation is how scientists deal with numbers; scientists deal with very large and very small numbers. For example, light travels at a speed of 300,000,000 m per second.

Written out, that number is three hundred million meters per second. In scientific notation, the speed of light would be written as 3.0×10^8 m/s. That is so much less clutter than writing it all out and when one deals with many large and many small numbers, reducing the clutter is important!

The Earth was formed about 4.54 billion years ago, or 4,540,000,000 years ago. In writing this out, one could say that the Earth began about four (4) billion five hundred forty (540) million years ago, or use scientific notation. Scientific notation allows scientists to use less space and write the number as 4.54×10^9 years ago.

Scientific notation consists of two parts: the first part, 4.54 is the coefficient. The second number is called the base and is always 10. The base number 10 is always written in exponent form, such as in the number 4.54×10^9; the number 9 is referred to as the exponent or the power of 10.

To write scientific notation, for example, 4,540,000,000, the decimal point is placed after the first digit, 4.54 then the zeros are dropped. The coefficient is 4.54. To find the exponent, count the number of places from the decimal point to the end of the number, in this case 9 places (10^9) which is the base. The number 9 is the exponent.

If the number (coefficient) is less than 1, the number is small and the exponent is negative.

For very small numbers, say 0.000001 or a millionth of a second is written as 1×10^{-6}. To find the exponent, count the places after the decimal to the end of the number.

Rules for Multiplication in Scientific Notation:

1. Multiply the coefficients
2. Add the exponents (base 10 remains)

$$\text{Example 1}: (3 \times 10^4)\ (2 \times 10^5) = 6 \times 10^9$$

What happens if the coefficient is more than 10 when using scientific notation?

$$\text{Example 2}: (5 \times 10^3)\ (6 \times 10^3) = 30. \times 10^6$$

While the value is correct it is not correctly written in scientific notation, since the coefficient is not between 1 and 10. One then must move the decimal point over to the left until the coefficient is between 1 and 10. For each place the decimal point moves, the exponent will be raised 1 power of 10.

$$30. \times 10^6 = 3.0 \times 10^7 \text{ in scientific notation.}$$

$$\text{Example 3}: (2.2 \times 10^4)\ (7.1 \times 10^5) = 15.62 \times 10^9 = 1.562 \times 10^{10}$$

$$\text{Example 4}: (7 \times 10^4)\ (5 \times 10^6)\ (3 \times 10^2) = 105. \times 10^{12}$$

In example 4, the decimal must be moved two places over and the exponent is raised by 2. Therefore the value in scientific notation is: 1.05×10^{14}

Rules for Division in Scientific Notation:

1. Divide the coefficients
2. Subtract the exponents (base 10 remains)

$$\text{Example 1}: (6 \times 10^6) / (2 \times 10^3) = 3 \times 10^3$$

What happens if the coefficient is less than 10?

$$\text{Example 2}: (2\times10^{7})/(8\times10^{3}) = 0.25\times10^{4}$$

While the value is correct it is not correctly written in scientific notation since the coefficient is not between 1 and 10. We must move the decimal point over to the right until the coefficient is between 1 and 10. For each place we move the decimal over the exponent will be lowered 1 power of 10.

$$0.25\times10^{4} = 2.5\times10^{3} \text{ in scientific notation.}$$

Scientific notation will be used throughout this work when dealing with very large or very small numbers as its practicality can be seen in the above examples.

Logarithms are another way scientists can use to deal with large and small numbers and these are usually taught in courses below the college level; but it should not take long to review. Prior to computers and hand-calculators, logarithms were usually calculated by use of a slide-rule. Logarithms are exponents.

Press coverage of the 2011 earthquakes in Christchurch, New Zealand and Japan, as reports of major earthquakes tend to do, has served as a reminder that many introductory science students have a relatively meager understanding of logarithms. After all, it is not a subject most think about every day or use very often unless one is a scientist or engineer, and most introductory science students are neither.

Both the Richter scale for earthquakes and the pH scale for chemistry are logarithmic and both are used in studying climate change and in other Earth sciences and engineering. A base 10 logarithm (log) is the number, x, so that 10^x gives the number one wants. For example, the log of 100 is 2. This means that $\log(100)=\log(10\times10)=\log(10^2)=2$. Similarly, the log of a million is 6, meaning that $\log(1{,}000{,}000)=\log(10\times10\times10\times10\times10\times10)=\log(10^6)=6$. The log of a number less than 1 is negative. For example, $\log(0.01)=\log(1/100)=\log(1/10^2)=\log(10^{-2})=-2$, compared to 2 for the log of 100.

Before ready access to calculators and computers, logarithms offered a convenient way to multiply large numbers. Now they are mostly used to compare numbers that differ by a very large relative amount.

Generally, if $x=b^y$, then y is the logarithm of x to base b, and is written $\log_b(x)$, so $\log_{10}(1{,}000)=3$.

For example, if we take the population of China (1,340 million), New Zealand (4 million), and India (1,270 million) then it can be hard to make comparisons, since the difference between China and India (70 million) is almost 20 times the population of New Zealand. But if we take the logs of the populations, New Zealand = 6.6, China = 9.13, and India = 9.10. It is now obvious that, relatively speaking, the populations of India and China are about the same while that of New Zealand is very much less.

Earthquakes can range from feeling like the whole Earth is shaking to having the ground shaken like a child with a toy, or to not feeling them at all. So to study and describe earthquakes scientists use the Richter scale. A magnitude 5 earthquake is 1,000 times weaker than a magnitude 8 earthquake because a log difference of 3 means $10^3=10\times10\times10=1{,}000$ difference.

Additional Readings

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