Abstract

This chapter provides the basic foundation for understanding the logic involved in scientific/biological reasoning. Topics include: inductive and deductive logic, hypothesis formulation (if ... then reasoning), the concept of “proof” in science, and the difference between truth and validity. The interplay of these elements are illustrated by the “dissection” of a specific set of investigations by Italian biologist Lazzaro Spallanzani in the eighteenth century concerning what elements of the male semen were causally involved in fertilization and embryonic development in animals. The chapter then moves to a discussion of the way in which hypotheses are formulated as different kinds of explanations in biology, such as teleological versus causal explanations, all illustrated by the question of why warblers begin to migrate south from New England in the fall. This section also examines some of the recent philosophical studies on the nature of mechanisms in biology, and what elements are necessary for a mechanism to be successful as part of a scientific explanation. After discussing the nature of cause-and-effect in biology, and how causal relationships can be distinguished from simply correlations or accidental coincidences, the nature of bias in science is introduced to emphasize that science cannot eliminate all bias, and indeed that sometimes biases (or points of view) are extremely fruitful. The final part of the chapter is devoted to philosophical issues in biology: the nature of paradigms and paradigm shifts in biology, the materialist (as opposed to idealist) foundations of modern biology, and a review of both the strengths and weaknesses of science.
2.1 Introduction

In the spring of 1985, a reporter for the British Broadcasting Company interviewed a biologist on the fertilization of human eggs and development of human embryos outside their mothers’ body. “Surely,” the reporter asked, “you must have done a lot of research to get this far?” The biologist nodded affirmatively. “Well, then,” the interviewer asked, “don’t you know everything you need to know?

The biologist was at a loss for words. It was a question no scientist would think of asking; one based on several widespread misconceptions about the nature of science. One such misconception is that science is largely a matter of collecting facts into a sort of encyclopedia of knowledge about a particular field, for example, biology, chemistry or physics. Related to the first, the second misconception is that the number of such facts is finite and, theoretically at least, we can expect to discover all of them if we search long enough. Yet it is doubtful that the reporter would have asked a historian if he or she knew enough about British or Russian history or a poet whether he or she had written enough poems. Science writer Ted Neild ended his report on the BBC interview with this observation:

Science is about ideas … and because … the unifying ideas [of science] … are in constant need of revision as new facts come to light, and the insight of new ideas redefines the implications of the old knowledge, we can never ‘know’ enough. This is so obvious to scientists, yet apparently obscure to everyone else. [New Scientist March 7, 1985. p. 46.]

What, then, is science, and why is it so often misunderstood? These questions lead us into the main topic of this chapter: the nature and logic of science.

2.2 Science as an Intellectual Discipline

Defining Science

The term “science” was first coined in 1851 by the British philosopher William Whewell (1794–1866) to refer to the study of the natural world. The term “science” comes from the Latin scientia, meaning “knowledge” or “knowing.” Prior to Whewell’s time, people who studied nature were called natural philosophers, a term emphasizing the close historical connection once existing between the sciences and the humanities (Fig. 2.1).

In more recent times, however, science has become an increasingly separate pursuit. Yet, definitions clearly distinguishing science from other fields of human thought are difficult to formulate. This is partly because science is not a single enterprise but rather a collection of activities that often vary widely from one scientific discipline to the next. Furthermore, none of the methods associated with science are unique to science alone. A paleontologist who studies fossils and tries to reconstruct their evolutionary history is likely to have as much in common with a historian than with those biologists who carry out laboratory research in fields such
as genetics or physiology. Both paleontologists and historians are attempting to reconstruct the history of events which occurred in the past and both must draw their conclusions from the only evidence available to them. By contrast, biologists studying processes taking place in organisms that are alive today have available to them a variety of methods, most especially the use of experimentation, not available
to paleontologists or historians. Despite these differences, few today would seriously question that paleontology is a science.

**Characteristics of Science**

Although we may not be able to define science as a unique activity, we *can* describe it as a specific combination of shared practices and assumptions. All science is based on **empirical knowledge** that is, knowledge obtained through our senses of sight, sound, touch, taste or smell. Empirical knowledge, even of the most tentative or casual sort—for example, observing a moth emerge from a cocoon—is often the starting point for any scientific investigation.

A second characteristic of science is its commitment to rationality. Rationality involves seeking explanations in terms of natural rather than supernatural causes. No astronomers today are satisfied with the medieval explanation that planets are moved through their orbits by angels and no biologists are satisfied with interpreting disease as the result of divine punishment. These latter explanations are considered **supernatural** because they involve entities and activities that have no counterpart in our everyday world and because, by definition, they are beyond the rational and we cannot investigate them using rational methods.

A third characteristic of science is its emphasis on repeatability. Scientific results are always subject to confirmation by other investigators. Along with repeatability goes another related characteristic: reliability. Numerous persons have claimed to have seen the Loch-Ness monster, a supposedly prehistoric reptile living in a very deep and ancient lake in northwestern Scotland. Photographs claiming to have spotted the creature are routinely indistinct and “Nessie” as it has been named is so elusive that biologists have never been convinced that it has ever existed. The observations lack reliable confirmation and are thus suspect.

A fourth characteristic of science is its commitment to testability. No matter how interesting or imaginative an explanation might be, it is of no value if it cannot be tested. Untestable ideas provide no basis for asking further questions or for carrying out further research. As fascinating as they might be, in science such ideas are usually an intellectual dead-end.

Following directly out of this fourth characteristic of science is a fifth: its commitment to the use, whenever possible, of experimentation. Experiments are planned interventions into a natural process to observe the effects of that intervention. For example, a biologist interested in how early stages in the development of frog embryos affect the later form of the adult may remove structures from embryos of different ages and record changes occurring as development continues. Such experiments allow the investigator to ask specific questions and obtain equally specific answers; they also allow him or her to make observations that might never be made under natural conditions. Of course, not all fields of science lend themselves to experimentation equally well. The films Jurassic Park I and II notwithstanding, evolutionary biologists cannot step back in time and experiment with dinosaurs, nor can astrophysicists experiment with stellar systems. Yet even in
those fields where experimentation is less often applicable, it remains a goal whenever possible.

A sixth characteristic of science is its search for generality, the establishment of general principles operating in the natural world regardless of differences in time or place. Physicists are interested in principles of motion or gravity that apply not only at different places on the earth but throughout the whole universe. Biologists are interested in understanding living processes in all organisms, not merely mice, maple trees or bacteria. While it is true that each type of organism will respond to its own unique set of environmental conditions and its own internal make-up, the same basic biological principles are thought to apply throughout the living world.

It should be clear that none of the characteristics of science described above apply to science alone. They are, in fact, shared characteristics of all rational human attempts to understand the world we live in, its past as well as its present. It is another way in which we can reiterate a major theme of this book: that as processes, that is, as ways of thinking, the sciences and the humanities are more similar than they are different.

The Relationship between the Sciences, Social Sciences and Humanities

The six characteristics listed in the previous section are not necessarily unique to science. Historians, writers, painters, musicians, auto mechanics and workers in many different fields often try to build more general concepts from specific and precise observations (the best poets, critics have noted, use the most concrete imagery) and all try to formulate these concepts in universally understandable terms. In the seventeenth century, for example, Sir Isaac Newton (1642–1728) formulated a concept of the universe as operating by mechanical principles: the solar system was depicted in terms of a common machine of the day, the clock. Indeed, the metaphor “clockwork of the universe” was commonly used to refer to the Newtonian model of the cosmos. Like writers, scientists use devices of language—analogs, metaphors, similes and often almost poetic descriptions—to convey their vision of the world. Take, for example, the final paragraph of Darwin’s On the Origin of Species, first published in 1859:

It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us … Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows. There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

This passage contains a wide variety of literary devices that convey a particular vision of the natural world as Darwin was trying to present it. It opens with an a vivid and esthetically alluring description of the interrelatedness and complexity of
nature (“an entangled bank”), while also emphasizing its harmonious qualities (the many different creatures so dependent on each other). Then Darwin the scientist steps in: These complex interactions have all come into being by everyday, observable “laws acting around us”—a direct appeal to our rational understanding. Darwin then introduces a new aesthetic, a more somber one, with a series of metaphors describing the processes of over-reproduction, competition, the resulting “war of nature, famine and death”, all parts of his mechanism (natural selection) by which evolution occurs. Yet despite this very nineteenth-century view of the “war of all against all,” Darwin concludes on a positive note: “There is a grandeur in this view of life”, including a not-too-subtle comparison of his own laws of nature to those of Isaac Newton’s laws of universal gravitation. Darwin’s prose is straightforward yet expressed with an almost poetic imagery. There is indeed a possible literary source for Darwin’s descriptions of nature in his writings from his expedition on the HMS Beagle: One of the few books he took with him on that five-year trip was John Milton’s Paradise Lost, and many passages describing the fascinating rain forests of South America are strikingly similar to Milton’s descriptions of Adam and Eve in the Garden of Eden, as historian David Kohn notes in his book, The Darwinian Heritage. Science has as much room for creativity and imagination as do any of the arts. Creative efforts in science are like a painter’s canvas that is constantly being reworked to obtain greater accuracy, completeness or aesthetic appeal. As physicist Albert Einstein (1879–1955) once stated: “After a certain high level of technical skill is achieved, science and art tend to coalesce in esthetics, plasticity, and form.” In this view, the differences between the sciences and the humanities shrinks to a difference in technicalities, not major processes of thought.

The sciences, social sciences and humanities have long interacted in ways that lend support to one another. Questions about the use of atomic energy, the application of our knowledge of biology to preserve the environment, or the ethical implications of new discoveries in genetics often make us keenly aware of some of the ways in which science inspires our social and humanistic concerns and vice versa. Science has inspired many creative writers (the vast literature falling under the heading of science fiction is but one of many examples) and poets. The reverse is also true, however. Social, political, philosophical and even artistic developments often interact with, and directly affect, the course of scientific discovery. Historian Samuel Y. Egerton has argued that studies in visual perspective by early Renaissance painters such as Giotto de Bondone (1337–1376) initiated precise, quantitative and mechanical methods of viewing nature that served as a crucial stimulus for the scientific revolution in astronomy and physics in the sixteenth and seventeenth centuries (Fig. 2.2). The resulting view, that of an infinite universe working by purely mechanical principles, greatly altered human beings’ view of themselves.

\[1\] That many of his contemporaries saw the comparison as apt is reflected in the fact that Darwin is buried next to Newton in Westminster Abbey.
Historian Robert Young has argued that if Darwin had not been familiar with the works on political economy of Adam Smith (1733–1780), David Ricardo (1773–1833) and Thomas Robert Malthus (1766–1834), all of whom emphasized the scarcity of resources and competition as a natural part of the capitalist economic system, he quite possibly would never have come up with the idea of evolution by natural selection. Borrowing these ideas from the social and economic sciences of his day was one of Darwin’s most creative efforts. For their part, Darwin’s ideas stimulated another profound revolution in how human beings viewed themselves as having evolved like other organisms from previously-existing forms. Thus, our

Fig. 2.2 The relationship between art and science. Woodcut demonstrating a technique developed by fifteenth-century sculptor-architect Filippo Brunelleschi (1377–1446). [From Leone Battista Alberti, On Painting (Florence, mid-1430’s); taken from I.B. Cohen, Album of Science, from Leonardo to Lavoisier, 1450–1800 (N.Y., Charles Scribner’s Sons, 1980): Fig. 3]
social views influence the way we form our picture of the natural world as much as our picture of the natural world influences our social views

**Science, Common Sense and Intuition**

A key feature of scientific thinking is that it tends to be highly suspicious of intuitively derived decisions lacking empirical backing; no matter how intuitively obvious an answer might seem, it must always be analyzed critically.

Consider the following problem. Imagine that you have ten marbles, identical in size and weight, of which eight are white and two are red. Now suppose you put these marbles into a brown paper bag and shake them up to randomize their distribution. Without peeking, you then reach into the bag and draw out a marble. If the marble is white, you put it aside and draw another. If that one, too, is white you put it with the other white marble you obtained on the first draw. You keep doing this until you draw a red marble. When that happens, you record the number of the draw on which you obtained the red marble—for example, the sixth draw. You then put all of the marbles you have drawn, both red and white, back into the bag with those remaining there and repeat the process 100 times or, better, 1000 times. The question to be answered is: on which draw are you most likely to get a red marble?

Quite obviously it cannot be the tenth draw, since you will never get to it—if one draws eight white marbles in a row, there can only be two marbles left, both of which must be red. This leaves only draws one through nine as possibilities.

The correct answer to this problem is not intuitively obvious. Most people to whom we have presented this problem figure that if there are eight white marbles and two red marbles, then that is a 4:1 ratio of red to white marbles and therefore the chances of getting a red marble on the first draw are one out of five, or 20%. This is most certainly correct. If you do get a white marble on the first draw, that leaves only seven white marbles in the bag to two red marbles and therefore the odds of getting a red marble on the second draw increases. Still more of an increase in the odds of getting a red marble on the third draw occurs if you get a white marble is drawn on the second draw, and so on. Generally overlooked, however, is the fact that, since the odds of getting a red marble on the first draw are 20%, this means that 20% of the time one never gets to the second draw! If we enter that factor into the equation, it becomes quickly apparent that the first draw is the most likely one to get a red marble, the second the next most likely, the third the next most likely, with the odds decreasing down to the ninth draw, which makes getting to the ninth draw the least likely possibility.

Despite many examples in which intuition has turned out to be wrong, there are many cases in which it has turned out to be correct. Such famous scientific ideas as Einstein’s theory of relativity and the molecular structure of the gene (DNA) were the result of a certain amount of intuition. However, neither these nor any other scientific concepts would have survived for long if they had not been subject to empirical verification (testing). It is no less so for much of ordinary human experience. Intuition may be highly useful both in analyzing problems and generating ideas but in science it must always be confirmed or rejected by empirical tests.
2.3 The Logic of Science

The elements of logic are at the heart of the methods employed in all rational thinking. To understand how we think logically, an examination of the components of empirical knowledge—observations, facts and conceptualizations—is in order.

Observation and Fact

The foundation of all empirical knowledge is a discrete item of sensory data known as an observation. The statement “The car is red,” or “This robin’s song consists of three notes,” all represent observations. Each encompasses a single item of sensory data, in these cases, sight or sound respectively. In science, investigators often employ various instruments to make observations that none of our unaided senses is able to detect. Microscopes, for example, magnify objects too small to be seen with the unaided eye, high frequency audio detectors pick up and record sounds that our ears cannot hear, and electronic sensors amplify subtle chemical changes in living tissue that we cannot see directly. Of course, as any trial lawyer will attest, two observers do not always see the same object or event in the same way. A color-blind person may see a red car as a shade of gray, while someone who is tone-deaf may hear a bird’s song as only a single tone rather than as three distinct notes. For observations to form the basis of our ideas they must be agreed upon by different observers. The criterion of repeatability discussed earlier means that any and all observations must be checked, not only by the original observer, but by other observers as well.

As they become repeated and agreed upon by some community of observers, observations often become established as facts. Facts, then, may be defined as individual observations that have been confirmed and accepted by consensus. For the group involved in that consensus, at least, the observations have been established as facts. It therefore becomes a fact that the car is red, or the bird’s song consists of three notes because and only because a group of observers has agreed it is so. Facts are not some sort of inalterable “Truth” handed to us by an impersonal nature, but are rather negotiated agreements between individuals as they compare their observations.

Does the preceding make the term “fact” into something arbitrary. After all, if a color blind person sees a car as gray is that not a fact for that person, even if other people see it as red? The answer is yes in one sense but no in another. Since knowledge is always obtained and becomes ultimately useful only in a social context, communication and agreement about what is and is not a fact is critical in verifying observations and establishing facts. For example, a small group of Elvis Presley followers have claimed that they have seen the singer alive and that he has spoken to them. For this group, it is a “fact” that “Elvis lives.” Similarly, for many, the existence of unidentified flying objects, or “UFOs,” is also a fact. As either of these two circles of observers widens, however, the consensus dwindles and such former “facts” may eventually be regarded by the majority as unsubstantiated. This is where the empirical component of scientific knowledge becomes important in deciding what will or will not be accepted as fact. No matter how many people
claim that some things are fact, if they cannot be observed repeatedly by a wider circle of observers, the “facts” become highly questionable.

One of the greatest strengths of science is its total commitment to putting observations or facts to empirical testing. It is this commitment that distinguishes science from areas such as religion or other forms of supernaturalism. Some advocates of the supernatural argue that it is necessary to be a “believer” in the phenomenon in order to be able to observe it. Such a claim amounts to little more than saying we can simply believe what we want to believe. One advantage of examining our thought processes is to be able to share with each other some common methods of understanding the world. Humans are social animals and the knowledge we generate is not merely individual knowledge. We could never exchange ideas if we did not employ some common methods of drawing conclusions and communicating with others about the phenomena we encounter.

Recognizing the social component involved in establishing observations and the facts that we derive from them does not lessen their value, but rather suggests that observations and facts are to some extent the product of a particular historical time and place. In other words, observations and the facts that derive from them are not independent of the observer, but rather are very much the product of humans interacting with the world and each other. Recognizing the social nature of observations and facts tells us that, if two or more people do not agree on the facts, they will have little success in discussing the conceptualizations that may be derived from those facts. It would be useless, for example, for two people to debate whether extra-terrestrial UFOs come from inside or outside of our solar system if they cannot agree that UFOs exist in the first place.

**From Fact to Conceptualization**

Human existence would be quite chaotic if our total experience consisted only of discrete observations, even if these were all quite well established. The agreed upon fact that the sun rose over the eastern horizon this morning would be relatively useless if we could not place it in some larger framework or conceptualization. Conceptualizations are abstract statements that go beyond individual facts and relate them to one another. Conceptualizations may be simple generalizations: “The sun always rises on the eastern horizon” or involve more complex explanations: “The sun rises in the morning and sets in the evening because the earth is turning on its axis.” In either case, the most important characteristic of such conceptualizations is that they bring a group of specific facts together into a more general and useful relationship, allowing us to organize these facts into patterns of regularity about the world and to make accurate predictions. Indeed, it has been said that science is the search for patterns in nature.

If it is true that conceptualizations depend upon the observations and facts at hand, it is equally true that the kinds of conceptualizations we generate determine something about the observations we make. We tend to perceive readily only that which we are prepared by our conceptualizations to see. Seeing or observing is not an automatic activity. Art teachers are fond of saying that “art teaches you to see,” which means that observation is something we all have to learn about as a process.
Our eyes or ears may be open but seeing and hearing involve the integrative mechanisms of our brain, which, in turn, is molded by our learning experience. Consciously or unconsciously, people often choose to overlook observations that do not fit with what they conceive to be true. The value of examining these philosophical issues is that it can make us more aware of how various factors influence the way we observe the world or put our observations together into conceptualizations. In turn, such awareness may help provide an antidote to any unintended biases that might influence our thinking.

**Types of Conceptualizations**

Although there are many categories of conceptualizations in science, we will limit our discussion here to three major types: generalizations, hypotheses, and theories.

**Generalizations.** A generalization is a statement that is meant to apply to a large class of objects or set of phenomena. The example given previously that “The sun always rises in the east” is a generalization about a daily occurrence. Similarly, the statement that “all dogs have four legs” is a generalization about a set of objects, dogs. Generalizations are based on summarizing a number of specific observations of the same processes or object. Generalizations are highly useful because they point to a regularity among phenomena in the material world. They become problematic only when they are based on a very small number of cases which may not adequately represent the whole.

**Hypotheses.** Hypotheses are tentative explanations to account for observed phenomena. For example, if you flip the switch on a lamp and it does not go on, you might formulate several simple hypotheses as an explanation: (1) The bulb is burned out, or (2) The lamp is not plugged in. Both hypotheses lead to simple predictions: (1) Replacing the bulb or (2) plugging the lamp into an outlet should make the lamp light up again. In science, hypotheses always lead to predictions that can be verified or refuted. *The formulation and testing of hypotheses lie at the very heart of any scientific or rational inquiry.*

**Theories.** The term “theory” is often used in everyday language to mean something rather vague, more like a “guess” than any highly reasoned conceptualization. However, “theory” generally has a more precise meaning to scientists and philosophers of science. While philosophers often differ as to a universal definition of “theory,” it is generally accepted among practicing scientists that a theory is an explanatory hypothesis that has stood the test of time and is well supported by the empirical evidence. Theories can be as simple as a generalization (all green apples are sour) or more complex causal statements such as nerve cells conduct impulses because electrically charged ions pass through the cell membrane. Theories are generally broader, more inclusive statements than hypotheses, and often relate two or more hypotheses to one another. The Darwin-Wallace theory of evolution by natural selection, for example, incorporates hypotheses dealing with the modifiability of organisms by selective breeding, the meaning of similarity of structure and
function, the role of competition for food, territory and other natural resources, factors involved in mate selection, and so forth.

**Observation, Fact and Conceptualization: A Case Study**

At the turn of the century, biologists made numerous observations to determine the number of chromosomes (Gr. *chroma*, color; *soma*, body) present in the cells of most plants and animals, including humans. To see chromosomes it is necessary to stain cell preparations for viewing under the microscope. Chromosomes so treated appear as dark, oblong objects surrounded by other partially stained material in the nucleus.

Figure 2.3a suggests some of the problems observers encountered in trying to make accurate chromosome counts. First, the chromosomes are usually clumped together in such a way that it was not always easy to tell where one ends and another begins. Second, females appeared to possess one more chromosome in each body cell than did males. Third, chromosomes usually curl and twist toward or away from the plane of the field of vision. Consequently, it was easy to count as two chromosomes what was actually one chromosome appearing at different focal planes under the microscope.

In the early part of the twentieth century, microscopists often used a device called a camera lucida for recording microscopic observations. The camera lucida projects what is observed under the microscope onto a flat surface and allows the observer to trace a pattern of the projected image (Fig. 2.3b). It was far easier to count chromosomes in camera lucida drawings than in the actual chromosome preparations. Yet even then, the same observers did not always see the same

![Fig. 2.3](image_url) **a** Photograph showing chromosomes from a stained spleen cell culture of a 17-week human fetus. Note how the chromosomes clump and overlap, making accurate counts difficult. **b** Camera lucida drawing of the same group of chromosomes. Such drawings help to elucidate detail more clearly, because they represent a composite of observations at different depths of focus—something no single photograph can generate [from T.S. Hsu, *Journal of Heredity* 43 (1952): p. 168]
number of chromosomes (Fig. 2.4). In 1907, German cytologist H. von Winniwart made the earliest counts of human chromosome counts, and reported 47 chromosomes as the total in humans: 23 pairs plus an extra, ‘
h accessory’ chromosome, called the X chromosome. Between 1921 and 1924, however, T. S. Painter, then at the University of Texas, developed new techniques for preparing and observing chromosomes. Using these methods, he reported a count of 48 chromosomes, or 24 pairs. Between 1932 and 1952, at least five other observers confirmed Painter’s count of 48 chromosomes. By the early 1950s, it was accepted that the correct chromosome number for the human species was 48 and all biology textbooks dutifully gave that number.

The certainty of Painter’s count had two negative effects. First, it stifled further investigation; the count became authoritative and people simply stopped counting human chromosome preparations. Second, it prejudiced the few chromosome counts that were made. The conceptualization that 48 was the correct number caused observers to believe they saw 48. In the 1930s and 1940s, however, several new techniques were introduced. One of these was the preparation of karyotypes, in which the cell’s chromosomes are first photographed and then the individual chromosomes are literally cut out of the photographic print. The chromosome images are then arranged on a sheet in a systematic fashion, making it possible to account for each individual chromosome and match it with its partner (Fig. 2.5). In 1955, Dr. Eva Hansen-Melander and her colleagues in Sweden had been studying the karyotypes of cancerous human liver tissue. They consistently counted 46 chromosomes. Eventually, after some doubts about the accuracy of their own observations, Dr. Hansen-Melander’s group challenged in print the long-established

Fig. 2.4 Three different camera lucida drawings of the same chromosome group, as drawn by by three different observers. a Evans, b von Winniwarter, and c Oguma. Note the difficulty in determining whether some parts of chromosomes are attached to or separate from other parts. To see how this affects actual counting, observe the chromosome labeled 2 in image A. Evans saw number 2 as a long, crescent-shaped chromosome, whereas both von Winniwarter and Oguma saw it as two shorter, separate chromosomes. On the other hand, Evans saw chromosome number 3 as a single chromosome, whereas von Winniwarter and Oguma saw it as two separate ones. Such problems greatly confused early attempts to get an accurate count of human chromosome numbers [From King and Beams, Anatomical Record 65 (1936): p. 169]
notion that human beings have 48 chromosomes. By 1960, after many confirmations of the number 46, it was agreed that the older count of 48 was wrong.

What can we conclude about the process of observation from the history of establishing the chromosome count in humans? First, observation is not a passive process in which the observer simply lets sensory data flow into his or her brain. It is an active process that involves a good deal of input or active construction on the part of the observer. We have to “learn to observe.” Second, since observations depend upon sensory data, if the material being observed is itself ambiguous (such as clumped chromosomes) the observations will reflect that ambiguity in one way

Fig. 2.5 Karyotype of a human male. The chromosomes are arranged in their natural pairs by number (numbers start with the larger chromosomes). Characteristically, the 23rd pair is the sex-determining pair, shown here as XY for a male (females would be XX) [courtesy, Dr. Thomas Ried, M.D. and Dr. Hased. M. Padilla-Nash, Cytogenetics Laboratory, National Cancer Institute, NIH, Bethesda, Maryland]
or another, either in disagreements among different observers or failure of a single observer to confirm their own earlier findings. Third, observations generally contain some subjective input. Determining whether a particular stained mass represents one or two chromosomes is often a judgment call. Fourth, people often find what they expect to find. The expectation that human cells contain 48 chromosomes caused many workers actually to “see” 48 chromosomes. Thus even when something else is observed, the force of accepted dogma may cause investigators to disbelieve their own sensory impressions. Fifth, it should be pointed out that Painter was working with testicular samples taken from a patient at a Texas mental hospital. This individual may well have possessed an extra chromosome, a condition sometimes found associated with certain types of mental retardation. Thus, Painter’s observations may have been accurate but his starting material atypical. This case also shows how the introduction of a new technique or procedure, in this case karyotyping, may change a conceptualization in science by improving the accuracy of observations.

This case also illustrates something about the role of gender context in scientific process. In the early twentieth century men far outnumbered women in the sciences, including biology. Men held the major faculty positions in research universities, had access to the most prestigious journals, and were major figures in professional societies such as the American Society of Naturalists or American Genetics Association. Many women went into science but often could obtain only low-paid positions as research assistants (to men) or technicians. In the face of claims by male authorities women often came to doubt their own observations or hypotheses when they found some disparities. In the chromosome case, Painter was a very well-known and authoritative figure, while Eva Melander was only a research assistant in a laboratory run by her male supervisor. The slow acceptance of her own count of 46 chromosomes may well have been the result of bias toward concepts advanced by authoritative men as opposed to those of less well-known women.

Creativity in Science

A popular stereotype maintains that creativity is a process reserved for poets, musicians and other artists, while science, by contrast, is coldly logical. In truth, science may be just as creative as any of the arts; the scientist as much an inspired creator as the poet. When Darwin and Wallace independently read Thomas Robert Malthus’ *Essay on Population*, the concept of natural selection as a driving force in evolution occurred immediately to both of them. In each case it was an act of creativity resulting in the formulation of a bold new concept. Exactly how each individual arrived at this concept is impossible to pinpoint precisely; as in the artistic world, the process of creativity remains always elusive. The momentary insight, the creative flash of inspiration, often happens so quickly that even the individual involved may have difficulty in reconstructing the actual process. Thus, in our discussion of the nature of scientific thought, we will not be able to say much about the creative act of concept formulation itself. This should not be taken to mean, however, that creativity is unimportant in science. On the contrary, it often
plays a central role. What we can understand more fully is the process of verification, that is, how we formulate and test hypotheses in a logical way.

2.4 The Logic of Science: Induction and Deduction

We now turn to the more formal aspects of hypothesis formulation and testing by examining the processes of induction and deduction.

Induction and Deduction

A major pattern of thought involved in forming conceptualizations is known as induction, or inductive logic. Induction is the process of making general statements based upon a set of individual observations. Consider for example, the series of integers below: 2 4 6 8 10 12 14 16 18, *et cetera*. Here, individual observations might lead to the formulation of a hypothesis proposing that the entire series, including any yet-to-be-revealed numbers indicated by the *et cetera*, is composed of the positive, even integers. Or, suppose a person tastes a green apple and finds it to be sour. If the same person tastes a second, third, and fourth green apple, and finds them to be sour also, he or she might reasonably hypothesize that all green apples are sour. The concepts that the entire number series is composed of positive even integers and that all green apples are sour are examples of hypothetical generalizations formed by inductive logic, that is, they are inductive generalizations. Such inductive generalizations not only summarize a set of observations, they may also serve to provide predictions concerning as yet unobserved events: for example, the identity of the next number in the series or the expected taste of the next green apple.

Going beyond the formulation of hypotheses by induction to test their validity involves the use of deduction or deductive logic. Often referred to as "*If …, then*" reasoning, deductive logic is the heart and soul of mathematics: for example, "*If* two points of a line lie in a plane, *then* the line lies in the same plane." Deduction is no less important in science. The "*if*" portion of the "*if … then*" format represents the hypothesis: the word "*if*" stresses the tentative, or conditional nature of a hypothesis, while the word "*then*" stresses that the conclusion follows inevitably from acceptance of the hypothesis.

A deduction is said to be valid if the conclusion follows necessarily from the original hypotheses from which it is derived. We can see this more clearly by laying out the logical sequence involved in what philosophers call a deductive syllogism, merely a formal sequence of *if … then* statements:

*If* … the number series consists of positive even integers
*then* … the next number to appear in the number series will be 20, and
*If* … all green apples are sour, and
*if* … this object is a green apple
*then* … this green apple must be sour.
Both syllogisms are valid: as a long as we accept the two hypotheses as stated, we have no choice but to accept the conclusion. The following, however, is an invalid syllogism:

\[
\begin{align*}
\text{If} & \quad \text{all green apples are sour, and} \\
\text{if} & \quad \text{this fruit is sour} \\
\text{then} & \quad \text{it is a green apple}
\end{align*}
\]

Here, the conclusion does not follow logically because “sour fruit” is a larger set than green apples and may include many other sour fruits in addition to green apples. Since the conclusion does not necessarily follow from the hypotheses, it is said to be invalid.

Note that the conclusion of a deductive syllogism is also a prediction—that is, it makes a statement about some future event. If a number series consists of positive even integers, then the number following 18 would be predicted to be 20; similarly, if all green apples are sour, the next green apple you taste should be sour. The fact that deductive syllogisms lead to predictions means that the conclusions can be tested. Testing hypotheses is one of the cornerstones of scientific investigation. This general method of reasoning is often referred to as the hypothetico-deductive method.

Thus far we have been talking about validity in a strictly logical sense. But what about the “truth” of a statement in the real world? The fact that the first syllogism concluding that this green apple must be sour does not mean that it is sour. Validity and truth are not the same. Validity has to do with logic; truth with our experience in the real world. For example, we can set up a perfectly valid deductive syllogism that has nothing to do with truth in terms of human experience:

\[
\begin{align*}
\text{If} & \quad \text{all geometric figures have four corners, and} \\
\text{if} & \quad \text{this circle is a geometric figure} \\
\text{then} & \quad \text{this circle must have four corners}
\end{align*}
\]

This syllogism is valid, yet clearly in the world of plane geometry it is not true that all circles have four corners.

**Logic, Predictions and the Testing of Hypotheses**

The use of either observations or experimentation to test hypotheses implies that there is a distinct relationship between hypotheses and the predictions they generate. This relationship is shown in the “truth table” (Fig. 2.6):
Note first that, barring an error in carrying out the experiment itself, obtaining a false prediction automatically implies that the hypothesis must also be false since, as the truth table shows, a true hypothesis can never give rise to a false prediction. This becomes obvious if we go back to our number series and sour green apples example. If the next number after 18 turns out to be 19 rather than 20, clearly the hypothesis proposing that the series consists of positive even integers is false. Similarly, if the next green apple is sweet, the hypothesis proposing that all green apples are sour must also be false. Logically speaking, therefore, we must reject both hypotheses. In the real world of formulating and testing scientific hypotheses, however, seldom does a single counter-example lead to the full-scale rejection of a hypothesis, especially if it is a widely accepted one. More likely, the “all green apples are sour hypothesis” would be modified, perhaps to “Most green apples are sour.” There are good reasons why logic alone does not necessarily prevail here. A green apple that is sweet might be a different variety of apple that remains green when ripe; most certainly there are such varieties and their existence does not deny the reality that some other varieties of green apples are, indeed, always sour.

The truth table also shows that only a false hypothesis can give rise to a false prediction. The importance of this last statement cannot be overemphasized, for it is the only instance in which we can establish absolute certainty in evaluating scientific hypotheses. Note, on the other hand, that obtaining a true prediction cannot achieve absolute certainty concerning the truth of scientific hypotheses, because false hypotheses may also give rise to true predictions. The relationships outlined in the “Truth Table” are the logical basis for the claims by philosopher of science Karl Popper that the only truly scientific method is falsification. That is, to falsify a hypothesis is provides certainty, and is therefore logically rigorous: we must reject the hypothesis as originally stated if its predictions are falsified. Popper’s claims have been controversial since many areas of science (for example, evolutionary theory) are not easily falsified, yet they are still considered by most practitioners as science. Yet, falsification remains a goal of scientific work, even if sometimes unattainable.
The Concept of “Proof” in Science

As noted earlier, deductive logic is the heart and soul of mathematics. It is no less so for science. In mathematics, however, proofs by deduction are the standard. Scientific “proofs”, on the other hand, are a combination of induction and deduction and as we have just seen, and therefore are never more than probable. Indeed, the word “proof” should not be used in the context of science at all.

Let us see why this is the case. You may recall from high school algebra the proof that the square root of two (\(\sqrt{2}\)) is an irrational number, that is, cannot be expressed as a ratio of two integers, e.g., 1/2 or 3/4. It is possible to prove this because the set of all numbers is divisible into two subsets, those that are rational, (that is, can be expressed as a ratio of two other numbers), and those that are irrational (that is, cannot be so expressed). The first step in the proof involves putting forth the hypothesis that the square root of 2 is a rational number, that is, is to be found in the set of rational numbers. The algebraic manipulations that follow lead eventually to a contradiction of this hypothesis, that is, to a false conclusion or prediction. As we know from the truth table, this means that, since the square root of two is not in the set of rational numbers, it can only be in the other set, that of the irrational numbers.

This situation of “if not a, then b” is usually not attainable in the real world of the scientist. The experimental disproof of any one scientific hypothesis does not mean that an alternative hypothesis must be true; instead, there may be large number of alternative hypotheses that might account for the phenomenon being researched such as the cause of a disease (there may be no one cause in all cases, but multiple causes). The conclusion here is an important one: science cannot prove anything. Popular reporting to the contrary, science has not “proved” that cigarette smoking causes such conditions as lung cancer, emphysema and/or heart failure. On the other hand, there exists a vast amount of evidence in support of the scientific hypothesis proposing a link between smoking and these conditions and it would be foolish to ignore this just because it cannot be “proven” in the mathematical sense—that is with utter certainty.

Many hypotheses that today we believe to be false today were once accepted by scientists and lay persons alike because they led to accurate predictions. For example, in the seventeenth and eighteenth centuries one of the most intriguing questions was how did an egg, like that of a frog or chicken, develop into a fully-formed organism with highly differentiated structures? Some naturalists believed in what was known as the theory of embryonic preformation. This theory held that that every egg or sperm (as we will see in the next section, at the time knowledge about fertilization and the role of egg and sperm in development was quite rudimentary) contained a minute, fully-formed organism, sometimes referred to as a “homunculus” that simply grew into the more mature form during embryogenesis. Relying on a familiar process, growth, the theory of preformation explained what otherwise seemed incomprehensible: the formation of a complex organism out of unorganized matter (the alternative theory at the time was known as epigenesis). This theory led to two predictions. The first was that if we could
examine the egg (or sperm) microscopically we ought to be able to see the very tiny but fully-formed embryo inside. And in fact, some early microscopist claimed to have seen a tiny “homunculus” encased in the head of a sperm or within the egg. Many other observers failed to see a homunculus, but proponents of preformation claimed that the microscopes were not good enough to reveal the tiny individual. But as microscopes improved dramatically in the eighteenth century, it became clear that the predicted “homunculus” was simply not there. A second prediction was that in any series of generations of organisms, all the individuals back to the original progenitor, must have had every future offspring encased in their testes or ovaries. This prediction led to the absurd conclusion that the number of generations of every organism must be limited to however many preformed individuals were present in the original ancestor. Since both of these predictions turned out to be false, by the nineteenth century most naturalists had rejected the preformation theory. The alternative theory epigenesis, difficult as it was to imagine, seemed to offer a more fruitful path for research, and more predictive experiments in the long-run.

2.5 The “Dissection” of an Experiment

We turn now to an early example of a scientific investigation that demonstrates the logical nature of science in practice.

Today we know that a fluid called semen, produced by male animals, including humans, contains spermatozoa, or sperm. Sperm are living cells, possessing a headpiece and a tail and convey the inheritance factors (genes) of the male to the female ovum, or egg. In sexual reproduction, the sperm and egg unite in the process of fertilization, leading to the subsequent embryonic development of the resulting embryo.

This is what we know today. In the eighteenth century scientists were still uncertain as to just how the male semen managed to fertilize the egg. Two possibilities were recognized:

**Hypothesis I:** The semen of the male must make actual contact with the egg before fertilization and embryonic development could begin, or,

**Hypothesis II:** It is only necessary that a gas or vapor, arising from the semen by evaporation, make contact with the egg.

From their knowledge of the female reproductive system, as determined primarily through anatomical dissections, physicians could see that the semen must be deposited a considerable distance from the female ovaries where the eggs are produced. (Since the role played by the sperm cells was not understood, the fact that they were capable of swimming toward the egg was not taken into account.). Thus it seemed reasonable to hypothesize that only a vapor arising from the semen could possibly reach the egg and fertilize it.
In 1785, the Italian natural philosopher Lazaro Spallanzani (1729–1799) put the vapor hypothesis to an experimental test using the toad as his model organism. In the following presentation of this experiment, Spallanzani’s own words, which provide an excellent example of the underlying logical structure of good scientific procedure, are printed in regular type, while our editorial commentary, which clarifies and emphasizes important aspect of Spallanzani’s methodology is interspersed in italics.

Is fertilization affected by the spermatic vapor? It has been disputed for a long time and it is still being argued whether the visible and coarser parts of the semen serve in the fecundation [that is, here, in the early development] of man and animals, or whether a very subtle part, a vapor which emanates therefrom and which is called the aura spermatica, suffices for this function.

Here the problem is defined: Does the semen itself cause the egg to develop? Or, is it merely the vapor arising from the semen that does so?

It cannot be denied that doctors and physiologists defend this last view, and are persuaded in this more by an apparent necessity than by reason or experiments.

Here Spallanzani points out the lack of experimental evidence to support the vapor hypothesis

Despite these reasons, many other authors hold the contrary opinion and believe that fertilization is accomplished by means of the material part of the semen.

In the full text of his report he cites some of the anatomical observations noted in the introductory part of this section.

These reasons advanced for and against do not seem to me to resolve the question; for it has not been demonstrated that the spermatic vapor itself arrives at the ovaries, just as it is not clear whether the material part of the semen that arrives at the ovaries, and not the vaporous part of the semen, is responsible for fertilization.

He next states the alternative hypothesis: that the semen must actually make contact with the egg for fertilization to occur. Two alternative hypotheses can be tested. The statement “it has not been demonstrated that” again shows Spallanzani’s recognition of the lack of empirical evidence to support or refute either hypothesis.

Therefore, in order to decide the question, it is important to employ a convenient means to separate the vapor from the body of the semen and to do this in a way that the embryos are more or less enveloped by the vapor;

An experimental design is suggested. Some sort of apparatus must be constructed to properly test the two alternative hypotheses.

… for if they are born, [then] this would be evidence that the seminal vapor has been able to fertilize them; or [if] on the other hand, they might not be born, then it will be equally sure that the spermatic vapor alone is insufficient and the additional action of the material part of the semen is necessary [boldface ours, for emphasis].

Note the occurrence here of the if … then format, as Spallanzani identifies the deductive logic behind his experiment. He had shown earlier that the semen could be diluted several times, yet still remain capable of fertilization. In terms of what is known today, this is not surprising. However, Spallanzani interpreted these results
as support for the vapor hypothesis, since he considered vapor to be merely diluted semen. The next experiment, however, seems to have convinced him otherwise.

In order to bathe the tadpoles [eggs] thoroughly with this spermatric vapor, I put into a watch glass a little less than 11 grains of seminal liquid from several toads. Into a similar glass, but a little smaller, I placed 26 tadpoles [he means eggs as explained below] which, because of the viscosity of the jelly [a coating around the eggs] were tightly attached to the concave part of the glass. I placed the second glass on the first, and they remained united thus during five hours in my room where the temperature was 18 °C. The drop of seminal fluid was placed precisely under the eggs, which must have been completely bathed by the spermatric vapor that arose; the more so since the distance between the eggs and the liquid was not more than 1 ligne [2.25 mm]. I examined the eggs after five hours and found them covered with a humid mist, which wet the finger with which one touched them; this was however only [the] portion of the semen which had evaporated and diminished by a grain and a half. The eggs had therefore been bathed by a grain and a half of spermatric vapor; for it could not have escaped outside of the watch crystals since they fitted together very closely …. But in spite of this, the eggs, subsequently placed in water, perished.

Like many of his day, Spallanzani believed in the preformation theory, hence the only role of the sperm for him was to initiate growth of the miniature form, that is, in the case of the frog the tadpole stage. This is why he refers to the unfertilized egg as a “tadpole” in the passage above. Spallanzani goes on to describe his next experimental set-up as shown in Fig. 2.7. The fact that development did not occur when the sperm were placed in the dish below, but not in contact with the eggs, meant that the prediction necessarily following from the vapor hypothesis was false; hence the hypothesis itself must be false.

Although the experiment overthrows the spermatric vapor theory … it was nonetheless unique and I wished to repeat it.

Spallanzani recognizes the need for further experimental evidence demonstrating that the vapor hypothesis is, indeed, incorrect. His results in this second series of experiments were the same.

Having previously used spermatric vapor produced in closed vessels, I wished to see what would happen in open vessels in order to eliminate a doubt produced by the idea that the circulation of the air was necessary for fertilization …

![Fig. 2.7](image-url) Experimental set-up similar to the one used by Spallanzani to answer the question “Is fertilization effected by the spermatid fluid?” Vapor rising from the seminal fluid freely bathed egg, but no contact between the egg cell and fluid occurred. The egg did not become fertilized [from J.J. W. Baker and G.E. Allen, The Study of Biology (Addison-Wesley, 1st ed., 1967): p. 41]
He recognizes a variable factor is recognized that might influence the results; the experiment is modified to eliminate this variable i.e., If air plays a role in fertilization, then the eggs should develop if air is allowed to circulate, etc.

but fertilization did not succeed any better than in the preceding experiments. 
Again, negative results. The prediction is shown to be false.

The last experiment of this type was to collect several grains of spermatic vapor and to immerse a dozen eggs in it for several minutes; I touched another dozen eggs with the small remnant of semen which remained after evaporation, and which did not weigh more than half a grain; eleven of these tadpoles hatched successfully although none of the twelve that had been plunged into the spermatic vapor survived.

He performs yet another variation of the original experiment. This experiment yielded additional evidence against the vapor hypothesis: Even immersion in the condensed spermatic vapor did not result in fertilization! Certainly if the vapor hypothesis were valid, it would have predicted otherwise.

The conjunction of these facts evidently proves [supports the view] that fertilization in the terrestrial toad is not produced by the spermatic vapor but rather by the material part of the semen.

Expressed in deductive format, Spallanzani’s results show the vapor hypothesis to be false. Despite his use of the word “proves” these results do not mean that the alternative hypothesis is correct, but only provide support for it

As might be supposed, I did not do these experiments only on this toad, but I have repeated them in the manner described on the terrestrial toad with red eyes and dorsal tubercles, and also on the aquatic frog, and I have also had the same results.
I can even add that although I have only performed a few of these experiments on the tree frog, I have noticed that they agree very well with all the others.

Note also that Spallanzani is careful not to generalize beyond the species of animal used in his experiments.

Shall we, however, say that this is the universal process of nature for all animals and for man?

Spallanzani now wishes to extend his results to other organisms and so performs other experiments using different species. In other words, can the generalization be extended to other organisms not yet tested in these experiments?

The small number of facts which we have does not allow us, in good logic, to draw such a conclusion. One can at the most think that this is most probably so …

Spallanzani is properly cautious in considering an extension of his generalization about the necessity of contact with the semen (rather than its vapor) beyond the small group of species on which he actually carried out his experiments. He shows his awareness that while organisms of various types share many functional characteristics in common, they also show differences or variations that prevent the experimenter from automatically generalizing from one species to another.

… more especially as there is not a single fact to the contrary … and the question of the influence of the spermatic vapor in fertilization is at least definitely decided in the negative for several species of animals and with great probability for the others.
Spallanzani shows his awareness of the nature of scientific “proof” with this statement; no false predictions have been obtained in the experimental testing of this hypothesis (i.e., hypothesis I) but the conclusion can still only be expressed in terms of probability. *Note, too, Spallanzani’s awareness that his negative results give him clear disproof of the vapor hypothesis, yet provide only probable verification rather than absolute demonstration for this being the case with other species.*

Spallanzani later performed other experiments that further contradicted hypothesis II, the vapor hypothesis. For example, he discovered that if he filtered the semen through cotton, it lost much of its fertilization powers and that the finer the filter the more those powers were diminished. He also found that several pieces of blotting paper completely removed the semen’s ability to fertilize, but that the portion left on the paper, when put into water, did successfully fertilize eggs. Despite the obviousness (to us) of the role played by the sperm in fertilization—a role to which these experiments certainly point—Spallanzani had previously decided that semen without sperm was capable of fertilization and he was unable to shake this belief even in the light of his own experimental results. If nothing else, this demonstrates nicely that scientists are just as prone to overlook the obvious as anyone else and may often refuse to give up a preconceived notion despite clear evidence to the contrary. It was not until the nineteenth century that the distinct role of sperm in fertilization was first established.


2.6 The Logic of Science: Hypotheses as Explanations

Although generalizing hypotheses are important in science, hypotheses that actually *explain* a phenomenon are preferable. In case of the sour green apples, for example, a hypothesis might be developed to explain why they are sour. One such explanation might be that green apples contain high concentrations of a particular acid such as acetic or citric acid, components of many fruits. This explanation is readily testable by carrying out chemical analyses and comparing the amount of acid found in the sour green apples with the amount found in sweet apples. It is only those hypotheses that actually explain observed natural phenomena that may rise to the level of being considered theories.

**Teleological versus Causal Hypotheses**

Throughout the history of biology, there have been two types of explanatory hypotheses put forward. Teleological (Gr. *telos*, end or goal-oriented) hypotheses suggest that certain events or processes occur for some purpose or are directed toward some end. In contrast, causal hypotheses focus specifically on the direct factors that lead from event A to event B.
Consider the following example. In the 1970s, Harvard University biologist Ernst Mayr (1904–2005) observed that a warbler living all summer in a tree next to his house in New Hampshire began its southern migration on August 25. This single observation raised a question in his mind. Why did the warbler begin its migration on that date? A teleological answer to this question might be: “Because the warbler decided to move to a warmer climate where food was more abundant.” Teleological explanations imply conscious or at least some form of pre-determined, goal-oriented behavior. Although it may be appropriate to ask teleological questions concerning human activities, it is not meaningful to ask such questions about other organisms. To ask “For what purpose did the warbler begin to migrate?” implies that the warbler made the same kind of conscious, goal-oriented choice that a person might make in deciding to go shopping for a particular item of merchandise. There is no way to test teleological hypotheses scientifically; one obviously cannot ask a warbler to tell us its reasons for leaving New Hampshire in late August! This is why biologists seek non-teleological, or causal explanations, ones that focus on more specific, testable reasons for why a bird might begin its migration at a certain time of year. Mayr’s original question can be rephrased in a more precise manner: “What factor or factors caused the warbler to begin its migration on August 25?” It is possible to answer this question without making ungrounded assumptions concerning a conscious purpose on the part of the warbler in starting its migration.2

Before we try to answer Mayr’s question, we need further clarification. His original question was phrased in the singular: “What caused the warbler to begin its migration on August 25?” In science, such questions are more likely to be posed in a general form: “What causes warblers to begin their migration around August 25?” No two warblers are exactly the same; no two August 25ths have absolutely identical conditions. Although biologists investigating such problems may have to deal with individual cases, it is important to frame the question in as broad a manner as possible. In general, scientists are more interested in explaining the principles underlying collections of events than in accounting for individual events such as the behavior of a single warbler. The greater the number of warblers studied, the more likely will be the validity of any hypotheses generated concerning the migratory behavior of warblers in general.

Types of Causal Explanations
In response to the general question regarding the causes of warbler migration, at least three different kinds of causal explanations are possible (Fig. 2.8):

(1) **An Internal Hypothesis.** Warblers begin migrating towards the end of August because a physiological mechanism (for example, a hormonal change) is activated, leading to migratory flight behavior. This explanation focuses on a physiological mechanism within the organism that may trigger migratory behavior.

2There are certain processes in biology that are teleological in the sense that from the initial events the end-point is pre-determined. The most obvious example is embryonic development, in which from the moment the sperm fertilizes the egg the subsequent course of events (barring outside disturbance) leading eventually to the final goal, the formation of the adult organism.
(2) **An External Hypothesis.** One or more specific environmental factors, such as the short day-length associated with fall, or a decline in the insect population comprising the warbler’s food supply, may activate the physiological trigger for migration described in explanation 1. This hypothesis emphasizes external factors that may trigger the onset of migratory behavior.

(3) **A Historical Hypothesis.** Warblers begin moving south because, through the course of evolution, they have acquired a genetic constitution that programs them to respond to certain environmental changes associated with the end of summer. This historical hypothesis relates warbler migration to an adaptive response to environmental changes developed through evolutionary processes over long periods of time.

These three types of explanations are not mutually exclusive, and the most complete explanation may well involve aspects of all of them.
Mechanisms in Biology
Most scientists, biologists among them, are interested in explanatory hypotheses that suggest a mechanism for how a given process actually works—for example, the physiological process that starts the birds’ migration, or, the visual and physiological processes by which birds navigate in their migrations. Mechanisms in this sense have been described by philosophers of science Peter Machamer, Carl Craver and Lindley Darden as consisting of entities and activities that begin with some initial state and end with some outcome that is different from the initial state. For example, in bird migration the initial state might involve the birds’ physiological and ecological (environmental) conditions on August 25; the entities might include its sensory apparatus (visual or temperature receptors) and specific hormones or enzymes that trigger a flight response; the activities would involve the means by which the hormones or enzymes actually caused an increase in response of flight muscles; and the outcome would be the initiation of migration.

The level of detail involved in describing any mechanism is obviously a function of the techniques available at any point in time. If it could be determined that changes in day-length as perceived visually by birds triggers a hormonal change that leads to migratory flight, but it as not possible to figure out how the hormone actually interacts with the nerve and muscle apparatus that causes the bird to start flying, that would still count as a mechanism—as far as it goes. If more refined analytical techniques were available to determine how hormone molecules interact with nerve or muscle cells that would make the mechanism more complete. Biologists, like all scientists, are constantly refining or reformulating the mechanisms for processes they are investigating.

It is sometimes tempting to think that the only mechanisms of importance in biology are those that can be traced to the biochemical and molecular levels. While having knowledge at the molecular level is always desirable, meaningful mechanisms can be put forward at all levels of biological organization, from the molecular to the cellular, tissue, organ, organismic, population or ecosystem levels. Indeed mechanisms for higher-level processes, for example the pattern formation of migratory birds (the familiar V-shape of a flock of geese, for example), may be best understood at the level of the population (flock) and not at the molecular level (though there would certainly be molecular mechanisms involved). The level at which mechanisms are proposed and investigated are appropriate for the question being asked.

There are many cases in the history of biology, or science in general, in which a process can be described in considerable detail but for which no mechanism can be postulated at a given point in time. Ernst Mayr could determine with considerable reliability that his warblers in New Hampshire started their southward migration on August 25 due to the interaction of day-length, temperature, and declining food supply, and yet have no hypothesis as to the mechanism by which this occurs in the birds’ physiology. What happens within their bodies becomes a black box, that is, an unknown. A black box in science usually refers to a situation in which there is an input to a system leading to an outcome, but with as yet no understanding of how that outcome is generated. It relates cause (input) to effect (outcome), which is a
valuable starting point for scientific research. A black box does not invalidate the empirical observations relating the input to the output, but it remains a region of the unknown, and therefore an area for future investigation.

**Cause-and-Effect**

As the preceding discussion suggests, modern science is built on belief in **cause-and-effect**: for every observed effect, there is some cause or set of causes. Yet, causal hypotheses have distinct limitations. One lies in our ability to test them. For example, the hypothesis proposing that warbler migration is the result of a delicate change in hormones is a reasonable one, but if a technique for measuring small hormonal changes within the organism is not available, the hypothesis remains untestable and is therefore of limited value (as pointed out above it can, of course, emphasize the need to develop new chemical techniques to detect slight hormonal changes and thus prove valuable in that sense). Further, many cause-and-effect relationships may be more apparent than real. Suppose, for example, that a cold air mass from Canada arrived in New Hampshire on August 25 just when the day-length was appropriate to trigger the warbler’s migratory response. It might **appear**, therefore, that the primary cause for onset of migration was the drop in temperature, an example of a spurious cause. Such spurious relationships are common in nature, for many events occur simultaneously and thus may often **seem** to be causally related, when they are merely coincidences.

### 2.7 Bias in Science

Science is not an abstract process isolated within the ivory towers of colleges, universities or independent research institutions. Rather, science is always situated in a social context where economic, political and philosophical values influence everything from the precise nature of the research undertaken to the actual kinds of hypotheses considered acceptable. Like all people, scientists grow up within particular cultures and learn to accept certain values related their time and place in history. These values may often represent general biases that people in a given society may share. Individuals also have their own personal biases. For example, some biologists are biased against explanations that cannot be expressed in mathematical or molecular terms while others feel that such explanations lose sight of the fact that it is the whole organism that is the most significant unit of biological function. Religious and political biases may also play a role in influencing individual scientists. In the seventeenth and early eighteenth centuries, for example, religious convictions motivated many individuals to study natural history in order to reveal the wisdom of the Creator in generating so many intricate adaptations. Despite stereotypes to the contrary, individual scientists are no less prone to various kinds of biases than anyone else.
Two kinds of bias may appear in scientific work. One is conscious bias, a deliberate manipulation or alteration of data to support a preconceived idea. Conscious or intentional bias in science is, in reality, simple dishonesty. Although there are examples of such dishonesty, since science is based on repeatability, fraudulent work will eventually be uncovered by other investigators. So, while there are documented cases of such conscious dishonesty, they are relatively rare. Far more common, and important to understand, is unconscious bias, of which the individual may be totally unaware. Because science is a human activity, unconscious bias is almost inevitably present to some extent in all research. In order to present a more realistic view of the scientific process, it is important to examine the way in which biases of various kinds function in science.

First, let us clarify what we mean by “bias.” In the English language, the term has a negative connotation, implying an undesirable component of the thinking process. When we say that a scientist may be “biased” we can also be saying that he or she may have a particular point of view that influences the selection and formulation of their hypotheses. Sometimes these points of view act as blinders, preventing scientists from seeing the value of new ideas. At other times, however, points of view may also act as catalysts, providing new insights or ways of looking at a problem. To understand both the positive as well as the negative role that bias can play in science, we will examine briefly one example involving conscious bias and another involving unconscious bias.

**Conscious Bias.** The inheritance of acquired characteristics is the idea that traits acquired by an organism in its own lifetime (for example, a large body musculature acquired by exercise) may be passed on to its offspring. A concept prominent from antiquity, by the twentieth century belief in the inheritance of acquired characteristics had been rejected by virtually all biologists. A few researchers, however, persisted in trying to show that acquired characteristics could be inherited. One was the Austrian biologist Paul Kammerer (1880–1936). In the years immediately after World War I (1914–1918), Kammerer studied inheritance in the “midwife toad” *Alytes obstetricans*.

Most toads and frogs mate in the water. In order to grasp onto the female during mating, the males develop rough “nuptial pads” on their palms and fingers during the mating season, enabling them to hold onto the slippery female. However, since midwife toads mate on land and the female’s skin is rough and dry, there is no selective advantage in the males possessing nuptial pads, and they are absent in *Alytes*. Kammerer, who was very talented at raising and handling amphibians, was able to induce midwife toads to mate in water. After only a few generations, he claimed that the males showed nuptial pads and, far more significant, transmitted this trait to their male offspring.

Kammerer’s results received criticism from many quarters. For one thing, for all his skillful experimental abilities, Kammerer was not a good photographer and many of the published photos of his specimen were difficult to see or appeared to be retouched. For another, visitors to Kammerer’s lab in Vienna were never able to see live specimen with nuptial pads. The final blow to his hypothesis and to his reputation came when several biologists, including the American G. K. Nobel, finally
examined the one surviving preserved specimen and he observed that the so-called nuptial pad was a blotch on the skin induced by what appeared to be the injection of India ink under the surface.

There was some evidence suggesting that Kammerer himself did not fake the data but that the injections were made by one of his assistants. Even so, had he not been such a zealous advocate for the idea of inheritance of acquired characters, Kammerer might have examined his own results more carefully and avoided becoming publicly discredited by the episode. Whether this revelation of fraud was responsible for his suicide some months later has never been established (Kammerer was also involved at the time in an unhappy love affair that was about to end), but it seems likely that the accusation of fraud must have played some role.

**Unconscious Bias.** Unconscious bias is less straightforward than conscious bias and is far more common in scientific work. We will here discuss just one example.

In 17th century Italy it was a common observation that meat left out in the open would soon contain maggots, the larval stage of flies. The hypothesis put forward to explain this observation was that the maggots were spontaneously generated from the organic matter of the meat in contact with air. This hypothesis led to the prediction that any meat placed out in the open would soon show the presence of maggots, a prediction confirmed frequently by experience.

An alternative hypothesis, however, had also been proposed: the maggots develop from eggs laid by adult flies on the meat. This was not a trivial or purely academic issue, since the infestation of meat by maggots in open air markets in seventeenth-century Italy was a major economic and health problem. If maggots really came from flies, then a method of protecting meat immediately suggested itself. In light of this alternative explanation, the Italian naturalist Francesco Redi (1636–1697) realized that he could test the spontaneous generation hypothesis with a simple experiment:

**Hypothesis**  
If ... spontaneous generation is responsible for the appearance of maggots in meat exposed to air, and If ... meat is exposed to air in a jar covered by gauze to exclude adult flies,

**Prediction**  
then ... maggots should still develop in the meat

Redi set up the experiment a shown in Fig. 2.9. He used two jars, into each of which he placed the same amount and kind of meat of the same age obtained from the same butcher. One jar was left open (Fig. 2.9a) and the other was covered with gauze (Fig. 2.9b). The first jar served as the control jar, while the second served as an experimental jar. The experimental element in this experiment is that which has been modified (in this case covered with gauze) to test a particular hypothesis, while the control element remains unmodified and serves as a comparison. For example if it were very cold on the day of the experiment and there happened to be no flies around, then the control group should not develop maggots either. In setting up

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3Kammerer’s life and work has been treated a number of years ago sympathetically by writer Arthur Koestler in *The Case of the Midwife Toad*, and more recently, and critically by historian of science Sandor Gliboff.
controls for experiments, it is important that all factors except the one being tested are kept the same. Thus, Redi used the same kind of meat of the same age from the same butcher (note that if the meat already contained fly eggs when it was bought it would obviously invalidate the experimental results). The two jars would all have to be placed in the same part of the room, kept at the same temperature, etc. As the experiment was proceeding Redi observed flies hovering around the top of both jars. Because jar A was uncovered they could enter and come in contact with the meat, but because of the gauze, they could not get inside jar B. The meat in B eventually spoiled through bacterial decay, but no maggots appeared, while the meat in A developed maggots. In this way Redi was able to show that the spontaneous generation hypothesis led to a false prediction and could therefore be rejected.

Or could it? History shows the outcome was not so simple. Proponents of the spontaneous generation hypothesis had a comeback. They argued that the gauze changed the quality of the air getting to the meat, thereby preventing the normal process of maggot generation from occurring. It required further experiments and observations; for example, observing flies actually laying eggs on the meat and microscopic observation of eggs developing into maggots before this modified version of the hypothesis of spontaneous generation could also be rejected.
Despite Redi’s experiments, biologists in the 1860s were again debating the issue of spontaneous generation, this time in France. In this version, however, the debate occurred in a different context. Attention was now focused on the spontaneous generation of bacteria that routinely appeared in milk, beer and wine, causing them to sour. The germ theory of disease, championed by French microbiologist and chemist Louis Pasteur (1833–1895), and German microbiologist Robert Koch (1843–1910) was just gaining ground at this time. This theory proposed that the souring was caused by the presence of bacteria. An important component of Pasteur’s championing of the germ theory was his opposition to spontaneous generation of any sort: all bacteria he claimed, came from the reproduction of previously existing bacteria, and were not spontaneously generated from non-living organic matter.

An opposing hypothesis, invoking spontaneous generation, was put forth by another French biologist, Felix A. Pouchet (1800–1873). He argued that although bacteria were certainly able to reproduce themselves, they could also be formed spontaneously from the right combination of organic materials. Pouchet performed a simple set of experiments that appeared to support his spontaneous generation hypothesis. He found that, if a series of flasks of hay infusion were heated to about 100 °C for a few minutes so as to sterilize their contents, and then were sealed and left at room temperature, after a short time they were seen under the microscope to be teeming with bacteria. In response to Pouchet’s claims, and in defense of his own view, Pasteur countered that bacteria existed everywhere around us, on our hands, in our food, wine, beer and milk, and could be carried by the air from place to place. He argued that Pouchet had either not fully sterilized the original broth or had not plugged up the flasks quickly or carefully enough, thus allowing bacterial contamination of the liquid. This contention led Pouchet to repeat his own experiments several times, always with the same results.

The two scientists proceeded to exchange comments and letters in scientific publications. So intense was the debate that, in 1861, the French Academy of Sciences arranged a series of public presentations and a contest on the topic, with a cash prize to be awarded by a jury of scientists to the best presentation. Pasteur and Pouchet were the main contenders. For his part, Pasteur first demonstrated that boiling beef broth in a flask and then immediately sealing it by melting the glass at the top so that the contents were not allowed contact with air prevented the growth of bacteria and hence decay of the broth. (Bringing organic material close to the boiling point is the basis for “pasteurization,” now used routinely to prevent the souring of milk, wine, beer and other foods.). However, Pouchet countered with a perfectly reasonable argument: he pointed out that boiling might have changed the chemical composition of the organic material in the broth, as well as the air inside the flask, rendering both unsuitable for the spontaneous generation of microbes.

In response to this claim, Pasteur performed another simple but elegant experiment. He boiled beef broth in a specially designed long necked flask (Fig. 3.11a) that allowed air to diffuse back and forth between the broth and the outside. The lower portion of the neck of the flask served as a trap for the heavier dust particles and bacteria carried in the air. This apparatus, what became known as the
“swan-necked flasks”, Pasteur reasoned, would allow air to come in contact with the broth but no airborne bacteria would make it beyond the trap. If spontaneous generation could occur, then it ought to do so under these circumstances. The results of Pasteur’s experiment were quite dramatic. Even after several months, there was no decay in the flask. Moreover, he made another bold prediction: If bacteria were airborne and getting caught in the “trap,” and if he tilted the flask so that some of the broth got into the trap and was returned to the main receptacle (Fig. 2.11b), then the broth in the receptacle should show bacterial growth. When he carried out this experiment, as his hypothesis predicted, bacteria appeared in the broth in just a few days. To Pasteur, this was strong support for his hypothesis and a clear rejection of Pouchet’s. The French Academy of Sciences agreed and awarded the prize to Pasteur.

In the course of the debate, Pasteur *seems* to have shown by the sheer force of logic and ingenious experimental design that the theory of spontaneous generation of bacteria could be rejected and, indeed, this is the way the episode is presented in most biographical and textbook accounts. Pasteur himself promoted this interpretation and his work on spontaneous generation has often been used to illustrate the ideal of pure, unbiased science at work.

The story is not quite so simple as it might at first appear, however. Other factors also appear to have been at work in motivating the controversy, especially on Pasteur’s part. Through a detailed study of Pasteur’s published and unpublished writings, historians of science Gerald Geison (1943–2001) and John Farley have suggested that his position on spontaneous generation was very much influenced by his political and religious views. After the radical revolutions of 1848 that had spread throughout Europe, the period of the 1860s in France became one of growing political conservatism. Pasteur himself was especially conservative in his political and religious outlook. In the 1850s he had become an enthusiastic supporter of Emperor Napoleon III (nephew of the legendary Emperor Napoleon I) and the restoration of the French Empire, which stood for law and order, anti-radicalism, anti-socialism and for the suppression of ideas such as the separation of Church and State. Pasteur himself enjoyed the French government’s financial support and, on several occasions, was an invited guest of the Emperor at one of his country estates. Pasteur was also a member of the French Academy of Sciences, composed of the most pro-government, scientific elite of France. Pouchet was a Corresponding member of the Academy, working in the provincial town of Rouen and thus was not among the inner circle that dominated the Academy in Paris. Indeed, the Committee designated to judge the contest was so dominated by Pasteur’s elite supporters that at one point Pouchet withdrew his entry, feeling the cards were stacked against him. He was finally persuaded by friends to re-submit the reports of his experimental work, but with some misgivings.

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4 At one point, Pasteur even ran for the French Assembly (analogous to the United States Congress) as a member of the Conservative Party.
On the religious side, Pasteur was a devout Roman Catholic. As early as 1850, he had enthusiastically supported Emperor Napoleon III’s use of French troops to restore Pope Pius IX to the Papacy in Rome, from which the Pope had been driven by Italian insurgents. Pius IX was strongly interested in restoring the Church to its former place of political prominence in France. He became noted for his condemnation of all tendencies toward what he termed “religious tolerance” and “modernism” and for his convening the Vatican I Council meetings in Rome in the 1860s, at which he proclaimed the Dogma of Papal Infallibility (1870). By the early 1860s, both the Church and the French government had formed powerful allegiances to combat any tendencies, political, religious or intellectual that appeared to challenge orthodox views.

Geison and Farley suggest Pasteur viewed the idea of spontaneous generation as a serious challenge to the established religious views of “special creation” then officially supported by Church and State. Charles Darwin’s *Origin of Species* had been published in 1859, just two years before the Pasteur–Pouchet debates began, and the same year that Pouchet had published a major work advocating the possibility of spontaneous generation and presenting some of his experiments. Darwin’s book had raised the inevitable question of how the first forms of life had originated on earth and the theory of spontaneous generation of simple forms like bacteria seemed to provide an answer. A belief in the connection between Darwinism, philosophical materialism and atheism was further reinforced by the fact that the translator of Darwin’s book into French, Clemence Royer (1830–1902), was herself an avowed materialist who saw *The Origin* as promoting a thoroughly naturalistic account of the formation of species. Although he explicitly denied any connection, Pouchet’s ideas were viewed by many of his contemporaries, including Pasteur, as advancing the cause of materialism and therefore supporting attacks on the fundamental tenets of established religion.

In a lecture he gave in 1864 at the Sorbonne, perhaps the most famous of the French universities, Pasteur himself made clear his view of the relationship between the theory of spontaneous generation and liberal, “atheistic” ideas. The great question of the day, Pasteur began, was the permanence of species in contrast to the Darwinian idea of their slow transformation. “What a triumph it would be for materialism,” Pasteur told his audience, “if it [the theory of evolution by natural selection] could claim that it rests on the [scientifically] established fact of matter organizing itself, taking on a life of its own … To what good, then, would be the idea of a Creator, God?” Although he goes on to tell his audience that questions of science cannot be decided by religious doctrine, it seems quite likely that Pasteur’s own deep-rooted political and religious convictions played an important role in determining which side of the debate he supported. This interpretation is further strengthened by the fact that Pasteur did not bother to repeat Pouchet’s most controversial experiments, asserting without providing experimental evidence that the apparent spontaneous generation of bacteria Pouchet observed must have been due to contamination of the broth.
The Pasteur *versus* Pouchet case illustrates that bias may have both a positive and a negative influence on scientific work. On the positive side, Pasteur’s opposition to spontaneous generation led him to champion an opposing view, the germ theory of disease, which emphasized that disease may be transmitted by bacteria through personal contact between people or through the air. The germ theory was to have an enormously beneficial impact on medicine and public health in the ensuing decades. Yet Pouchet’s view also had its positive side. By promoting the idea that the origin of life could be studied by chemical and physical means, he pioneered a line of research that has become increasingly fruitful and important in biological research today. Conversely, Pasteur’s opposition to spontaneous generation prevented him from evaluating Pouchet’s own evidence more carefully and from seeing that the question of the origin of life could be approached from a purely chemical and physical point of view. Ironically, although he privately entertained the possibility of a chemical explanation for the origin of life, Pasteur did not pursue such possibilities extensively, nor did he repeat them publicly. At the same time, Pouchet’s advocacy of spontaneous generation led him to de-emphasize the importance of transmission of bacterial infection and thus the significance of the germ theory of disease.

Perhaps the greatest irony in this story is that both Pouchet and Pasteur were right. You may have noted in the description of their experiments that the two men were using different sources of organic matter: Pasteur’s was beef broth while Pouchet’s was a hay infusion, a liquid prepared by soaking hay in water. Because he did not repeat Pouchet’s experiments using the hay infusion, Pasteur did not discover that the natural bacteria found in hay include some species that can form spores, which enable them to survive severe conditions like drought, cold or heat. The spores present in Pouchet’s preparation were heat resistant enough to survive the short boiling time to which he subjected them, thereby being able emerge from their dormant stage and start reproducing once the flask cooled down. It was to be another several decades before the existence of heat-resistant spores was recognized by microbiologists.

### 2.8 The Concept of Paradigms

In June, 2000, the National Aeronautics and Space Administration (NASA) announced that new photographs, taken by an orbiting satellite, provided evidence that their might be sub-surface water on the planet Mars. This water is thought to occasionally break through the surface and erode the Martian surface, creating meandering, river-like channels revealed by satellite and other photographs.

Since the presence of water on Mars suggests strongly the possibility of past or present simple forms of life there, the NASA announcement received wide coverage in the popular press. However, as one astronomer noted, the discovery did not mark a major “paradigm shift” in his field. In essence, what the astronomer was conveying by this comment was that the announcement was “no big deal” and that,
while the new pictures may have provided greater detail than before, the presence of channels on Mars (some of which, like those identified in the early part of the twentieth century resembling dried up riverbeds) had been known for decades. Thus the NASA announcement was not that new to anyone familiar with the field of Martian geography.

The expression “paradigm shift” is one that has received increasingly wide use over the past few decades. In his 1962 book, *The Structure of Scientific Revolutions*, historian Thomas Kuhn (1922–1996) introduced the term “paradigm” (Gr., *paradigma*, pattern) to refer to a broad collection of ideas, assumptions and methodologies that guide research in any field of science. Kuhn recognized that, once established, paradigms often resist change, even in the light of considerable contradicting empirical evidence. When the evidence against an established paradigm reaches a certain level, a “scientific revolution” or what Kuhn called a paradigm shift occurs, and a new way of viewing the world, or a particular set of problems, emerges. Kuhn noted that there may be large scale paradigm shifts—for example from the geocentric to the heliocentric view of the universe—and more restricted paradigm shifts—for example, from viewing the blood as ebbing and flowing in the body (as viewed in ancient times) to seeing it as circulating in a one-way path from arteries to veins back to arteries through the heart (from the 17th century onward).

According to Kuhn, all paradigm shifts, large or small, share certain characteristics in common and reveal a number of important features about how science is practiced. Before listing some defining characteristics of paradigms and paradigm shifts, it will be useful to examine two historical examples.

**Darwin and the Theory of Evolution by Natural Selection**

One of the most profound shifts in our way of thinking about the living world came with the publication in 1859 of Charles Darwin’s *On the Origin of Species*, in which he put forward his theory of the transformation of animal and plant species over time by the mechanism of natural selection.

Since the earliest written records, human beings have wondered how the myriads of types of animals and plants found on earth—what we today refer to as biodiversity—could have arisen. In western culture from the ancient world through the nineteenth century, the traditional explanation for biodiversity has been the doctrine, (paradigm) of special creation. The various types of organisms, called *species* (borrowing Plato’s terminology for ideal, fixed categories), were thought to be each a separate entity, created by God in their present forms, stable and unchanging (immutable) over time. Although species were recognized as separate entities, it was also apparent that they could be grouped into similar types (e.g. as members of the dog family, or the cat family, oak trees, pine trees), which shared many characteristics in common. Such groupings were interpreted under this older paradigm as representing God’s plan for “Nature”. As well as being part of religious dogma, this older paradigm of biodiversity also formed the basis for the work of important naturalists such as Karl von Linné (Carolus Linnaeus, in the Latinized name under
which he wrote), whose widely used classification system grouped species by shared traits.

By 1800, however, the older paradigm (which we may call the Linnaean paradigm, since that is the explicit form in which most naturalists would have encountered it) was facing some unexplained observations. In his work on paradigms, Kuhn referred to such unexplained observations as anomalies. For one thing, geologists had unearthed multitudes of fossils. Some of these fossil forms were strikingly similar to forms still living today, while others (dinosaurs, feathered reptiles) were bizarre and had no living counterpart. Why should so many forms have perished? Why were large groups of organisms, like vertebrates, or flowering plants, all built on the same basic plan? Why were there certain patterns of the geographic distributions of organisms rather than a random distribution?

Between 1831 and 1836 Darwin traveled around the world as an unpaid naturalist on board a British exploratory vessel, the H.M.S. Beagle. He saw an enormous variety of life in an equally enormous range of habitats. From this experience and from copious reading, Darwin gradually came to accept the idea that species were not fixed and immutable, and that the species we see on earth today must have descended with modification from species that existed in the past. For example, species that share many characteristics in common, such as the orchids, must have all descended from a common ancestor. Darwin thus embraced the theory of transmutation of species (today known as evolution), which a few other naturalists had already put forth in one form or another, though not very successfully.

Darwin went on to propose a second theory, that of natural selection, as the mechanism for how evolution might occur. The theory of natural selection is based upon several observations: (1) More organisms are born than can survive, resulting in competition for scarce resources. (2) All organisms vary from one another; those organisms that have favorable variations will survive a little bit longer or be more vigorous, and as a result will be more fit for the environment in which they live. (3) The more offspring the individual leaves, the more fit that individual is said to be. (4) Many of these offspring will carry the favorable variations they inherited from their parents, and will in turn leave more offspring than other members of the population who lack this variation. In this way new and more favorable variations will spread gradually through the population, transforming its overall characteristics. (5) Since variations occur more or less randomly, if two portions of a single population are somehow isolated from each other for long periods of time, different variations will accumulate in each population, producing divergence in their characteristics. The result will be that eventually two species will have been derived from one common ancestral form, an evolutionary process known as speciation. Continuous speciation has led to the wide variety of organisms that have populated the earth in the past and today.

Darwin’s paradigm challenged every aspect of the older Linnaean paradigm. Species were no longer viewed as fixed and immutable, but plastic and ever-changing; they arose not by a supernatural act of creation but by natural processes going on every day. Species were not composed of a single “type” representative of the whole, but by populations that exhibited a range of variability
for every trait. Extinction was not a result of God’s displeasure with species, but of competition and the constant struggle for existence between various species for material resources. Most important, from the point of view of scientific methodology, Darwin’s paradigm was thoroughly naturalistic (materialistic in the philosophical sense, as described in the previous section), and did not invoke any supernatural or occult causes.

The shift from the Linnaean to the Darwinian paradigm was neither easy nor quick. Many older naturalists simply could not accept the notion of species changing from one form to another; the idea of the fixity of species was too ingrained in their world-view. Others gradually accepted evolution—descent with modification from common ancestors—but could not accept the mechanism of

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**Fig. 2.10** Drawings of Louis Pasteur’s swan-necked flasks used for his studies on spontaneous generation of microbes (1860–61) [original art from authors]
natural selection, especially the idea that variations occurred by chance rather than in response to the needs of the organism. Though we often speak of a Darwinian “Revolution,” it took until the mid-twentieth century for most of the initial objections to be resolved in favor of Darwin’s basic paradigm.

From the start, the Darwinian paradigm encountered enormous opposition from organized religion. As we have seen, even so eminent a scientist as Louis Pasteur found the Darwinian paradigm unacceptable on religious and philosophical grounds. Although many religions found ways to reconcile the Darwinian paradigm with broad theological doctrines, many, especially those that emphasize the literal interpretation of the Bible, continue to object to the evolutionary paradigm right down to the present day (see Chap. 5, Section on “Scientific Creation” and “Intelligent Design”). As Kuhn emphasized, paradigm shifts do not come easily.

A Paradigm Shift in Molecular Biology: From the “Central Dogma” to Reverse Transcription

In the 1960s the major paradigm of how deoxyribonucleic acid, or DNA, the molecule that made up the genes of most organisms on earth, controlled hereditary traits was referred to as the “Central Dogma” of molecular biology. It was called “dogma” (despite the negative connotation of this term in scientific circles) because it was supposed to be a universal paradigm. The “central dogma” stated that DNA exerts its effects by serving as the template for transcribing a second form of nucleic acid, ribonucleic acid (RNA) that in turn guides the assembly of a specific protein molecule. The central dogma is often represented as a simple flow diagram:

\[
\text{DNA} \xrightarrow{\text{Transcription}} \text{m-RNA} \xrightarrow{\text{Translation}} \text{Protein}
\]

The first step (first arrow), in which messenger-RNA (mRNA) is synthesized from DNA is known as transcription, while the second phase (second arrow), in which mRNA guides the production of a specific protein, is known as translation. As it was conceived in the early 1960s, both phases of the process were thought to be unidirectional. The central dogma became the paradigm for how genes function chemically in all organisms.

In 1958 a young graduate student named Howard Temin was working with Rous sarcoma virus (RSV), a virus found in chickens and the first cancer-causing virus to be described. Viruses are very simple structures consisting, in this case, of a protein coat surrounding a nucleic acid core (Fig. 2.11a). It was widely known that RSV belonged to a special group of viruses, the retroviruses, whose hereditary material was made up of RNA rather than DNA. All viruses replicate themselves by attaching to a cell surface, injecting their DNA or RNA into the host cell, where the viral nucleic acid proceeds by one mechanism or another, to commandeer the cell’s metabolic machinery to produce more viruses (Fig. 2.11b, c). One of the distinguishing features of RSV is that it does not usually kill the cell it invades but rather causes the cell to start dividing uncontrollably, thereby producing a sarcoma, or cancerous tumor. In 1964, while attempting to develop a chemical means of
identification (assay) for cells infected with RSV, Temin made several interesting observations: (1) Cells infected with RSV showed recognizable modifications, which were passed on to the progeny cells even when no further viral replication inside the cell was observed. (2) Substances (such as cytosine arabinoside), known to block DNA synthesis prevent viral infection if applied within 12 h of the first contact between virus and susceptible cells. (3) Substances (such as actinomycin D) that inhibit the synthesis of RNA from DNA (transcription) allow infection to occur

Fig. 2.11 Replication cycle of Rous Sarcome virus (RSV), showing the mode of infection of the host cell by the virus. RSV is an RNA virus, meaning its genetic material is RNA and DNA. By means of surface markers, the virus attached to the cell membrane and injects its RNA, along with a molecule of the enzyme reverse transcriptase, into the host cell. Reverse transcriptase, as Temin predicted, is able to catalyze the transcription of viral RNA into viral DNA, which is then integrated into the host cell genome as a “provirus.” When the host cell’s DNA is transcribed to make proteins, it also makes proviral proteins. Presence of these proteins stimulates uncontrolled cell division, producing a cancerous tumor. Moreover, the provirus replicates every time the cell divides, thus increasing dramatically the number of cells with provirus in them. Eventually, enough viral RNA and protein coat material is present and new viruses are assembled, breaking out of the cell and infecting other cells nearby. [original art from authors]
but block viral replication. These data suggested that RSV replication appeared to be a two-step process that somehow involved DNA replication, a rather surprising finding for an RNA-based virus.

To explain these results, Temin proposed what he called the **DNA provirus hypothesis**, which suggested that when RSV first enters a host cell it uses its own RNA as the basis for synthesizing DNA, DNA that now carries viral genetic information. Moreover, Temin argued, the new viral DNA becomes integrated into the DNA of the host cell (in which form it is known as a **provirus**), and is replicated with it every time the cell divides. The provirus DNA, when transcribed and translated into protein (by the central dogma pathway) leads to uncontrolled cell division, or cancer. What was so novel, and troubling, about Temin’s new paradigm was that it postulated a reversal of the central dogma: in particular situations, RNA could guide the production of DNA.

The first reaction to Temin’s paradigm was almost universal rejection. Not only did it go against the entrenched paradigm of the central dogma, but repeated attempts to detect the presence of proviral DNA in the host cell proved fruitless. Temin continued to search for ways to detect the presence of proviral DNA or other tell-tale signs of proviral activity. Then, quite independently, in 1970 Temin and another researcher, David Baltimore, discovered a new enzyme (enzymes are proteins that catalyze biochemical reactions in organisms) in RSV-infected cells. This new enzyme was called reverse transcriptase because it catalyzes the synthesis of DNA from an RNA precursor. Later, other varieties of reverse transcriptase were found as a normal component of animal cells not infected by RSV. These findings clinched the story and from the mid-1970s on, the provirus and reverse transcription paradigm has gained wide acceptance.

**Characteristics of Paradigms**

It may be useful to ask at this point why do we bother to talk about “paradigms” at all? Why not just refer to Darwin’s “theory” of evolution by natural selection, or Temin’s “theory” of reverse transcription? What has been gained by Kuhn’s new terminology and analysis of scientific change?

Paradigms are more comprehensive than theories. A paradigm is a collection of theories; but also has embedded in it a variety of assumptions, particular methodologies, and is shared by a particular community of investigators. As we have seen, the Darwinian paradigm encompasses not just the theory of evolution, but also the theory of natural selection, theories about the nature of heredity and variation, about adaptation of organisms to particular environments, and about speciation, among others. An advantage of seeing a paradigm as consisting of a variety of theories is that it helps us understand how scientific ideas gain acceptance (or rejection). For example, Darwin’s view that hereditary variations were always very small changes has been challenged by biologists at various points in the past (and even at present), although these critics do not oppose the concept of evolution or natural selection.

Paradigms embody certain methods that are agreed upon as appropriate by the community of investigators in the field. For example, molecular geneticists agreed that, if Temin’s paradigm were to be accepted, it was necessary to use biochemical
methods to identify an enzyme that would carry out reverse transcription. Agreement on the methods and instruments that are used in a field is one of the main components of a paradigm that knits its adherents together into a social as well as intellectual community. Agreement on methods is also crucial if workers are to evaluate each others’ data and discuss its interpretation meaningfully.

Particularly important, paradigms, more than theories in the traditional sense, represent world views, or global ways of seeing nature. A Darwinian paradigm of species transformation is a very different view of the natural world than the old Linnaean view of static, immutable species. The Darwinian world is ever-changing, dynamic, never at rest. Change is both expected and celebrated, for it is the means by which organisms survive and adapt to an ever-changing environment. Similarly, the Temin paradigm presents a view of the cell that is more flexible, with a repertory of processes that can meet a larger variety of physiological needs. By contrast, the paradigm represented by the central dogma presents a view of the cell that is more rigid and mechanical. More than just discovering the nature of reverse transcription, Temin’s paradigm suggests we should not so readily accept the idea that cells (or any biological system) have only one way of doing things. As one of the characters says in the movie Jurassic Park I, “Life will always find a way.”

Kuhn’s analysis is particularly helpful in understanding how scientific ideas change. Paradigm shifts are more difficult than merely substituting one theory for another, precisely because paradigm shifts involve a whole change in world view. In Darwin’s case that world view encompassed not only naturalists’ conceptions of species as fixed or immutable, but the religious doctrine of Special Creation and the role of God as Creator. It is no wonder that the reaction against the Darwinian paradigm was so violent, and has been so long-lasting. In a smaller way, the paradigm shift from central dogma to reverse transcription had its initially strong opponents, who ridiculed the idea that DNA could be made from an RNA precursor. The shift in world view to reverse transcription cast the fundamental relationship in molecular genetics between DNA (genes), RNA and proteins in a completely different light. Reorienting that relationship required a shift in world view, at least for those working in molecular genetics.

Indeed, in recent years, the idea that DNA can be made from RNA has had major implications for understanding the origin of life. This view suggests that the first living forms on Earth contained RNA as their basic genetic material, giving rise to what molecular biologist Walter Gilbert called the original “RNA World.” The concept of RNA as a primordial self-replicating, genetic molecule can be found in theoretical papers by Francis Crick (co-discoverer with James D. Watson of the structure of DNA), Leslie Orgel (1927–2007) Carl Woese (1928–2012) and others in the 1960s and 1970s. The fact the certain forms of RNA also have catalytic as well as self-replicating properties gave this hypothesis further credence. Scientists today hypothesize that DNA eventually became the molecule of heredity in most forms later, because of its overall greater chemical stability. The idea of reverse transcription thus allowed biologists working on the origin of life to formulate a much clearer picture of how earliest living forms could have evolved with a simpler form of hereditary molecule.
Old paradigms are replaced with new ones when “dead-ends” are reached; for example, when it is simply no longer intellectually satisfying to account for every aspect of species diversity or the fossil record by simply claiming that “God made it that way.” Old paradigms also tend to get overthrown when they act to restrict rather than expand the scope of the questions being asked. One of the positive outcomes of a paradigm shift is that new areas of research open up, new sets of questions are asked and research projects designed to answer them. Resistance to paradigm shifts emanating from within the scientific community merely suggests that scientists, like other specialists, may get so hung up on their own tiny set of problems that they can see the world from only one viewpoint and are blinded to alternatives. In many historical examples, paradigm shifts occur not simply because scientists become intellectually convinced that new evidence is so overwhelmingly in favor of the new paradigm, but because the older scientists retire or die and younger scientists, with fewer ties to the old paradigm, take their place.

Kuhn’s analysis has also provided a more realistic understanding of how science works. An older and more traditional view of science was that it changed by adding more and more information to its basic storehouse of facts and an increasing refinement of its conceptual foundations. In this view, science is cumulative, with each successive generation progressing toward a more accurate views of nature. Kuhn’s view suggests that while the measurements and data of science may in fact accumulate in some sort of linear way, conceptualizations of science can undergo radical change. Old paradigms are completely discarded and are replaced lock, stock and barrel by new paradigms. A Darwinian view of species is not just a modified Linnaean view—after Darwin, species, even old data about any given species, were seen in a different light. To Linnaean taxonomists, variations among members of a species were a nuisance that they had to look beyond to make a proper classification. To Darwinians, variation is the crucial feature by which species evolve to meet new challenges from their environment. Far from being a nuisance, variation is now seen as a creative force in the history of life.

2.9 Modern Science, Materialism and Idealism

Mechanism and Vitalism
Distinct differences between living and non-living matter are obvious. The ability to move, ingest materials from the environment and convert it into more living material in the process we call growth; indeed, all of those properties we associate with living organisms, are clearly qualitatively different from anything observed in non-living matter. In the late nineteenth and early twentieth century, recognition of this fact led to a resurgence of a much older philosophical debate among biologists. The debate was between those who called themselves mechanists and those who called themselves vitalists. Vitalists explained the unique features of living matter by postulating the existence of a “vital force” (élan vital). This vital force was
assumed to be wholly different from other known physical and chemical forces and ultimately to be unknowable, that is, not subject to physical and chemical analysis. The postulated vital force departs from a cell or an organism at death. It should be stressed that vitalists did not deny that chemical analyses of living organisms are valuable, but felt that what we call “life” involved something more than that which can be described by the principles of chemistry and physics.

A classic example of vitalist thinking appears in the memoirs of Assistant Surgeon Edward Curtis of the Washington, D. C. Army Medical Museum. On April 14, 1865, president Abraham Lincoln was shot in Ford’s Theater in Washington and died the next morning. An autopsy was performed in the Northeast Corner guest room of the White House. In the words of Dr. Curtis:

Silently, in one corner of the room, I prepared the brain for weighing. As I looked at the mass of soft gray and white substance that I was carefully washing, it was impossible to realize that it was that mere clay upon whose workings, but the day before, rested the hopes of the nation. I felt more profoundly impressed than ever with the mystery of that unknown something which may be named “vital spark” as well as anything else, whose absence or presence makes all the immeasurable difference between an inert mass of matter owing obedience to no laws but those governing the physical and chemical forces of the universe and, on the other hand, a living brain by whose silent, subtle machinery a world may be ruled.

This example illustrates clearly a vitalistic belief in some sort of supernatural factor differentiating living from non-living matter. In brief, the vitalist philosophy may be expressed as one that viewed the whole as being greater than the sum of its parts.

Mechanists, on the other hand, maintained that organisms were simply physical and chemical entities composed of material parts whose functions could be investigated and ultimately explained by the ordinary laws of physics and chemistry. In contrast to vitalists, mechanists viewed organisms as merely complicated machines. Basic to the mechanist view was the idea that organisms are composed of separate parts (molecules, cells, organs) and that we need to merely study these parts in isolation to explain the working of the whole. In stark contrast to vitalists, mechanists maintained that the whole is equal to the sum of its parts, no more, no less. Thus to learn about how the heart works, for example, a physiologist might remove the heart from an experimental animal, place it in a perfusion chamber where it could be exposed to fluids with different hormones or chemical transmitters, and the effect on the rate of the heartbeat measured. By such procedures, mechanists thought that all the characteristics of the heart or, indeed, any component of the organism, could be understood.

Experiments by two German biologists played a role in the late nineteenth and early twentieth century will serve to illustrate how the vitalist-mechanist controversy played out in an actual research context. A major question of interest among embryologists at the time was what caused cells of the early embryo to eventually differentiate into the many different cell types (nerve, muscle, skin) that make up the adult organism. Wilhelm Roux (1850–1924) hypothesized that the fertilized egg
was made up of particles that determined each cell type of the adult organism, and that as the cells divided during embryonic development these particles were parcelled out differentially to daughter cells, so that ultimately each cell type ended up only the particles for its own characteristics. This was known as Roux’s mosaic hypothesis and was obviously a very mechanical hypothesis to explain differentiation. However, it had the advantage of being testable. Roux worked with frog eggs, which he fertilized and allowed to undergo one cell division, creating a two-cell embryo (Fig. 2.10 left). According to the mosaic hypothesis the particles determining the right and left side of the organism should already be parcelled out into the two separate cells. He then killed one of the cells with a red hot needle, predicting that if his hypothesis were correct, the resulting embryo should only develop one half of its body. The result was the formation of an incomplete, “half” embryo (Fig. 2.10 right). Roux interpreted these results to support the mosaic hypothesis, and the view that differentiation was indeed the result of a physical, mechanical process.

Hans Driesch (1865–1941), a younger contemporary of Roux’s, performed a similar experiment, but because he was working at a marine laboratory (the Naples Zoological Station), he used fertilized sea urchin eggs instead of frogs. However, after the egg divided into the two-cell stage, instead of killing one of the first two cells, Driesch separated them from one another by shaking the solution vigorously. The result was that both cells formed complete sea urchin larvae (Fig. 2.11). For Driesch, these results indicated that embryos were not merely some sort of mechanical entities but were harmonious systems that had the power of self-regulation and adjustment to altered circumstances. After a decade of using a variety of physical and chemical methods to investigate this problem, Driesch became a champion of vitalism, eventually giving up science completely and becoming a professor of philosophy. To him, the ability of the separated blastomeres to adjust to the new conditions imposed on them yet still undergo normal development, argued strongly in favor of the presence of some inherent, non-physical/chemical force that guided development. He was opposed vigorously in this view by Roux, who became one of the major exponents of the mechanistic view, developing a comprehensive research program known as “Developmental Mechanics.” The written arguments between the two scientists became long and often highly polemical. Despite the controversy the two men remained cordial friends until Roux’s death in 1924. However, the controversy their work engendered continued well into the first half of the twentieth century (Figs. 2.12 and 2.13).

The mechanist-vitalist debate was part of a much larger philosophical dispute that has recurred in one form or another from the ancient Greeks to the present day between two broad, but mutually exclusive philosophical systems: idealism and materialism. These philosophical terms should be distinguished from their more familiar counterparts, in which “idealism” refers to an unrealistic and naïve view of the world and “materialism” to an undue concern with material possessions and wealth. Philosophical idealism and materialism have quite different meanings. Philosophical idealism derives much of its modern content from the writings of
Wilhelm Roux’s experiment, in which he pricked one of the first two blastomeres of the frog egg with a hot needle, killing it. The result was development of a half-embryo that only reached partial development. These results supported Roux’s mechanistic interpretation of development: each blastomere was already determined at the first cell division to produce half the embryo [from Viktor Hamburger, The Heritage of Experimental Embryology (N.Y., Oxford University Press, 1988): p. 10]

Hans Driesch’s experiment, separating the first two blastomeres (top) of the sea urchin egg. To the left a normal sea urchin larva developed from unseparated blastomeres, and to the right two slightly smaller but otherwise perfectly formed larvae developing from each separated blastomere. These results contradicted Roux’s interpretation by showing that embryos have remarkable abilities to adjust to changed circumstances and are thus not mechanically determined in the way Roux had imagined [from Viktor Hamburger, The Heritage of Experimental Embryology (N.Y., Oxford University Press, 1988): p. 10]
Plato and the Platonic tradition in western philosophy. The basic claims are that ideas or non-material causes are the initial and prime movers in the world. Plato saw all material objects, for example, as crude reflections of the ideal object existing as a category, in the mind of the Creator. The Linnaean species concept described earlier is an example of idealist thinking in that each species existed in the mind of the Creator prior to its taking material form on Earth, e.g., all cats reflect the ideal or essential category of “catness.” There are real cats in the world, of course, but the category of “catness” existed prior to and apart from the appearance of actual cats on the earth’s surface and represents the idealized form underlying the group as a whole. Aspects of most contemporary religions are based on idealistic philosophy: for example, in the belief in a supernatural creator, in the power of prayer, or in miracles (see Chap. 5). Though they may not necessarily express their idealistic views in religious terms, vitalists are clearly idealists in this sense. Idealists do not deny the existence of material reality; they simply relegate it to a secondary role as a causal agent behind many biological processes.

By contrast, philosophical materialism is the view that all processes in the universe are the result of matter in motion. Matter is primary; everything else, including abstract ideas about matter and how it functions, are derived from that material reality through our interaction with it. Species, for example, do not exist as an abstract or idealized category apart from the material populations of organisms that form them in nature; we may, of course, create species categories, but they derive from observing actual organisms in nature, not from any a priori existence in themselves. Evolution does not occur because of God’s plan or abstract “drives toward perfection” but because organisms are competing with one another for scarce material resources and their physical variations give them different survival and reproductive potentials. Materialists maintain that nothing is unknowable, though, of course, at any one point in time vast amounts remain unknown. For materialists, the methods of physics and chemistry are the proper tools for understanding the natural world. Modern science since the seventeenth century has rested firmly and increasingly on a materialist foundation.

In the vitalist-mechanist debates, vitalists were clearly arguing from an idealist position and mechanists from a materialist position. Although both sides made important points, the debate ultimately became counterproductive. Mechanists saw clearly that since, by definition, vital forces were beyond the reach of scientific study, vitalism put limits on scientific research. They therefore rejected it. By the mid-twentieth century, however, many biologists came to the realization that the mechanistic view was too simplistic to account for many functions known to occur in living organisms: the self-replication of molecules, the self-regulation of physiological processes, embryonic development, and a host of other activities that had no counterpart in known machines of the day.

Is there an alternative to the mechanistic materialist approach other than vitalism? Biologists, and philosophers often inspired by biological examples, have developed a second form of materialism, holistic or dialectical materialism, which avoids the pitfalls of both idealism and of mechanism. The basic tenets of the holistic-dialectical approach are:
1. No part of any system exists in isolation. For example, one of the functions of the liver is to remove sugar from the blood and convert it to animal starch (glycogen) for storage. The liver is changed by removing sugar from the blood and the chemical conversion to starch, as is the blood by virtue of having sugar removed from it. Thus while both blood and liver may be described partially in isolation, neither can be understood fully except in their interactions with each other and other parts of the body.

2. Unlike machines, living systems are dynamic entities, constantly in a process of flux and change. This change results from the constant interaction of internal and external forces.

3. The internal processes of any living system undergo change as a result of the interaction of opposing forces. For example, all living organisms carry out both anabolic (build-up) and catabolic (breakdown) chemical reactions. The growth and development of a seed represents a change in which the overall effect of anabolic reactions is greater than that of catabolic reactions. Maturity occurs when the two are balanced and aging and death result from the dominance of catabolic over anabolic processes. Far from being accidental, this developmental process is programmed into the genetic makeup of the organism. At all stages, the overall process may be studied most fruitfully by investigating the interaction of anabolic and catabolic process, rather that either process alone. This is the part of the approach that is dialectical, meaning two opposing tendencies or processes.

4. The accumulation of many small quantitative changes may eventually lead to a large scale, qualitative change. For example, the heating of water from 90 to 91 °C represents a quantitative change since, although it is one degree warmer, the water is still a liquid. However, when the temperature goes from 99 to 100 °C, the water begins to boil and become the gas we call steam. This represents a qualitative change, since water and steam have quite different physical properties. Thus an accumulation of many quantitative changes has resulted in an overall qualitative change. This is as true of the biological as of the physical world. For example, if a nerve attached to a muscle is stimulated with a low voltage electric shock, the muscle may not respond. With an increase in voltage, a quantitative change, a qualitative change is eventually achieved in the nerve, an impulse is transmitted, and the muscle contracts.

If organisms are viewed as just described by these four tenets, the vitalists were correct: the whole is greater than the sum of its parts. Organisms do function as wholes, not as a mosaic of separate parts. In many respects, however, the mechanism-vitalism dichotomy is artificial. Vitalism and the idealistic philosophy it represents is limited because it presupposes a mystical, unknowable force in living organisms that, by definition, lies beyond scientific investigation. Mechanistic materialism, on the other hand, in trying to ground biological investigations in knowable but separate physical entities, has found it impossible to account for the holistic properties of complex systems like living organisms. Biologists are today developing new ways to understand the many interactions inherent in complex
systems like organisms, including the mathematical theory of systems analysis combined with the power of modern computers. These new approaches do not preclude the mechanistic, analytical approach to studying individual components of organisms in isolation; in most cases this is the only way to begin to understand the parts that make up any complex system. But we now know this is not enough—it is only the first step. Biologists are increasingly adopting a more holistic, yet still materialist approach that transcends the old mechanist—vitalist debates.

2.10 Conclusion: The Strengths and Limitations of Science

Since its origins in the 17th century, modern western science has proven to be by far the most powerful way of understanding the natural world. As we have seen, one of the greatest strengths of science lies in its emphasis on logical thinking and on formulating testable hypotheses in ways that lead to accurate or refutable predictions. A second strength, growing out of the first, is the insistence that hypotheses and the predictions that follow from them must be testable. A third strength of science is its emphasis on repeatability. A single empirical test, even one repeated by the same experimenter many times, is seldom enough to convince most scientists; the results must be capable of being replicated under the same conditions by others. Thus a fourth strength of science lies in its critical, self-correcting nature. By checking their own results as well as those of others, any errors are far more likely to be uncovered.

Still, as powerful as it may be as an intellectual tool, science also has distinct limitations. For one, science is limited to dealing with observable phenomena; the empirical data on which hypotheses must ultimately be based. Without empirical data, even the most intriguing hypothesis has little value. Thus, science has absolutely nothing to say one way or the other about the existence of a God or gods, a human soul or vital forces; empirical data on such entities are simply not obtainable. Similarly, science is also limited by the availability of the tools and techniques by which scientific data are gathered. Prior to the development of the microscope, for example, we knew nothing of the sub-microscopic world; prior to the telescope, we could only speculate about the universe beyond what our eyes could directly see.

Through the self-critical process that characterizes their activity, scientists are forced to constantly modify and many times reject cherished hypotheses. This is not because scientists are necessarily more honest and conscientious than persons in other fields, but rather that honesty is reinforced in science by virtue of its system of peer review; all scientists are well aware that others in their field are monitoring their research to make certain that its results can be replicated. No scientific idea is likely to remain unchallenged or unchanged; indeed, scientists are probably as more often wrong than right. The 19th century physiologist Johannes Müller asserted that the velocity of a nerve impulse would never be measured; six years later, his student Hermann von Helmholtz measured it in a frog nerve only a few centimeters long.
The chemist Ernest Rutherford stated that the energy in the atomic nucleus would never be tapped; the first atomic bomb exploded just seven years after his death.

Clearly if scientists can be wrong, as we have seen, so can scientific hypotheses. Yet, although it may appear to be a limitation of science that it cannot “prove” anything and that its hypotheses and theories are always open to rejection or modification, in fact, this limitation is actually its greatest strength. As biologist Garrett Hardin (1915–2003) has put it:

It is a paradox of human existence that intellectual approaches claiming the greatest certainty have produced fewer practical benefits and less secure understanding than has science, which freely admits the inescapable uncertainty of its conclusions.

Hardin is correct: the strength of science does not lie in any claim to infallibility but rather in being an ongoing intellectual process with no pretense of providing final answers or absolute truths. Nor does this strength lie solely in its logical underpinnings, for the conclusion of a perfectly logical argument may well be utter nonsense. The inherent self-criticism of science and its constant search for a better understanding of the natural world through the elimination of false hypotheses, is the source of its immense intellectual power.

2.11 Exercises

1. Distinguish between observation, fact, hypothesis and conceptualization in science.
2. Each statement below (a–e) can be described as either
   - An observation
   - A fact
   - A conceptualization

   Indicate which of the three above possibilities best characterizes each of the following statements:

   (a) All 100 observers agreed that the sun rises in the east every day.
   (b) This green apple is sour.
   (c) Planets move from west to east against the background of fixed stars because they are revolving around the sun just like the earth.
   (d) The United States fought in Vietnam to preserve democracy from communist aggression.
   (e) All green apples are sour.
   (f) The report said the witness was lying.
Explain your choices in each case.

3. Devise hypotheses to account for the following observations, and design an experiment or suggest further observations to test your hypotheses.

(a) There are more automobile accidents at dusk than at any other time of day.
(b) When glass tumblers are washed in hot soapsuds and then immediately transferred face downwards onto a cool, flat surface, bubbles at first appear on the outside of the rim, expanding outwards. In a few seconds they reverse, go under the rim, and expand inside the glass tumbler.
(c) In mice of strain A, cancer develops in every animal living over 18 months. Mice of strain B do not develop cancer. If the young of each strain are transferred to mothers of the other strain immediately after birth, cancer does not develop in the switched strain A animals, but it does develop in the switched strain B animals living over 18 months.

4. A biologist reported the following set of observations:

“While sitting on my porch during the afternoon and early evening, I could not help but notice the chirping of the crickets. I noticed that the rate of their chirping slowly diminished as the sun approached the horizon. I wondered why this should be so. At first I guessed that it was due to the loss of light as the sun disappeared and night came on. Accordingly, I counted the number of chirps given by ten individual crickets in the laboratory as they were exposed to less and less light intensity.” The following data were obtained:

<table>
<thead>
<tr>
<th>Candlepower</th>
<th>Chirps per minute</th>
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<tbody>
<tr>
<td>10</td>
<td>48</td>
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<tr>
<td>8</td>
<td>46</td>
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<td>6</td>
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<td>0</td>
<td>48</td>
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(a) Formulate the hypothesis being tested in a deductive syllogism (If … then format).
(b) Do the results confirm or reject the second hypothesis? Explain your answer.

“I then wondered if temperature might be affecting the number of chirps. I reasoned that as the sun set, the temperature would drop as night approached. Accordingly, in the laboratory I kept the crickets exposed to constant light, but exposed them to varying temperatures.” The following data were obtained:
At 34 °C  55 chirps per minute  
At 30 °C  48 chirps per minute  
At 26 °C  39 chirps per minute  
At 22 °C  20 chirps per minute  
At 18 °C  8 chirps per minute  
At 14 °C  no chirping

(c) In this second experiment what hypothesis is being proposed, and what prediction(s) is (are) made from it?  
(d) Do the results confirm or reject the second hypothesis? Explain your answer.

5. Indicate for each of the following deductive syllogisms whether they are examples of valid or invalid reasoning, and whether each represents  
A true conclusion deriving from a true hypothesis(es)  
A true conclusion deriving from a false hypothesis (es)  
A false conclusion deriving from a false hypothesis (es)  
A false conclusion deriving from a true hypothesis (es)  

(a) If … All residents of the USA are Martians and  
   if … all Martians pay taxes,  
   then … all residents of the USA pay taxes.  
(b) If … All dogs have four legs and  
    if … this animal is dog  
    then … this animal has four legs.  
(c) If … All residents of the USA are Martians  
    if … all Martians are green and have tentacles  
    then … all residents of the USA are green and have tentacles.  
(d) If … All dogs are four-legged animals  
    If … this animal is four-legged  
    then … this animal is a dog.  
(e) If … All Martians are residents of the USA and  
    If … all humans are residents of the USA,  
    then … all Martians are humans.

6. Think of something in your personal life that might represent a paradigm shift—for example, switching from a typewriter to a computer, learning a new language, or recognizing that a personal relationship is not going to work out.  Describe some of the changing feelings, realizations and behaviors you encounter during this shift.

7. P.F. and M.S. Klopfer of Duke University have studied maternal behavior in goats. The following facts have been established: A mother goat (doe) will reject her young (kid) if deprived of it immediately after birth, even if it is given back an hour later. If allowed contact with her own kid for five minutes after birth and
then separated from it, the doe immediately accepts the kid and its littermates, if any, when returned an hour later. If allowed contact with her kid immediately after birth and then deprived of it, the doe shows obvious signs of distress. However, if this early contact is denied, the doe acts as if she had never mated or given birth to young.

(a) Propose a hypothesis to account for these observations, along with an experiment to test your hypothesis. Do not read the remainder of the exercise until you have finished this part.

Now consider the following additional facts about maternal behavior in goats established by the Klopfers: under the conditions described above, the doe will not accept a kid of the correct age that is not her own (an alien kid) if it, instead of her own kid, is returned to her. Denied her own kid immediately after birth, but allowed five minutes with an alien kid, the doe will not only accept the alien kid but also her own when returned. However, only the alien kid with which she is allowed contact will be accepted; all other alien kids are rejected.

(b) How do these facts affect your hypothesis? (Do not change your hypothesis as given in the previous question, even if it did not fare too well, only consistency with the facts given and experimental design are of primary importance.)

(c) If necessary, propose a new hypothesis to account for all the Klopfers’ data as given above and suggest an experiment to test this hypothesis. If your original hypothesis stands, fine. If needs modifying, do so.

Further Reading

Conant, J. B. (Ed.) (1957). *Harvard case histories in experimental science* (Vol. 2). Cambridge, MA: Harvard University Press. (The Harvard Cast Histories have been extremely useful in teaching the nature of science by selecting a series of controversies in the physical and life sciences. The cases include explanatory material setting the context (mostly intellectual rather than social or political) in which the controversy took place with extended excerpts from the writings of the scientists involved. This approach provides students with the chance to learn how to read and analyze material from primary sources as well as understand the scientific issues of earlier times in their own terms. Cases range from the verthrow of the phlogiston theory by Lavoisier’s oxygen theory, to the nature of plant photosynthesis in the work of Joseph Priestly and others in the late eighteenth and early nineteenth centuries, and Pasteur’s and John Tyndall’s work on spontaneous generation in the 1860s and 1870s.).

Farley, J. (1977). The spontaneous generation controversy from Descartes to Oparin. Baltimore, MD: Johns Hopkins University Press. (This book is a very readable introduction to the history of ideas of spontaneous generation from the seventeenth to the twentieth centuries. It includes discussions of Spallanzani, Redi and Pasteur-Pouchet.).

Grinnell, F. (1987). The scientific attitude. Boulder, CO: Westview Press. (Written by a practicing scientist for undergraduates and graduate students in science, this book is a simple, straightforward introduction to many aspects of science as a process. Topics include problems of observation, experimental design and interpretation, science as a collective activity and “thought-style,” how scientific ideas are perpetuated and become entrenched.).

Kuhn, T. S. (2012) The structure of scientific revolutions (4th ed.). Chicago, IL: University of Chicago Press. (This edition contains revisions and was published on the 50th anniversary of the original appearance of the book in 1962. Kuhn’s work has had a powerful effect on scientists, historians and philosophers of science alike, as well as in realms of social science and literary studies. In this book, Kuhn lays out his concepts of paradigm, normal science, puzzle-solving, anomalies and describes the development of science as a series of paradigm replacements, (shifts) or what he calls “scientific revolutions.”).

Longino, H. E. (1990). Science as social knowledge: Values and objectivity in scientific inquiry. Princeton, NJ: Princeton University Press. (A clear introduction to problems of science as a social process, the author steers a solid course between the stereotype of science as objective truth and the view that it is nothing but subjective social construction. Longino deals with such issues as sex bias in research, the nature of evidence, values in science and science as social knowledge.).


Numbers, R. L., & Kostas Kampourakis (Eds) (2015). Newton’s apple and other myths about science. Cambridge, MA: Harvard University Press. (Contains a number of case studies of how science has been traditionally mythologized, and thus presented in an unrealistic way. Among other myths covered is a more detailed version of the Pasteur-Pouchet controversy.).

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