Foundations of Biology

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Front cover
American egret, Gainsville, Florida.
Photograph by Samuel Scheiner

Chapter 2
Science

Ways of Knowing

One of the most important aspects of the human mind is its ability to organize and process information about the world around us. It is this ability that has allowed humanity to grow into what we are today, and it is what will determine what becomes of us in the future. Science is a way of organizing and processing infrmation – understanding the world – that systematically combines logical thinking with observations of the world. It provides explanations for how the universe works and where it came from. The methodologies of science – the procedures scientists use for coming up with those explanations – have developed over thousands of years, with a particularly swift advance in the past 400. Science as we know it today is a child of the Enlightenment, the movement in western Europe that claimed that rational thought could provide guidance in humanity's endeavors to understand and manipulate the world around us. In this chapter we will explore what science is and how it operates, both as a rational enterprise and as a social enterprise; that is, how it helps individuals understand the information they acquire, and how scientists themselves interact with each other (Table 2.1).

At is most basic level, science is built on a tripod of pattern, process, and theory. Patterns consist of the relationships between the phenomena or entities of the natural world, processes are the causes of those patterns, and theories are the explanations of those causes. Theories – what ultimately allows us to understand the world – are built with logic and tested against those patterns and processes. The work of a scientist is to document patterns, investigate and understand processes, and ultimately to put together theories that explain what they have found out. Although a single scientific study may be focused on only one of those three aspects, science seeks to understand all the parts of a system and how that system functions as a whole. This is particularly true of the science of biology; life is amazingly complex with properties that are more than the sum of the constituent parts, so biologists are always faced with this duality of taking things apart and then putting them back together.

Alternatives to science

The easiest way to understand the nature of science is to contrast it with other ways of knowing and understanding the world. Mathematics, for example, is a way of knowing separate from science. Science tells us about the empirical world, while mathematics tells us how logical symbols can be manipulated to provide knowledge of patterns of time, space, and numbers. Science can not apply value judgments. Although science can tell us about the physics of light and color and about how our eyes interact with our brain to affect our perception, it cannot create standards to judge whether one painting is better than another – for that we need aesthetics. Aesthetics is a separate way of knowing about the world with a goal of reflecting on art, culture, and nature so as to render judgments on sentiments or taste. Science tells us that we are capable of eating both animals and plants, but cannot tell us whether we should live as strict vegetarians. To answer questions of proper behavior, we turn to ethics; ethics is a separate way of knowing about the world with a goal of helping us decide how we should live our lives. What science can do is provide information about the consequences of those decisions, for example, how to achieve a healthy diet as a vegetarian and the alternative effects on the environment of eating or not eating meat.

Table 2.1. The structure of science

A. Premises
   1. One’s senses provide reliable information about an external reality.
   2. All scientific explanations must rely on phenomena that are the result of natural processes.

B. Methodologies
   1. Science provides explanations through theories and models.
   2. Scientific theories should be consistent with each other.
   3. Theories are built on observations.
   4. Theories are tested by building models that generate hypotheses.
   5. Hypotheses are falsified through experiments.
   6. Experiments can be of various types: manipulative, natural, or observational.
   7. Theories are revised based on experiments and additional observations.

C. Science as a human endeavor
   1. Research is affected by its social environment.
   2. Science is self-correcting.
   3. Peer review provides feedback between a scientist and the rest of the scientific community.
   4. Science proceeds according to ethical rules and norms.

The most contentious border between these different ways of knowing lies between science and religion. To understand how they differ, consider the bases of each: science as a way of knowing rests on two basic premises. The first is a statement about the world, while the second is a statement about the domain of science.

The premise about the world is science’s single, fundamental assumption, that one’s senses provide reliable information about an external reality. The alternative is that one is a disembodied intelligence and that the universe is all an illusion or a dream. It is impossible to prove that the world is not an illusion, since the only evidence one has is the evidence of one’s senses. This assumption is the nearest thing that science has to an article of faith or belief. Although specific theories rely on a host of assumptions, all of those assumptions share a common property: they are potentially refutable by observations. It is only the assumption that those observations are actually real that cannot itself be tested.

The premise about the domain of science is that all scientific explanations must rely on phenomena that are the result of natural processes, the “naturalism” premise. Science does not deny the existence of supernatural phenomena, this premise simply states that any such phenomena lie outside the realm of science. The reason for this premise is that explanations that rely on natural processes can be refuted by observations of the natural world, while supernatural processes are inherently beyond the world and thus cannot be so refuted. Thus, the naturalism premise is not a claim about the world, but a statement about the boundaries of science.

Some assert that science is just another form of religion, but that assertion is based on a misunderstanding of the two basic premises. Religion also has two basic premises that are mirror images of those of science. First, religion makes a basic claim about the world, that supernatural phenomena exist. Second, religion relies on faith, in addition to observation, to understand those supernatural phenomena. Notice that science makes no claim about the existence of supernatural phenomena, just a statement about the admissibility of those phenomena as scientific explanations. In contrast, religion makes no claims about the reliability of one's senses, instead indicating that knowledge can come to one from something beyond the senses.

Interestingly, science and religion are each based on two premises – claims about the world and what counts as evidence – that are complementary. Science is not a form of religion; rather, both are differing systems for trying to understand the world. The two systems clash only when each tries to make assertions about the premises of the other: when scientists claim that supernatural phenomena do not exist and when proponents of religion claim that data about the world can come from sources other than one's senses. While either assertion is consistent within the worldview of science or religion, respectively, neither are consistent with the other's worldview. Science can no more refute religion than religion can make claims about scientific theories. Because of this, sometimes conflicts occur between religion and science, especially when religion tries to make claims that affect the realm of science (see Chapter 4).

Biology's special assumptions

The science of biology has two assumptions that are unique to itself. First, related to the naturalism assumption, biologists reject vitalism, the notion that living systems are imbued with some sort of nonmaterial life force. The discoveries of the chemical bases of life in the past few centuries, along with our understanding of the properties of living systems, has led to the understanding that life is something that can emerge from nonlife through purely material processes without the necessity of invoking any nonmaterial force (see Chapter 1).

Second, life as a whole is not goal directed, although individuals can certainly show goal directed behaviors. When you are hungry, you eat in order to stop that hunger. But wolves did not evolve sharper teeth because they wanted to be better hunters and acquire food more easily. A cell does not produce more of a particular protein because it wants to perform a specific chemical reaction. These are both examples of feedbacks that are simply part of living systems. We would no more say that a boulder wanted to roll down a hillside after the ground underneath it eroded away. Goal directedness is called teleology, and in biology it is very easy to fall into teleological explanations because the many feedback systems appear to be goal directed. Biologists are often guilty of using teleological sounding explanations because it is a convenient shorthand. However, you should always be suspicious of any such explanation and should always remind yourself that there is always a nonteleological, albeit more complicated, explanation.

How We Know

The philosophy of science

One of the concerns of the discipline of philosophy is trying to understand how it is that we know things. The study of how we know is called **epistemology**. In this book we are concerned with just one branch of epistemology, the philosophy of science. The philosophy of science has a very long and complex history (Box 2A) and, like all of philosophy, contains many different schools of thought, some with very subtle distinctions. For our purposes, we will collapse that complexity into three broad classes: empiricism, social constructivism, and realism. Understanding these three main approaches tells us how science lets us know about the world.

Empiricism approaches the world with the goal of producing theories that can make useful predictions through logical deduction from basic assumptions combined with data gathered from previous experiments. For example, we can use Newton's laws of motion to tell us how to aim a spaceship so that it will travel from the Earth to the Moon. Fundamental to this approach is the notion that even when a theory makes correct predictions, we have no reason to believe that the theory tells us anything about how the world really works. Although we can use Newton's laws to guide our spaceship because the theory works under some circumstances, physicists have replaced Newton's theories with those of Einstein. At some time in the future, Einstein's theories may, in turn, be discarded.

Like empiricism, **social constructivism** also posits that we have no reason to believe that theories tell us how the world really works. Theories are seen as consensus agreements by communities of scientists; they are consistent with the data because the community of scientists concur on which data are relevant to those theories. When data disagrees with a theory, the theory is tweaked while retaining its core structure. Only when disagreements between data and theory become overwhelming is a theory replaced, again through a social consensus. Social constructivism differs from empiricism with regard to which aspects of the scientific process are the primary drivers: logic and data (empiricism) or social conventions (constructivism).

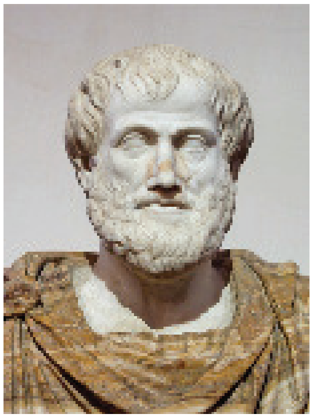
In contrast, **realism** posits that theories do tell us about how the world works. Theories make accurate predictions because they capture some true aspect of the world. Scientists do not merely discard one set of theories for another, but as theories are refined or replaced, we get closer and closer to the underlying truth. Going from a theory that the Sun goes around the Earth in a perfect circle to one in which the Earth goes around the Sun in a perfect circle moves us closer to reality. Later, that theory was refined from movement in a circle to movement in an ellipse and combined with Newton's laws of motion to make predictions about the movement of all of the planets. Later, it was discovered that those laws could not account for the motion of the planet Mercury around the Sun. That discrepancy was one of the factors that resulted in the replacement of Newton's laws by Einstein's theory of relativity which could account for movement close to a large gravitational object. In contrast to both empiricism and social constructivism, realism posits that as scientific theories get refined they get closer to the truth and thus are less likely to be overturned.

The science of biology has had similar changes in its basic theories, although most of them have not been nearly as dramatic as those in the field of physics. The major foundations of biology were built in the 19th century with the establishment of the chemical and cellular bases of life (see Chapter 5), the theory of evolution (see Chapter 4), and the roots of genetics (see Chapter 3). Studies of the functioning of organisms go back farther (see Chapter 6), while the discipline of ecology emerged from natural history near the end of the 19th century (see Chapter 7). The 20th century can be seen as a period of refining those broad theories, including some notable debates and the refuting of some widely held theories. By the 1960s, the broad outlines of the theories presented in the rest of this book were in place (see Tables 1.2, 3.1, 4.1, 5.1, 6.1, 7.1). While we are still refining the details, most biologists from that decade would not quarrel with most of those fundamental concepts.

Since the science of biology has not seen the sorts of major upheavals that have roiled the history of other disciplines, biologists now believe that a realist position is warranted. As we keep refining our theories and making better predictions we are able to produce better crops, cure more diseases, and predict the effects of overfishing on population sizes in the ocean. One reason for this realist confidence is that biology very often deals with things that we can directly see and feel. Biologists, using that assumption of the reliability of our senses, can directly observe the agreement between theory and the world.

Most philosophers of science can be classified as either empiricists or social constructivists, while the vast majority of scientists are realist, perhaps because scientists are the ones who are constantly confronted with observations. Given this difference in outlook, many scientists question the value of the philosophy of science. However, the philosophy of science is valuable because it provides scientists with tools for gaining a deeper understanding of themselves and their chosen vocation, in particular a basis for the building and testing of scientific theories, which we explore next.

Box 2A
Aristotle



Copy of Lysippus, Ludovisi Collection, National Museum of Rome (Source: Wikipedia)

No discussion of the history and foundations of Western thought is complete without Aristotle. One of the founders of Western philosophy itself, he was the first to fully create a comprehensive system of thought systematically encompassing everything from morality, politics, and aesthetics to scientific inquiry, mathematics, and metaphysics. His views on physical science stood as unquestioned fact well into the Renaissance and formed the basis for Medieval Scholasticism. His writings had a profound influence on the philosophical and theological system of all three major monotheistic religions. His system of formal logic, the first of its kind to be created, is still used today. This influence exists despite the fact that most of his writings have been lost; it is thought that only one-third of his works are still extant.

Aristotle was born in Strageira, Chalcidice in 384 BCE, the son of Nicomachus, who was the personal physician to King Amyntas of Macedon, and as a result received the training and education appropriate to the aristocracy. Around the age of 18 he traveled to Athens to attend Plato's Academy and stayed there about 20 years until Plato's death in 347 BCE. Afterwards, he traveled with Xenocrates to the court of Hermias of Atarneus in Asia Minor, then with Theophrastus to the Isle of Lesbos, where they engaged in a major botanical and zoological survey of the local plant and wildlife.

He recorded his observations and dissections in three major works, History of Animals, Generation of Animals, and Parts of Animals. He recorded incredibly detailed observations on the marine life around Lesbos, making entries on catfish, electric fish, angler fish, octopus, cuttlefish, and the paper nautilus. He created an early form of systematics for the animals he documented, separating aquatic mammals from fish and naming sharks and rays as a group called Selache, or selachians.

Figure 2A.1
Detail from Raphael's The School of Athens showing Plato and Aristotle arguing over the source of knowledge. (Vatican)

After Hermias' death, he was invited by Philip of Macedon to be the tutor of his son Alexander. After his tutoring post he returned to Athens where he established his own school, called the Lyceum, in 335 BCE. This was his most prolific era in his writings, producing many dialogues, few of which survive today. Most of his extant writings are in treatise form, and were probably intended as lecture aids for his students. Aristotle's writings were separated into two categories, esoteric and exoteric; his treatises, which were meant for his students and other philosophers, were the former, while his dialogues, meant for the general public, were the latter. However, what history would come to regard as his most important works, his writings on Physics, Metaphysics, Nicomachean Ethics, Politics, De Anima (On the Soul), and Poetics, would fall into his category of esoterics.

Aristotle's style of philosophy differed from his teacher's in some striking ways. Plato studied the "forms" of things as a universal truth existing in a spaceseparate from the physical world, then moved into the realm of the physical particulars (considering them pale imitations of their pure forms). In contrast, Aristotle's natural philosophy looked for the higher "essence" in the physical phenomena he studied, aiming to uncover the universal truth via the things themselves. Aristotle referred to the entirely of human inquiry as "science," dividing disciplines into "practical science," which would encompass disciplines such as politics and ethics, "poetical science," encompassing poetry and the fine arts, and "theoretical science," which would be most of what we call science today, as well as mathematics and metaphysics.

His investigations blazed new ground in nearly every discipline known at the time, although it was qualitative rather than quantitative. He lacked concepts like mass, velocity, force, and temperature, and was severely limited by the simple technological lack of instruments like clocks and thermometers. Perhaps because of this (and a lack of human dissection), his scientific laws are a mix of ideas centuries ahead of his time and complete errors. He claimed, for example, that heavier objects fall faster than lighter ones (which Galileo would famously disprove) but refuted Democritus' claim that the Milky Way was brighter because the stars there were shielded from the sun's light by the earth, citing the relative size and distance of the sun to the earth and the rest of the stars to assert that the sun's light would strike all stars equally.

The Aristotelian universe was geocentric, and based on far too little empirical observation when it came to astronomy and physics. However, he performed an immense amount of firsthand research in the life sciences, from his cataloguing of the life of Lesbos, describing ruminants' (e.g., cows) four-chambered forestomachs and making an extensive study of embryonic chick development, breaking open fertilized chicken eggs at intervals during incubation to track the generation of visible organ systems. He classified organisms in a hierarchical Ladder of Life, placing them according to their complexity of structure and function. His systematic classifications would encompass vertebrates (as animals "with blood") and invertebrates (animals "without blood"), further divided into live-bearing (mammals) and egg-bearing (birds and fish), and insects, crustaceans (with non-shelled and shelled cephalopods) and testacea (mollusks), respectively. With his studies of biology, he introduced the idea that nature is composed of things that change, and by studying the changes, one can discover the underlying constants. Despite his focus on observations of the natural world, the concept of the experiment, the manipulation of nature to reveal causal relationships, never occurred to him. Aristotle's scientific systems would stand unchallenged for centuries, forming the basis of Western knowledge and thought through the Renaissance, until Sir Francis Bacon (Box 2C) initiated the creation of the modern scientific method.

Unfortunately for Aristotle, after Alexander the Great's death in 323 BCE, anti-Macedonian sentiment bloomed in Athens, and Eurymedon the hierophant denounced Aristotle for not honoring the gods. Unwilling to be executed as Socrates had been, he fled to his mother's family estate in Chalcis, dying of natural causes within the year.

Theories and models

Science provides explanations about the world through theories and models. The word “theory” has a very different meaning in science than it does in common usage: a scientific theory is a broad, comprehensive explanation of a large body of information that, over time, must be supported and ultimately confirmed (or rejected) by the accumulation of a wide range of different kinds of evidence (Box 2B).

In popular usage, the word theory usually refers to a limited, specific conjecture or supposition, or even a guess or hunch. Equating the meaning of a scientific theory with a guess has caused no end of mischief in the popular press and in public debates on politically charged issues. A well-known example is the theory of evolution. While sometimes portrayed as “just a theory” by creationists and advocates of intelligent design, it is actually a comprehensive explanation of a large number of observed patterns in nature – in fact, it is one of the best-tested theories in biology (see Chapter 4).

When a theory is buttressed over many years with strong evidence, with new findings consistently supporting and amplifying the theory while producing no serious contradictory evidence, it becomes an accepted framework or pattern of scientific thought. This is what has occurred with Newton’s theory of gravity, Darwin’s theory of evolution, and Einstein’s theory of relativity. Scientists use such overarching theories to organize their thinking and derive additional predictions about nature.

Theories are intertwined, just as all life on Earth is interconnected. The five theories of biology presented in chapters 3-7 are not independent of each other; rather, each of them relies on aspects of all of the others so that causes in one show up as consequences in all of the others. For example, the process of evolution (see Chapter 4), influences the properties of the genetic system (see Chapter 3), cells (see Chapter 5), organisms (see Chapter 6), and ecological systems (see Chapter 7). Conversely, genetics, organismal structure, and ecological interactions all influence the process of evolution. This interdependence of scientific theories requires that they be consistent with each other, which is termed **consilience**. Consilience extends beyond biology, so that biology must be consistent with other areas of science such as chemistry, physics, geology, and astronomy. For example, understanding the origin of life (see Chapter 1) draws on aspects of all of those disciplines.

Theories are, in turn, used to generate and organize models. A **model** is an abstraction or simplification that expresses structures or relationships. Models are one of the ways in which the human mind attempts to understand complex structures and relationships, whether in science or in everyday life. Building a model airplane from a kit can tell you a lot about the basic form of an airplane; civil engineers often build small models of structures such as bridges or buildings (either physical models or three-dimensional images on a computer) before construction is begun.

Models can be abstract or tangible, made of words or plastic (e.g., Watson and Crick’s ball and wire model of a DNA molecule; see Box 3A), diagrams on paper, sets of equations, or a complex computer program. In science, models are used to define patterns, summarize processes, and generate hypotheses. One of the most valuable uses of models is to make predictions. All models are necessarily based on simplifications and rest on a set of assumptions. Those (implicit and explicit) simplifications and assumptions are critical to recognize because they can alert you to the limitations of the model, and because faulty assumptions and unjustified simplifications can sink even the most widely accepted or elegant model.

Box 2B
The Nature of Theory

Theories provide generalizations of data and concepts, playing many roles and coming in many different forms depending on their use and on the breadth of the phenomena they attempt to explain.. This book deals with foundational, general theories consisting of a framework of broad principles (see Tables 1.1, 3.1, 4.1, 5.1, 6.1 and 7.1). Conversely,a theory can also be a highly specific model that makes precise predictions about a particular circumstance. Between these two ends of the continuum are theories that generalize beyond a single model, but have a somewhat limited scope. A good example of this intermediate form is the theory of evolution by natural selection (see Box 4C). While theories are purely intellectual constructs, models are where the theoretical rubber meets the empirical road. Models generate hypotheses that are then tested with experiments (Figure 2.1). The results of those tests along with additional observations are then used to further refine theories and generate new models and hypotheses. Each theory defines a domain, the scope of the theory. For example, the domain of the theory of genetics (see Chapter 3) is the form and process of information storage, transmittal, and usage. Theories may have overlapping domains, and such intersections between theoretical domains are where some of the most exciting science can take place. Often, these places are where new and seemingly disparate elements are being brought together. Currently there is great interest in joining our understanding of how an individual changes during its life time (development; see Chapter 6) with how change occurs over generations (evolution; see Chapter 4). It is important to remember that theories and their domains are not real properties of the natural world, but human constructs, how we put structure on the world so that we can understand it.

At the heart of a theory is a set of broad statements (fundamental principles) about empirical patterns and the processes responsible for them. Fundamental principles are meant to be broad in scope, often encompassing multiple, interrelated patterns and mechanisms. They define the guiding questions of a domain. For example, the central question for evolution is why organisms change over generations in the way that they do (see Chapter 4). For genetics it is why offspring resemble their parents (see Chapter 3), and for organismal biology it is how organisms maintain themselves (see Chapter 6). The principles of the general theories of these disciplines are the statements necessary to answer those questions. Of course, those theories are not the entire story; for that, we have to examine all the details of the more specific theories and models within each general theory, a level of detail beyond the scope of this book.

Scientists are often looking for laws, statements of relationship or causation. Laws describe how particular processes result in specific outcomes or patterns. For example, Mendel's Laws of Genetics (see Chapter 3), describe the pattern of offspring appearances, given the appearances of their parents. In biology, laws reside within specific theories but not at a more general level, because within biology there is no law that holds true across the entire domain of a given general theory.

Another role for theories is to provide a framework for guiding and evaluating research. They tell scientists where to look and how to do the looking. For example, theories about how organisms are distributed across the globe (see Chapter 7) tell us that we are likely to find many new types of organisms in forests near Earth's equator. Scientists would then use other theories about how organisms are related to each other (see Chapter 4) to recognize a new type of organism. By providing guidance, theories help scientists be much more efficient in their search for knowledge.

Testing theories

The testing of scientific theories, especially biological ones, is a more subtle, nuanced, and complicated endeavor than nonscientists often realize. The popular image of the scientific method portrays it as a process of testing and falsifying hypotheses. This approach was codified by the German philosopher of science Karl Popper and is a form of empiricism. In this framework, we are taught that we can never prove a scientific hypothesis or theory. Rather, we propose a hypothesis and test it; the outcome of the test either falsifies or fails to falsify the hypothesis. While hypothesis testing and falsification is an important part of theory testing, it is not the whole story, for two reasons.

First, the falsification approach fails to recognize knowledge accumulation. In a strict Popperian framework, all theories are held to be potentially false. We never prove anything to be true; we merely disprove ideas that are false. This assumption goes against our own experience and the history of the accumulation of scientific understanding. Today we know that the Earth revolves around the sun, even though this was once just a hypothesis. We know that the universe is approximately 14 billion years old and began with the Big Bang, even if we still do not know the details of that event. We know that life began and assumed its present shape through the process of evolution. We know that many diseases are caused by microbial infections, not by the imbalance of “humours,” and that hereditary traits are conveyed by DNA (or in a few viruses, by RNA), not by blood itself. While we may acknowledge that all of this knowledge has not, in a strictly philosophical sense, been proven true, but has only failed thus far to be falsified, we also recognize that some knowledge is so firmly established and bolstered by so many facts that the chance that we are wrong is so small as to be nearly nonexistent. In contrast to empiricism, realism recognizes this progressive accumulation of knowledge.

Second, and more important, the Popperian framework fails to account for a second type of question that we very commonly ask in biology. Often the issue is not one of falsifying a hypothesis, but of the relative importance of different processes. When we examine the structure of a community (see Chapter 7), we do not ask, “Is it true or false that competition is occurring?” Instead, we ask, “How much, and in what ways, do the processes of competition and predation each contribute to shaping this community?” When we are building our theories about community structure, our activities are more akin to estimating the necessary quantities and assembling a complex model than to falsifying a set of propositions.

Falsification does play a role in science, but a more limited one than Popper envisaged. Theory construction is like assembling a jigsaw puzzle from a pile of pieces from more than one box – we can ask whether a particular piece belongs in this spot by erecting a hypothesis and falsifying it. We may even conclude that this particular piece does not belong in this puzzle. Occasionally we are attempting to completely throw the piece away, saying that it does not belong to any puzzle.

Science and other ways of knowing, revisited

Science demands internal and external consistency: ultimately, theories must be consistent with one another, and data must be consistent with theories. Other ways of interpreting the world do not share this characteristic; systems of morality or religion may or may not include obvious contradictions, but none demand consistency with data, in any sense of the term. Making science internally and externally consistent is a constant effort. Theories–even successful ones–contradict one another in places. Some experimental results seem to contradict theory at times, and even well-designed studies can contradict one another because chance events result in different outcomes.

The fact that we find contradictions simply means that we are still learning, and it is often through discovering inconsistencies that scientists are able to expand our body of knowledge about the world. One reason for inconsistencies, and one that requires closer examination, is multicausality.

Multicausality

Living systems have a critical property that affects the structure and evaluation of biological theories: **multicausality**. We distinguish two types of multicausality: first are instances in which a single outcome can arise as a consequence of a number of different components, even though they are all isolated from each other. This aspect of multicausality is important for the structure of many models. If a model includes all of the multiple causes, it will provide accurate predictions or explanations.

If a model does not include all causes, the utility of the model depends on how those causes interact. For example, weight gain and loss is caused by both the amount of food eaten—energy taken in—and the amount of exercise an individual performs—energy expended. A model that attempted to predict weight loss based just on the amount of food eaten would accurately predict that people eating less food would lose more weight. However, it would fail to predict the actual amount of weight loss without accounting for the amount of exercise. This shows that the excluded factors in a model may affect absolute predictions of a model, but not relative ones. This aspect of multicausality is important for the evaluation of models and theories. The fact that diet and exercise are not the only factors that affect weight loss, for example the different rates at which people absorb the energy from food, just makes the job that much more difficult. In practice, biologists must often use multiple lines of evidence to discern the relative role of different biological processes in producing patterns.

The second type of multicausality are instances in which multiple causes act together to create an outcome. For some types of interactions, conclusions about the relative magnitudes of the processes included in the model are still accurate. For example, exercise might also affect the amount of food that someone ate. If exercising caused all people to eat less, a model might still accurately predict that more exercise led to lower weight, even if the exact amount of weight loss was not accurately predicted. But what if the effect of exercise on the amount of food eaten depended on the mass of the person, so that a thin person ate more food while a fat person ate less? In that case, a model of the effects of exercise on weight loss would also need to account for the weight of the person to predict weight gain or loss. At minimum, it is necessary to acknowledge that any particular model may not include all possible important causes and that those other causes might have unexpected effects.

Another aspect of multicausality is that some effects come about through the short-term circumstances of an individual, and others through long-term effects such as an organism’s evolutionary history. Consider the question: Why are male lions larger than female lions? A short-term explanation involves an individual’s development and food intake during growth, while a more long-term explanation involves how male lions compete with each other for mates, thus affecting how many offspring a larger lion produces. Beyond that may be effects that are common to all types of cats or carnivores. These alternative explanations often derive from different domains, so theories need to either draw on those multiple domains or to acknowledge the limitations of their explanatory scope.

Explaining the characteristics of life

The characteristics of living systems can be studied from four perspectives: functional, developmental, historical, and adaptational. These perspectives are alternative explanations for why those characteristics exist in the form that they do; these perspectives are often intertwined in biological studies, and it is necessary to take all of them into account in understanding living systems.

The functional perspective asks what the constraints or limitations are on how a living system can be put together and operates. For example, if you compare the legs of a deer and an elephant, the latter has much thicker legs. Those legs are not just thicker, though, they are also proportionally thicker. If you simply expanded a deer to the size of an elephant its legs would snap under the much greater weight. A functional perspective is especially important for molecular, cellular, and organismal biology (see Chapters 5 and 6).

The developmental perspective asks how the process of building an organism constrains or limits its form. For example, some types of ants can develop an amazing array of forms among genetically identical individuals (see Figure 6.ANT), while most other types of insect have only a single form. Ants are able to produce such diverse forms because of key differences in their growth processes. A developmental perspective is central to much of organismal biology (see Chapter 6).

Delving further into the past is the historical perspective, which asks how the past history of a system determines and constrains its current and future characteristics. For example, ants have six legs while elephants have four because, by chance, the ancestors of each had six and four legs, respectively. There is no necessary reason why ants could not function with four legs or with eight. A historical perspective is particularly important for studies in evolution and ecology (see Chapters 4 and 7) and understanding organismal function (see Box 6D).

Lastly, the adaptational perspective asks how the ways in which a living system interacts with its environment mold its characteristics over many generations. For example, although an elephant has difficulty standing on just its hind legs, its trunk allows it to reach parts of trees it could not otherwise. The length and flexibility of its trunk came about because of the ways in which those properties of the trunk affected feeding and other activities which, in turn, enhanced the survival and reproduction of the elephant's ancestors. The adaptational perspective is explored in detail in Chapter 4.

Methodologies

Scientists gain knowledge by using the **scientific method**. They carry out a particular series of steps designed to structure their questions in as controlled and well-designed a method as possible, although not always in a fixed order (Figure 2.1). These steps can be summarized as follows: observation, description, quantification, posing hypotheses, testing those hypotheses using experiments (in a broad sense of the word, as discussed below), and verification, rejection, or revision of the hypotheses, followed by retesting of the new or modified hypotheses.

Throughout this process, scientists gather various kinds of information, look for patterns or regularities in their data, and propose processes that might be responsible for those patterns. They often put together some sort of model to help in advancing their understanding. Eventually, they construct theories, using assumptions, data, models, and the results of many tests of hypotheses, among other things. The building of comprehensive scientific theories proceeds simultaneously from multiple directions by numerous people, sometimes working together and sometimes at cross-purposes. Science in operation can be a messy and chaotic process, but out of this chaos comes our understanding of nature.

A scientific hypothesis is a possible explanation for a particular observation or set of observations. A **hypothesis** is smaller in scope than a fully developed theory, and must be testable: they must contain a prediction or statement that can be verified or rejected using scientific evidence. Experiments are the heart of science, and we discuss their design and use in more detail in the next section. A crucial characteristic of science

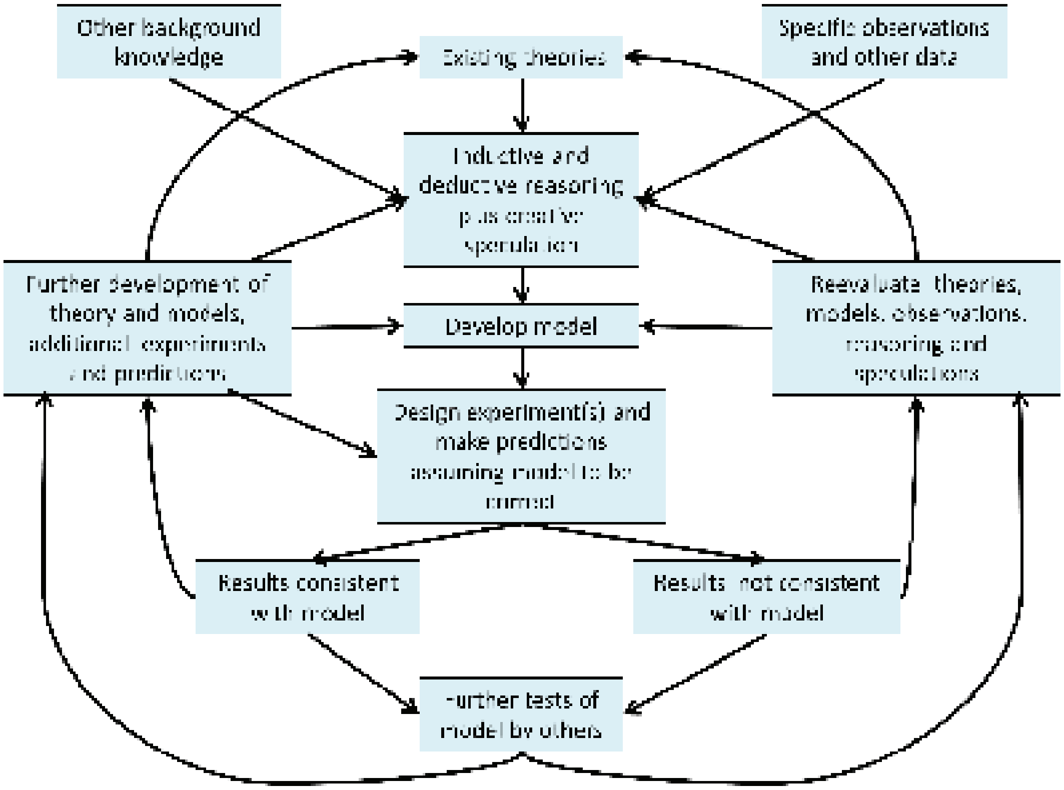


Figure 2.1
The scientific method. The cycle of speculation, model building, and experimentation is a spiral with our overall understanding of the world increasing, as new questions constantly emerge from the answers scientists obtain.

is the need to revise or reject a hypothesis if the evidence does not support it. Science does not accept hypotheses on faith and scientists must at all times retain a healthy skepticism. A scientist needs to remain open to the possibility that any hypothesis, model or theory may be wrong or incomplete, but recognizes that some models and theories are so well established and so well buttressed by evidence that it would be unreasonable to act as if they might be wrong.

Box 2C
Francis Bacon

Portrait of Francis Bacon by Frans Pourbus the younger, Royal Baths Museum (Source: Wikipedia)

Most people know Sir Francis Bacon as a scholar, the man whose writing formed the basis of what we know today as the scientific method. Along with a student of everything from biology and systematics to philosophy and metaphysics and a prolific writer, he was also a lifelong courtier and politician, constantly striving to raise his position in English society. His twin lives were interconnected as he sought royal patronage for his works while standing as a political adviser and minister for Elizabeth I and James I.

His political ambitions began with his father, Sir Nicholas Bacon, who was a lawyer (in a time when that profession was closely connected with Parliament and the peerage), a statesman, a privy councilor and Lord Keeper of the Great Seal, England's highest judicial position, for Elizabeth I for over 20 years. Francis was a younger son by his second wife. He entered Cambridge University when he was 12 and studied there for two and a half years before beginning his study of law. His father arranged a posting to France, which was cut short when his father died in 1579. Bacon was consequently forced to return to England.

Left out of his father's will (apparently by accident), Bacon had to work for his living, returning to his study of law, and beginning his work in 1582. His ambition, however, was to obtain a position in service to the crown, which was partially fulfilled in 1581. He was elected to the House of Commons, an event which marked the commencement of his occasionally rocky public career. In his political ambitions, he didn't scruple to use people to gain advantage; in his private writings he spoke of others as merely means he could exploit to his own ends, and of using flattery and craft to aggrandize himself. He made plans to ingratiate himself with his cousin, Salisbury, who was the Lord Treasurer to Henry Prince of Wales, James I's principal minister, while simultaneously currying royal favor with an eye to replacing his cousin in his position. Unfortunately for Bacon, his attempts at subterfuge did not work; while he did rise in position, he was ultimately used as a scapegoat in a public legal scandal.

Through his politicking, Bacon became solicitor general, later attorney general, and finally Lord Chancellor. He also was promoted to the peerage with the title of Lord Verulam and then Viscount St. Alban. He was the presiding judge of the Court of Chancery, the nominal head of England's judiciary. Perhaps because of his further ambitions, he granted repeated requests from Buckingham for his favor in particular disputes, and was lax enough to accept gifts from suitors to court. Because of this, in 1621 when the House of Commons attacked royal grants of monopoly, financial peculation and corrupt officials, Bacon was accused of bribery. The charge against Bacon was headed by his longtime enemy, Sir Edward Coke, who he had gotten dismissed from a judgeship in 1616. When the case was sent to the House of Lords, the king let Bacon become the scapegoat for the whole mess. Bacon, knowing appearances were against him (although he maintained impartiality and could point to many cases in which he had actually ruled against those who had given him gifts) submitted to trial and confessed guilt.

He received a fine of 40,000 pounds, imprisonment at royal discretion, and was barred from holding state office, sitting in Parliament, or coming within verge of the court. Essentially, he was banished from London. However, the king showed leniency, imprisoning Bacon for three or four days, essentially remitting the fine and awarded him a partial pardon. Afterward Bacon threw himself into his writings while continually striving in vain to regain political office.

Despite his mostly thwarted ambitions in the political sphere, Bacon was a prolific writer and philosopher on the nature and role of science for mankind. In Bacon's time, the number of disciplines and subdisciplines of knowledge was much smaller; in addition, the boundaries between the disciplines were much vaguer, or drawn differently. Great thinkers still practiced an encyclopedic approach to knowledge, although Bacon himself was unique in the sheer number of disciplines he investigated, both in what is now considered the life and physical sciences, and medicine, psychology, music, social science and crafts. He lived during the Protestant Revolution, and was necessarily concerned with religion and the ethics thereof; he urged mercy for Catholics and Puritans, although he looked to former ministers for their value in the fight against popery, urging that Catholics be discouraged but not driven to desperation.

His primary intellectual goal was to restructure what he knew as philosophy – what we today would consider science – as a form of inquiry, enabling a systematic, continual progress of knowledge. In an astonishingly modern attitude, Bacon believed that the purpose of science was for the betterment of humanity, and hoped that by establishing a more systematic approach, many improvements and benefits to human life would emerge as a result. He knew that in order to bring this about, he would have to completely reform and restructure the methods of acquiring and testing scientific knowledge. Bacon wanted to do away with the old modes of natural philosophy, with all energy aimed at preserving the knowledge of the ancient world as current.

Interestingly enough, Bacon's motives for creating his new method of investigating the world were based in religion; he desired to use science to restore humanity to the pristine condition it had before the Fall - being cast out of the Garden of Eden. However, his philosophy had a consistent naturalism, being concerned with empiricism and the reformation of practical investigative procedure. The mix of religious or mystical inspirations for eminently practical methods was the hallmark of Bacon's new system of philosophy; he owned his most basic inspirations – the understanding and manipulation of the natural world for the benefit of humanity – to the medieval practice of alchemy. According to Bacon, true understanding of a phenomenon and the ability to create said phenomenon were interchangeable; to know a cause of nature (verum) is to be able to manipulate nature to your own designs (factum).

Bacon's greatest break from previous thought was the idea of the experiment as a way of manipulating nature to reveal its secrets. Previous thinkers had made a sharp distinction between the natural and the artificial. He also conceived of the use of observations for the generation of theories and hypotheses that would be tested by new observations and experiments. Previously, knowledge was conceived as a much simpler process of inducing generalizations from a few observations. Bacon also saw science as a collective enterprise based on communication among its practitioners. At the same time, he also firmly believed in secrecy where the transmission of knowledge was concerned. He wrote about publishing knowledge in such as way that either held back part of what was being taught, or obfuscated it so much as to render it incomprehensible to everyone but the most erudite and determined students. Bacon was a child of his time, an elitist and aristocrat who had a strongly paternalistic, albeit benevolent, view of most of humanity. Bacon was a key influence to the coming explosion of scientific thought in the seventeenth century, and without Bacon's contributions, modern science would be drastically different. Bacon died on April 9, 1626 of pneumonia, possibly contracted while stuffing a chicken with snow as an experiment in using cold to preserve meat.

Box 2D
Ronald Aylmer Fisher

A brilliant statistician and geneticist, Roland Fisher was a rarity in modern science, making enormous contributions to both fields. Coming from rather unlikely origins, he was born in East Finchley, London, on February 17, 1890. His father was a successful fine arts dealer, but lost his business in a series of bad transactions eight months after Fisher's mother died when he was 14. Fisher showed an early aptitude in mathematics; because of his poor eyesight, he was tutored in math without the use of pen and paper, with allowed him to develop the ability to visualize complex problems in geometric models instead of step-by-step algebraic calculations. This later became his legendary ability to produce mathematical results to problems without having to go through any intervening steps. He won early accolades for his scholarship, including the Neeld Medal (a competitive math essay) at the Harrow School when he was 16, and later winning a scholarship to Gonville and Caius College, Cambridge. It was there he discovered his passion for genetics and evolutionary science, and saw the growing range of statistical methods as a way to reconcile the discontinuous nature of the traits studied by Mendel (see Chapter 3) with the continuous variation and gradual evolution of Darwin (see Chapter 4).

He also had a keen interest in eugenics, the scientific improvement of the human condition, at a time that its reputation was still unblemished by the atrocities and gross human rights violations that would occur in Europe and the United States. Fisher saw eugenics as both a social and scientific issue in statistics and genetics, dedicating much of his professional time and energy to their study. He co-founded the Cambridge University Eugenics Society in 1911 and became the Professor of Eugenics at University College London in 1933.

Fisher graduated in 1913, at the height of World War I, and was eager to join the war effort. He failed the physical due to his eyesight, and instead began working as a statistician for the City of London, and teaching physics and math at public schools, including Bradfield College in Berkshire and aboard the H.M. Training Ship Worcester. During the war, he met and married his wife, Eileen Guinness. The couple set up a subsistence farming operation on the Bradfield Estate, raising animals and a large garden. At this time he did some of his rare empirical work by carrying on selective breeding experiments. Fisher also started writing book reviews for the Eugenic Review, and was hired in a part time position by Major Leonard Darwin, one of Darwin's sons, with whom Fisher claimed a close friendship. He began publishing articles on biostatistics, including the groundbreaking "The Correlation Between Relatives on the Supposition of Mendelian Inheritance," written in 1916 and published in 1918. In it, he laid the foundation for what came to be known as biometrical genetics and introduced the methodology of analysis of variance, a huge improvement over the correlation methods used previously. He showed that inheritance of traits could be measured by real values (values of continuous variables) and that it is consistent with Mendelian principles. Remarkably, in a single paper he established two entire fields, one in genetics and one in statistics, and laid the foundation stone for the evolutionary Modern Synthesis (see Chapter 4).

After the war, he was offered a job at Galton Laboratory by Karl Pearson, but because of a developing rivalry between the two men, instead he accepted a post at Rothamsted Experimental station, a small agricultural research station in Harpenden, Hertfordshire. This decision was very fortuitous because it put him in close contact with empirical researchers who needed advice on experimental design and data analysis. There he began a major statistical study of the data the station had collected over many years, resulting in a series of reports titled "Studies in Crop Variation." Over the next seven years, he pioneered the principles of the design of experiments and elaborated studies of analysis of variance, a systematic approach of analysis of real data as a springboard for the development of new statistical methods. He developed practical and rigorous methods for the labor necessary in statistical computations, in 1925 publishing Statistical Methods for Research Workers and ten years later publishing The Design of Experiments, which became standard reference works for scientists in many different disciplines. It was during this time he made huge strides in the field of statistics, analyzing the technique of maximum likelihood, which fits a statistical model to data, extrapolating parameters for a large population based on actual data from a smaller representative sample. He introduced the "randomization test" beginning the field of non-parametric statistics.

Along with his major contributions to statistics, Fisher was also one of the founders of the evolutionary Modern Synthesis. Fisher's work on the mathematical underpinnings of the theory of evolution culminated in his major biological work, The Genetical Theory of Natural Selection, which he began writing in 1928 and published in 1930. In this book he summarized his work showing how the evolution of continuous traits could be explained by changes in the frequency of Mendelian genes, as well as developing ideas on the evolution of mating, mimicry and genetic dominance. Despite the enormous influence of the ideas presented in that book, it is notorious for being nearly impossible to read. Fisher used his own, very obscure system of notation, and it was mostly through the translation of his work by others that his ideas became widely understood.

In keeping with his interest in eugenics, a third of the book was concerned with the application of these concepts to humanity. He attributed the decline and fall of civilizations to their arrival at a state wherein the fertility of the upper classes is forced down. Using 1911 British census data, he showed an inverse relationship between fertility and social classes, and believed it partly due to the rise in social status of families not capable of producing a large number of children, who rose because of the financial advantage of a smaller family. To rectify this, he proposed subsidies to families with a large number of children, proportional to the wages of the father.

With the onset of World War II in 1939, University College tried to dissolve its eugenics department; although Fisher fought his decision, he was exiled back to Rothamsted with a significantly reduced staff and resources. WWII was a bad time for Fisher; he was unable to find war work, his marriage dissolved, and his oldest son George, a pilot, was killed in action. In 1943 he was offered the Balfour Chair of Genetics at Cambridge (his alma mater), which had also been nearly destroyed by the war. Fisher accepted the position with promises from the University that he would be able to rebuild it, but he was given very few resources, and it grew very slowly.

Fisher's evolutionary theories were built around the notion that the traits of organisms were determined by many genes, each having a small effect that added up to the final phenotype. The primary mode of evolutionary change was through selection on those genes in large populations. As a result, his theory saw natural selection as the sole determinant of evolutionary change, denying any role for contingency. His collaborations with the field biologist E. B. Ford were aimed at demonstrating these effects in natural populations. He clashed frequently with one of the other founders of the Modern Synthesis, Sewall Wright, whose theories emphasized evolution in small populations and importance of genetic drift.

Fisher was marked by an intense loyalty, both to his friends and his country. He was conservative politically and a scientific naturalist as well as member of the Anglican Church, writing articles for church magazines. Despite this, he held a firmly rational view of the world; in a 1955 broadcast on science and Christianity, he said, “The custom of making abstract dogmatic assertions if not, certainly, derived from the teachings of Jesus, but has been a widespread weakness among religious teachers in subsequent centuries. I do not think that the word for the Christian virtue of faith should be prostituted to mean the credulous acceptance of all such piously intended assertions. Much self-deception in the young believer is needed to convince himself that he knows that of which in reality he knows himself to be ignorant. That surely is hypocrisy, against which we have been most conspicuously warned.” In later years, a certain reputation for laxness in manners and dress blossomed into an archetypal nature as an absentminded professor; despite this, he was often sought after as a conversationalist. He was well recognized and well-traveled for his work, being inducted into the Royal Society in 1929 and two years later spending six weeks at the Statistical Laboratory at Iowa State College. In 1937 he visited the Indian Statistical Institute in Calcutta, which at the time consisted of a single part-time employee, P. C. Mahalanobis. Fisher returned often, encouraging their growth and development, and attended as the guest of honor in their 1957 twenty-fifth anniversary, when it had grown to 2000 members.

Fisher was dubbed a Knight-Bachelor by Queen Elizabeth II in 1952, and retired from Cambridge five years later in 1957. After Cambridge, he spent some time as a senior research fellow in Australia, and died there of colon cancer on July 19, 1962. He was awarded the Linnean Society of London’s Darwin-Wallace Medal the next year.

Experiments

A cornerstone of the scientific process is the **experiment**. We use the term “experiment” here in its broadest sense: a test of an idea. Experiments can be classified into three broad types: manipulative, natural, and observational. **Manipulative**, or **controlled**, **experiments** are what most of us think of as experiments: A person manipulates the world in some way and looks for a pattern in the response. For example, a biologist might be interested in the effects of different amounts of nutrients on the growth of a particular type of plant. She can grow several groups of plants, giving each of them a different nutrient treatment, and measure such things as their time to maturity and their final size. This experiment could be done in a controlled environment such as a growth chamber, in a greenhouse, in an experimental garden, or in a natural community in a field setting.

This range of potential settings for the experiment comes with a set of trade-offs. If the experiment is conducted in a laboratory or growth chamber, the scientist is able to control most of the possible sources of variation so that the differences among treatments can be clearly attributed to the factors being studied in the experiment. These sorts of controlled experiments exemplify the scientific method as it was first laid out by Francis Bacon in the seventeenth century (Box 2C). Baconian experiments are the mainstay of most of molecular, cellular and organismal biology (see Chapters 5 and 6) as well as the physical sciences. By working in a controlled environment, however, the biologist sacrifices something. The controlled environment is highly artificial, which compromises realism, and it is also narrow in scope, sacrificing generality because the results apply only to a limited range of conditions

If an experiment is conducted in a field setting, it is more realistic or more natural, but now many factors may vary in an uncontrolled fashion. In a field experiment, the only factors that are controlled are the ones being studied. Instead of attempting to control all variation, variation due to factors other than the experimental ones is randomized among replicates, and conclusions are based on the use of statistics to separate effects due to the factors being manipulated from other, uncontrolled factors. Such experiments can be carried out in many settings and are not restricted to the field. The design and analysis of these sorts of experiment relies heavily on the pioneering work of Ronald A. Fisher in the early twentieth century (Box 2D). Fisherian experiments are a mainstay of ecology and evolutionary biology as well as the social sciences. They are typically less narrowly defined than Baconian experiments, and thus their results may be more readily generalized. A biologist must decide where along this continuum of control versus realism she needs to carry out her experiment based on her scientific goals as well as practical considerations.

Experiments are usually designed as tests of hypotheses. If the hypothesis is partially or wholly falsified, the scientist goes back, revises his ideas, and tries again. If the hypothesis is not falsified by the outcome of the experiment, the scientist gains confidence that his hypothesis might be correct. Sometimes, however, scientists design experiments to “poke at it and see what happens.” Even here, one or more hypotheses are being tested (though they are sometimes not stated as such): by creating a difference between groups (such as feeding some animals more than others) and then measuring some quantity (like the time until adulthood), a biologist implicitly generates hypotheses about the relationship between the manipulation and the things measured. Such experiments are common throughout the biological sciences. Scientists have studied in detail only a few hundred of the millions of species; of these, only a few such as humans, mice, rats, fruit flies, and corn approach being well studied. A biologist beginning the study of a new species or other component of living systems must do many of these general types of experiments. Of course, she is guided by her knowledge of other similar species and ecosystems. Each species is unique, however, which is why each study expands our scientific knowledge.

Manipulative experiments are powerful tools for two major reasons: first, because the scientist can control which parts of the natural world will be altered to study their effects, and second, because she can separate factors that typically occur together to test them individually. So, manipulative experiments are well poised to separate out some types of multicausality. Such experiments have limitations, however. If multicausality is due to complex interactions of many factors, it may not be practical to create an experiment that considers all possible combinations of those factors, even if you know what they are. Sometimes manipulative experiments are plagued by artifacts—outcomes caused by a side effect of the experimental manipulation itself rather than being a response to the experimental treatment being tested. Good experiments avoid artifacts or take them into account in evaluating the results.

Another limitation is that of scale. Evolution (see Chapter 4) and ecology (see Chapter 7) are often concerned with patterns and processes that occur across large scales of space and time—for example, the causes of differences in the numbers of species on different continents, or the responses of populations to climate change over the next two centuries. We cannot do manipulative experiments at these great scales of time and space, and in many cases no true replicates might exist (continents, for example) even if we could work at these scales. Biologists are, however, increasingly making use of longer-term and larger-scale manipulative experiments in ways that mimic natural processes (see Box 7C).

Some types of manipulative experiments would be unethical to carry out. For example, we would not cause the extinction of a species just to study the effects of such an event. In such cases, biologists must rely on two other types of studies – these are natural and observational studies, which may be thought of as two different kinds of experiments.

Natural experiments are “manipulations” caused by some natural occurrence. For example, a species may go extinct in a region, a volcanic eruption may denude an area, or a flash flood may scour a streambed. Natural and manipulative experiments represent a trade-off between realism and precision, similar to the trade-off between laboratory and field experiments. Just as with a manipulative experiment, the biologist compares the altered system either with the same system before the change or with a similar, unchanged system.

The major limitation of natural experiments is that there is never just a single difference before and after a change or between systems being compared. There are no guarantees, for instance, that the altered and unaltered systems were identical prior to the event. For example, if we are comparing areas burned in a major fire with others that remained unburned, the unburned areas might have been wetter, might have had a different site history or different vegetation before the fire, and so on. Therefore, it can be difficult to determine the cause of any one particular change.

The best natural experiments are ones that repeat themselves in space or time. If a biologist finds similar changes each time, then she gains confidence about the causes of those changes. Another approach is to combine natural experiments with manipulative experiments.

Observational experiments consist of the systematic study of natural variation. Such observations or measurements are experiments if an biologist starts with one or more hypotheses (predictions) to test. For example, one could measure patterns of species diversity across a continent to test hypotheses about the relationship between the number of species and rainfall. Or, one could compare the process of growth of different species of fish, with some that live in the ocean and some that live in freshwater, to test hypotheses about how organisms cope with differences in water salinity. An advantage of natural and observational experiments is that biologists can let nature tell them what the multiple causes are. Statistical procedures developed in recent decades are able to tease apart complex, causal relationships, adding a third alternative to the approaches of Bacon and Fisher.

An important limitation of this type of experiment is the need for the scientist to know which of the many possible factors should be measured. Again, as with natural experiments, there is the potential for multiple factors to vary together. If several factors are tightly correlated, it becomes difficult to determine which factor is the cause of the observed pattern. This circumstance is when multiple or repeated studies become extremely beneficial; as with natural experiments, observational experiments repeated in space or time or among different groups of species add confidence to our conclusions. Other sciences, notably geology and astronomy, also rely largely or exclusively on observational experiments because of the spatial or temporal scales of their studies or because direct manipulation is impossible.

Creativity, objectivity, and subjectivity

When you read a typical scientific paper, it may at first seem esoteric and dull. The format follows a rigid protocol, designed for efficiently conveying essential information to other scientists. Ideas are tightly packaged, with a clear logical line running from start to finish. It may seem as if the researchers knew exactly what they would find even before they began. We will let you in on an open secret: That is not usually how real science works. The justifications for the research presented in a paper's introduction may have been thought up or discovered long after the research project began, or even after the work was finished. Because of serendipitous discoveries, laboratory or field disasters, or unusual natural occurrences, the original purpose of a research project is sometimes modified or, occasionally, entirely discarded and replaced with something else.

Ideas in science, especially in biology, come from a variety of sources. While everyone knows that science is objective and rational, that is only half the story. In order to reach a genuinely new understanding, subjectivity and creativity must also come into play. While one must be objective in, for example, examining the weight of evidence in support of a hypothesis, subjectivity plays a subtle but important role throughout all of scientific research. What one chooses to study is a subjective decision. Given that choice, there is usually a range of possible places to look for answers – another subjective decision. All of these choices largely depend on the questions one asks, and while determining the answers must be objective, choosing what questions to ask, and how to ask them, is largely subjective.

Many scientific endeavors are highly creative as well. Coming up with a good experiment, looking at a seemingly intractable problem from a new perspective, switching gears after a disastrous laboratory failure to extract a successful outcome from the jaws of catastrophe, and pulling a large number of disparate facts together to build a comprehensive theory all require a high level of creativity. A scientist must be able to come up with multiple courses of action when faced with problems, and cannot become too rigid in his work, or risk failure or stagnation.

As with other creative endeavors, the inspiration behind an experiment can come from almost anywhere. Many discoveries start with casual observations, such as Newton's apocryphal apple. An idea might also arise as a "what if" thought: What if the world works in a particular way? A scientist may draw on precious discoveries or earlier experiments of her own which have raised new questions. What makes a scientist successful is the ability to recognize the worth of these casual observations, what-if thoughts, and new questions. From these sources, a scientist constructs hypotheses and designs experiments to test them.

There is a distinction between the kind of research a scientist does and the kind of research done for a term paper, or by any member of the public trying to gather information about a topic using textbooks (such as this one), other library books, or material posted on websites. Although there are exceptions, research carried out by students or the general public is usually **secondary research**: gathering data or confirming facts that are already known. This sort of research is not only useful, it is essential: every scientific study must begin by assessing what is already known. But the heart of what research scientists do is **primary research**: gathering information that no one has ever known before, or coming up with new, testable ideas about how nature works. In recent decades, with the explosion of scientific publications and the advent of electronic databases, synthetic analyses of existing data has burgeoned as a new form of primary research; these efforts differ from secondary research in that they aim at assembling data in new ways and testing hypotheses using those data. These experiences of discovery are what makes doing science so incredibly exciting and fun.

Science as a Social Activity

Obviously, scientific research is not carried out by a cadre of mindless robots. Scientists are human, which means that human concerns and aspirations affect the scientific process. While that process is designed to maximize our ability to understand the world and decipher reality, sometimes aspects of human behavior can intrude and hamper the process. In some cases, however, those aspects can enhance the process. Today, the publication of results is central to the scientific process; as the goal of science is to provide understanding, a scientific study is incomplete until its new piece has been added to the overall puzzle. It is not sufficient to simply announce one's conclusions, either; the scientist must describe how she arrived at those conclusions and provide the data used to reach them so that others can independently decide if the conclusions are justified and can replicate the study if necessary. However, science was not always done in this fashion. In the Middle Ages, the practice was to hoard one's knowledge, or to provide conclusions without justification. This began to change in the 17th century when the British Royal Society and the French Royal Academy established the first scientific journals. Scientists were encouraged to put their studies, including complete descriptions of methods and results, in those publications for others to read. A social contract was forged. In return for publishing one's research, a scientist received recognition in the form of citations to that research in later papers. In this key respect, science differs from nearly all other professions in that the primary reward is neither money nor power, but recognition and status.

There are other, sometimes more tangible rewards for scientists as well. Scientists may be driven by a desire to alleviate a societal problem, such as curing a disease or preventing global warming. Such goals create enormous satisfaction when achieved. If the scientist is also an academic, he may enjoy the lifestyle. For the most part, you are your own boss and able to pursue projects of your own choice, although the continual scramble for research funding can interfere with that ability. Finally, there is simply the desire to know. Scientists spend long hours in the laboratory or slogging through miles of swamp because they have a question that they want answered. In this regard, scientists are like the private detective in a crime novel who keeps on looking for the murderer despite being beaten up and threatened with death.

Sometimes the questions that a scientist tries to answer are driven by her own curiosity, and sometimes they are determined by others. Frequently, those others are the ones who hold the purse strings, who can be members of a government, a not-for-profit foundation, or a for-profit company. Such control is not necessarily bad as it can push scientists towards questions that will have immediate benefits to society. Often the benefits of research may not be immediately obvious; the payoff may not come for decades. That is why foundations and governments fund curiosity-driven research, because they hope for that long-term benefit. Even then, some standards need to be applied to decide which research is more promising than others; that is one role for peer review.

Peer review

Despite the popular image of the lonely scientist toiling away for years, science is a highly social activity, albeit carried out by people who may lack some social skills. Central to the scientific process is peer review, the notion that one's scientific peers are the best judges of the worth of a scientific study. Peer review happens most notably as part of the publication process. Before a scientific paper or book gets published, it is evaluated by multiple people. A manuscript may be revised several times, and sometimes additional experiments may be necessary, before a study is deemed ready for publication. Research grant money is given out based on the results of peer review. In academia, tenure and promotion decisions frequently rely on evaluations of scientists from others outside the institution who can judge the quality of the science that has been done. The bestowing of academic degrees, especially the all-important Doctor of Philosophy (Ph. D.), happens through a review of a panel of people who themselves have Ph.D.s. The scientific community decides what counts as good science and who gets to call themselves scientists.

Such self-regulation by the scientific community is not just insularity for its own sake. Peer review makes science more efficient, and helps the scientific community reach consensus on the most important questions to pursue and the most appropriate methods for achieving the answers. In the biological sciences, there are millions of species that could be studied, each one with its own unique natural history. However, some species are better at illuminating a general truth than others; for example, Charles Darwin's formulation of the theory of evolution came about, in part, because of his studies of a particular set of finches on the Galapagos Islands (see Box 4A). While he or someone else would undoubtedly have eventually formulated a similar theory through other observations, those Galapagos finches had the virtue of clearly laying forth critical pieces of the puzzle. Today, the methods for determining the information contained in a molecule of DNA is changing continuously and, importantly, the costs keep dropping with each advance. Peer review of funding requests helps ensure that the most up-to-date and cost-effective methods are used. Peer review of manuscripts helps to clarify the writing, if not always as much as it should, and to make sure that conclusions match the data.

But does such constant peer review just result in conformity rather than achieving better understanding? While the social constructivist viewpoint would say that it does, there are two ways that a scientist can gain recognition. On the one hand, she can follow the crowd, accept the reigning consensus on some problem, and add one more brick to the scientific edifice. Or she could be an iconoclast and challenge the consensus (see Boxes 3C, 4E and 5D). Challenging a consensus involves more than simply claiming that you are right and everyone else is wrong. In science, ultimately the evidence prevails.

You might think that the process of peer review would work against such iconoclasts. It does to the extent that scientists are skeptical of any attempt to throw out a well established consensus involving either a fundamental principle or a methodological approach. If peer review is about achieving efficiency, then you need a good reason to throw out something that is working. But scientists are well aware that well established ideas and good methods have been tossed in the past. Ideas prove to be wrong, methods are shown to be inaccurate, and scientists are always willing to give alternatives an opportunity to prove their worth. There are many examples of vigorous debates in the scientific literature where the participants have not just allowed, but encouraged the airing of the views of the other side. Sometimes the scientific community can be pigheaded and a scientist must be willing to spend years convincing her peers that she is correct. In the long run, however, it is these rebels who get remembered and cited.

Ethics

Scientific ethics involves three central components: maintaining the integrity of the conclusions reached by the research, taking responsibility for the consequences of how a study is conducted, and taking responsibility for the way that the results are used. Scientific misconduct consists of data fabrication or falsification, plagiarism, or other serious deviations from accepted scientific practices. Data fabrication or falsification means that the results of the research were either made up or were manipulated in some way so as to alter their meaning. Plagiarism means using someone else's ideas, results or words without giving proper credit. Both types of activities are treated as serious breaches of community norms.

Unlike what you hear about the treatment of misconduct in other professions, the scientific community tightly polices itself and deals with such breaches harshly. The reason is that unlike other professions, those most harmed by scientific misconduct are other scientists. If a doctor or lawyer commits misconduct, the victim is the patient or client, not other doctors or lawyers. But if a scientist publishes false data, other scientists may spend years of effort and hundreds of thousands of dollars pursuing a phantom. Because citation is a primary currency of the scientific community and scientists strive for recognition, stealing another's ideas violates the heart of the scientific enterprise. Thus it is no surprise that misconduct receives thorough, if not always swift, punishment. It also explains why misconduct by scientists is much rarer than in other professions. False or misleading data, if important enough to be worth publishing, will eventually be discovered when used or checked by others. And plagiarism is almost impossible to hide in today's world of electronic publications.

When it comes to any particular subdiscipline or question, the number of scientists working in that area is typically rather small, no more than would be found in a small village or town. Just like in a small town, everyone knows everybody else and gossip travels fast. A scientist must trust the data published by others. While in theory any experiment must be repeatable by others, in practice very few experiments are exactly repeated because to do so is inefficient. Why repeat an experiment when there are many more questions to be answered and experiments to be conducted? So, scientists must trust the other inhabitants of their small town and once you lose that trust it is hard to regain it. Scientists learn to be honest and careful, or they quickly stop being scientists.

When is it not misconduct?

Scientific misconduct does not include honest error or differences of opinion. Controversy actually plays an important part in science. During the process of amassing evidence regarding the validity of a theory, different interpretations of experimental data and different weight given to various pieces of evidence will lead scientists to differing opinions. These opinions may be passionately held and forcefully argued, and discussion can sometimes become heated. As the evidence supporting a theory accumulates, some scientists will be willing to accept it sooner, while others will wait until a larger bulk of the evidence is accumulated.

It is not misconduct to assert a particular conclusion even if others think that the data do not warrant that conclusion, as long as the data themselves are available for examination. Honest errors occur, either in conducting experiments or in preparing manuscripts for publication. Sometimes the rush to publish and establish priority can result in sloppiness. As long as you clearly correct the record as soon as you discover your error, it is not considered misconduct. However, continued sloppiness may lead others to not completely trust your results.

There is one important nuance that scientists must consider when preparing their results for publication. Since data falsification includes omitting data so that the research is not accurately represented, it raises the question of whether you must always publish every single bit of data collected. Part of the purpose of a scientificpaper is to provide understanding of the world in the most efficient way possible. To that end, it would be counterproductive to obscure a result with all of the false starts and missteps along the way. Instruments malfunction and humans make mistakes. Experiments may be done to refine a method or to gather preliminary data that will inform the design of a much bigger study, and while these studies are useful for a scientist in getting to the important data, the greater bulk of the information may not be of interest to anyone else. It is legitimate for a scientist to decide which components of a study merit publication and which data are erroneous. These are judgment calls, and, as with any other opinion scientists may disagree on the correct course of action. The scientist is responsible, however, for keeping a record of all that went on during a study in case questions ever come up about how it was conducted and so that other scientists, who may disagree on these issues, can make their own judgments.

Responsibilities for ethical conduct

Scientists must take responsibility for the conduct of their research and the use of their conclusions. For example, ecologists study the effects of interactions among species (see Chapter 7). One method for measuring such effects is to exclude one species from an area, say a fence that keeps foxes out while letting in the mice that they feed on. One way to conduct such an experiment would be to make a species go extinct, the ultimate exclusion. Clearly such an experiment would be unethical. Other situations are more complex, however, involving instances where one must weigh the ethical values on either side of an issue. For example, what amount of pain or harm to animals should be allowed if the experiment will lead to the prevention of human disease? These sorts of questions can arise even when the subjects are humans; since humans must be allowed to give informed consent about their participation, how do you obtain informed consent if the individual is not conscious, for example in a study of the best treatment for an accident victim? These and other such issues are continually being wrestled with by scientists in conjunction with ethicists.

When data are collected in an unethical manner, they are shunned. The Nazis performed horrible experiments on people to see how they would respond to traumatic conditions, and while those data are unique and might provide life-saving information about the treatment of severely injured people, by consensus of the scientific community, those data are never used. Today, scientific funding agencies and journals require that studies of humans and many other animals be reviewed by special boards to ensure ethical treatment before they will be funded or published.

Scientists must see that their conclusions are used in an accurate manner. Scientists are not policy makers, although the results of science are often, or should often, be used to inform policy decisions. For example, global climate change is a critical issue today, and one approach to ameliorate the problem is to replace fossil fuels with fuels made from plants growing today, such as ethanol made from corn or sugar cane. Another approach would be to replace those fossil fuels with electricity generated by wind turbines. Scientists cannot make decisions about which alternative to pursue. However, scientists have a responsibility to see that all of the positive and negative effects of the alternatives are presented fairly. The use of various crop species have different effects on both the human food supply and the conversion of forests or prairies into agricultural fields. Wind turbines can cause mortality of birds and bats. While a scientist might have his or her own preferences, for example favoring saving tropical rainforests over temperate songbirds, that scientist must present all of the information needed by the policy makers for informed decisions.

Because scientists need to trust each other, it is important that scientists report on any possible biases that they might have. Some sorts of biases are inevitable because scientists are human. If a scientist has presented a new or daring theory that, if proven true, would earn a Nobel Prize, then that scientist will be looking for results that support the theory. Those sorts of biases are generally obvious and other scientists can be suitably skeptical. More pernicious are hidden biases and conflicts of interest, such as when a scientist has a monetary stake in the outcome of a study. Many journals require authors to provide information on such conflicts when submitting a manuscript for review.

Peer reviews are usually done blind so that the person being reviewed does not know who the reviewer is. Such anonymous reviews are felt to be more honest because the reviewer does not need to worry about a negative review leading to retaliation or a friendship destroyed. In such cases it is the responsibility of the referee, the editor of the journal or the grant-giving agency, to ensure that the reviewer does not use that anonymity to promulgate a biased opinion. Scientists are members of their cultures and not immune to prejudices based on race, sex or other conditions. Unfortunately, the conduct of science has been affected by such prejudices (see Boxes 4D and 5B). Today, several journals use a double-blind review process where the identity of the author(s) is not known to the reviewer. One comforting result is that in at least some areas of biology, it has been shown that the acceptance rate of manuscripts by women is no different using single-blind and double-blind review. While scientists are not angels, ultimately scientists are interested in understanding the world and are willing to accept information from all types of people to gain that understanding.