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The Joy of Science

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PREFACE

Scientists have great passion. What could be more exhilarating than to go to work every day feeling as if you were once again a nine-year-old called up to he stage to help the magician with his trick? To be a researcher is to always be in the position of having the chance to see how the trick works. No wonder that many researchers feel that each new day is the most exciting day to be a scientist.

It therefore is not surprising that scientists have such trouble communicating with non-scientists. It is difficult for the scientist to understand a life not focused on the desire to understand. But the differences are not that. Everyone wants to understand; that is one of the factors that make us human. The difference is more that scientists limit their definition of comprehension to specific rules of logic and evidence. These rules apply and are used in everyday life, but often with less rigor or restrictions on evidence.

The structure of this book is therefore tripartite. On the first level, we wish to demonstrate that, far from being arcane or inaccessible, the scientific approach is simply a variant of normal, common experience and judgment, easily accessible to any educated person. The second goal is to explain the structure of scientific thinking, which we will describe as the requirement for evidence, logic, and falsification (experimental testing). The third goal is to illustrate the scientific method by looking at the story of the development of the idea of evolution.

Evolution is a branch of scientific inquiry that is distinguished by its minimal level of laboratory experimentation, as least in its early period. Nevertheless, the story of evolution seems for several reasons to be an excellent choice to examine the nature of scientific inquiry. First, it is, almost without doubt, the most important idea of the 19th and 20th centuries. Second, it is often misunderstood. Third, understanding the story does not require an extensive technical background. Finally, it is very multidisciplinary.

This latter point may be confusing to some – what do Einstein's Theory of relativity, X-rays of molecules, or the physics of flight have to do with evolution? But all knowledge is interconnected, and the best science (and the best ideas generally) come when thoughts range across disciplines. If you are unfamiliar with, or uncomfortable with, this approach, try it! It is much easier than you think, and making the connection between history and biology, or between any two disciplines, makes our understanding of both much richer and deeper. Furthermore, the facts will make more sense and be easier to remember. If you understand, you don't have to memorize, because the facts will be obvious. This is why the questions at the ends of the chapters are essay style. Isolated facts are the basis for a trivia contest, while connected facts are the gateways to understanding.

Finally, for those concerned about using this book for teaching or learning within the confines of a course: all knowledge is connected, and it would be possible in taking a topic as global as evolution to expand into every realm of science and theology. I have found it useful in my teaching to allow the curiosity of students to redefine the directions I take, and the book reflects some of these directions. It is not necessary to address evolution through an excursion into molecular biology, but molecular biology is relevant, interesting, and currently in the headlines. I therefore have included excursions such as these into the text, but I highly encourage teachers and others planning a course to omit these excursions, as they see fit, or to use them as supplementary materials. I have also included several comments on the relationship of history and culture to the development of science. Since the book is written for those who do not intend to major in sciences, these comments should help these students to connect the various trains of developing thought and culture to the growing science as well as providing launchpads for teachers more comfortable with these subjects.

It is possible to use this book for a one-semester or two-semester course. Each of the chapters may be treated briefly or in more detail—for instance, in developing the story of quantitation and statistics in Chapter 32 or following in greater or lesser detail the excursion into molecular biology in Chapters 14–16. It will also be possible to spend more time on such issues as the distinction among the various historical eras, the modern classification of animals and plants, or the relationship between ecology and evolution. If possible, it would be best to use this book in the setting of small classes in which discussion is encouraged.

For further resources, more technical sources and interesting web pages are listed at the end of most chapters. Of course, nothing beats reading Darwin's original books, *The Origin of Species, The Descent of Man, and Voyage of the Beagle*, or any of several books and essays by Stephen Jay Gould, Ernst Mayr, or other more recent giants of the field. A more popular summary, written by a science reporter, is Carl Zimmer's *Evolution: The Triumph of an Idea*, Harper Collins, 2001. It was written in conjunction with a PBS series on Evolution, which is likewise available from the Public Broadcasting System (http://www.pbs.org). Some of the references that you will find in this book are to Wikipedia (http://www.wikipedia.org). They are used because they are readily accessible–the function of Wikipedia. However, readers should appreciate that most articles are written by graduate students, who may have good understanding but rarely a historical perspective, and the articles are usually not written by established authorities. Most of the articles, however, contain appended references that are generally reliable.

Finally, there are of course many people to whom I am indebted for assistance in the preparation of this book. Many readers will recognize my indebtedness to many excellent writers in this field such as Steven Jay Gould (several writings, but especially *The Mismeasurement of Man*) and Jared Diamond (*Guns, Germs, and Steel* and *Collapse*). I attempt to summarize some of their arguments. Hopefully, readers will be encouraged to read the more voluminous but exciting and challenging full works. In addition to the many teachers and lecturers from whom I have profited at all stages of my career and the administrators at St. John's University who encouraged and supported the development of the course from which this book is derived. Among the friends who have read and commented—with excellent suggestions—on various sections and drafts, and offered many worthwhile books and readings, I count (in alphabetical order) Mitchell Baker, Dan Brovey, Andrew Greller, and Michael Lockshin. My colleague, friend, and wife, Zahra Zakeri, has offered many cogent criticisms and, of course, has been most helpful and tolerant of my endless searches, writings, and musings. I dedicate this book to her None of these individuals has any responsibility for any weaknesses, errors, or other problems.

PART 1

HOW SCIENCE WORKS

CHAPTER 1

SCIENCE IS AN ELF

Evidence, Logic, and Falsification as the criterion for scientific decision-making. A question beginning with the interrogative "Why" is not a good scientific question. The art of structuring a question so that it can be tested. The controlled experiment

WHY BOTHER WITH SCIENCE?

This book has several goals. In the first instance it is about how scientists evaluate information and draw conclusions. Understanding this process is a requirement for modern life and it is an important aspect of every part of our lives. Thomas Jefferson is reputed to have said, "An informed citizenry is the bulwark of a democracy…" Today, to be a participant in the community of "informed citizenry," one must be able to interpret scientific information. It is difficult if not impossible to function effectively in society without some knowledge of the scientific process.

Every day the newspaper or television brings forth a large issue of some concern to each of us, but how prepared are you, really, to evaluate the arguments that global warming is real, will affect your way of life, will threaten coastlines, is responsible for severe hurricanes? Can you truly compare moral vs scientific arguments concerning stem cells, correction of genetic defects, medical manipulation of fertility (to achieve conception or prevent it), or maintenance of life by use of machines? Should you vote to protect wetlands, to prevent future floods, to maintain a fishing industry, or to allow resting places for migratory birds? Or are wetlands simply breeders for mosquitoes and places that could be profitably developed for housing or commercial purposes? Can you participate in a meaningful discussion of the dangers of nuclear reactors, or the merits or disadvantages of genetically engineered foods? On a more personal level, can you evaluate different potential diets, or interpret an advertisement for a medication? Can you read and understand the information inserts in medicine?

Ultimately, each of these discussions, and many more, depend on highly technical details that are not readily presented to the non-scientist. On the other hand, all scientists are expected to present their data in a manner that a layman can understand. Much scientific research is supported by your tax dollars through government-sponsored research programs. Each proposal for research is presented to a scientific board for evaluation, but the proposal typically also contains a summary that is expected to be meaningful to a congressman or congresswoman who will vote on the subsidy for the overall program, and meaningful to interested citizens who would like to know how their money is spent. That means you.

The goal of the scientist in this abstract is not to teach a lay audience the highly technical details of a complex proposal but to make the goals, limitations, and potential of the proposed research clear enough that you will understand the purpose and agree that it is a good idea and has the potential of producing knowledge of interest and value to you. Thus the first goal of this book and this course is to prepare you for this role as a citizen. What we hope to achieve is to give you a sense of how scientific data are collected and evaluated, so that you will be able to interpret the information inundating you. Thus throughout this book we will be emphasizing the scientific method.

EVOLUTION

We have chosen the approach of illustrating the scientific method through the study of evolution. We have chosen evolution for several reasons. First and foremost, evolution is the most important idea of the 19th Century and the most influential of the 20th Century. (Scientists almost never speak in absolutes, and almost inevitably qualify or restrict any statement that they make. I was therefore tempted to state, “evolution is arguably the most important idea…” but in this case there seems to be little reason to deny these claims.) Second, unlike, for instance, astrophysics or molecular biology, one needs relatively little technical background or familiarity with very abstruse and abstract topics to understand what is going on. For these reasons the topic seemed a logical choice.

SCIENCE IS AN ELF

Evolution, like astrophysics, lacks one essential of laboratory science, the ability to readily design and carry out experiments. It is possible to make predictions, which are in a sense thought experiments, and in some instances it is possible to design and conduct experiments, and we will address these issues as best we can. In all other senses, evolution is in every way a full science and illustrates the logic and construction of scientific thinking. That is, it depends fully on three elements that I define as an “ELF” principle: **E**vidence, **L**ogic, and **F**alsification. A scientific idea must be based on **evidence,** whether obtained by observation or experiment. The evidence suggests a link between two phenomena. A scientist will attempt to understand the link by establishing that one phenomenon causes another, or in other words he or she will form a hypothesis of cause and result. For instance, every year as spring approaches the sun gets higher in the sky and the days get longer. This is the **evidence**—both the length of the day and the mean temperature—that we can observe and measure. A reasonable hypothesis would be that the increased sunlight warmed the earth, rather than that the warming of the earth caused the days to get longer. This is the **logic** of the hypothesis, associating the heat that one feels in sunlight with the larger issue of gradually-increased warmth. Finally, the scientist will wish to test the hypothesis. The way that a hypothesis is tested is to try to disprove it: Can I create or envisage a situation in which the days will get longer but the earth will NOT get warmer? If so, does this disprove my hypothesis, or can I explain the seeming contradiction in a manner that still preserves the hypothesis? This is the **falsification** step (See Table 1.1). We will discuss these steps in considerable detail in the next chapter, and then use the principles throughout the book.

This means of analyzing information is not only not very difficult, it is something that humans do every day of their lives. Hunting-stage humans must have done it by observing, "if animal tracks from here go toward the setting sun (west), but when I am two days walk toward the setting sun, the animal tracks go toward the rising sun (east) then the animals must be heading towards a water hole between here and two days' walk west of here," (Fig. 1.1) or, "if that fat plant (cactus or succulent) contained water to drink, perhaps this fat plant also contains water" (Fig. 1.2). These are basically examples of classical syllogisms:

"If all antelope go to water in the evening
And if all antelopes here go west in the evening
Then there is water to the west."

Table 1.1. Evidence, Logic, Falsification

Evidence	Logic	Falsification
Weather gets warmer as days get longer	Sunlight warms the earth	Prevent all sunlight and warmed air from reaching an object
The lamp does not light when switched on	Perhaps it is unplugged	Verify that it is plugged in; plug it in. If it is plugged in, or plugging it in does not work, the hypothesis is falsified and we have to go to another hypothesis (bulb is burned out?)
Animals go west at twilight	Animals go to water	Follow animals, or determine when they return that they have drunk water
Cactus type A contains water; cacti type B and C have similar fat appearance	Fat plants contain water	Open cactus type B and C to see if they contain water
See bus leave stop; buses run every half hour	I walk 3 miles/hour and want to go 1 mile; walking is faster than waiting for next bus	Walk the distance; time yourself; observe if another bus passes

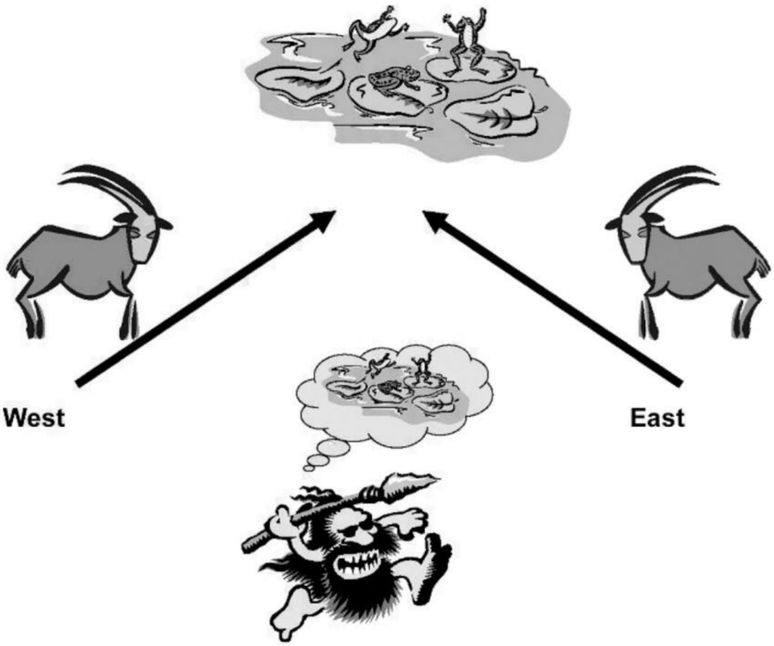

Figure 1.1. Inference and logic in a simple decision. The hunter-gatherer knows that antelopes seek water in the evening. When the antelope comes from the west, it heads toward the northeast. When antelopes come from a position several kilometers to the east, they head toward the northwest. Our hunter infers that water can be found somewhere at the intersection of these two tracks, or toward the north

When you buy a pen, and you say to yourself, “I really like that pen, but it costs five times more than this pen, and I usually lose pens in three days, so I had better buy the cheap one,” you are using scientific logic, prediction, and evaluation; if you choose the more expensive pen, in spite of the evidence, you are conducting the experiment, “If my motivation—budgetary or desire—is strong enough, I will remember where I put the pen and gain the pleasure of owning it.” Or again, suppose a candidate for mayor announces a platform of being “against crime in the streets”. You are likely to say, “That’s nice, what are you going to do?” If the candidate says, “I’ll put all the criminals in jail,” you are likely to say, “How are you going to do that?” If the candidate continues, “I’ll arrest them all,” you are likely very soon to wonder, “Is what the candidate suggests practical? Is he or she going to be threatening or harassing specific groups of innocent citizens? Can we afford the plan, whether it is better lighting, more police, more judges, more jails? Will the plan demand too much information about my life? If it includes restrictions on access to guns, knives, spray paint cans, box cutters, is this a good idea? How much will it restrict my life?” In other words, the candidate has hypothesized that a specific number of habitual criminals are the primary cause of crime (as opposed,

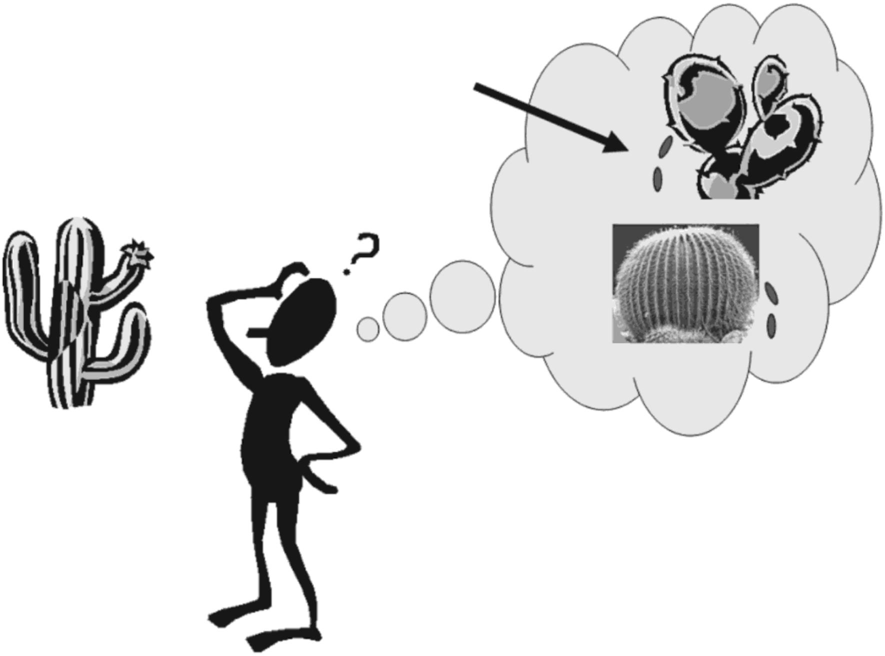

Figure 1.2. Generalization. Our hunter-gatherer is aware that, in dry lands, some plants with thick stems and leaves (which may be cacti, shown here, or succulents such as jade plants) store water in the stems and leaves. He is thirsty when he encounters a new type of plant, which has some resemblance to the cacti that he knows. He generalizes the first information to deduce that the new plant also stores water in its leaves, and thus finds something to drink

for instance, to poverty, lack of employment, insufficient care and protection of objects, lack of activities for teenagers and young adults, or other causes) and has proposed the experiment that isolating these individuals will eliminate the problem. You are asking for evidence that you will test against your own logic. You may well apply a form of falsification to the candidate's hypothesis: "Arrest rates differ from city to city and state to state. Do states with higher arrest rates, or more aggressive prosecution of criminals, have lower rates of crime? Do other factors, such as numbers of young men, play a role? How about the availability of employment, or of youth centers?" Collecting any or all of this information would in essence be an experiment in the same sense that a laboratory scientist designs an experiment. In other words,

IT AIN'T ROCKET SCIENCE (OR, IT IS UNDERSTANDABLE)

You apply the logic of science (hopefully) every day of your life. A local fast-food chain offers a huge ice-cream sundae that contains "only five calories"; you wonder if that's true (what the evidence is; how logically it can be sweet without sugar).

One mild day in winter, a friend remarks that the mildness is due to global warming; it crosses your mind that last week was a record low temperature. On television, an ad touts a “miracle brush” that can remove spilled dry paint with a single swipe; you are very skeptical and look very closely at the ad to judge if what is being shown actually happened. You notice, on another ad, for a weight-loss regime, that the actors in the “after” pictures are smiling, flexing their muscles, holding in their stomachs, and are turned so that their least flattering parts are hard to see, whereas in the “before pictures” they are not smiling and are making no efforts to hide their flab. Even a decision whether or not to walk to the next bus stop rather than wait, or to take a taxi rather than wait for the bus, is based on a hypothesis about the time on the route and your fatigue or energy.

This point cannot be made too strongly: The logic of science, and the structure of science, is simply human logic. It requires the same skills that we use on a daily basis, and is no more complex than that. There are only three things that seem to be difficult about science: its use of mathematics, its large and complex vocabulary, and the abstractness of many of its concepts. None of these presents an insuperable barrier to the student who wants to understand how science works.

MATHEMATICS AND TECHNICAL TERMS

Working scientists need to understand mathematics because quantification is a very important aspect of what we do. For obvious reasons, we need to know more than the fact that a volcano is a volcano. We need to know if it will erupt, which is a calculation based on the location of its magma (molten rock, lava), its past history and the history of similar volcanoes, what the earth is doing under the volcano, etc. If the volcano is not completely dead, we need to know when it is likely to erupt, and how severe the eruption is likely to be. All of these require extensive calculations, but even a non-mathematical person is likely to understand a scientist who says, “The molten rock moved this week from a half mile beneath the cone to within 600 feet of the cone, and the surface temperature at the cone rose 50° F. We consider the volcano dangerous.”

Likewise, statistics is a large part of medical and sociological research. New medical treatments, and the licensing or banning of drugs, are based on comparisons of groups done by elaborate mathematical procedures. These procedures are based on analyses designed to eliminate inadvertent bias (smokers might also be heavy drinkers; a group of aspirin users might on average be considerably fatter than the non-aspirin users to whom they are compared; vegetarians may differ in lifestyle from non-vegetarians in more ways than in diet). The non-statistician needs to know how reliable others judge these statistics to be, and what the implications are, not the mathematics of how it is done.

Scientists use technical terms such as magma because they need other scientists to understand exactly what they mean. This is an important distinction from casual speech (though not from careful writing in any discipline). Listen to how many times “y’know” as in “It’s like y’know, cool, man” translates to, “I haven’t explained this coherently. I hope that you can fill in the gaps." This is not to say that common language is wrong or is not appropriate; it just does not have a place in scientific communication. One summer I worked in a factory, and a fellow worker liked to engage me in conversation. Unfortunately most of his conversation consisted of one obscenity, used as a noun, verb, and adjective: "That bleepin' son of a bleep of a bleepin' son of a bleep bleeped me!" My participation in the first part of most conversations usually consisted of non-committal responses as I trolled (in frustration) for the meaning of what he said. Was he talking about our boss? Politicians? His friends around home? His wife? Had someone insulted him? Short-changed him?

The vocabulary does not need to be daunting. Scientists use complex vocabulary partly because sometimes what the words describe have no counterparts in common language—no Biblical or other early writer truly imagined a molecule structured like DNA—but mostly because of a need for precision. Scientific language strives for a precision that assures that any worker throughout the world, on seeing a specific word, will have the same mental image. This is very different, and sometimes much drier, than common or poetic language. A poet may describe a lovely woman as having diaphanous skin and hair like gossamer, but the beauty of the poetry is that these phrases conjure an image rather than paint a picture; the language evokes an image unique to each reader, based on that reader's experiences and desires. Each reader will imagine a different woman and different circumstances, collecting impressions from his or her experience, and hopefully each reader will generate a different very personal but equally compelling and pleasurable image. Poetry frequently loses its value as it becomes more specific, as a film based on a very romantic novel may prove disappointing if the hero or heroine in the film is very different from the person one imagined. This is nothing like a police report, giving height, weight, hair shape, length, and color, age, skin color, shape of eyes, nose, lips, etc. … not very exciting, but everyone will have same image. Again: Which of the following passages better *evokes* autumn? Alternatively, if you had never heard of the word "autumn" (for instance, if you spoke Tibetan and were learning English) which would give you a better and more precise idea of the term?

"SEASON of mists and mellow fruitfulness!
Close bosom-friend of the maturing sun;
Conspiring with him how to load and bless
With fruit the vines that round the thatch-eaves run;
To bend with apples the moss'd cottage-trees,
And fill all fruit with ripeness to the core;
To swell the gourd, and plump the hazel shells
With a sweet kernel; to set budding more,
And still more, later flowers for the bees,
Until they think warm days will never cease,
For Summer has o'er-brimm'd their clammy cells.

Keats, Ode to Autumn

Compare Keats' poem to this description of autumn:

> "The season starting at the fall equinox (normally September 21 in the Northern Hemisphere, March 21 in the Southern Hemisphere) and ending with the winter solstice (December 21 and June 21, respectively). In popular use, the dates are often constrained by holidays, as in the U.S., between Labor Day and either Halloween or Thanksgiving; or are defined by climate, as in northern North America many people consider that autumn ends with the first killing frost or the first snowfall."

A scientific report is far more similar to a police report than to poetry—the goal is that everyone have as close to the same image as possible.

Common spoken English does not have this requirement. When an Englishman refers to a robin or to robin redbreast, he is describing a very different bird from the thrush that Americans call a robin (because the first English in the new world thought that the bird was the same). To prevent confusion, scientists would use a 300 year old tradition, from a time in which all educated persons spoke Latin, and would refer to the European bird by the Latin name of *Erithacus rubecula* and the American bird as *Turdus migratorius*. (The two-name system functions like the first or given name and last or family name system by which people in western societies are known. In the case of Latin names for animals, the capitalized first word is the equivalent of the family name. For the American bird, the name simply translates to "the thrush that migrates". We will discuss the definition of a species and the terminology in Chapter 11, begining on page 157.) Likewise we know a turkey by the name of a country because of confusion with a large bird from that country. If one asks for "regular" coffee, in some parts of the United States one will get black coffee and in others coffee with milk. We also use several words to describe the same thing: a long sandwich with several types of meat, cheese, and lettuce may be called a submarine sandwich, a hero (sometimes even jiro), or a hoagie, depending on the region of the country.

As a more specific illustration of the point, let's look at the word "significant," which has several meanings. One, its original meaning, was "giving a sign," as in "To the Greeks, it was significant that the general saw a meteorite the night before the big battle". Another common meaning is "important," "large," or "considerable," as "the loss was not significant", and there are several variants of these, as in "significant other," referring to a person with whom one is romantically involved. In biomedical sciences, the word has *only* a statistical sense: A difference between two groups that would occur so rarely by chance alone that the difference most likely supports the hypothesis of a relationship. For instance, if one measured lung cancers among 100 gum chewers and 100 non-chewers, and found 2 cancers in the first group and 3 in the second, the chances are that a repeat of the same assessment would the next time find 3 cancers in the first group and 2 in the second. There was no real difference, only a minor one dependent on chance. On the other hand, if one compared lung cancers among smokers, and found 10 cancers among the smokers and 1 among the non-smokers, the chances are that a repeat of the assessment would find a similar difference the next time, supporting the hypothesis that smoking can cause lung cancer. Statisticians can mathematically determine the probability that the results would be repeated, and biomedical scientists would call the difference between smokers and non-smokers significant. This is the only sense in which the word would be used by a scientist. In a scientific paper, "significant" NEVER means "important" or "meaningful". We will explore the precise meaning of the word "significant" in page 126.

SCIENTIFIC THEORIES AND HYPOTHESES

In common conversation, a theory is a guess as to how something works: "My theory is that the thermostat turns on the pump that circulates the water." To a scientist, a theory is not a guess but a hypothesis—that is, a logical inference as to how something works, or about the relationship of two phenomena—that has been tested many times, and each time supported by the test. When scientists review applications by other scientists for the support of their research, they often ask, "Is the work hypothesis-driven?" meaning, "Has this scientist created a model, based on preliminary evidence, as to how this works?" When many scientists have done this, and attempted many times to disprove their argument (falsification), and all the scientists come to the same conclusion, the hypothesis earns the title of theory. In general, calling something a theory means that it is logical, (logic); in many situations it is a plausible explanation of the relationship of two phenomena (evidence); and that many attempts to disprove it have failed (falsification). Thus other scientists can with some confidence consider the hypothesis sufficiently valid to base further, extrapolated, work on the assumption that the hypothesis is true. This is as close as we get to a higher level of certainty, a law. For a law, for instance, the law of gravity, we are sufficiently confident that all bodies produce and respond to gravity that we can base everything from planning the orbits of space ships to calculating tides to building very exotic medical and analytical machinery to aspects of atomic physics on the assumption that the "law" of gravity will apply, and we would be genuinely astonished if it did not. Although the terminology is a bit fuzzy at the borders, we do not have quite this level of confidence in a theory. We are only quite certain that a theory is true. A theory, and even a law, can potentially always be disproved, if an experiment or an observation can contradict it and no reasonable explanation can place the result into a category of interesting but comprehensible exceptions. The essence of science is testability, and thus everything is tentative pending the next experiment. It is quite humbling, and it is a source of considerable friction between scientists and public understanding. To a scientist, "the theory of evolution" means that the idea is well thought out, based on lots of evidence, and not disproved by any of myriad experiments—but there is always the outside chance that something that we have not imagined may someday disprove it, in the sense that we cannot predict that a lake will not suddenly appear in the middle of Arizona. To a scientist, the "theory of evolution" does NOT mean "a rather casual guess by a bunch of people who have not thought of other possibilities". And in any case, science addresses only the mechanics of how things work (which therefore can be tested) and never addresses the untestable.

ABSTRACT CONCEPTS

Finally, science demands abstractions, because in most instances the subject of the science is something that is not part of common experience. For instance, we cannot see a molecule. We can create an image of it, using specialized technology such as electron microscopy or atomic force microscopy, and we can view the image, or we can use various complex machines to detect the presence of molecules and determine their properties. What scientists do is to use their training about what these machines do so that they can construct mental images of the molecules as if they were 1,000,000 times bigger. In brief, the ability to think abstractly is the ability to make the abstract concrete. Throughout this book, we will attempt to help you, the reader, imagine some of these abstract and seemingly difficult concepts.

SCIENTIFIC PRESENTATION: FIGURES, GRAPHS, AND TABLES

There you have it! Science, its logic, and its findings can be understood by all students. One task that you should undertake, however, is something that is often neglected but is important, and which will considerably simplify your effort: look at the tables and figures that appear in the subsequent chapters. To working scientists, figures are not sidebars or attempts to render the text more fun. Well designed figures summarize important points, indicate relationships, and suggest further expansion of an idea. A figure such as that in Fig 1.3 can contain the ideas and relationships that would take pages to explain, and if one can grasp how it does so, one has saved oneself all of this memorization. Note how long it takes to explain in words what is shown in the graph, and how much clearer the graph is than the verbal explanation.

This figure illustrates the cost of printing magazines. One can read it as follows: Before a single magazine is printed, there is a cost of approximately $20,000 (point A). (This cost presumably includes the cost of the conception and design of the magazine, the collection of articles and pictures, the machines, and the building in which the press is housed, as well as salaries and incidentals. For someone trying to handle the budget, it would be important to know this initial cost.) For the first 20,000 magazines published, the real cost per magazine is approximately 2 dollars per magazine (calculated from the slope of the line between points A and B; the initial cost at 0 magazines is $20,000, and the cost at 20,000 magazines is $60,000. $60,000-$20,000 = $40,000, which is divided by the 20,000 magazines produced. The effective cost for the first 20,000 magazines, including the initial cost, is $60,000/20,000 or $3/magazine. After the first 20,000 magazines have been printed, presumably some basic costs have been met, and the cost per magazine falls to $5 per magazine. (Between 20,000 magazines and 40,000 magazines (point C), the cost has risen from $60,000 to $75,000, or $15,000 for 20,000 magazines.) The effective cost per magazine is $75,000/40,000 or $1.875/magazine. Beyond 40,000 magazines, presumably all background costs have been satisfied, and the

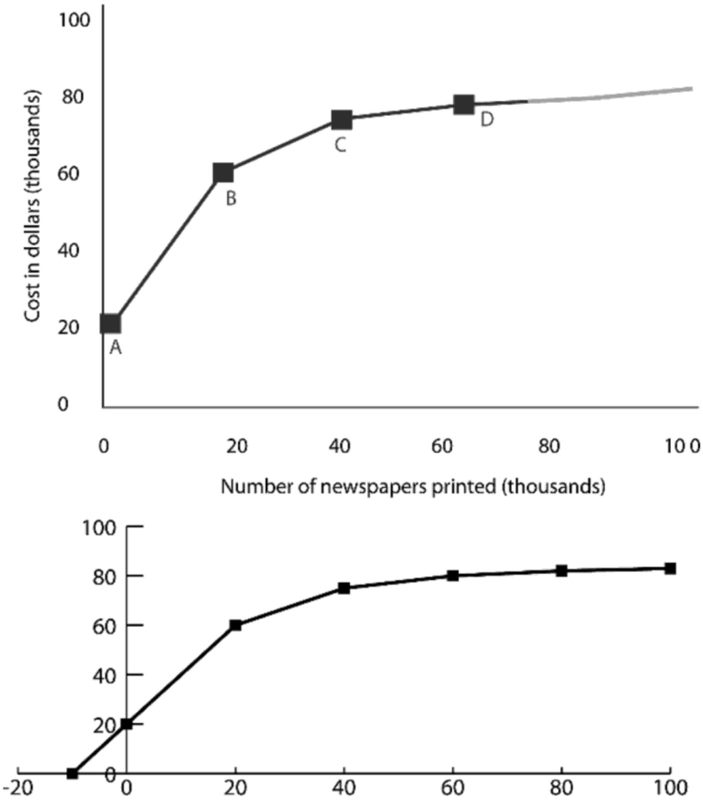

Figure 1.3. Graphical representation. As shown in the upper curve, before the first magazine is printed, $20,000 must be spent (point A: $20,000 for 0 magazines). This money represents paper stock, ink, staples, and costs for the building and personnel. If 20,000 copies are printed, the cost rises to $60,000 (point B), representing the baseline cost plus an incremental cost of $2.00/magazine ($60,000–$20,000 = $40,000/20,000 magazines). These costs presumably include the electricity, transport and delivery, and extra hours of labor. Between 20,000 and 40,000 copies (B to C), the incremental cost drops to $0.75/magazine ($15,000/20,000 copies), presumably because delivery costs do not increase much once the first shipment has been made. Between 40,000 and 60,000 magazines (C to D), the cost rises only $5,000, or $0.25 per magazine, for a total cost per magazine of $1.33/magazine ($80,000/60,000 magazines). Obviously there is higher profit in a larger production run if all the magazines can be sold. It is possible to extrapolate beyond point D (grey line) to see what higher numbers would per print run would cost, but extrapolating backwards to see what number of magazines would cost nothing, as shown in the lower curve (–10,000 copies), would be meaningless. Note how much simpler it is to read this information from the graph than to have to listen to an explanation

only remaining costs are supplies and salaries for the extra time, as the cost per magazine has fallen to approximately $0.25 per magazine between points C and D, for an effective cost of $80.000/60,000 or $1.33 per magazine at 60,000 magazines. One could even use the graph to predict the cost should the press decide to publish, for instance, 100,000 magazines.

CURIOSITY AND VALID SCIENTIFIC QUESTIONS

The last point to understand about how science works can be summarized in a single word: curiosity. All children are curious (just listen to conversations between 2- to 6-year old children and their parents) and some retain this curiosity throughout life, so that everything evokes a question: “How did this mountain get here? Why are male birds more brightly colored than female birds? How do insects survive freezing in the winter? Why do leaves turn color?” This curiosity can be summed up in an aphorism that is worth keeping in mind throughout this course: *“Phenomena are questions”*. In other words, there is a mechanism to explain how cells migrate to their proper places in an embryo, how the body fights an infection, how trees move water as high as 300 feet, how a bird or a whale finds its way half way around the world, or how the world is constituted such that flightless, ostrich-like birds are found in Australia, New Zealand, South America, and Africa, but not in Europe, Asia, or North America.

There are two related modifications to this last statement. The first is that science is about the mechanics of how things work. For this reason a question beginning “Why” is almost never a legitimate scientific question. Science is about the how, not the why, and a good question suggests a means of testing the how. It is rarely possible to test a “why”. This is also why the scientific method presents far less confrontation with religion than many assume. A question beginning “Why”, when it is not meaningless, is a religious question rather than a scientific one. For instance, “Why are rabbits brown?” may have a religious answer (“Because God made them brown so that they could hide”), but the scientific question could be any of several: “What is the selective advantage of brown color?” “What is the mechanism of inheritance of brown as opposed to other colors?” “What developmental mechanism arranges for pigment to appear on the back, but not the belly, of the rabbit?” “In what cells is the brown pigment?” (The cells are called melanocytes, or “black cells”.) “How do the melanocytes carrying the brown pigment get into the skin?” “What is the biochemical pathway by which the pigment is synthesized?” “What is the biochemical structure of the pigment?” “How does a pigment molecule absorb light?” These questions can be carried deep into sub-atomic physics, and all are legitimate scientific questions, because, at least indirectly, they suggest possible mechanisms that can be tested. For this reason they differ from the non-scientific question “Why are rabbits brown?”

In summary, science is not an incomprehensible subject. The scientific method is an approach to understanding that is identical to the approach we use to understand any aspect of our lives. It differs only in that it has a series of specific codes and disciplines that allow a very structured means of asking questions, together with specific rules concerning what constitutes a meaningful answer. Understanding how these rules operate can demystify the world of science.

This book is primarily about the rules of science–how science works–as illustrated through examples of experiments, thought processes, and incidents in the lives of scientists, taking as a primary intellectual issue the development of a major theory. The subject of our inquiry and analysis will be evolution or, more properly, natural selection. The story of evolution encompasses three major steps that were accomplished in the mid 19th Century. The first was that thinkers had to conclude that the world was much older than the biblical approximation of 6000 years. Second, they had to accept the idea that species of plants and animals could evolve, or change with time (descent with modification). (This step also required a firm sense of what was meant by the term ‘species’, which itself depended considerably on new and confusing findings as Europeans explored the New World.) Finally, they then had to accept Darwin’s contention that this descent with modification was directed by the non-random survival of certain favored individuals in an intense competition for food, protection, nesting resources, and mates (natural selection). As we shall see, none of these ideas was particularly new or original in the mid 19th Century, but it was the connecting of all of these ideas that revolutionized the world. It was known, for instance, that farmers could improve crops by using only the seeds of plants displaying the desired characteristics. Breeders of dogs were aware that numerous variations of dogs were produced by selective mating. Thus species could vary considerably. Within a few hundred years, one could breed dogs to produce dachshunds, great danes, and bulldogs. What was not obvious, however, was how it would be possible to generate all the varieties of plants and animals in the world in 6000 years. Furthermore, the exploration of the new world had produced new conundrums or puzzles, based on the realization that different continents contained different animals and plants—a finding not readily obvious from the story of Noah’s Ark. We shall address each of these issues in turn. We will, however, branch into other, related subjects where appropriate. After all, all subjects are related in some sense: the exploration that led Europeans to reach the Americas would not have been possible without advances in astronomy and physics, and the history of 16th C Europe would have been very different without the struggles to acquire the riches of the Americas. Donne[1] would never have marveled at a woman, “Oh my America, my new found land!” It is sometimes very confusing, but ultimately exhilarating, to see these connections. Look for them. There are many rewards. First, you will be thinking like a scientist. Facts will become richer and more meaningful. Most of all, you will see that you will reduce the amount of tedious rote memorization you have to do because, once you see the connection, one fact necessarily leads to the next. For instance, Spain did not become a major power in Europe until it could draw on the resources of the New World. Once you know the date 1492, you can approximate the dates of the next events in Europe. No more getting the dates wrong by 200 years.

One last note: a well-developed, mature college-level vocabulary helps greatly to clarify issues. Therefore we will not attempt to “talk down” to you, the student, by using a less mature, less specific vocabulary. We will, however, in introducing a less common word attempt to explain it in passing. In doing so, we will use the trick of the King James Version of the Bible. The authors of that translation

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[1] John Donne, To His Mistress Going to Bed

were faced with the problem that some of the English, mostly peasants, spoke Saxon, derived from the Germanic languages, while the upper class spoke French. They therefore repeated many terms, giving a Saxon and a French version of the same statement:

Gen.4

[**1**] And Adam knew **Eve** his wife; and she conceived (FRENCH), and bare (GERMANIC) Cain, and said, I have gotten a man from the LORD.

[**14**] Behold, thou hast driven me out this day from the face of the earth; and from thy face shall I be hid; and I shall be a fugitive (FRENCH) and a vagabond (GERMANIC, FROM LATIN) in the earth; and it shall come to pass, that

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STUDY QUESTIONS

1. Give an example from daily life and from a scientific/technical situation in which you can identify evidence, logic, and falsification. Clearly indicate which aspects are evidence, which logic, and which falsification.
2. From television or daily news, choose an example of a claim being made for a political or scientific issue and dissect the claim into evidence, logic, and falsification.
3. A medical report notes that there was a significant difference in survival between patients who walked at least one mile per day and patients who did not walk much. Explain what this statement means.
4. A weight-loss treatment is advertised using testimonials from satisfied customers. How would you evaluate the advertisement?
5. Why do we give Latin names to animals and plants?
6. Give examples of theories, laws, and hypotheses.
7. Choose a graph from a newspaper or news magazine and write a verbal description of the information found in the graph. Pay special attention to the

logical relationship between the data on the abscissa (horizontal or X axis) and the data on the ordinate (vertical or Y axis).

8. Describe three questions that you have asked at some point concerning how something works. What evidence would you need to answer your question?
9. What words did you not know when you read this chapter? What is the meaning of these words?

PART 2

ORIGIN OF THE THEORY OF EVOLUTION: TIME AND CHANGE

CHAPTER 2

THE ORIGIN OF THE EARTH AND OF SPECIES OF ANIMALS AND PLANTS AS SEEN BEFORE THE ENLIGHTENMENT

WHERE DID I COME FROM? THE EARLIEST INTERPRETATIONS

All societies have faced the issue of “Where did I come from?” and have usually assigned a divine cause for creation. Few have pondered the issue more deeply, owing to two factors: First, for all societies, the world is tolerably constant. Second, in western society, the influence of Aristotle, Plato, and the Old Testament, which heavily relied on the assumption of constancy, mitigated against further exploration and analysis, even when logical contradictions were acknowledged.

As is discussed in Chapter 4, page 45, at a given time and place the world appears to be constant. One summer may be warmer or a winter colder than another, and there may be other modest changes in climate or the precise bed of a river, but by and large the old-timers can remember hotter summers or heavier snowfalls. The biological world also appears to be constant and discrete. To take an oversimplified but illustrative example, any reasonably observant person realizes that there are different kinds of birds in his or her neighborhood. In a northeastern urban or suburban neighborhood, for instance, there are pigeons, robins, cardinals, gull, sparrows, mockingbirds, crows, and Canada geese. There are also several others, such as owls and hawks, but they might not be commonly noticed by the casual observer. The point is that one does not mistake one species for another. Pigeons might have many colors, but they are certainly not robins. A female cardinal might be greenish-brown, rather than red, but her body shape, her crown, her beak shape, and her markings make her distinguishable from any other bird in the vicinity. We do not find birds that are half-way between a pigeon and a robin, or birds that we could not with little effort classify and identify. Even if a species becomes extinct, it is known in its last stages as a rare species and, unless one is specifically attempting to document its existence, its disappearance is simply perceived as a lack of a recent sighting until, in a few years, it is forgotten. With these observations, there is little reason for assuming that the world is not as it has always been, other than by the divine placement of humans into the scene. The concept of change does not become obvious until one has a long historical (written) record of the world. Furthermore this record must sufficiently preserve earlier writings and later generations must be able to read them, so that the differences between then and now become apparent.

Ancient Greece constructed a world image that did not depend on divine creation. Thus it was that earlier Greeks, Anaximander, Anaximenes, Empedocles, and Democritus, argued that humans arose from the earth or a primordial moist element, being engendered by the sun's warmth and spontaneously arising as maggots appeared to do in rotting flesh. In general, perhaps by noting the obvious biology and by understanding a hierarchical world in which animation (life) was superior to inanimation (rocks), movement (animals) superior to immobility (plants) and thinking (humans) superior to reactive behavior (animals) they perceived a creation in which plants preceded animals and animals preceded humans. They recognized but did not however address the logical problem of the state of the first human. If the first human appears as a baby, it must be cared for, but then who (or what) cares for it? With divine creation, it is possible to accept the idea of the first humans appearing on earth as adults, but for the Greeks this was a conundrum. As far as we know, they did not pursue this problem with great enthusiasm or to any depth, partly because of the rising influence of Plato and his student Aristotle. Plato felt that each object in the universe was an imperfect representation of an ideal type or archetype, and that the universe consisted of more- or less-successful approaches to that archetype. Note, however, the inference: if there are archetypes, then by definition the archetypes do not change. Therefore, in the biological world, species do not change. A robin is a better or worse approximation of the ideal of "robin-ness" but that ideal, or archetypical, robin persists and will remain in all generations as the goal of robins. Aristotle carried this idea further in attempting to systematize or classify all forms of animate and inanimate nature, in his Scale of Life (page 55). As with Plato, each species was an attempt to replicate an absolute ideal, but beyond that, the archetype of each species occupied a particular rank in nature. Thus animals were above plants, vertebrates were above invertebrates, birds and reptiles (which had perfect or shelled eggs) above fish (which had imperfect or soft eggs), mammals above reptiles and birds, and humans above mammals. He counted over 500 links in the chain, or species. His classifications improved on the earlier versions such as with or without feet or wings. All this is well and good, but it ultimately gets complicated, as the Aristotelian scale allowed no ambiguity or ties in rank. Thus, for instance, a peach tree had to be above or below a cherry tree, a trout had to be above or below a bass, a cat had to be above or below a dog, a sheep above or below a goat. Life could be created, but new organisms would join their appropriate rank. So, by this argument, not only was there no possibility of change of a single species, there was no possibility of movement among species. It was not possible for a goat to pass a sheep, or vice versa. In this world view, evolution is an absurdity. Each species is fixed in its type, and fixed in relationship to every other species. Together with the Judeo-Christian view of Creation, as expressed in Genesis, this view dominated western culture for two thousand years.

In Genesis, the world was created at one time. Thus all species were formed at that period, and by this argument again, there was no logical means by which species could change or evolve from one type into another. Fish, frogs, reptiles, birds, and mammals first appeared during creation and have been present on earth since then.

Thus, between the teachings of Genesis (written approximately 450 B.C. recounting tales of 1000 years earlier) and the teachings of Plato (427–c347 B.C.) and Aristotle (384–322 B.C.) from a logical standpoint as well as from the evidence at hand, species were fixed and there was little reason to worry about, or even concern oneself with, the relationship of one organism to another. The similarity of monkeys to humans had been noticed, as had the similarity of organs and bones among different vertebrates, but these resemblances were considered to be examples of God's choice or God's wisdom, rather than peculiarities of the world that deserved attention and analysis.

WHERE DID I COME FROM? INTIMATIONS THAT NOT ALL WAS STABLE

By the 17th C, however, the European world had changed. The world now had a long tradition of literacy, coupled with printing presses that made knowledge accessible to a much larger population, and explorers were describing the strangeness of the new continents that they were exploring. Philosophers, who at that time were not distinguished from scientists, were pondering the meaning of all of the new knowledge, and the evidence that life in 17th C Europe was very different from what had been described in the Bible and in Aristotle. They were susceptible to the concept of change. In terms of social structure, economic structure, political order, and even values and mores, the world today (17th C) is different from what it once was. There have been periods of wealth and poverty, pestilence and health, democracy and tyranny; and what had been a rural society (Germany, England, Ireland) became a society with great cities. Islam had appeared in the 8th C and grew strong enough to compete with Christianity, and the religions of the Orient and of the New World were very different.

Thus the world could be restructured, perhaps not in front of one's eyes, but over time. Where did it come from? What caused the restructuring? Was it possible that the natural world could change as well? Perhaps the similarity of the bones of a dog to those of a human told us more than we had suspected.

It may strike many as surprising, but many of the main elements of the story of evolution were well known long before 1859 and were the subject of popular discussion among intelligent and educated, but not professional, members of upper-class society. The Enlightenment had not truly invented but had brought to the forefront of intellectual life several attitudes that continue to pervade our society: an emphasis on material evidence and human logic, as opposed to mysticism or unquestioning faith, as the basis of rationality (Galileo & Copernicus); a powerful sense of the mechanical or physical construction of the universe (Galileo, Newton, Pascal); and a widespread but quintessentially British assumption of continuous progress in the history of the earth, leading of course to the summum bonum (maximum good) exemplified by contemporary British society. Each of the episodes that we now identify as landmarks in the history of science originated in the attempt to address a specific practical problem, and each had generated spectacular and immediate success. These successes validated the assumption that much could be learned from the physical world, and led to further inquiries about the anomalies of the earth, ranging from curiosity about the origin of mountains to efforts to understand fossils in the context of or opposed to the biblical description of the history of the earth. We will discuss these below, but to give a sense of the pragmatism that allowed natural philosophers to gain ascendancy over theologians and philosophers, we can cite a few examples: One was that motion was associated with life, and thus its laws were worthy of exploration. Furthermore, issues such as the trajectory of cannonballs and, for the purposes of armies and explorers, measuring movement around the earth provided plenty of work for those who would ultimately become physicists. Galileo was well known for his studies of trajectories and compasses. Others needs included the measurement of longitude and interpretation of disease, as is described below.

THE USES OF SCIENCE AND THE DISCOVERY OF THE MECHANICS OF THE EARTH

Both philosophical inclination and practical considerations drove a 17th C interest in movement. From the philosophical viewpoint, movement, or at least directed movement, was one of the few features that separated the living from the inanimate. Thus the difference between a dog, horse, or human one minute after death and one minute before death was manifest primarily in movement, of the chest, heart, limbs, or eyes. Thus, as the value of mechanics impressed itself more on European society (see below) attention turned to an understanding of motion as part of the deeply philosophical and even holy quest to answer the age-old question, “What is life?” Rather than address this question from purely theoretical or philosophical terms, thinkers turned to mechanics, or experimentalists, to help them understand. There was plenty of reason to view this approach with optimism.

Greek scholarship had returned to Europe via Spain, since the Islamic unlike the Christian world had never lost it and the Moslems, though eager to keep their distance from “heathens,” nevertheless would communicate through intermediaries, frequently Jews. It was no accident that Maimonides, the greatest of the Jewish philosophers, and certainly a great physician and philosopher by any criteria, had a strongly Aristotelian attitude, including the argument that God’s miracles worked through, and did not violate, physical laws. Likewise, Nostradamus’ writings arose from an effort to reconcile a profound logic with apparent contradictions in holy writings—the effort that gave rise to the Kabala (Page 403). Thus the role of (perhaps) Archimedes (287–212 B.C.) in devising catapults and other instruments of war based on the theoretical understanding of the physics of levers, and the practical benefit of his correlating density of matter with displacement of water, so that he could tell whether gold had been removed and substituted in the king’s crown, were familiar to scholars. The question became whether such approaches could contribute to various practical problems, ranging from the construction of

Likewise Andreas Vesalius scorned a slavish following of ancient texts, leading the world to a new understanding of anatomy and the function of the body (page 406), in the same year (1543) that Copernicus rejected elaborate mathematical models of the universe in favor of simple calculations based on the idea that the sun, not the earth, was the center of rotation. By the 17th C the experimentalists, like their counterparts in physics and geology, were in charge: Francisco Redi had established that maggots on exposed meat had come from the eggs of flies (page 141), leading Harvey to the conclusion "Ex ova omnia" ("All [life] from eggs"). Harvey also showed in 1628 that the heart circulated blood in the body, leading to better insight into the importance of dehydration and bleeding. There were many other scientific activities at the time, including of course the work of Sir Isaac Newton on optics, gravity, and the laws of motion.

Europe meets the Americas

This increased respect for, and interest in, the mechanics and the tinkerers, led to the subjects of the nascent scientific research becoming a matter of interest for all educated citizenry. In fact, since all exploration costs money; money was available only in the noble and mercantile classes; and merchants were, by and large, too busy trying to earn the money to be very philosophical, scientific exploration was to a large extent a hobby or amateur (literally, lover) occupation of the more relaxed (idle?) nobility. As such, these activities were widely discussed in the upper classes. Curious findings (in the broader, original sense, meaning unusual enough to provoke wonder about their meaning or origin) were considered, marveled upon, and discussed. In the age of exploration, there were many curious findings. New animals and plants, and reports of wonders, were being brought from abroad, and explorations of the geology of Europe were forcing people to ask questions about their meaning. The level of excitement over new wonders can be appreciated in a few anecdotes: chocolate, brought from Mexico, was presumed to be a powerful aphrodisiac, and therefore sequestered to nobility; tulips, brought from Turkey, were considered so precious that there was a tulip frenzy, with rare bulbs being sold, in a stock market-like structure, at today's equivalent of hundreds of dollars per bulb; and newly-met indigenous peoples were routinely interpreted as being descendents of one of the lost tribes of Israel. As is described in Chapter 7, page 81, the realization that the rest of the world contained novel species initiated the query of how all of this fit in with the story of Genesis, but at home the new-found interest in the structure of the land meant that, instead of simply accepting phenomena, the mechanism-based scientists began to ask how the phenomena came to be. In common terms, the transition was from "Yes, those hills have funny [or pretty] stripes" to "What made those stripes in those hills, and why do they look like the stripes on the hills on the other side of the valley?" This was the basis of Steno's identification of the principles of geology, but in terms of evolution the argument is much more cogent: "I know that I can get limestone for making my mortar from the white areas of the earth, but those white areas are white because they are filled with old shells. The shells look a bit like the ones on the beach, but they are not the same and, besides, they are on the top of a mountain. What is going on?"

The Discovery of Anatomy Raises New Questions

Georges Cuvier, the director of the Musée d'Histoire Naturelle, was a master anatomist. As is described in Chapter 3, page 35, there are specific correlations among organs and structures such that it is possible to assess the lifestyle of an animal from its general appearance. Any person, and indeed any animal, can distinguish between a dangerous carnivore such as a shark or a lion and a peaceful herbivore like a zebra or a goose. Our films and our creative fiction exploit this ability, showing dangerous fictitious predators such as werewolves, zombies, and aliens from outer space with the appropriate paraphernalia of a predator: large, sharp, tearing teeth like canines, strong arms with claws or other lethal cutting weapons, and forward-facing, distance-judging eyes. A hypothetical science fiction movie showing people terrified by an invasion of cows or guinea pigs would be laughed out of a theater. Cuvier was one of the men who verbalized these intuitive judgments, but he went much further. To Cuvier, each part of the anatomy necessarily related to every other part, in the sense that, if one takes a femur (upper leg bone) from an unknown animal, the shape of the joints indicate how it attached to the pelvis and the tibia (lower leg bone) and from this one can determine if the animal was truly quadruped (four-footed) or walked upright. In fact, it was said of Cuvier, and he did not deny it, that he could reconstruct an entire animal from a single bone. For this talent, he was justly famous and, in the structure of society at the time, he and his colleague and to some extent mentor Geoffroy Saint-Hilaire associated with and were admired by such prominent literary figures as Wolfgang Goethe, Etienne Balzac, and Georges Sand. (Goethe was also an outstanding botanist, having recognized that flowers and other appendages of plants were modified leaves.) In the midst of the French revolution of 1830, Goethe was far more excited by the prospect of a debate between Cuvier and Geoffroy than by news of the war. Balzac was sufficiently interested in the debate to describe it in his introduction to *The Divine Comedy.*

The social structure however is another story, and told at greater length and in more detail elsewhere (see bibliography for books by S. J. Gould). Of interest here is what Cuvier learned from his skills and knowledge. First, he realized that the fossils in his museum and being collected at an increasing pace represented real animals, and ones that he could classify and for which he could describe lifestyles. Second, as Geoffroy would summarize in an aphorism ("There is only one animal."), all the tetrapod (four-legged) vertebrates had essentially the same bones in their limbs, whether the limbs served for swimming (whales), flying (birds or bats), walking (dogs), digging (moles) or carrying (humans). Third, many of the animals represented by the fossils were unlike anything seen on earth. Fourth, understanding Steno's principles of stratigraphy pages 40–42, the ones most like today's creatures were closest to recent times, and they never appeared in the earlier layers. Fifth, many species had finally disappeared. Geoffroy had studied the anatomy of different organisms to the extent of trying to identify in fish the homologs (parts related by ancestry) of the bones of the inner ear of mammals. To the logical and analytical Cuvier, the data had only one interpretation: the stratification of fossils told the history of animal and plant life. The creatures found on this earth had changed over time, with some types of animals completely disappearing from the record. The similarity of bones betokened a common ancestry. He stated this argument clearly in his first major book on the subject, in 1812, *Research on the fossil bones of quadrupeds, from which one reestablishes the characteristics of several species of animals that the upheavals of the earth*[2] *appear to have destroyed.* Could one state more clearly the concept of extinction and possibly evolution? Why then do we mark 1859, the year of the publication of "*Origin of the Species*," as a turning point, rather than 1812?

Cuvier saw what had happened, but he lacked two crucial points: First, he understood sequence, but he had no conception of the time that it took. In other words, if you live in a big or industrial city, you are familiar with the fact that every day a little bit of soot accumulates. You can imagine that, over the space of 1000 years, on an undisturbed space a few inches will accumulate—let's say, five inches. If you now find a soot layer four feet deep, you might reasonably conclude that the soot had been accumulating for approximately 10,000 years. However, suppose that there is a volcano not too far away. A single eruption of a volcano might produce a foot of ashfall, or two feet of ash, or four feet of ash. You surely can establish the sequence of the accumulation, but without sophisticated modern technology, can you unequivocally argue that it represents 10,000 years of accumulation, as opposed to a single day of volcanic eruption, or anything in between?

The second problem that he had was the inability, because of lack of this sense of time as well as the social context that led to his asking the specific questions, to conceptualize a new, grand theory of mechanism. In the world of Cuvier and Saint-Hilaire, the issue was much more how the fact that vertebrate bones were homologous would demonstrate the wisdom and beneficence of God. What was the genius of using the same basic plan for all vertebrates? There was surely method, but what advantage did it bring? The great debate of 1830, fervently followed by the intellectual community and continued with follow-up books and pamphlets, was not over the issue of evolution, but whether God's plan ordained specific types of creatures, each containing a modest variation on a theoretical ideal type (Geoffroy) or whether God's wisdom was displayed in the excellent fit that He had constructed from a basic sketch to serve each animal's unique needs (to swim, run, fly, walk, or dig—Cuvier). What Darwin brought to the picture was the certainty that the fossil record was a true representation of a sequence of historical events; that the species had changed rather than been replaced; that the earth was old enough to account for

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[2] The French title that I have translated as "upheavals of the earth" is "les révolutions du globe," literally "revolutions of the globe" but the term "révolution" is more similar to the meaning "revolt" or "American Revolution" than to the concept of turning in a circle.

these changes (this information was inaccessible to Cuvier but was widely believed forty-some years later); and, above all, a MECHANISM by which it could have occurred. The mechanism, the Logic of the ELF triumvirate, was obligatory for a theory of evolution. The function of the preceding discussion is therefore to argue that the evidence of the fossil record had been available, and that its implication—the true existence of antecedent animals, and their successive replacements over time—was well accepted. Furthermore, there was extensive knowledge of the anatomy of common and exotic animals, and their relationships were puzzled over, from the obvious homologies of the bones even to bewilderment over the existence of vestigial and completely useless pelvic bones in walruses and some whales. They worried about such issues as, if the failure of the skull bones to fuse before birth in mammals is Divine provision to allow the head to be smaller and to mold during birth, thus demanding less distention of the birth canal, why were the skull bones of birds not fused before hatching? All the birds had to do was to break the shell, not push through the narrow pelvis of the mother. These issues were being hotly debated in England as well, most notably by Richard Owen, "the British Cuvier," who likewise was deeply concerned by the similarity of bones in limbs of such different functions. As he wrote in 1848, "The recognition of an ideal Exemplar for the vertebrate animals proves that the knowledge of such a being as man must have existed before man appeared. For the Divine mind which planned the Archetype also foreknew all its modifications."

Embryology was also appearing on the scene, as microscopes and techniques improved to allow the first embryologists to preserve, dissect, and observe the typically tiny, watery, and mushy early embryos of animals. What Ernst von Baer observed and correctly interpreted by 1828 was quite startling: embryonic humans had tails like other mammals, and all vertebrate embryos had gills. Human tails disappeared by failing to grow at the same rate as the rest of the embryo, ultimately being seen as the internal curved end of the spine, the coccyx. In land animals, the gills ultimately ended up as (morphed into) structures of the throat. If he had not traced their development, he would have never recognized the relationship in the adult. In any event, to von Baer it was clear that the embryo of a human contained also the embryonic stages of aquatic and tailed creatures. He considered that they were there by inheritance, but did not extend the argument. Once the story of evolution had broken, Ernst Haeckel made the connection with his famous aphorism, "Ontogeny recapitulates phylogeny," meaning that the developmental stages indicate the evolutionary line of descent.

What do the Relationships Mean?

Jean-Baptiste Lamarck is today somewhat unfairly ridiculed for one of his extrapolations of his findings, but at the beginning of the 19th C his careful observations and interpretations contributed another step on the ladder to the story of natural selection. What Lamarck saw was the marvelous fit of form to function, such that wings of birds allowed them to fly while the limbs and overall shape of porpoises were well adapted for swimming. Giraffes had long necks to feed on tall acacia trees, and ducks had webbed feet to allow them to swim. The perfection of these matches, according to Lamarck, could only be explained by (God's generosity in arranging) the adaptation of animals to their needs. Taking his cue from the obvious adaptation of individuals to changing circumstances—muscles grow in individuals who do hard physical labor, and atrophy in immobilized limbs, and plants send leaves toward the light and roots to the soil—he proposed that the adaptations of animals to their surroundings was a direct growth or other response to their situation. Furthermore, he studied fossil mollusks, which are shells often with a long and continuous history. He saw, in the series that he studied, substantial evidence for a gradual change in form and size from the archaic to the modern forms. From what he knew and saw, he proposed that animals adapted to their environments and that the adaptations would be inherited. In this latter point he was wrong, as he had no idea that the cells of inheritance, the germ cells, which produce the gametes (eggs and sperm) are independent of the body cells (somatic cells) and cannot pick up what we today call acquired characteristics. This distinction was discovered only in 1888 by August Weissmann (page 178), in direct test of Lamarck's theory, and even Darwin assumed that the body's characteristics drained into the gametes. However, the fundamental observation that species changed over time was provocative. It challenged Linnaeus' assumption that the species were fixed, instigating a controversy and opening the speculation as to exactly what would have been taken onto Noah's Ark. What was important to this story is that he put onto the table for all, including Darwin, to see the evidence that species were not fixed. He did not believe in extinction, which substantially undercut his argument. Although many argued vehemently with his theory, emphasizing such evidence of imperfect adaptation as vestigial organs and the massive teeth of sabertooth tigers, the evidence of the gradual change of at least the molluscan species was not denied. Cuvier later demonstrated that many fossils represented creatures no longer found on earth. As Pietro Corsi notes, Lamarck's was "the first major evolutionist synthesis in modern biology" (quoted in Browne).

THE SEARCH FOR MEANING AND THE DISCOVERY OF TIME

The other major limitation to a theory of evolution was time. To anatomists and interpreters of fossils such as Cuvier, the biblical accounting, as interpreted by Ussher and others, was dubious, but they had no measuring rod against which to judge the scale of events. This measuring rod, if not precisely constructed, was at least given a meaningful existence by Charles Lyell. Lyell, who combined a scientist's precision and attentiveness to detail with a persuasiveness derived from his career as a lawyer, had set out to deny the theory of catastrophism, the theory that all events and changes on earth had resulted from (bible-described) catastrophes and cataclysmic events. He argued that the great changes now recognized on earth could result from gradual changes over great periods of time. For instance, one might encounter massively folded sedimentary rocks (see Chapter 2, page 27) overlying or underlying horizontal layers. (Fig 2.1). According to Steno's rules (page 41),

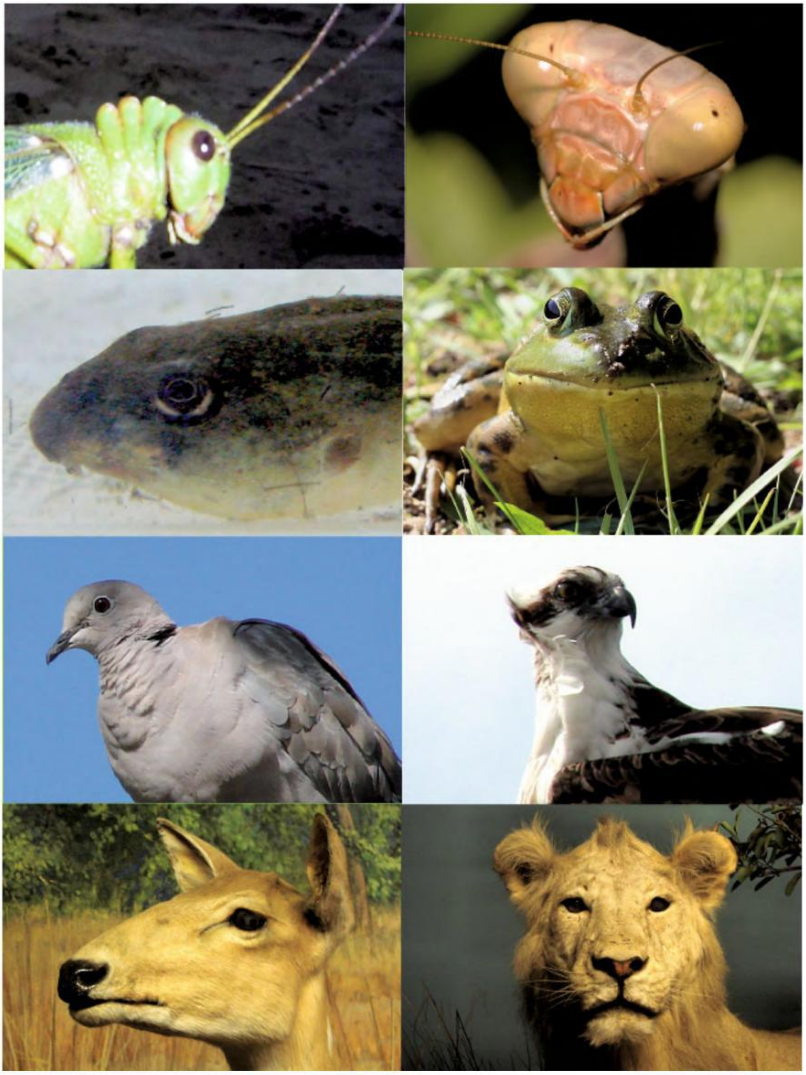


Figure 3.1. Reading the function of animals from their forms and, ultimately, their skeletal systems. Herbivores (left), whose noses are often in grass, have a high need to see what is coming from behind and would ideally be suited with 360° vision. They therefore have eyes on the sides of their heads. Carnivores (right) need good depth perception, achieved when both eyes register the same image, in order to capture prey, and so they have forward-facing eyes. Carnivores also have tearing claws, teeth, or beaks. Closely-related pairs are shown, the herbivores on the left, and the carnivores on the right. From top to bottom on left: grasshopper or locust; bullfrog tadpole; mourning dove; antelope. From top to bottom on right: praying mantis; bullfrog; bald eagle; lioness. Credits: Praying mantis - © Photographer: Rogelio Hernandez | Agency: Dreamstime.com, Bullfrog - © Photographer: Loricarol Lori Froeb, Yorktown Heights NY | Agency: Dreamstime.com

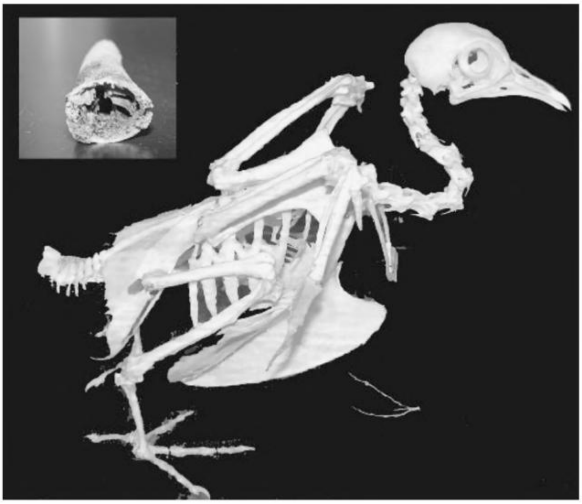


Figure 3.2. Reading the function of animals from their forms. The large keel or breastbone of a pigeon gives a location for attachment of the flight muscles, indicating that this creature is a good flyer. Other indicators of course are the wings and the fact that the weight is well balanced for flight in that there is a beak, but no heavy teeth, in the mouth. Inset: even the bones are very lightweight and even hollow. (Birds use spaces in their skeletons both to lighten the density of the bone and to increase the efficiency of air circulation so that their lungs can work more efficiently, both when they are working hard and when they are at high altitude.)

seen a living trilobite (Fig. 3.5b) we can recognize a certain similarity to that of living horseshoe crabs (Fig. 3.5b) and we can certainly conclude, based on its general body plan, legs, mouthparts, and gill structures, that it was a creature that crawled along ocean bottoms and lived a life fairly similar to that of the horseshoe crab.

This brings us to the main argument, which was an issue that was known to Aristotle and which became more important from the 17th to the mid-19th centuries. There are fossils, unequivocally of marine animals, near the tops of mountains (Fig. 3.6).

Why are they there? Over the centuries, several explanations were posited: The sea was once that high; the fossils are evidence that life can be generated out of rock; the animals were deposited there during Noah's flood; God put them there; the Devil put them there to confuse and challenge humans. Some thinkers were more analytical. Ovid wrote in *Metamorphoses* (Book XV), "Nothing lasts long under the same form. I have seen what once was solid earth changed into sea, and lands created out of what once was ocean. Seashells lie far away from ocean's waves, and ancient anchors have been found on mountain tops." In one of the most remarkable and illustrative stories of the history of science, a group unfettered by commitment to a specific theology or philosophy had clearly worked out an understanding of rock strata 500 years before the first Europeans dared suggest

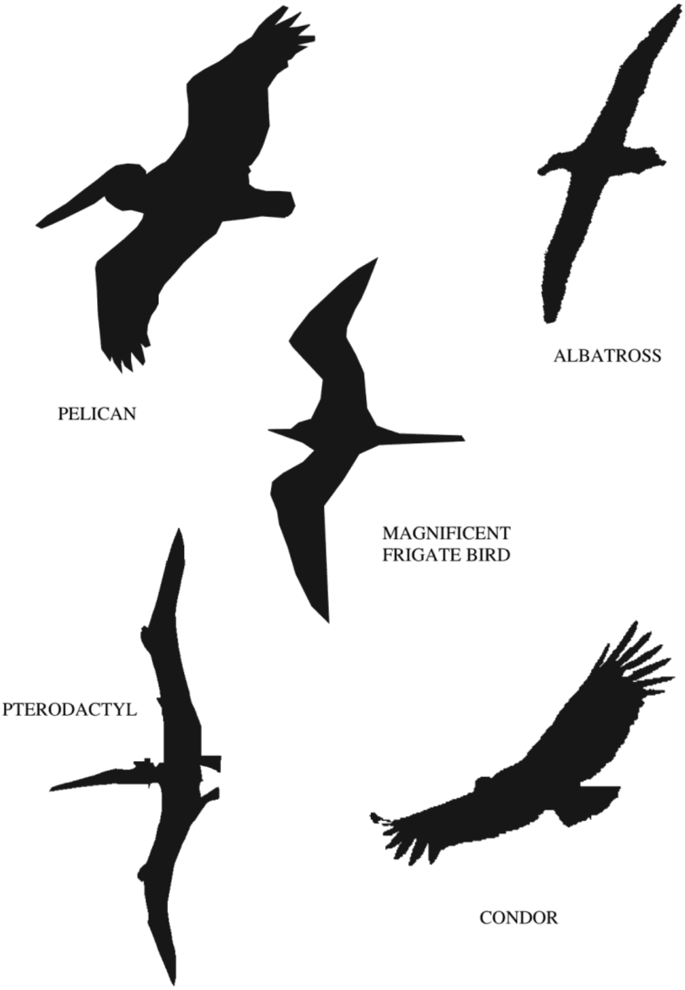


Figure 3.3. Reading the function of animals from their forms. The physics of flight dictates that only certain types of shapes can efficiently collect the updrafts of thermal currents to soar well. Illustrated are the silhouettes of four birds known as excellent soaring birds: the pelican, magnificent frigate bird, and albatross, all of which soar over oceans; and the condor, which habitually soars away from its mountain nest at elevations of 10,000–16,000 feet. Darwin watched condors soar for over an hour without once flapping their wings. Also illustrated is a reconstruction of a fossil pterodactyl, a flying reptile. From its shape it appears to have been similar to a soaring seabird. The figures are not drawn to scale

it. Aristotle had thought that the world was eternal. In Syria, a mystical sect of Shiite Muslims, the "Brothers of Purity," had a motto, "Shun no science, scorn no book, nor cling fanatically to a single creed." In an encyclopedia they wrote, they clearly described the erosion of mountains and hills by rivers, the carrying of the pebbles and rocks to the sea, the conversion of the larger particles to sand by

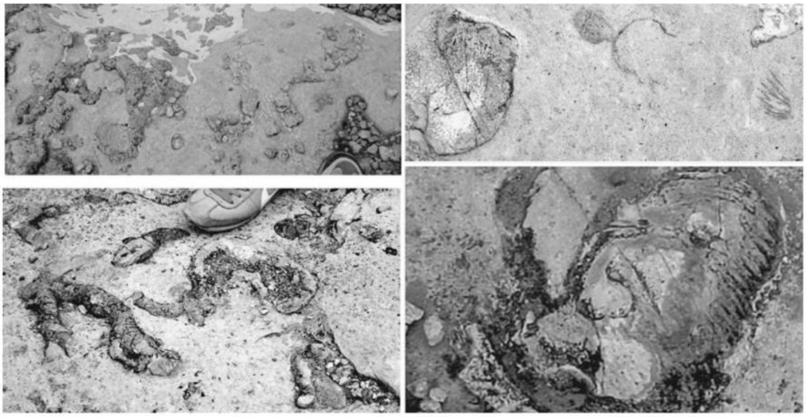


Figure 3.6. Marine fossils at the top of the Grand Canyon (7,200 feet elevation). Upper left: Tracks of marine worms. Upper right: Scallops and clam shells. Lower left: Marine worms in their burrows. Lower right: clam. All of these fossils and tracks are very similar to those that can be found today near seacoasts

they were. The most common interpretation was that they were magical, curative agents deposited in Malta in commemoration of the Apostle Paul's miraculous survival of a snake bite on the island. They were eagerly collected and sold for substantial profit. Although in the previous century Guillaume Rondelet had noted that they resembled shark teeth, this idea did not carry much weight. There was substantial financial and ideological support for not changing the story. It was also considered possible that these and other embedded structures grew spontaneously in the rocks and were an example of the spontaneous generation of life. Unfortunately for this trade, Steno recognized the obvious, that these were the teeth of sharks. Following the dissection of a great white shark that had been captured and the head of which brought to Florence for him to dissect, he published this argument with its implications that the island of Malta had at one time been under the sea and that giant sharks, no longer seen on earth, had lived in that sea (Fig. 3.7).

Several other fallacies were subject to Steno's merciless logic. One was the possibility that the shells grew in the rocks. He pointed out that, if a living organism were to grow while buried deep within a rock, the growth would necessarily split the rock. Anyone who has seen roots push through sidewalks or basement walls will appreciate this argument. Furthermore, Steno pointed out, if mud comes to overlay a rock, the mud will conform to the shape of the rock. He generalized this argument to a principle: if something plastic or semi-solid buries a hard substance such as a rock, or a salt crystallizes around it, the later material will conform to the shape of the earlier. In other words, if mud settles on a rock and, through chemical processes, the mud itself becomes hard or rock-like, the mud will be molded around the rock. He went on to point out that the rock molded around the shells. Therefore,

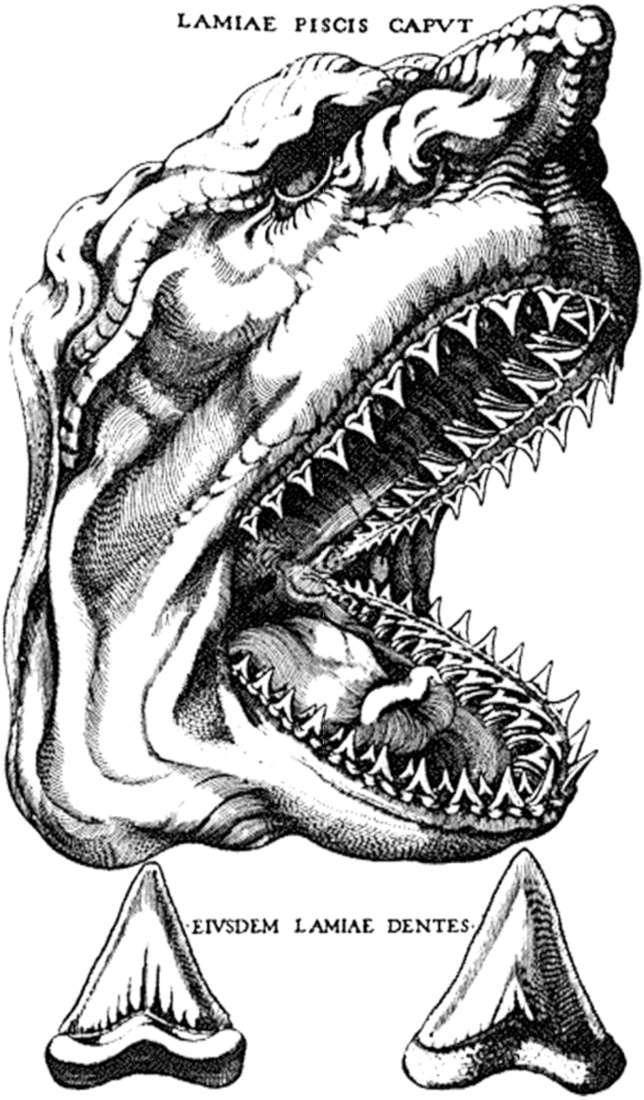


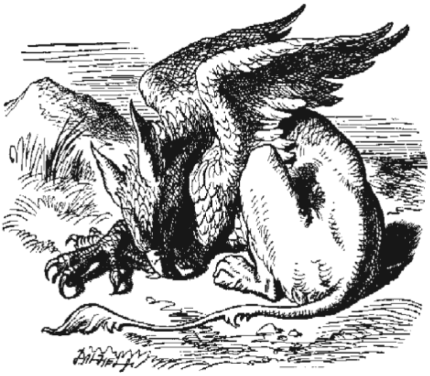
Figure 3.7. Fishermen brought the head of a great white shark that had been captured off the coast of Italy to Steno to dissect. Although coastal fisherman had seen the teeth of sharks, they were not familiar with teeth the size of the "tongue stones" that had been found as fossils. Steno realized that the teeth of the great white shark were identical in almost every detail to the tongue stones and argued that these fossils were indeed the remnants of gigantic sharks. This is his illustration of the comparison of the teeth to the tongue stones. Credits: Steno glossopetrae - http://earthobservatory.nasa.gov/Library/Giants/Steno/Images/sharkhead.gif

according to Steno, the shells had been buried in sedimentary mud, and the mud had eventually turned to rock. The shells were not growing in the rock.

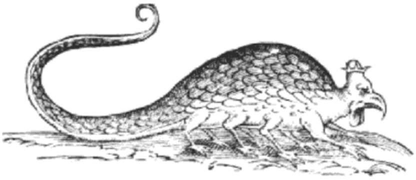
Why did he assume that the rocks had been sedimentary mud? He had observed what happens during floods and when streams meet the sea. Floods carry a lot of mud, which settles out on the flood plain when the flow rate decreases and the waters retreat. This is a major means of nourishment of soils such as those of the Nile River. Also, for physico-chemical reasons, much more sediment can be suspended in fresh water than in salt water. When streams enter the sea, because of the slowing of the flow rate and the mixing of the waters, the mud of streams settles into large deltas, as is seen in many parts of the world, such as where the Mississippi meets the Gulf of Mexico (Figure 8.3, page 99). Steno had seen all of this and realized that the hillsides surrounding rivers and bays seemed to be a continuum of the flooding and sedimentation of the valley, even if the hillsides were now rock. This conclusion was not an idle guess. To convince himself, he studied the rocks of the hillsides. Besides the evidence of the sedimentation lines, he looked at the fine structure. They bore the characteristics of floods. First, when mud settles onto a surface, by the law of secondary deposition it takes the form of the uneven surface onto which it settles, but the upper layer, now settling by gravity, will be flat or flatter. The lines of the rocks displayed this characteristic. Second, when material begins to settle out, the heaviest (largest) particles will settle out first, followed by the smaller particles. One can easily see this by suspending any sample of mud or sand in water in a glass, and letting it settle out undisturbed. There will be a distribution of particles, with the largest ones on the bottom (see Fig. 8.4). Steno found this characteristic also to be true of the sedimentation lines of his rocks. Finally, he formulated his (obvious) Law of Superposition: When sediments are laid down, the newer ones will be on top of the older ones. Therefore, even if stones are found at strange angles (Fig. 2.1) it is possible to determine which is the top and which is the bottom.

This logic led Steno to recognize both that the earth was likely to be very old; that much had been formed by sedimentation in water; that the height of the land relative to the sea had changed drastically; and that, from the folds and angles of the sedimentation, the land had undergone violent and tortured existence. In spite of the facts that his logic was impeccable; that he was sufficiently highly considered that he became a bishop and in 1988 was canonized (on October 23, the anniversary according to Bishop Ussher of the formation of the world—see page 51; and he is now considered to be the father of modern geology, his findings and theories were not universally recognized, and it would be two hundred years before the world would come to be comfortable with similar arguments presented by Lyell, as is discussed elsewhere (pages 82 and 168).

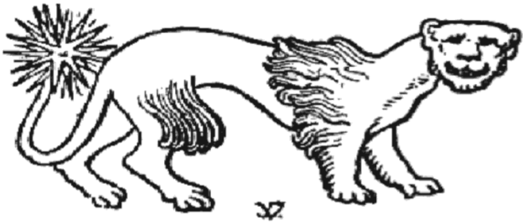
Although the ideas were growing, the biggest intellectual limitation was the sense of time. According to Steno, it was evident that the earth had changed. He was aware that during his lifetime he could measure very slow and gradual change, but it was not yet totally acceptable to extrapolate the rate of change. Massive floods such as Noah’s flood might leave hundreds of feet of sediment, though one would have



Gryphon



Basilisk



Manticora. From ancient Bestiaria.

Figure 4.1. Mythical creatures from medieval and early renaissance times. With limited ability to travel and otherwise explore the world, most literate people saw no important differences between creatures such as these and other fantastic animals such as the rhinoceros, the giraffe, or the crocodile. Credits: Gryphon - Gryphon illustration by Sir John Tenniel for Lewis Carroll's Alice in Wonderland (Wikipedia) Basilisk - Source: Ulisse Aldrovandi, "Monstrorum historia", 1642, Austrian National Library, Signature BE.4.G.23 (Wikipedia) Manticore - A manticore from an ancient bestiary (Wikipedia)

ornithologist (one who studies birds), counted all the birds he could identify on one island in New Guinea. Like Ernst Mayr who had preceded him, he asked the pre-literate tribesmen how many types of birds there were, and came up with essentially one-to-one correspondence. (Diamond recognized differences between two extremely similar species of moderate interest to the native population; the native people considered the two to be the same species. In at least one instance the New Guineans were more perceptive in distinguishing species than he was.) Diamond did not conclude that all his education and training had led to no greater sophistication than a pre-literate hunter. He concluded instead that, in a limited territory such as an island, species were quite distinct and easily discriminated. It was only when a zoologist ranged over larger territories and found geographical a zoologist variation—for instance, a frog from western North America might be bigger and fatter, with a slightly different coloring pattern, than a frog from the and classify all living things. Remember that he was working approximately 250 years after Columbus first reached the Americas. It seemed necessary to undertake this classification, because explorers were bringing back plants and animals that had not been known in Europe, and the list of known creatures was beginning to expand. The project, however, still seemed reasonable. However, clouds were beginning to appear on the horizon. We can describe it as the problem of the kangaroo.

The Australian kangaroo is a marsupial, meaning that although it is warm-blooded and fur-bearing, its young are born extremely immature and promptly migrate to a pouch, where they physically attach to a milk-producing gland that is not quite the same as the nipple of a true mammal. There are a few other differences that separate kangaroos, opossums, and their relatives from most other mammals. Using the kangaroo as an example is somewhat misleading, since the first kangaroos were not known to Europeans until 1770, but they illustrate the problem introduced by the raccoons, skunks, and opossums of the new world: How did they get from Noah's Ark to North and South America without being seen, either alive or as fossils, in Europe or the Middle East? One could adjust to the idea that, for instance, lions were seen in northern Africa or the Middle East but not in Europe because, after all, Europe was colder. It was theoretically possible for lions to be in Europe, walking across the land links of the Eastern Mediterranean. Lions simply did not like to be in Europe. However, the climate of North America was not that different from that of Europe, and there was no obvious reason why a raccoon or opossum or skunk could not live in Europe. The same could be said for the true cacti, the spiny flat, branched, or ball-like plants native to the New World deserts. Contrary to old cowboy films and popular images, they did not exist in European, African, or Asian deserts. The world could live without poison ivy (though for a brief period the English considered it to be an attractive houseplant), but creatures of considerable benefit to humans, such as corn, tomatoes, and potatoes, sugar cane, sunflowers, and chocolate, were quite popular among the natives of the New World, as was tobacco, but were unknown in the Old World. Why had God not given Europeans the benefits of tomatoes, potatoes, and corn? Surely the Ark was not a holy Greyhound bus, dropping off passengers on different continents.

Even the explorers were confused. The great explorers were courageous but also extremely knowledgeable people. They had to orient themselves on the ocean so that they would return, for instance, to Spain rather than going too far north and running into England or too far south and running into Africa; they had to be able to locate fresh water and to successfully hunt for food whenever they reached land; they had to locate trees suitable for repairing and waterproofing their boats (pitch pines, named for the waterproof sap they exuded); they had to be able to defend themselves or, preferably, barter and trade with people whose language they had never encountered. The translators, the physicians, the naturalists on these boats were very important members of the crew. Thus it was that Columbus, reaching Hispaniola (Haiti/Dominican Republic) knew that he had landed on an human control of breeding, and it was very clear that horses, cattle, goats, sheep, birds, and (in China) fish could be markedly altered by human choice of breeding partners. It was less obvious but at least intuitively understood that domestic crops could be improved and changed markedly from their wild ancestors by selective breeding. So, did Noah take on board a German shepherd or a poodle? By 1809 Jean-Baptiste Lamarck was arguing on this basis as well as that of Cuvier's fossils, that Linnaeus was wrong, that species were not fixed but could change over time. Lamarck proposed that animals and plants changed in response to their environment. He is subject to some ridicule today because we now know that he misinterpreted the causal relationships (see Chapter 12, pages 167–168) but in fact he was a highly intelligent, perceptive scientist who heavily influenced the theory of his time and led to later advances.

Thus the biology of the herbals and zoological books was becoming less and less certain. These concerns were joined with a similar growth of concerns regarding the physical world that had begun to grow in Eastern Europe. The Pole Nikolai Kopernik, better known by the Latin form of his name, Nicolaus Copernicus, in 1514, about 25 years after Columbus' voyage, proposed that the sun, not the earth, was the center of the solar system. Copernicus' ideas were not readily accepted, both for ideological reasons and for reasons having to do with the ELF rule: His evidence was not very good. Copernicus described perfectly circular orbits, but with the calculations of perfectly circular orbits the match to the actual paths of the planets was not exact. The great astronomer Tycho Brahe, who believed in epicycles (wheels spinning on the edges of other spinning wheels, Fig. 4.2) calculated epicycles that came far closer to matching the actual positions of the planets. Copernicus argued on the basis of Logic, similar to that of William of Occam, who argued that the simpler hypothesis was the one to be believed (Occam's Razor), that epicycles were an affectation. However, Brahe's Evidence was stronger. It was not until Johannes Kepler demonstrated that the

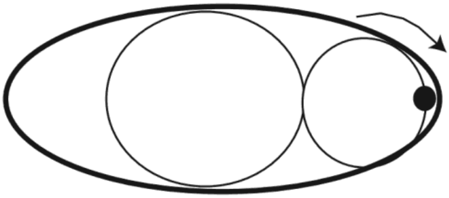


Figure 4.2. Epicycles. If one circle (or sphere) rolls along another, depending on the relative sizes of the two spheres, a single spot on the external sphere will appear to trace an ellipse through space or even go backwards. Since the trajectories of the planets as viewed from the earth follow such patterns, elaborate mathematical schemes based on the position of the spot were devised. Calculations such as those of Tycho Brahe predicted quite well the positions of the planets, but the theory was abandoned when Copernicus and later Kepler argued that there was no physical reason for epicycles and that a simpler model was orbits around the sun. As the concept of gravity developed, it became possible for Kepler to calculate elliptical paths based on the laws of motion and gravity. These proved more accurate than the calculations of Brahe

orbits of the planets were elliptical, that logic and evidence merged. The result of epicyclical movement would be an ellipse, but the hypothesis of an ellipse around the sun was much simpler than the hypothesis of epicycles around the earth. This argument continued to build for almost 100 years, until in 1609 Galileo received a telescope, which had recently been invented, and used it to demonstrate that the heavens were not constructed as had been believed. By 1612 Galileo was convinced that the earth revolved around the sun, leading to the well-known trial of 1616.

The stability of the earth was also less certain, and again the Age of Exploration had some impact. First, mapmakers had been making maps for a few hundred years. Although the outlines of the continents were rather imprecise, coastlines were important to sailors, and especially the locations of small islands and shoals that were hazards to the ships. It was beginning to become apparent that in these details river mouths could change over the years as silt accumulated in some areas and erosion opened others. By 1795, James Hutton from Scotland was suggesting that the features of the earth were not permanent but were gradually changed over time by erosion, sedimentation, and similar processes. His theory was called **gradualism.** And the exploration of the New World was raising other questions. For instance, the Grand Canyon was first reported by Garcia Lopez de Cardenas of Spain in 1540. Though scientists did not really try to understand its construction until 1870, it was clear that the Colorado River had cut it, and any reasonable estimate of how fast a river cuts a channel made one wonder about the age of the earth. In 1650 the Irish Bishop James Ussher had published the first part of a monumental work, in which he had assiduously counted all the dates and ages backward through the Bible, compared some dates with Greek records, and made an assumption or two. Using these calculations, he came to the conclusion that the world had been created on October 23, 4004 B.C. This calculation seemed in line with previous assumptions, based on estimates of the Bible; it was hailed as an achievement, and accepted without excessive circumspection for almost 200 years. However, geological formations like the Grand Canyon made one wonder: was approximately 6000 years enough to cut such a canyon?

Between the 16th and the 19th centuries, many of the apparently solid beliefs on which the interpretation of Genesis was based were increasingly in difficulty. The increasing confusion as to exactly what a species was made it difficult to understand whether Noah would, for instance, have brought on board a pair of eastern bullfrogs and a pair of western bullfrogs, or just one pair of bullfrogs, and it made no sense that the Ark had specific drop-off points or stops on route. God seemed to have made some species only to let them die out. Barkless dogs did not serve humans in the way that Europeans understood. The Bible gave a maximum age for the earth of 6000 years, less if one assumed that the 800+ years of the patriarchs of Genesis were allegorical, but there was indication that some features of the earth would take longer to form. And why were there seashells in the mountains? Several of the changes that came about are described in Fig. 4.3. This figure should be used in reference to the several Chapters 3–8.

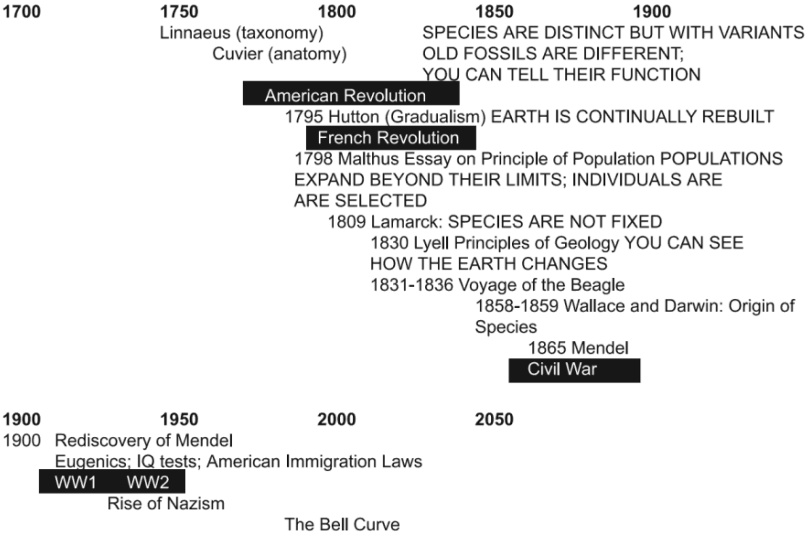


Figure 4.3. The historical context in which the story of evolution was born

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STUDY QUESTIONS

1. Look at any type of organism that you commonly encounter: sparrows, pigeons, dandelions, tropical fish, maple trees. Do you have any difficulty identifying it as a member of a specific species or type? How much variation is there among individuals? How does this variation compare to that of domestic organisms such as cats or dogs?
2. Describe any animal or plant of which you have heard but which you have never seen. In what characteristics does it differ from animals or plants that you know? Do these characteristics match any animal or plant that you consider to be fictitious? How do you know which are real and which are fictitious?
3. Look at a riverbank, a lakeshore, a river delta, a mountain range, a fault that has generated earthquakes, or any geological structure near you that may have changed over the history of the earth. Is there any way that you can estimate the