2 What is science?

Scientists, therefore, are dealing with doubt and uncertainty. All scientific knowledge is uncertain. This experience with doubt and uncertainty is important. I believe that it is of great value, and one that extends beyond the sciences. I believe that to solve any problem that has never been solved before, you have to leave the door to the unknown ajar. You have to permit the possibility that you do not have it exactly right. Otherwise, if you have made up your mind already, you might not solve it.

Feynman, 1998

Certainly a book for prospective scientists ought to explain what science is. Still, despite numerous books that treat the philosophy, character, and practice of science, there is no agreed-upon nor clear-cut and unambiguous definition of science. This holds not only for the many fields of study that have adopted methods patterned on those of the natural science, e.g., social science, psychology, economics, managerial science, and military science, but also for the natural sciences themselves. In a broad sense one might define science[1] as the activities aimed at understanding the world around us, but it could be well argued that the arts, humanities, and many other endeavors in modern society likewise aim at understanding of the world, albeit understanding of a different sort than that sought in the natural sciences. So let's focus on the practice of *natural* science, which might be defined as the activities aimed at understanding of the *natural* world.

The key word in this still broad definition is "understanding." This word, which itself is vague, has a number of differing aspects

[1] Science is understood by many to include the body of findings and understanding discovered through the practice of science. Throughout this book, where we use the word *science* we mean the *practice of science* as opposed to its findings.

FIG. 2.1. The painting "this is not a pipe" of the Belgian painter René Magritte.

that are found at the core of the scientific method.[2] These include the following:

- *A logical framework.* Adherence to the precepts of logic is fundamental to any activity that claims to be following the scientific method. For example, from the statement that "hoofed animals cannot fly" and the observation that "pigs have hooves," one can logically conclude that "pigs cannot fly." A conclusion that "pigs can fly" would either mean that the premise "hoofed animals cannot fly" is false, or that the observation that pigs have hooves is in error, or that one uses a system of thought that defies rules of logic. If the latter, then this system of thought would be inconsistent with the scientific method. The scientific method would, however, have a place in ascertaining the validity of the premise.

  In some endeavors other than science, there is nothing wrong with deviating from rules of logic, and, as shown in Fig. 2.1, those rules are not difficult to defy. The picture of the pipe (not a pipe?) satisfies a legitimate goal of a work of art in challenging and stimulating the viewer's powers of questioning – indeed of logic – and perceptions; art can spark inventive thinking on the part of the viewer. For example, it

[2] Much has been written about the intricacies of the scientific method (see Appendix A). Our discussion here will be kept at a broad level so as to emphasize a few key points as they relate to the meaning of *understanding* in the *practice* of science.

can reasonably be concluded that Fig. 2.1 truly doesn't show a pipe, but rather a picture of a painting of one.

  Despite such quite acceptable departures from rules of logic, however, reasoning that is not firmly rooted in a logical style of thinking does not form part of the scientific method. This is not to say, nevertheless, that the scientific method always follows methodically or linearly from accepted paradigms in the sciences. The dramatic breakthroughs that initiate significant and exciting advances – sometimes 90-degree changes – in science have often been the result of free-ranging intuitive thinking by the most creative of scientists; we often call them *geniuses*. Such intuitive leaps, nevertheless, must always be followed up by thorough engagement along paths of logic and consistency.

- *A foundation in observations.* Science is no mere mind exercise of following paths solely of logical thought toward predictable consequences, mentally stimulating as that process might be. Mathematics is just such an exercise – typically a most demanding one – with the goal of arriving at indisputable truths, always however on the condition that its starting premises themselves are valid. Because science is aimed at understanding of the natural world around us, it needs something more than logic. As a result it arrives at vastly more than does mathematics or logic alone. At the same time, however, science cannot provide unassailable *proof* that its understanding and interpretation of the natural world is correct.

  Science's connection with the natural world is made through observations (today largely through use of sophisticated and sensitive instrumentation that vastly extends the range of our human senses) – typically painstaking and repeated, and often lifelong – chasing down implications and always seeking consistency across the observable world. Such observations can involve quantitative measurements, for example, measuring the normal body temperature of the highland gorilla. Others might be aimed at a simple yes/no answer, such as whether pigs have ever been observed to fly. (Note that the fact that no pig has ever been seen flying does not in itself *prove* that pigs can't fly,[3] but the contrary observation would indeed prove that they can.) The first type of observation is of a quantitative nature, the second a binary one. An observation need be neither quantitative nor binary; it can be more vague. For example, one might wonder to what extent a certain disease depends on nutritional habits. While such a dependency might ultimately be quantified by computing correlations based on observations, in early parts of the investigation more intuitive guidance would be necessary in order to establish this connection. Moreover, interpretation of the correlations themselves might be subject to the qualifications of uncertainty, verification of cause-and-effect, and clearing out of the way of various (sometimes many) competing factors.

- *Predictive power.* One of the great strengths of science is that from a known theory – possibly tested and calibrated with observations – one can predict physical[4] behavior in new situations. It is its predictive power that makes science of great use because it provides means for understanding, indeed influencing and changing (for the better, one can hope) the world around us.
- *Falsifiability.* All possibilities of error in understanding (or in a hypothesis) must be available for detection and evaluation; any hypothesis being tested "must be one that contains the seed of its own destruction" (Stenger, 2007). In the scientific method, the author of a hypothesis should do her utmost to try to "break" that hypothesis.
- *Repeatability and testability.* The methods and results of any scientific investigation must be amenable to being repeated and corroborated through independent testing by other investigators.

[3] Using logic alone, one could conclude that pigs might well be able to fly. They are hoofed animals, so if the starting premise were that "hoofed animals *can* fly," the *observation* that pigs are hoofed animals would lead one to conclude that pigs possibly could fly. The body of understanding in physics, however, indicates that pigs lack the equipment, e.g., wings or mechanical engines, and have an overabundance of mass-to-volume for them to be able to fly. Application of the scientific method would therefore lead one to conclude that it is highly unlikely that pigs can fly.

[4] Throughout the book, we shall use the word *physical science* as shorthand for all of the natural sciences, e.g., physical, chemical, biological, astronomical, geological.

To the above list of characteristics, we can add that science is challenging and difficult, features that are by no means unique to science. What makes science hard is worth elaborating and emphasizing, as we will do below.

Note that, contrary to the situation for mathematics and logic, in the description of science given here the word *truth* does not appear. The notion of truth implies that it is possible to establish once and for all (that is, to prove) that a finding or interpretation is *true*. This is, of course, a circular statement, but that is exactly the problem. In science, we have no *truth-meter* that allows us to establish that a given theory always holds with perfection. What we can do is compare the predictions of a theory with observations of physical phenomena. A favorable outcome does not, however, mean that the theory holds or can be validly used in every imagined situation. One can carry out a thousand measurements that support a theory, with no hard guarantee that the theory also holds for the 1001st measurement, especially when that measurement is carried out under somewhat different conditions.

The notion of truth implies the binary concept that something either is or is not strictly valid. In science one sees truth on a sliding scale. A case in point is mechanics. Classical mechanics, as originally formulated by Isaac Newton, has been and remains a foundationally powerful tool for addressing a broad range of phenomena in science and engineering. Yet it is not always accurate. After more than 200 years of success in predicting physical phenomena, it was found lacking (by Einstein). For bodies that move with a velocity on the order of the speed of light, classical mechanics needed to be replaced by the theory of special relativity. Moreover, small bodies at the molecular or atomic scale follow rules, seemingly bizarre at times, of quantum mechanics instead of classical mechanics. So is classical mechanics true? Well, this depends on the velocity and the size of body in which one is interested, as well as on the accuracy that one desires for predictions made with the theory. In science, it is more appropriate to speak of the *accuracy* than of the *truth* of a theory. Thus, the outcome of science can never be truth in an absolute sense; rather, science has the agenda of an unbiased search to discover ever more accurate understanding of the natural world. In the words of Moore (1993)

> *Erasistratus's beliefs, like all statements of science, are approximations to the elusive goal of "truth." Science is an accretive and self-correcting discipline and, generation after generation, its concepts become more precise and accurate.*[5]*

As mentioned above, much has been written about the scientific method and about the philosophy of science (e.g., Popper, 1965; Kuhn, 1962). Rather than attempting to give an overview of this topic, we present in the following two sections examples of different ways to categorize the scientific method.

2.1 DEDUCTION VERSUS INDUCTION

> *Induction is not an automatic procedure for advancing science. It depends on the brilliance, perseverance, knowledge, and luck of the scientist. And deduction is an effective and powerful procedure when one uses it to make testable deductions from provisional hypotheses.*
>
> Moore, 1993*

Scientific methods can be divided broadly into those of *deduction* and *induction*. The deductive approach follows the path of logic most closely. The reasoning starts with a theory that leads to a new hypothesis. This hypothesis is put to the test by confronting it with observations that either lead to a confirmation or a rejection of the hypothesis, again not the truth of the hypothesis but its accuracy under the conditions associated with the particular phenomena being studied. Portrayed in a flowchart, the deductive method thus takes the form:

Theory ⇒ Hypothesis ⇒ Observations ⇒ Confirmation/Rejection

Note again that agreement of the observation with the hypothesis does not mean that the hypothesis is always valid. For this reason,

[5] Erasistratus Chios was a Greek anatomist and royal physician (304–250BC).
* Reprinted with permission of Harvard University Press.

the confrontation of the hypothesis with observations can, in the most optimistic scenario, give support (sometimes, strong) for, but not proof of, the validity of the hypothesis.

An example of a deductive approach is the discovery of the neutrino, an elementary particle without charge and rest-mass. According to theory, mass, energy, and electric charge are conserved. It turned out that, with the decay products of beta decay that were known in 1930, mass and energy appeared not to be conserved during beta decay. This led Enrico Fermi to propose the existence of an electrically neutral particle without rest-mass. Because of its resemblance to the neutron, he called it the *neutrino*. In 1930, the presence of the neutrino was a hypothesis, and the hunt for its detection was on from that moment. It took until 1956 before the neutrino was detected (Cowan *et al.*, 1956) and its existence thus confirmed.

This example shows the amazing power of deduction. Logic applied to an existing theory led to a new and bold hypothesis – the existence of a new elementary particle. Finally the observation of the neutrino confirmed the bold conjecture of Fermi. It took an intense effort of 26 years finally to detect this particle, exemplifying that devising and carrying out definitive observations can be exceedingly difficult; one should not reject a hypothesis because the observations are as yet inconclusive.

In the deductive approach one works from theory to observations. In induction this order is reversed. Observations might reveal patterns that lead to the formulation of a hypothesis for an underlying cause for these patterns. The hypothesis, or a combination of hypotheses, can lead to new theory. The inductive method thus corresponds to the following flowchart.

Observations ⇒ Pattern ⇒ Hypothesis ⇒ Theory

An example of induction is the discovery, by John Snow in 1854, of the spread of cholera by contaminated drinking water (Goldstein and Goldstein, 1984). At that time, the existence of bacteria and viruses was unknown; how and why contagious diseases spread thus were not understood. Snow noticed a pattern in patients who contracted cholera; many of them had been drinking water from a particular pump in London. This led him to hypothesize that cholera had been spreading through drinking water, a major step that ultimately led Louis Pasteur to formulate the germ theory in 1857. The presence of bacteria and viruses was later confirmed by observations, thus establishing their connection with various diseases.

It might appear naïve for practitioners of medicine not to have realized that the spread of disease is caused by the presence of microbes in drinking water. This appears so, however, only in hindsight now that the existence of bacteria, and their role in spreading disease, has been firmly established. Without this knowledge, it was not at all obvious that disease should be spread by water: why would water make someone ill? It took an immense intellectual step to formulate the hypothesis that cholera was spreading through micro-organisms in drinking water.

These examples illustrate the power of both deduction and induction. Neither approach is better or more valid than the other. For any particular problem, one or the other of these contrasting approaches might be the more effective. In general, they are complementary; it is the combination and interplay between these methods that makes them so powerful. It could be said that many of the largest paradigm shifts in science have resulted from inductive, often intuitive, reasoning driven by observations. Examples include the quantization of energy (Planck) and natural selection as an explanation for evolution of species (Darwin).

2.2 REDUCTIONISM AND WHOLISM

Another way to characterize the different approaches is to divide scientific methods into those of reductionism and wholism. In reductionism one reduces a complicated problem into its constituents and aims to understand that complex problem through study of different components of the problem.

An example of a reductionist approach is the synthesis of protein. Protein consists of amino acids that are assembled in organelles

in the cells called *ribosomes*. The order in which the amino acids are assembled is encoded by ribonucleic acid (RNA) after it has been copied from deoxyribonucleic acid (DNA), the genetic material in cells. The structure of proteins is incredibly complicated, but the reasoning above reduces it to an assemblage of amino acids. The assemblage itself is reduced to the coding of RNA, which in its turn is reduced to the structure and properties of DNA, which forms the blueprint of cells. Here, the large and complex problem, the synthesis of complicated proteins, has been reduced to simpler building blocks. And this reasoning goes further. DNA is a polymer that consists of four units, called *nucleotides*. The properties of the nucleotides can, in their turn, be described in terms of their chemical structure, further relating them to properties of their constituent atoms.

It might appear that the reductionist approach is the most useful because it reduces large problems to a combination of smaller ones that are easier to solve. This approach is, however, not suitable for every problem. As an example, consider an ant heap, an extremely complicated physical, chemical, and biological structure that is built and sustained by the collective effort of millions of ants. One cannot understand an ant heap by reducing ants to their constituent components, for example by dissecting them or by making NMR scans of their tiny brains. It is the complicated interactions among ants, as driven by their genetic material, the chemical and behavioral signals that are exchanged, and the way in which different types of ants are raised, that govern the behavior of the ants, leading ultimately to the construction of the ant heap. This is a problem that does not lend itself to a reductionist approach. The essence of the ant heap is its complexity, and one needs to view the ant heap as a whole in order to begin to understand its structure. Such an approach is one of *wholism*.

Just as with the distinction between deduction and induction, neither the reductionist nor wholistic approach can be considered universally superior or inferior to the other. It turns out, for example, that the reductionist approach for the synthesis of protein is not the full story: the interplay among different genes is essential for the activation or deactivation of specific genes. One cannot completely reduce the action of DNA to the action of isolated genes that spontaneously are copied into RNA. Moreover, genetic material is also passed on through mitochondria, the power plants in cells, that are transferred from mother to child. This is an example of a problem that seemingly can be handled well by a reductionist approach, but gains from wholistic elements for a larger understanding. A key reason that neither the reductionist nor the wholistic approach ought to be taken in isolation is that any view of the natural world (considered by some as *reality*) that a scientist devises is just a *model* loaded with assumptions and approximations of that world.

2.3 WHY SCIENCE IS HARD ... AND WHAT MAKES IT AN ART

When you take a step where there is no framework, you trust in your humanness. It's your humanness that gives you your edge. There are computer programs now that can do mathematics better than we can, that can arrange equations, and that can solve equations. Our edge is first of all understanding what it means, interpreting it, and going where that manipulation can't go because there is no logic step yet.

Weglein, 2003

As mentioned earlier, the scientific method is rooted in logic, but this does not mean that the path it follows is simply linear nor that the underlying logic is always easy to detect. In order to see this, let us view science as a collection of "facts." We introduce this rather vague term here to denote either a theory, a hypothesis, a pattern, or an observation. Thus, here, a *fact* is some element in the deductive or inductive method of Section 2.1.

Consider a scientific study that works through facts arranged in a linear sequence, as illustrated in Fig. 2.2. Here, the practice of science might appear to be simple – an application of the rules of logic

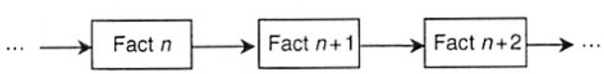

FIG. 2.2. Science as a logical chain of facts.

stringing together the facts. The situation, however, seldom will be so simple. While fact $n + 1$ can be a pattern inferred from observations that constitute fact n, it can be extremely difficult to recognize this pattern. Recall that it was not until 1854 that someone noticed that patients with cholera had been drinking from a well that was contaminated (the very notion of a well being contaminated was still unknown at that time). People had contracted cholera for thousands of years before that date, and the pattern with which cholera spreads had existed for a long time prior to its discovery in 1854. It took the imagination and creativity of John Snow to recognize this pattern. Similarly, in the deductive method, much creativity might be required in order to formulate a new hypothesis on the basis of a given theory. Sometimes, it takes courage to take the next step in science when devising a new theory or hypothesis that conflicts with "common wisdom" (e.g., how much "common sense" is there in quantum theory?). It can even take courage to carry out measurements that are controversial, such as when these observations could overthrow an accepted theory.

Science is hard for yet another reason. It can often happen that one of the facts – perhaps a theory or set of measurements – in the chain of Fig. 2.2 is wrong in that it conflicts with reality and yet the error is not obvious right away. It could be many steps down the chain of Fig. 2.2 before the error or inconsistency is recognized as being essential, requiring backtracking through the chain to find the erroneous link. The task of finding mistakes in earlier work can be extremely difficult, especially when the underlying assumptions being used have not been explicitly formulated. Beyond identifying a previous error, it also can take courage to acknowledge that one's earlier scientific finding might be incorrect.

The linear chain of Fig. 2.2 itself is a simplification. Often, it's not just a single fact that leads to the next, but, as illustrated in Fig. 2.3, a number of facts are required in order to take the next step. In this more realistic view of how scientific investigation proceeds, it can be difficult to determine that Fact E follows from a combination of several facts, say, A, B, C, and D. One might not know which of these

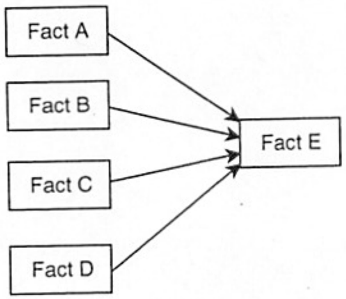

FIG. 2.3. Science as a complicated web of facts.

facts need to be taken into account in order to progress to the next step. Another complication is that, while Facts A, B, and C might be correct, Fact D could be in error. It often is no simple matter to discover such a problem and set the error right.

You might be surprised that we speak of facts that are wrong; this seems to be a contradiction. Keep in mind, however, that a fact that is assumed to be correct, but actually is wrong, is still a fact in the eye of the scientist pursuing the study. For yet another reason, errors are bound to be made. Consider once more the linear chain of Fig. 2.2. Where does the chain start? This is a deep metaphysical question that mankind has struggled with in various forms for thousands of years, and science does not tell us the answer. In science we aim to work our way down a chain, or web, of facts, but we don't know what was the first step. This is an unavoidable aspect of science that inevitably requires making assumptions. In investigations involving pure mathematics, a theory always starts with axioms, a set of "self-evident" rules that form the basis for the theory. In other fields of science, the initial assumptions are often not explicitly identified or even obvious. Always keep in mind that an assumption is nothing more than what it claims to be – an assumption. If it is invalid, conclusions based on that assumption are likely to be in error as well.

Considering the above discussion, while logic indeed forms the basis for stringing together facts, such as those illustrated in Figs. 2.2 and 2.3, strict application of logic does not always provide the rules for discovering the next step. Often such discovery requires imagination,

creativity, intuition, inspiration, and sometimes courage. These qualities differ from just the ability to apply the rules of logic effectively. For this reason, science (always founded on or checked through observation) often is not a purely logical thought process. Because the qualities of creativity, intuition, inspiration, and courage, in addition to the ability to reason logically, are needed for doing original research, science is an art – an especially demanding and difficult one.

2.4 MANY WAYS TO PRACTICE SCIENCE

As we have seen, science is a mix of logic and intuitive approaches, so it should be no surprise that scientists have differing styles of working. Some are particularly strong at logic, but find it difficult to break out of this way of thinking in order to make bold leaps forward, while others operate in a much more intuitive way by relying on their gut-feeling, and afterwards use the logic necessary to justify the steps they have taken. Within the scientific community are many different approaches to research. Here, we sketch some of this variety, demonstrating that there is no uniform approach to doing science.

Some scientists choose to take a deductive approach and others an inductive one. The choice can depend on personal background, taste, and skills, but it can also be governed largely by characteristics of the specific field of research. In general, science with a strong theoretical emphasis, such as theoretical physics, tends toward the deductive, while scientists who deal with complex interconnected systems, such as ecology, gravitate to the more inductive. The distinction is not a rigid one. For example, in ecology, population dynamics often relies on mathematical models that follow a deductive line of reasoning. Most scientists use a mix of the two approaches; fortunately the scientific community is not divided between pure "deductors" and pure "inductors."

Similarly, some scientists heavily rely on a reductionist approach, while for others a wholistic approach is more suitable. Just as with the distinction between deduction and induction, the approach taken can be influenced by the taste of the scientist involved, as well as by the type of problem that is being investigated. In general, again, the reductionist approach typically works better for relatively well-defined problems that can be broken down into a limited number of simpler sub-problems, while the wholistic approach is better suited to problems involving complex systems with numerous interacting components.

Some scientists are drawn toward problems that require theoretical treatment, while others tend more towards challenges in experimentation. Even within these categories, one can work in different ways. A theoretical approach can involve mathematical work, numerical simulations, or literature studies carried forward by clear reasoning. Experimental work is not limited to laboratory experimentation; it could involve field work, patient trials, or other activities dictated by the purpose for which the science is conducted, e.g., curing patients, finding resources, or developing new technical devices. Note that both deductive and inductive approaches can involve either theory or observation, or a combination of the two. Ultimately, one needs to combine these different aspects of science: without a theory, observations are disconnected and their meaning cannot be understood, while theory without observations is a mind game ungrounded in our natural world. Many scientists gravitate solely toward either a theoretical or experimental approach, but often most progress is made at the interface of the two.

The scientific career can be pursued in different environments. Scientists do not work solely at universities, but also in industry and government laboratories. The type of institution in which the work is carried out tends to influence the character of that work. In general, research in academia is less focused on particular applications and is less restricted to producing specific deliverables; that is, it is more "academic." Research in industry is ultimately driven by the goal to make a profit. When the emphasis of such a research organization is on the short term, the science tends to be driven by the production of deliverables. Even within industrial research laboratories with relatively short-term targets, however, the research environment can offer the freedom, not to mention stimulation, of the best of university

programs. Moreover, industrial laboratories with long-term goals have often given their researchers great freedom to push science forward without the need to develop applications that are profitable in the short term. One of many examples of such a laboratory is Bell Labs, which for a long time was a think tank noted for its innovative science.

A scientist usually wants to discover *how* and *why* things work. In contrast to this, the engineer's primary aim is typically to *make* things work. Thus, in general, it might be said that the engineer takes a more pragmatic approach than does the scientist. The distinction between science and engineering, however, is to a large degree artificial. In order to make things work, the creative engineer needs to know why they work. Similarly, in order to reach her goals, the scientist often has to construct devices, for example, by designing or building experimental equipment. Moreover, without a pragmatic outlook, the scientist in academia can readily get stuck unnecessarily. The distinction between science and engineering therefore is another example that operates on a sliding scale.

Thus, there is no single way in which all scientists (and engineers) work; one cannot speak of the generic scientist as one who approaches her task in a particular, narrowly defined way. As in other walks of life, diversity of style and approach, which is essential to the enrichment of the scientific endeavor and community, is based on the make-up of the individual. So, how you might be influenced by a particular scientist, such as your adviser, will not necessarily define the kind of scientist that you grow into and become. It is important to be exposed to the different ways in which scientists work, and to synthesize a personal style of scientific research that fits your skills, ambitions, and outlook. (This is sure to happen, in any event, whether explicitly or implicitly.)

2.5 WHY WOULD YOU WANT TO BE A SCIENTIST?

Just as there are many approaches to science, there also are many different motivations for being a scientist.[6] For many scientists, a natural

[6] There were no scientists prior to about the middle of the nineteenth century. But, how could this be – think of Newton, Hooke, Cuvier? Prior to then, those we know

curiosity is the prime motivation. This curiosity comes naturally for humans since it is its intellect that has made mankind so successful as a species. For many scientists, science simply is fun. The game of discovery and creativity is akin to solving a puzzle, with the potential reward not only of recognition by the community but of gaining further, deeper understanding.

Other factors motivate scientists. As mentioned earlier, science allows us to predict what happens if we do something novel, for example by building a new protein with novel properties in molecular biology, or by developing a new mathematical theory and using it for a new application. In general, society uses science to acquire power over the surrounding world. We use science to develop drugs that cure disease, to grow food more effectively, to explore and develop resources, to develop technology, and to find approaches that mitigate environmental damage caused by intensive application of technology. In short, science is useful, and for many scientists participating in the enhancement of this utility is a strong motivation.

For others, science means a career – an exciting and rewarding one. For those who are intellectually talented and highly disciplined, a career in science is a great way to make a living, whether at a university, in a government laboratory, or in industry.

Just as in our description of the various approaches to science, it is a mix of different factors that motivates scientists. However fascinating is the challenge of discovery, one still needs a job in order to pursue this challenge. For some scientists it is a mix of the pleasure and utility of science that is the main motivation.

2.6 WHO IS DOING SCIENCE?

The scientific community consists of a variety of different players. We focus first on those in an academic environment. Students often

of as pillars among scientists were individuals who followed what would have been called *natural philosophy* in pursuit of satisfying their elevated level of curiosity about how the world works, but they were not called *scientists*. The term was coined later.

divide the academic community into students and professors, but this is a gross over-simplification. Professors have differing positions and ranks, and, in general, play differing roles. Some professors spend most of their time and effort teaching, while other devote themselves almost completely to research. Many universities even have professors who do not teach at all. Some of these individuals are "on soft money," which means that they are not being paid by the university; rather, they generate their income solely through research grants.

Much of the research in some university programs is carried out by post-doctoral fellows, usually called *postdocs*. These researchers usually have just finished a Ph.D. degree and do full-time research that typically is funded by research grants. Since postdocs often have finished graduate school recently, their skills, knowledge, and recent experience can be a great resource for graduate students. Postdocs typically view their positions as essential for building the credentials necessary in order to attract offers for academic faculty positions.

Perhaps as much or more of the research at universities is carried out by graduate students who either work toward a masters (M.Sc.) degree or doctorate degree (Ph.D. or Doctor of Engineering). Research is an essential component of the graduate education. Graduate students learn by being trained on the job, led and aided by a faculty member, the *adviser*. As we discuss in Chapter 4, the adviser is the graduate student's principal mentor and coach, she or he plays a crucially important role in the success of that student's educational program and, no less, in the satisfaction that the student can have with the graduate experience.

Science is carried out at a variety of institutions other than universities, and, as shown in Fig. 2.4, the spectrum of activities in research and development is wide, ranging from fundamental research to the commercialization of knowledge. Fundamental research has no direct specific application; it is research that is driven by scientific curiosity "to know and understand" only. An example of this research is the detection of gravitational waves (e.g., Barish and Weiss, 1999). In contrast, applied research has the aim to extend existing knowledge

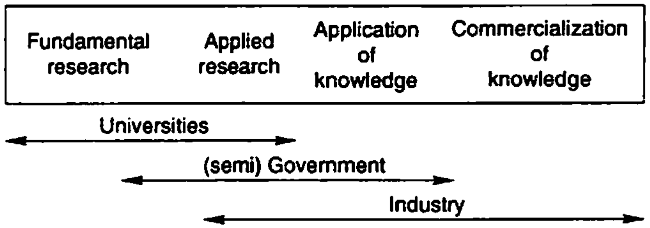

FIG. 2.4. The different stages of knowledge-based activities and the different players in the field. Modified after Speelman (1998).

to a specific goal such as developing a new product, or solving a societal problem. An example is the use of genetic engineering in the development of a new drug. The application of knowledge involves routine use of knowledge previously gained to a new and different set of problems. An example is the application of Geographic Information System to an existing database in order to map the urbanization in a region more accurately. The commercialization of knowledge has the goal to make a profit from existing techniques.

As seen in Fig. 2.4, a given type of research is not the sole province of one or another particular type of institution. The universities are predominantly concerned with both fundamental research and applied research, while the National Institute of Health, the Geological Survey and other (semi) government organizations have a focus on applied research and the application of knowledge. The activities of industry and other commercial organizations cover the spectrum from applied research (and even fundamental research) to the commercialization of knowledge. The boundaries in Fig. 2.4 are in practice somewhat fuzzy. For example, fundamental research on the quantum Hall effect was carried out in the Natlab, the physics laboratory of Philips. It is not clear (to us) whether that work should be called fundamental or applied research.

The Art of Being a Scientist

A Guide for Graduate Students and their Mentors

ROEL SNIEDER AND KEN LARNER

Department of Geophysics and Center for Wave Phenomena
Colorado School of Mines, Golden, CO 80401, USA

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