THE *Truth* OF SCIENCE

PHYSICAL THEORIES AND REALITY

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PREFACE

ALTHOUGH I was prompted to write this book by my irritation at the way a currently fashionable group of sociologists portray science and its results—a portrayal that has led to the so-called *science wars*—it is not intended as a polemic aimed at those who propagate such views; in only one chapter do I specifically go after them in detail. My purpose is constructive: to describe the intellectual structure of physical science and the understanding of reality that modern physics, the science with the most advanced and mature theoretical development, engenders. On a number of occasions, I will venture beyond that discipline, but some of the most important issues I tackle, particularly those concerning the role of theories and the nature of reality, assume a somewhat different cast in other sciences. As for the large question of truth, however, the outcome of the deliberations that I describe in terms of physics may well be taken to apply to all of science.

This book is intended for anyone with some scientific education; it is not addressed to professional philosophers or sociologists of science. No specific knowledge of physics on the part of the reader is assumed, and the many examples I draw on for illustrative purposes are fully explained. Some chapters will be more intellectually demanding than others, most particularly Chapter 10, which deals with the troublesome problem of reality at the submicroscopic level, where the quantum theory holds sway. I am afraid this is unavoidable; the questions at issue are difficult, even for physicists who routinely use quantum mechanics. There is no point in giving them a superficial presentation, with the mistaken implication that they are no different from other questions we will have to answer. Indeed, even though philosophers have struggled with many of the problems discussed for a long time, I may occasionally give the impression that their solution is simpler than it really is, and for this I apologize in advance to the reader. However, I see no reason for kicking up a lot of dust and then complaining one cannot see, as Leibniz accused many philosophers of doing.

I am indebted to many people for instructive discussions; among them I want to mention particularly Ciprian Foias, Howard Scott Gordon, Edward Grant, Noretta Koertge, and the late Richard S. Westfall. Most of all, I want to thank my wife Ruth for invaluable, tireless editing assistance in the writing of this book.

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INTRODUCTION

AS heirs of two clashing cultural progenitors, the Enlightenment (rational, orderly, measured) and the subsequent reaction of Romanticism (liberating, creative, irrational, and destructive), we approach the end of our millennium riding the wave of science but threatened by an undertow. From the crest we observe that the meteoric ascent of modern science allowed the West, and large parts of the rest of the world, to enjoy an economic prosperity previously unimaginable. The greatly accelerated pace of scientific advancement during this century has made all earlier human knowledge of the universe seem primitive and shallow. We have reason, now, to be confident that we understand a large part of the structure and constitution of the universe, from the interior of atoms to the farthest stars; we can successfully explain the mechanisms underlying the processes of matter and the forces between its constituents; and we are beginning to fathom the secrets of life from the gene to the brain.

The fruits of this knowledge in our "age of science" are visible everywhere; they have transformed our lives and, with the conquest of many dreaded and devastating diseases, doubled our life span. Communication through radio and television, transportation by auto and plane, transmission of information through computers have shrunk our planet into a global village. Justified or not, these developments have given scientific pronouncements an unprecedented authority; scientists are called upon to make judgments and predictions concerning the fears and hopes of a population that trusts them perhaps more than any other group in our society.

Nevertheless, we find everywhere, as well, a deplorable ignorance about the contents and character of science, which is identified more with technology and therapeutic medicine than with basic research: science is thought to be the improvement of television, the building of faster planes, the construction of more powerful weapons, or the curing of cancer and AIDS. And the ubiquitous confusion between science and its applications, between the plant and its fruits, leads some to imagine they can continue reaping the fruits while cutting back on the plant. Others see only the dark side of the rapid advance—increasingly destructive weapons, environmental degradation. A century ago there was a largely unalloyed enthusiasm for the harvest of technology (witness, for example, the public reaction to the World's Columbia Exposition in Chicago in 1893 and the St. Louis World's Fair in 1904). Today the reaction to science is just as likely to be hostility, as many in the West now question the value of science as the source and underpinning of a technological structure other parts of the world can only envy. The very success of science has spawned resentment against it.

This antagonism, aimed primarily at the physical and biological sciences, comes from two diametrically opposed directions. Those who are in despair over a widespread deterioration of moral and cultural values blame the skepticism and eternal uncertainty of science for eroding the comfortable feeling of certitude and security they drew from their spiritual beliefs. These critics envisage a return to a simpler age, in which people of faith, undistracted by an understanding of the world acquired through science, would take preachings based on religious authority as their sole guides to ethical and moral behavior. From the opposite direction, some practitioners of the more recent and less developed social and political sciences question the claim that the world truly is understood through science. They maintain that all of us, including scientists who in the past have been portrayed heroically as disembodied intellects, are creatures of our milieu: the origins of our ideas and the formulations of our ratiocinations and observations bear the imprints of ethnicity, gender, and class. Intellectual and philosophical arguments that start from valid observations, however, are often stretched to a point where they end up distorting—sometimes beyond recognition—what they are designed to illuminate, and so they are in this case. Influential sociologists announce with great confidence that the results of science—painstakingly gained by much observation, experimentation, and thought over the last four hundred years—have nothing to do with Nature and the external world under investigation, but are simply narratives, like myths and fairy tales, or the outcome of social agreements. Scientific "truths," they say, express the special perspective of the group from which they originate and are designed to further the group's political advantage.

The large majority of physical and biological scientists, of course, continue their work unperturbed. Nevertheless, in an age when pseudo-science flourishes, astrology parades as a science in the popular game Trivial Pursuit and shapes the daily schedule of a recent President of the United States, and some schools are forced to teach "creation science" as an alternative to the theory of evolution, the relativistic notions now fashionable at universities and among intellectuals exert a powerful influence on future legislators and the educated public. These ideas, hardly the harmless errors of a few misguided ignoramuses, are bound to have results detrimental to our society and corrosive to civilization as a whole. A world full of ignorance and superstition is a world full of fear, hatred, and panic.

That social influences exist—on the questions science asks and the problems it posits—can hardly be denied; this idea is neither new nor particularly controversial. I well remember Philipp Frank, a member of the Vienna Circle of positivists, talking about such ideas in his lectures at Harvard when I was a student almost fifty years ago. The results of science are not based on pristine apperceptions of naked facts, obtained by pure intellects working in isolated laboratories or ivory towers, but neither are they agreed-upon narratives or myths for political ends, linguistic artifacts produced in response to internal or external social pressures, as they are portrayed by some influential and vocal intellectual commentators today. Science stands or falls on the validity rather than the origins of its large structure of ideas. Those who, in light of the turbulent social currents in which we are all immersed, claim that the content of these ideas is of little rational relevance can be fairly accused of engaging in what the philosopher Larry Laudan calls "the most prominent and pernicious . . . anti-intellectualism in our time."[1] Operating most successfully at universities, they are robbing rational thought of all intellectual and cognitive value, leaving its expression a hollow rhetorical shell. This, ultimately, is why scientists, who value rationality above all else, are deeply offended by a misrepresentation that claims their work has as much epistemic value as the invention of fairy tales.

While arguing against this portrayal of science as myth, we should not assume that the scientific method that has evolved and flourished over the last 400 years was an inevitable development—it was valued consistently, after all, in only one culture. For this reason, we may regard it as a convention, albeit one with far-reaching consequences. My starting point is therefore the philosophical notion of *conventionalism*. In the first chapter I discuss this point of view within science itself—the notion that theories, and perhaps even experimental results, are largely conventions. In examining particular theories, I find that some parts, but certainly not all, are indeed conventional, though the assertion that even logic and mathematics are conventions proves unconvincing.

Chapter 2 takes up a recent version of conventionalism. I first examine the contention that science is subject to influences from sources other than Nature itself. It is certainly the case that extraneous social and political influences exist, though sociologists and historians may at times exaggerate their importance. But the malignant variant called "relativistic social constructivism" maintains, in its extreme form, that all scientific theories, and even their underlying facts, are social constructions quite uncorrelated with anything in Nature. I examine and criticize in detail the writings of some of the most prominent of these constructivists, with whose contentions I strongly disagree. The remainder of the book is devoted to the task of laying bare the structure and aims of the physical sciences, leading up to the question of their truth.

The primary aim of most physical scientists is to understand and explain the workings of Nature. In Chapter 3, I explore what is meant by an explanation, and I examine a variety of theories used for this purpose. Some of them, like the arrow of time in statistical thermodynamics, which keeps Humpty-Dumpty in bits and pieces, lead to the discovery of emergent properties, properties that were absent at a lower level. Most subfields of physics are formed by local theories derived from general ones on the basis of special approximations and assumptions. Since these theories are much closer to the phenomena, they lead their specialists to develop that most important quality for any scientist or mathematician, intuition. Unavoidably, there are hierarchies, not of value but of dependency, among the subfields and the various sciences; in that sense, all science is reductionist, and properly so.

In the fourth chapter I discuss several of the main tools scientists use for understanding. Models, which are taken seriously as descriptive of reality in some cases and less so in others, have always played an important part in scientific explanations. Analogies and metaphors are also important explanatory instruments that help us to understand novel phenomena in terms of familiar ones. I briefly examine a special category of theories that deal with history: geogony, cosmogony, and biological evolution. In my review of the anthropic principle, I find it wanting as a mode of scientific explanation of the universe.

By common assumption, science is based on facts. In the fifth chapter, I distinguish between individual and general facts, arguing that, outside the three history-related theories, only general facts are of interest to science. How are facts established? Many of them depend on theories, and therefore are said to be "theory laden," yet there are good reasons why they are, nevertheless, reliable and stable. I offer a number of examples of notorious pseudo-facts.

Chapter 6 explores the question of how theories arise from facts, emphasizing the distinction between the origins of theories and their establishment on the basis of evidence. Though the source of these theories lies in the imagination, which is often irrational and subject to social and psychological influences, their origin has no bearing on what earns them acceptance. The same can be said for mathematical theorems, whose proofs are independent of their imaginative source. How are theories tested? I examine in what sense Karl Popper's criterion of falsifiability may be regarded as more important than verifiability. Are there crucial experiments? What happens when theories are superseded? A useful general guide is provided by the "scientific method," but this method must not be interpreted as constraining. The most important criterion for or against acceptability in science is openly accessible evidence; for mathematics, acceptance is gained through general proofs that can be checked by every mathematician. This is what ensures the objective validity of the results and the stability of the ensuing structure.

Mathematics plays an enormously important role in science, most prominently in physics. From what source does its power derive, I ask in Chapter 7, and why is it so effective? Reviewing its changing historical role, we find that the computer now plays a significant auxiliary part in influencing what kinds of problems can be solved. The nature of mathematics determines its relation to science. Are theorems invented or discovered? What is a mathematical proof, and could modern science have developed using a kind of mathematics in which the idea of a proof is missing?

Causality, the primary explanatory principle of science, is the subject of Chapter 8, which begins with the remnant of Aristotle's notion of efficient causes left over after David Hume had ripped it apart. As a matter of universal experience, causes always precede their effects, a characteristic that is crucial in some areas of physics. I review the doctrine of determinism and its modern origin in Newton's equations, concluding that the definition of the state of a physical system subject to determinism depends on the nature of these equations. An analysis of the quantum theory shows that, despite frequent assertions to the contrary, it, too, is deterministic. Knowing the quantum state of a system, however, is different from knowing a classical state. At this point probablilites enter the picture. I discuss the notion of probability in some detail, including the frequency definition and Popper's propensity theory, both of which have an important bearing on the interpretation of quantum mechanics and the view of reality to which it leads.

The last three chapters explore more deeply the basic problems arising in the physical sciences concerning reality and truth. After contrasting realism with idealism, Chapter 9 turns to the entities that are considered real in classical physics. Though their reality remained unclear in the minds of some scientists, two concepts were dominant in the nineteenth century: particles, which, as Democritus had taught long ago, formed the basis for the structure of all matter, and fields, introduced by Michael Faraday, which transmitted the forces between the particles. Doubts about the reality of all fundamental physical notions began to intensify early in the twentieth century, when Einstein's theory of relativity raised questions concerning "real" length and time, but it was the quantum theory—its particles without identity or trajectories of motion—that brought forward the most basic problems about reality. Everything now seems dissolved by the universal wave-particle duality, and we wonder what is meant by the reality of minute objects that "live" for a tiny fraction of a second and then decay, or by the existence of particles such as quarks that can never be found in isolation. Much of what is real appears to become "virtual," and I conclude that realism depends on the scale of the beholder's view. The principal difficulty arises from the limitations of our language, which is tied to the scale of everyday life and seems ill-adapted to the micro world closed to our senses.

Chapter 10 delves into the difficult problems raised by physical reality at the submicroscopic scale, where we have no choice but to confront the puzzles and paradoxes of the quantum. After a discussion of the wave function, its interpretation and its mysterious "collapse," I turn to the most serious reality questions in the quantum theory. With Bohr and Einstein on opposing sides, the famous EPR debate and "entanglement" are introduced. Bell's inequality presents a way of subjecting to experimental test Einstein's search for the existence of "elements of reality" without "spooky action at a distance," and the evidence favors Bohr. Quantum field theory comes to the rescue by automatically producing both particles and waves, if we prefer using these concepts. My view of submicroscopic reality is based on this quantum field, while I conclude that both particles and waves are manifestations of our inadequate language.

Finally, Chapter 11 takes up the concept of truth as it applies to science. Distinguishing between the definition of truth and criteria for recognizing it, I adopt coherence as a test—a body of assertions is true if it forms a coherent whole and works both in the external world and in our minds. Science gradually approaches but never arrives at a truth that is, above all, public and openly sought. Attacks by cynics and ideologues notwithstanding, objectivity is an indispensable constituent goal, for which the scientist must strive in spite of personal biases, difficult as these often are to overcome. The pursuit of truth and the ideal of objectivity—purposes and values that scientists implicitly adopt and carry with them, not always with conspicuous success—constitute what might be called the "scientific attitude." Despite persistent current criticism, that attitude has served civilization well.

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CONVENTIONS

EVIDENCE obtained by experimentation for all to see, and general proofs sturdy enough to withstand scutiny—requirements neither obvious nor congenial to other cultures—were the foundation stones on which the ancient Greeks grounded our understanding of Nature and our knowledge of mathematical relations. The kind of mathematics pursued by the Babylonians, the Egyptians, the Hindus, and the Chinese led to many insights but never contained the idea of a *proof* as we know it. And while all these civilizations developed important technological advances through trial and error—watching and testing rather than simply following tradition—they did not arrive at general propositions about Nature grounded on observation and experiments that could be replicated, analyzed, and argued over. Rather, their views of Nature depended more on sacred books, the authority of prophets, private experience, or pure thought alone. The physicist Alan Cromer argues in *Uncommon Sense: The Heretical Nature of Science* that this Greek methodology was antithetical to what he calls the "egocentric" manner of gathering knowledge that pervaded other cultures and still largely dominates most of humanity: "Scientific thinking didn't—and couldn't—evolve from the prophetic tradition of Judaism and Christianity; it arose from a totally different tradition."[1] Similarly, the biologist Lewis Wolpert is convinced that "it is almost universal among belief systems not influenced by the Greeks that man and nature are inextricably linked, and such philosophies provide a basis for human behaviour rather than explanations about the external world."[2]

This invaluable innovation of the Greek culture lay dormant for centuries, held in memory, translated, and preserved by the Arabs. Later it was reintroduced to the intellectual consciousness of Europe by translations of the Arab texts into Latin in the late Middle Ages, induced to grow during the Renaissance, and brought to full flower in modern science. "The development of Western science," Einstein wrote in a letter,

> has been based on two great achievements, the invention of the formal logical system (in Euclidean geometry) by the Greek philosophers, and the discovery of the possibility of finding out causal relationships by systematic experiment (at the Renaissance). In my opinion one need not be astonished that the Chinese sages did not make these steps. The astonishing thing is that these discoveries were made at all.[3]

Thus modern science, Einstein, Wolpert, Cromer, and others argue persuasively, is not a natural way of looking at the world, bound to emerge among civilized people, but a very special, enormously productive methodology that historically arose only once and was fortunate to survive a long and perilous dormancy. Its emergence was neither inevitable nor its value immediately obvious. In fact, from the beginning it was strongly resisted, and it is resisted to this day, not only by religious fundamentalists but also by fashionable political groups. Opposition comes, for example, from New Age adherents and from radical feminists, whose science projects, the philosopher Sandra Harding declares, "emphasize personal experience as a source of knowledge."[4] But personal experience that cannot be publicly replicated is precisely the kind of evidence that has no place in modern science.

The Scientific Method as a Convention

The dispute between Robert Boyle and Thomas Hobbes offers a good historical example of the controversial nature of the rise of the concept of experimental science in the seventeenth century. Boyle had perfected the construction of a pump to evacuate the air from a vessel, producing a much better vacuum in his laboratory than had previously been available and allowing him to perform experiments with gases at various pressures. Among other conclusions, his data led to what is now called *Boyle's law:* so long as the temperature is held fixed, when the pressure or volume of a gas is changed, the product of the two remains constant.

Boyle is generally credited not only with specific discoveries, however, but with the development of the whole notion of laboratory science, the idea that experiments were not simply demonstrations performed by well-dressed gentlemen in front of an audience for the purpose of persuasion but were procedures for generating answers to questions about Nature. When Boyle's findings conflicted with those of others (Christiaan Huygens, for example), he relied on the superior quality of his air pump to give him a dependable answer that could be verified by those witnessing the experiment. He thus "question[ed] not [Huygens's] Ratiocination, but only the stanchness of his pump."[5] Anyone who had a pump as good as his could repeat the experiment and would obtain the same result. This important new line of argumentation had the additional virtue of being less personal.

The novel procedure of answering "philosophical" questions by resorting to witnessed and repeatable experimental tests was strongly attacked by Thomas Hobbes, to whom the vacuum was a metaphysical concept. In his view, what Boyle was doing had no philosophical relevance—his methods were not only wrong, they were actually dangerous. Instead of depending upon rational thought, Boyle's experiments had to be done with an expertly constructed piece of apparatus and witnessed by members of the Royal Society. As Steven Shapin and Simon Schaffer put it in their study of this controversy, "Hobbes maintained that the experimental form of life could not produce effective assent: it was not *philosophy.*"[6] In Hobbes's way of thinking, only rational argument mattered, and empirical data were regarded as ephemeral: "Hobbesian philosophy did not seek the foundations of knowledge in witnessed and testified matters of fact: one did not ground philosophy in 'dreams'."[7] The clash between Boyle and Hobbes had, of course, been foreshadowed long ago by that between Aristotle and Plato.

What such controversies show is that the method of science as we apply it now does not force itself upon the human mind as either logically necessary or inevitable. Therefore it would be fair to call it a convention. Science demands that "its standardised procedures be adhered to," David Bloor writes. "These procedures declare that experience is admissable only in as far as it is repeatable, public and impersonal. That it is possible to locate experience that has this character is undeniable. That knowledge should be crucially linked to this facet of our experience is, however, a social norm . . . Other activities and other forms of knowledge have other norms."[8] Indeed, in many cultures, both old and contemporary, knowledge is not assumed to be based on scientific procedures.

To say that something is a convention, however, as many conventionalists have stressed, is not necessarily to imply that it is a *mere* convention. By agreeing that the adoption of the scientific method is a convention, I do not mean to say that it is inconsequential or completely arbitrary, only that some people and some cultures have not adopted it and do not wish to put it to use in acquiring knowledge. That choice, however, has far-reaching intellectual and practical consequences. On the one hand, it has led both to a vast enrichment of our understanding of Nature and to all the benefits that flow from technology and therapeutic medicine based on science; on the other hand, it has led to what some regard as spiritual impoverishment and to the deleterious side effects of technology.

Conventionalism within Science

If we can agree that the adoption of the scientific method is a convention, must we conclude that the results obtained by this method—the laws and theories of science—are also conventions? This is the fundamental question raised by the school of conventionalism, called *nominalism* in its extreme form, which has sprouted malignant variants among some influential contemporary thinkers. All scientific results and theories are conventions, they contend, with the implication, at least in the minds of some, either that these results say nothing about the real world at all or that Nature and reality are simply *defined* by these conventions.

Einstein, on several occasions, expressed sentiments that superficially appear to be conventionalist: "Science," he wrote, "is . . . a creation of the human mind, with its freely invented ideas and concepts";[9] theories, he said in his 1933 Spencer lecture, are "free inventions of the human intellect." This phrase, however, it is important to note, appeared in a context that limited its validity: