1 The nature of things

I wrote this book for my friends who are not physicists, but who are curious about the physical world and willing to invest some effort to understand it. I especially had in mind those who labor to make the work of physics possible – technical workers in other fields, teachers, science-minded public officials – who read popular accounts but are hungry for a "next step" that might give them a firmer grasp of this puzzling material. Physics gives me great pleasure, more from its beauty than from its usefulness, and I regret that my enjoyment should depend on the effort of so many others who do not share it. Here I have tried to ease my sense of guilt by attempting to disclose in ordinary language what modern physics really is about. Many similar accounts exist.[1] In this one, I attempt to demystify the deep ideas as much as possible in a nonmathematical treatment. Some mathematical ideas are inevitable, and these I try to explain. Physics has entered an exciting phase with talk of new dimensions, exotic matter, and mind-boggling events of cosmic scale. These dramatic ideas rest on a solid conceptual framework, a product of the last century that is now old hat for physicists but remains exotic and impenetrable to most others. This framework, quantum theory and the Standard Model of matter, is an intellectual achievement of the highest order and essential for understanding what comes next. My intention here is to provide a reference and a guide to this known but still regrettably unfamiliar world.

Different physicists have different interests, but I think most would agree that the evolution of our field during the twentieth century stirs deep aesthetic feelings. I will try to explain why this is so, but cannot guarantee readers will have the same reaction. My account is not complete, nor faithful to the complex history of these ideas, but attempts a brisk, coherent sketch of the most important concepts and their links as I understand them. It is unhistorical because it assigns interpretations to past work of which its creators could hardly have been aware. It is personal because it presents my own perspective on the subject, which others may find eccentric. I mean it to be a useful as well as a provocative guide that focuses without much ornament on key ideas. Think of it as a quick review of the conceptual framework of modern physics that requires little prior technical knowledge. It does require patience and mental effort, and I recommend reading it sequentially in short segments. After a first reading, the book may serve as a reference for key concepts. I assume the reader has experienced high school algebra, but has forgotten its details. Notes at the end of each chapter support assertions, add information, and point to further reading. They are written for a wider range of readers who want more detail. Such readers may wonder why I chose to present the material this way. After teaching it for years from a more conventional point of view I realized that the relatively straightforward logic of the physics is easily overwhelmed by numerous fascinating historical or mathematical sidelights. Expert-level accounts let the mathematics carry the argument and omit the side issues entirely. I put them in endnotes. My overriding objective is to disclose the interconnectedness and internal logic of modern physical theory.

To be clear at the outset, my aim is to describe the mainstream view of Nature as expressed in the *Copenhagen interpretation of quantum theory*, and the *Standard Model of matter*. I have tried very hard to avoid saying what these theories are *like*, but rather to say what they *are*. This is notoriously difficult for reasons that will become apparent. I cannot make a difficult subject easy, but at least I can reduce the amount of special technical knowledge, especially mathematical knowledge, required to penetrate to the core of the matter. It is not my aim to probe the inadequacies of the Copenhagen interpretation, but to express it in modern form in the spirit if not in the language of its guiding author Niels Bohr.

The central question is: *If we agree that life is more than a dream, that our consciousness dwells in a universe that includes things other than itself, then what is the nature of those things?*

This vague, possibly meaningless question began, at least in Western culture, with philosophy in ancient Greece, and passed into science in the time of Isaac Newton (1642–1727). For many years thereafter it appeared that the philosophers (some of them) had guessed correctly that all is made of little particles, *atoms*, moving in a void (Leucippus, Democritus, minus fifth century). But in the middle of the nineteenth century the accelerating scrutiny of Nature began to reveal a world disturbingly different from what anyone expected.

1.1 NATURE DOES NOT CONFORM TO OUR EXPECTATIONS

Physics has an aesthetic aspect which, like poetry, depends on language and on context. Its context includes both philosophy and the history of discovery. The language of physics, as Galileo first insisted, is mathematics.[2] Many who have peeked at ideas like Einstein's relativity come away shaking their heads, convinced they will never understand them without mastering mathematics. That is a mistake. The difficulty of relativity has nothing to do with mathematics. The same is true of quantum theory. These two pillars of twentieth-century physics are conceptually difficult not because they are mathematical, but because Nature is essentially unhuman.

The linguist Noam Chomsky argued that we have a basic semantic structure hardwired in our brains that renders all human languages deeply similar.[3] Such a structure would have evolutionary survival value only if it resembled the physical environment that challenges our existence. So perhaps we have a reasonable picture of how the world works already embedded in our everyday language. The grammar of cause and effect, of action in the course of time, of place and order, all seem inevitably "natural." Our bodies too, as well as our minds, are equipped to see, hear, and feel "real" things. Immanuel Kant thought Euclid's geometry must represent reality because (to oversimplify his argument) it is physically impossible to perceive, and mentally impossible to conceive, any other kind of geometry.[4]

This anthropocentric view is unfortunately mistaken. The hard-wired structures beneath human language and human perception are not reliable evidence for the deep structure of Nature. Relativity and quantum theory are parts of this structure for which humans do not seem to have any built-in instinct. They fail to conform in deep and important ways to our intuitive preconceptions of how Nature should work.

The presence of "relativistic" and "quantum" ideas in the framework of science is the best refutation of the postmodernist claim that this framework has no independent reality, but is rather a product of social negotiation among disputing scientists.[5] On the contrary, the modern theories emerged painfully from a protracted disputation with Nature herself, and in the end Nature won. Perhaps we have not yet captured her subtlety with our imperfect language, but we are singing to Nature's tune, and not to some completely arbitrary composition of the human mind.

Today we have something called the *Standard Model* which has pieces like a child's toy from which all other ordinary matter can be constructed. Each piece has a name (quarks, leptons, bosons, . . .) and properties (charge, spin, flavor, . . .) which, together with rules of combination, lead to simple recipes for making *nucleons* (protons, neutrons), *chemical atoms* (clusters of nucleons clothed with electrons), and all else. A chart of the Standard Model (below) suggests the familiar periodic table of elements, of which all chemicals are made.[6] Think of Crick and Watson literally piecing together the structure of DNA with models made of carefully machined parts simulating groups of atoms.[7] We and all about us are made, in a sense to be explained, from the parts of the Standard Model.

This intuitive picture is appealing, and it is also seriously misleading. The pieces that physicists call "particles" are not like anything called by this noun in ordinary language. The broad canvas of "space" and "time" on which the Standard Model is portrayed

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u	c	t	γ
d	s	b	G
ν_e	ν_μ	ν_τ	Z^o
e	μ	τ	$W^\pm$

FIGURE 1.1 A conventional table of Standard Model pieces. No shading: leptons. Light shading: quarks. Dark shading: bosons. See Chapter 7 for a different arrangement and explanations of the symbols.

resembles human space and time only in a limited human-scale domain. Quantum theory, the very framework for the modern description of Nature, is strange almost beyond belief. As these deep awkwardnesses became part of physics early in the twentieth century, the field once again acquired a philosophical dimension. The philosophy is not much needed to work problems, but it is important for discovery, and it is essential if we are to make sense, upon reflection, of what it is that we do today when we "do" physics.

1.2 EXPLANATION VERSUS DESCRIPTION

Explanation usually means embedding a phenomenon in a more general framework that we accept as evident.[8] Euclid aimed to reduce geometry to a short list of self-evident axioms and definitions of terms. In the same way, physicists aim to reduce complex phenomena to the action of multiple simple, self-evident, mechanisms. From Newton onward, however, the simple mechanisms ceased to be self-evident. They could be described mathematically (the *how* of the mechanism), but they could not be related to a simple intuitive principle (the *why*). This is in sharp contrast to Aristotle's demand that explanation entail knowledge of the purpose or ultimate cause of a phenomenon, a demand that remains embedded in our culture because it is important in human affairs. We tend to explain human action in terms of motive and objective, but these terms are absent from modern science. In the generation prior to Newton, Johannes Kepler (1571–1630) hypothesized a force on the planets to keep them moving around the Sun, and felt the need to postulate a "soul" that caused it.[9] Newton did not care to explain gravity. He simply described its effect.

This unhuman decoupling of explanation from aim, while necessary, is a psychological impediment for many people. The two are linked by an anthropocentric bias that must be overcome for science to progress.

Mathematics is not the primary obstacle to understanding physics. Students beginning to study the subject are nearly always frustrated because phenomena are not "explained" in a way they expect. They learn to manipulate formulas that give results for various situations – swinging pendulums, falling weights – and this suggests that physics is somehow just mathematical manipulation. Beginners find it difficult to relate the formulas to something tangible. Terms like *force*, *potential energy*, *electric field*, are names attached to letters in equations. But what *are* these things, really? Knowing math provides no answer. After more or less experience with the formulas, students acquire intuitions about the behavior of whatever it is that is called by these names, but what the names really signify remains elusive.

It turns out, intriguingly, that the lack of "explanation" makes no difference to how physics is used in applications. No one really understands quantum mechanics intuitively, but hundreds of thousands of scientists and engineers use it in their daily work. The ability to analyze the questions quantum theory was designed to answer does not satisfy our hunger for deeper explanations.

1.3 PHYSICISTS KEEP TRYING TO EXPLAIN THE "UNEXPLAINED"

Its reticence toward explanation has encouraged a rather lifeless view of physics. As the nineteenth century turned, some philosophers embraced positivistic notions about knowledge that discarded concepts that were not rooted in some firm encounter with the commonsensical "real world." The success of "physics without explanations" suggested that attempts to explain were fruitless, and that science should be rid of such baggage. At its worst, this movement doubted the existence of atoms because they could not be seen.[10] At its best, it supported Heisenberg's search for a new atomic mechanics that would depend only on features of atoms that *could* be seen.[11] Some people still speak of scientific formulas as if they were no more than concise summaries of many direct observations, as opposed to statements about the behavior of abstract features of reality, like force and energy, that cannot be visualized.[12] In this view, physics is just a way of arranging experimental results systematically, and the elaborate theoretical structures are only mnemonic devices for the data.

Physicists themselves, however, and especially those who work at the frontier, despite all admonitions from philosophers, seem to believe in the reality of the things their equations describe. They are encouraged in this belief by the great value it has for discovery. In a symposium in 1998 at Stony Brook University, philosopher Bas van Fraasen asked why physicists believe Nature has to obey symmetry laws. I said that "it wins them Nobel prizes!" Throughout the twentieth century, physicists' conviction that abstract entities such as "fields of force" can be "explained" has been influenced by an extraordinary chain of events that I will now endeavor to describe.

NOTES

1. *Similar accounts*. At the same technical level as this book, the excellent account by Crease and Mann (Crease and Mann, 1996) follows the development of modern physics through the contributions of its leading scientists. A more technical presentation by one such scientist, full of insights of interest to the nonspecialist, is Abraham Pais's *Inward Bound* (Pais, 1986). Pais has authored important and well-documented biographies of Einstein, Bohr and others, cited in the References. Helge Kragh's *Quantum Generations* (Kragh, 1999) is a good nontechnical survey that places the subject in a broader social context. On the interpretation of quantum mechanics, David Lindley's *Where Does the Weirdness Go?* (Lindley, 1996) is a lucid account for a general audience. Other references are cited in the notes following each chapter below. *The Whole Shebang: A State-of-the-Universe(s) Report* by Timothy Ferris (Ferris, 1998) gives a snapshot in nontechnical terms of current topics, especially in cosmology, not covered in this book. All these accounts are broader and more general than the present work, which focuses narrowly on the Standard Model and the quantum world view, and not on the sweep of discovery or the state of

knowledge of the entire physical universe. Brian Greene's *The Elegant Universe* (Greene, 1999) is a good popular account of *string theory*, the current most promising attempt to resolve incompatibilities between our current understanding of gravity and the other forces in Nature.

2. *Galileo on the language of physics*. "Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth." Galileo Galilei, *The Assayer* (1623), translation by Stillman Drake. Reprinted in Drake (1957).
3. *Chomsky on hardwired linguistic structure*. "... the child has an innate theory of potential structural descriptions that is sufficiently rich and fully developed so that he is able to determine, from a real situation in which a signal occurs, which structural descriptions may be appropriate to this signal, and also that he is able to do this in part in advance of any assumption as to the linguistic structure of this signal." *Aspects of the Theory of Syntax* (Chomsky, 1965).
4. *Kant's view of geometry*. "... the space of the geometer is exactly the form of sensuous intuition which we find *a priori* in us, and contains the ground of the possibility of all external appearances (according to their form); and the latter must necessarily and most rigorously agree with the propositions of the geometer, which he draws, not from any fictitious concept, but from the subjective basis of all external appearances which is sensibility itself." *Prolegomena to Any Future Metaphysics* (Kant, 1783).
5. *Social status of scientific reality*. The sharpest statements of the postmodernist claim are made by its critics: " ... science is a highly elaborated set of conventions brought forth by one particular culture (our own) in the circumstances of one particular historical period; thus it is not, as the standard view would have it, a body of knowledge and testable conjecture concerning the 'real' world. It is a *discourse*, devised by and for one specialized 'interpretive community,' under terms created by the complex net of social circumstance, political opinion, economic incentive, and ideological climate that constitutes the ineluctable human environment of the scientist. Thus, orthodox science

is but one discursive community among the many that now exist and that have existed historically. Consequently its truth claims are irreducibly self-referential, in that they can be upheld only by appeal to the standards that define the 'scientific community' and distinguish it from other social formations" (Gross and Levitt, 1994). In striving for clarity, Gross and Levitt have excluded from this statement the essential socio-political aspects of the postmodernist case that make it comprehensible. But that is another story.

6. *Standard Model wall chart*. See the figures in Chapter 7 below. The Contemporary Physics Education Project website (www.cpepweb.org) has a popular version that contains more information.
7. *The DNA model of Crick and Watson*. "The brightly shining metal plates were . . . immediately used to make a model in which for the first time all the DNA components were present. In about an hour I had arranged the atoms in positions which satisfied both the X-ray data and the laws of stereochemistry. The resulting helix was right-handed with the two chains running in opposite directions" (Watson, 1968).
8. *"Explanation."* What is "evident" may not be familiar. "What scientific explanation, especially theoretical explanation, aims at is not this intuitive and highly subjective kind of understanding [reduction to the merely familiar], but an objective kind of insight that is achieved by a systematic unification, by exhibiting the phenomena as manifestations of common underlying structures and processes that conform to specific, testable, basic principles" (Hempel, 1966).
9. *Kepler on the origin of the forces that move the planets*. Kepler had inferred three famous "laws" from careful observations of planetary orbits by his predecessor Tycho Brahe (1546–1601). I. The planets move in ellipses with the Sun at one focus. II. A line from the Sun to a planet sweeps out an area as the planet moves which is proportional to the elapsed time of the movement. III. The square of the orbital period for any planet is proportional to the cube of the size of its orbit. Kepler was hard put to explain how the whole system operated: ". . . I admit a soul in the body of the sun as the overseer of the rotation of the sun and as the superintendent of the movement of the whole world." ". . . the philosophers have commented upon the intelligences, which draw forth the celestial movements out of themselves as out of a commentary, which employ consent, will, love, self-understanding, and lastly command; the soul or motor souls of mine are of a

lower family and bring in only an impetus – as if a certain matter of movement – by a uniform contention of forces, without the work of mind. But they find the laws, or figure, of their movements in their own bodies, which have been conformed to Mind – not their own but the Creator's – in the very beginning of the world and attuned to effecting such movements" (Kepler, 1618).

10. *Doubting the existence of atoms*. "However well fitted atomic theories may be to reproduce certain groups of facts, the physical inquirer who has laid to heart Newton's rules will only admit those theories as *provisional* helps, and will strive to attain, in some more natural way, a satisfactory substitute" (Mach, 1893).
11. *Heisenberg's search for a new atomic mechanics*. The complete abstract of Heisenberg's groundbreaking paper *Quantum-Theoretical Re-interpretation of Kinematic and Mechanical Relations* reads: "The present paper seeks to establish a basis for theoretical quantum mechanics founded exclusively upon relationships between quantities which in principle are observable" (Heisenberg, 1925).
12. *Formulas as summaries of experimental data*. This attitude was frequently expressed by the positivist anti-atomists. See Pullman (1998). Wilhelm Ostwald's declaration of 1895 is an example: "To establish relations between realities, that is to say, tangible and concrete quantities, that is science's responsibility, and science fails to meet it when it espouses a more or less hypothetical image."