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INTRODUCTION

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The Shores of Our Knowledge

THE DISCOVERIES MADE BY PHYSICISTS DURING THE LAST HUNDRED years, and their applications in medicine, industry, and the home, have transformed our lives. We take for granted as everyday necessities what were yesterday only fanciful dreams. Fundamental research has spawned new products and new industries, as well as deeper understanding of the natural world. The pace of discovery and its exploitation is exhilarating and relentless. For all the dangers which sometimes cloud these advances, I find them overwhelmingly positive and enriching.

Think of an expectant mother, attending a hospital clinic today. The position of the unborn child in the uterus is displayed on a screen—ultrasound scanning and computer display instantly combining to give information to the obstetrician and comfort to the mother-to-be (figure 1.1). Her phone call home is transmitted, along with hundreds of others, as laser pulses down an optical fiber thinner than a hair. The child who answers the phone turns off the television—a satellite broadcast—and calls her father. He comes to the

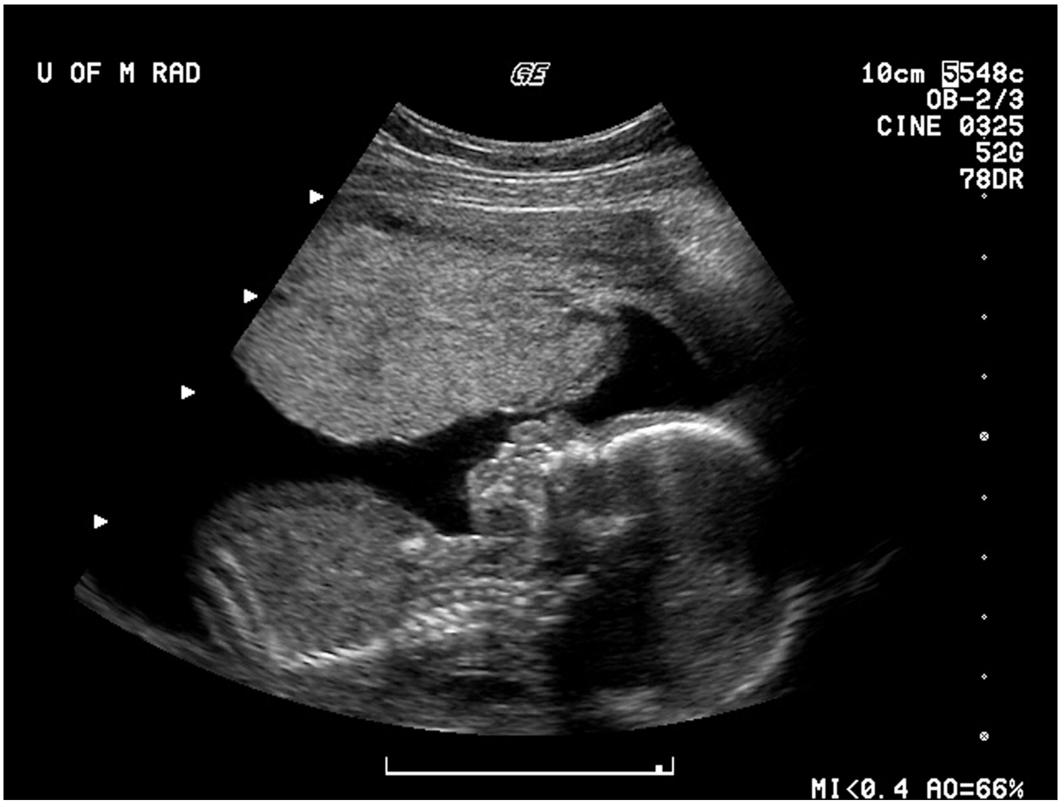

Fig. 1.1. Ultrasound image of an unborn child. Ultrasound imaging is one contribution of twentieth-century physics to medical practice. What future technologies will this child live to see? (Courtesy of GE Medical Systems)

phone, pleased with himself that the evening meal he has prepared can be ready to serve after only a few minutes in the microwave. In the meantime he will listen to a CD, a concert-hall performance recreated by a laser that scans microscopic pits etched in a cheap disc of metal. Nothing very special, yet this family has at its service, and uses with scarcely a thought, wonders that only a lifetime ago would have seemed miraculous.

In this book I have set out to describe the physicist's view of the world at the dawn of the twenty-first century. Most of us enjoy celebrating anniversaries, and we make special note of centenaries. They provide occasions for looking back over the past and also forward to the future. We often find it convenient to package events by centuries, fixing markers in the turbulent flow of events at hundred-year intervals. Fortunately, for this purpose, the dawn of modern physics can be justifiably pinpointed to the year 1900, when Max Planck introduced the law that was to lead to quantum mechanics. A conservative rather than a revolutionary, both by temperament and in his research, he was nevertheless aware that his discovery was of profound importance.[1] As the nineteenth century ended, other seminal discoveries—of the electron and of radioactivity, for example—were made that were also to mark the end of what we now call classical physics.

Before embarking on an account of some of the amazing advances in the twentieth century and looking into the future, it seemed appropriate to survey the prospect from the year 1900. There are people alive today who can recall their world a hundred years ago; and for most of us enchanting mementoes of times gone by, sepia photographs, historic movies, gramophone records, books and journals, can bring that past vividly to our present attention. Some things seem timeless and unchanging; some have vanished forever. But more than the immediately evident change in fashions and style, more even than the changes wrought by our enormously enhanced technological capacity, the last century has seen changes that truly justify the use of the description "revolutionary." These have been most profound in the way that we perceive the world, not least in science, not least in physics.

It is not only through their technological applications that the advances in physics have had such far-reaching consequences. The twentieth century saw profound changes in the way we understand the universe and the laws that codify its structure and content. We learned that the Milky Way, the galaxy of stars of which our sun is just one of a 100 billion others, is itself just one among at least a 100 billion other galaxies. The universe is now known to be not only unimaginably more immense than was conceived just a lifetime ago but also unimaginably older. Its birth in the "big bang" and the fascinating story of its transformation from a terrifying furnace of compressed energy through the successive condensation of matter into stars, planets, and the elements from which we ourselves are made is one of the triumphs of human intellectual elucidation, with mythic resonance the more potent because it is based on fact. In chapter 3 I look back on a century of discoveries in astronomy which have in this way so utterly changed our picture of the universe, and also look to the exciting prospects as new kinds of telescopes open new windows on the cosmos.

It is wonderful enough that matter, in all its variety of forms—from hydrogen, the simplest and most common element, to the most complex molecules, like the DNA that encodes our genetic inheritance—is made from atoms. But those atoms themselves were discovered to have a structure that cannot be properly described or understood without transforming the fundamentals of mechanics as passed on from Galileo and Newton. The invention of this new mechanics—quantum mechanics, the subject of chapter 4—was just one of the revolutionary "paradigm shifts" to punctuate the advance of physics in the twentieth century. The quantum mechanics that is needed to make sense of the structure of atoms has provided a robust underpinning not only for chemistry but also for nuclear physics and the physics of the elementary particles from which all matter is constituted. Today the implications of quantum mechanics for understanding the origin and overall structure of the universe are still being explored. And there are still mysteries to be unraveled in the very foundations of quantum mechanics itself. We know well how to *use* quantum mechanics, but there are still open questions on what quantum mechanics *means*. This is not just a topic for armchair philosophers! For there is a fascinating interplay between information theory and quantum mechanics which gives reason to suppose that we will in the near future have quantum computers far exceeding today's in speed of operation.

But it is not only through the inevitable uncertainties introduced by quantum mechanics that unpredictability enters into physics. Even in the deterministic world of Newtonian mechanics complex systems exhibit chaotic behavior. Chaos is not the same as disorder. There is a strange kind of order in chaos, and how this can emerge is described in chapter 5. The irregularities and discontinuities of chaotic systems need a fresh approach, more holistic than that of classical mechanics. The science of complexity, of the spontaneous generation of order by self-organizing systems, has profound implications for biology, economics, and sociology. It seems that, quite literally, life emerges on the edge of chaos. For it is there that complex adaptive systems flourish—and every living creature, and every ecology, is a complex adaptive system.

Another transformation from the classical worldview inherited from Newton and his rich and fruitful legacy was that wrought by Einstein in his theories of relativity, both special and general. Space and time, respectively the passive arena and ordering principle of classical physics, were unified by the special theory into a spacetime stripped of any absolute landmarks or preferred frame of reference. The general theory then endowed spacetime with a dynamic role as active partner in the dance of matter, and at the same time brought a new understanding of that most familiar of the forces of nature, the force of gravity. The marriage of quantum mechanics with relativity theory required heroic efforts, and even now the full integration of quantum mechanics with the general theory, and not just the special theory, is somewhat speculative and contentious. But undeniably the union of the special theory of relativity with quantum mechanics gave birth to a wonderfully rich and detailed explanation of the physics of elementary particles and the forces between them, an explanation powerful enough to embrace their behavior in high-energy physics laboratories as well as in the high-energy world of the birth and death of stars. For the moment we can only speculate on the fuller implications of quantum theory wedded to general relativity theory.

Those speculations are rich and wonderful. They have convinced most theorists who work at this frontier of physics that the basic entities of the cosmos resemble strings more than pointlike particles, that spacetime has more dimensions than those of which we are aware from our everyday experience, that there are profound interconnections and symmetries that constrain the possible structure of spacetime and matter. To some these ideas may seem to have no more foundation than the imaginings of ancient philosophy or New Age mysticism. But that is not the way I see it! I hope at least to be able to persuade you that they meet the rigorous demands of mathematical self-consistency, and the yet more rigorous demands of conformity with experimental observation. These probing speculations give us not only the dazzle and wonder of an imagined world but the added amazement of knowing that this imagined world may well be the world we actually live in!

The chapter “Your Place or Mine” is about the special theory of relativity and the change in our understanding of elementary particles brought about by bringing it together with quantum mechanics. Relativistic quantum mechanics led to the prediction of antimatter and to the recognition that particles were not permanent, immutable units, like the atoms imagined by the ancient Greeks, but rather could be created or destroyed. From this insight there emerged the idea that particles were best described as packages of energy associated with fields. This is relativistic quantum field theory, perhaps to date the most successful approach to understanding the basic structure of matter and the forces which act on it. Chapter 7 describes how this theory is used to yield amazingly precise agreement with the results of experiments in high-energy particle physics. Quantum field theory is also the setting for what has become known as the standard model of subatomic particle physics, which is the subject of chapter 8.

I have left until chapter 9 some of the developments following from Einstein's general theory of relativity. And in chapter 10, "Strings," I have outlined the fast-developing theory which for the first time has allowed us to bring together quantum mechanics and general relativity, and into the bargain gives a prospect of what has been called a "Theory of Everything." Quantum mechanics is needed to explain what happens on the tiny scale of the atom and its constituents. General relativity is needed to extend Newton's theory of gravity to the extreme conditions of black holes and the grand scale of the universe as a whole. What we now need is a quantum theory of gravity in order to describe the earliest moments after the big bang with which the universe began and so to trace the imprint left from that time on the heavens today. The search for such a theory is what today's cosmology and chapter 11, are about.

Of course there is much more to the physics of today than the exploration by theory and experiment and patient observation of those phenomena at the extremes of size, the microworld of the particle physicist and the macroworld of cosmology. So very much has been learned also on the scales between, the more comfortable scales of our own lives and experience. Many technological advances that have made the new physics possible have also enriched our lives, thus linking the extremes of nature to the everyday. At the dawn of the twentieth century, the then-recent discovery of x rays was already making possible a whole new approach to medicine, an approach that has been extended by subsequent advances in physics to give CT scanners, MRI scanners, ultrasound, and other noninvasive diagnostic tools. Therapeutic advances include laser surgery, radiotherapy and cyclotron beams for cancer treatment, and the whole electronic monitoring technology that has transformed hospital care. But in many ways it has been the advances engendered by the electronic revolution that have had the most pervasive impact on our lives. Transistors, lasers, microwaves, and optical fibers: these are some of the products of twentieth-century physics that have revolutionized our communications, entertainment, and industry. In ancient times, some technologies were developed without any scientific underpinning, based simply on the experience of those who used them. But most of the new modern technologies have been initiated by scientific discovery and driven forward by the ingenuity of the researchers in science laboratories. Whole industries have been spawned by the application of techniques and processes learned from research that was itself motivated by the pursuit of knowledge and understanding for its own sake.

Physics advances on many fronts. High-energy particle physics and astrophysics, glamorous and headline-catching as they are, are not the only fields of excitement and discovery. Even if we may fairly claim to know the fundamental laws governing the behavior of matter in situations less extreme than those of the high-energy laboratory or the outer limits of space and time, it does not follow that we fully understand the implications of those laws. And sometimes, though rarely, a new discovery requires that we revise them. Much more often, we are challenged to explain it within the framework of those laws as we know them.

Let me give an example. From the time he was appointed as director of the laboratory at Leiden in the Netherlands in 1882, Kamerlingh Onnes had sought to push back one of the frontiers of experimental physics: he tried to get closer to the absolute zero of temperature.[2] He was the first to liquefy helium. And in the course of systematic investigation of the optical, magnetic, and electrical properties of substances at low temperatures, he discovered that the electrical resistance of lead suddenly vanished completely at a temperature just 7.2 degrees above absolute zero. He had discovered superconductivity. It was not until forty-five years later, in 1956, that a satisfactory theory was found to explain the phenomenon.[3] But the theory did not require any revision of established laws; rather, it was an imaginative application of them. Superconductors have widespread application—for example, in the magnets used in MRI scanners in hospitals.

The story does not end here, for it was found that certain ceramic materials also lose their electrical resistance when cooled only to the modest extent attainable by using liquid nitrogen.[4] There is still no agreed-upon theory that explains this behavior (the theory that can explain superconductivity in metals such as lead cooled to the much lower temperature of liquid helium doesn't work for these "high-temperature" superconductors). But no one supposes that it will require a revision of the laws governing atomic and molecular structure, still less of the quantum mechanics and electromagnetic theory that underpin them. And though we don't have a theory to explain them, ceramic superconductors are already finding technological applications.

There is a stratified structure in physics which extends to the other sciences. We may believe that at the most fundamental level there are some deep principles and laws that govern all the myriad phenomena of the physical world. But it is unreasonable and unrealistic to start from these fundamentals in order to give a useful explanation for every phenomenon encountered in the laboratory—or in our everyday lives. There can be many steps between the succinct, general, fundamental laws and their complex, specific, and practical applications. What *is* necessary, however, as we move upward through the levels of explanations, of theory and experiment, is that at no step do we find a *contradiction* with what can be deduced from levels deeper down. At any level of explanation it is often useful to introduce what might be called secondary or subsidiary laws, appropriate at that level, encapsulating in a more readily applicable way the consequences of the laws derived from the deeper levels. In this way the pharmacologist, for example, may design a drug using empirical rules about the structure of molecules derived from more basic chemistry; these in turn have a theoretical framework built upon the behavior of electrons and atomic nuclei as governed by quantum mechanics and electromagnetism. But even the theory of quantum electrodynamics is an approximate, albeit effective, theory based on and derivable from a more fundamental level of understanding (figure 1.2).

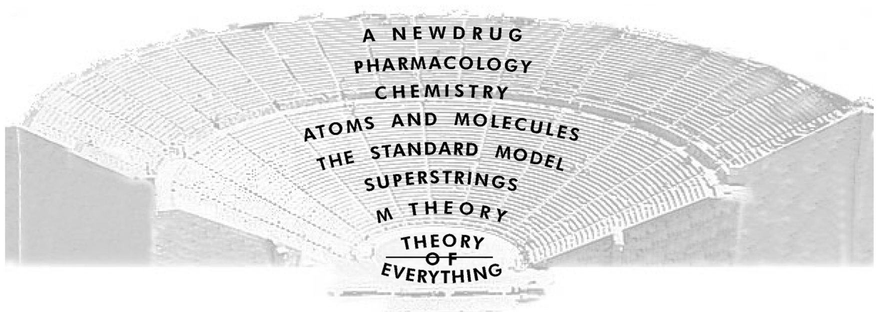

Fig. 1.2. The hierarchy linking basic laws of nature to practical application. There are many steps from a Theory of Everything to the design of a new drug.

The ability to trace back from one level of understanding to a deeper one is related to the *reductionist* approach to science, which is a source of some dismay and conflict, even within science itself. Steven Weinberg, in *Dreams of a Final Theory* (New York, N.Y.: Vintage Books, 1994), writes of "those opponents of reductionism who are appalled by what they feel to be the bleakness of modern science. To whatever extent they and their world can be reduced to a matter of particles or fields and their interactions, they feel diminished by that knowledge. [. . .] The reductionist worldview *is* chilling and impersonal. It has to be accepted as it is, not because we like it, but because that is the way the world works." And to those "scientists who are infuriated to hear it said that their branches of science rest on the deeper laws of elementary particle physics," he replies, "whether or not the *discoveries* of elementary particle physics are useful to all other scientists, the *principles* of elementary particle physics are fundamental to all nature."

One should neither ignore nor belittle the difficulty in moving upward through the strata of levels of understanding. At any step it may be not only convenient but necessary to introduce new laws, new structures, new modes of description, the better to account for the *emergent* phenomena there encountered. It would be not just arrogant, but also stupid, to try to design a drug by starting from quantum electrodynamics! The problems of the pharmacologist are complex and particular; the principles at the deeper level of quantum electrodynamics are simple and general. What is remarkable is that the consequences of these simple, general principles can be so rich and diverse. Quantum electrodynamics may be said to explain the diverse characteristics of the chemical elements, but the wondrous and unique properties of carbon that make it the basis for the chemistry of life must surely be said to be *emergent*. It is rather like an oak tree, in all its complexity, emerging from something as simple as an acorn—but there is a big difference. What emerges from an acorn is always an oak tree, never a zebra. *All* the rich variety of complex phenomena that delight and perplex us arise from the basic laws that physics seeks to determine.

The reductionist may seek for fundamental laws which account for the properties of the particles and fields which are believed to be more fundamental than oak trees or zebras. But that is not to deny that there are important and wonderful laws and regularities—for example, of genetics—which are basic for the understanding of biology. The point is that these are in some sense *consequences* of the chemistry of DNA, and ultimately of the physics of elementary particles. It would be crazy to seek to understand oak trees and zebras are in some ways so alike and in some ways so utterly different by studying elementary particle physics. The chemistry of DNA and the principles of biology that derive from it can be said to *emerge* from the underlying physics of atoms and molecules. And we encounter emergent phenomena within physics itself. The air in your room is made from molecules that collide and scatter from one another in a way well described by mechanics. As they collide, the energy of their motion is distributed among them, and the average kinetic energy accounts for what we call "temperature." The temperature of the air is thus a consequence of molecular dynamics. But it makes no sense whatever to speak of the temperature of a single molecule, nor even of a half a dozen molecules. Temperature is an *emergent* phenomenon, which only becomes significant when a great many molecules are involved.

Unfortunately, the reductionist approach can lead to a misunderstanding that turns some people away from science in general, and physics in particular, in favor of the more comfortable holistic claims of "New Age" beliefs. As one moves up through the levels of phenomena to ever more complex systems, it is not surprising that interesting and important questions are encountered that cannot be answered simply in terms of what is already known. Mysticism and magic have enriched our culture in the past, and science itself should be unashamed to acknowledge its own roots in that subsoil. But science and its offshoots are more reliable and effective aids to solving the urgent problems that confront us than muddy misunderstanding and superstition. Complex problems will often have complex solutions, and there is certainly more to a forest than a collection of trees. But I believe that one can better appreciate the forest as a whole by looking first at the individual trees within it.

More than 80 percent of the scientists who have ever lived are alive today. The pace of scientific discovery has increased and with it the benefits that science brings—and the challenge to ensure that the benefits outweigh the evils and misfortunes that have also arisen from the application of scientific knowledge. I believe it is timely to look back on the past achievements (and the follies) that we so often take for granted. And it is also a good time to take stock of our current picture of the physical world. With the benefit of hindsight, we can see that as the twentieth century dawned, there were premonitory hints of the revolutionary changes that were to come in our understanding of the physical world, changes that have proved necessary to encompass what experiment and observation have revealed. We have had to recast the elegant simplicities of classical physics, but they are still the enduring framework and foundation for the physics of the twenty-first century, and they still provide the context, and even much of the language, within which the subject is advanced. I do not believe that we have come to the end of the road. I do not believe that the modern relativistic quantum view, even when enriched by something like string theory, is the last word. But neither do I believe that we will ever need to completely jettison the theoretical framework we have constructed with so much labor and thought and within which we can fit so much of the subtle and extensive richness of our experimental knowledge. Science thrives on a continued dialogue between explanation and observation. I am convinced that as science spawns new technologies and new techniques, phenomena will be discovered that do not fit comfortably within our present theories. And we should welcome and relish such phenomena. For science can use them as a stimulus to deeper understanding and further advance.

In the following chapters I will try to present the view of the physical world as it now is revealed. The revolutions wrought by the theory of relativity and of quantum mechanics have had profound implications, and they have opened up problems still to be resolved. But relativity and quantum mechanics are now deeply embedded in the model of reality that I have as a physicist, and that I will here try to describe. Yesterday's revolution has become today's orthodoxy, and my views are mainstream, cautious, and, I believe, widely held. Nevertheless, the prospect as I look to the future is challenging and full of deep mysteries.