Introduction
The new physics for the Twenty-First Century

Physics is the science of matter – the stuff of the Universe around us, and of energy – the capacity of matter to act in different ways. Physics is the systematic study of how this matter and energy behave, the explanation of what this reveals, and the understanding it brings. A magnificent allegory of what a physicist does can be found in the Old Testament, the Book of Job, Chapter 28.

For he looketh to the ends of the earth, and seeth under the whole heaven; To make the weight for the winds; and he weigheth the waters by measure. When he sought a decree for the rain, and a way for the lightning and the thunder. Then he did see it and declare it. . .

If our surroundings are seen as being built up of matter, much of Nature is ultimately physics, so physics underpins many other branches of science. It is difficult to be more ambitious than that. But as though such boldness were not enough of a challenge, new physics has gone on to reveal that matter and energy can exist in forms and behave in ways very different from those we know in everyday life. The goal becomes even more ambitious. Nature, and therefore physics, has become much wider than what we normally see around us.

Progress in science comes from not looking at Nature at face value, but undertaking some voyage of discovery to reveal a different viewpoint. From this new vantage, the landscape takes on new aspects and dimensions, leading to fresh insights and new satisfaction. With this vision, the next step is perhaps even more fulfilling – predicting what can be seen from a higher standpoint.

Historically, there have been several major watersheds for physics, each of which could have warranted the publication of a book called *New Physics*. Many of these opened up fresh aspects of the Universe. One was the renaissance of learning in Europe in the middle of the second millennium. New insights from giant figures such as Kepler, Copernicus, and Galileo showed that the Earth is not the hub of the Universe. This was not easy to swallow, and the implications rumbled for many centuries, but for scientists the logical culmination came with Newton's masterpiece picture of mechanics and gravity. (The first edition of Newton's *Principia*, which embodied the new dynamics, was published by the Royal Society of London in 1687. An updated second edition, produced this time at Cambridge, appeared in 1713.) The flow of results from Newton's work encouraged the idea of determinism – that everything that happens follows from what went before, and that the future is merely history waiting to happen.

The New Physics for the Twenty-First Century, ed. Gordon Fraser.

Cambridge University Press
0521816009 - The New Physics for the Twenty-First Century
Edited by Gordon Fraser
Excerpt
More information

A subsequent watershed in physics strangely coincided with the hinge between the nineteenth and twentieth centuries. Until this point, physicists had tried to picture the world around us as an assembly of precision components that fit neatly together like a Swiss watch and moved according to immutable laws, giving a vivid mental image of how Nature worked on any scale in space and in time. However, the dawn of the twentieth century seemed to fire imagination across the entire spectrum of human culture. Science, as well as art and music, became imbued with new and unconventional directions. Within the space of a few years, the discovery of the electron, the introduction of the quantum principle, and the arrival of relativity theory had revealed unexpected aspects of Nature.

The first few decades of the twentieth century uncovered the implications of relativity and quantum mechanics. Still notoriously difficult for beginners, these major innovations dramatically showed how we have been conditioned by our limited everyday experience, and how Nature can appear enigmatic under unfamiliar conditions. In another physics direction, big telescopes revealed new depths of the Universe, showing that our Galaxy is only one of a multitude, and is hidden in an insignificant back row. This major reappraisal of astronomy had a similar impact to the revelations of Copernicus four hundred years earlier.

For many generations of twentieth-century physicists, relativity and quantum mechanics were the "New Physics." Cosy models with gearwheels and springs had to be jettisoned, and the early twentieth century showed that Nature instead works on a different plan. Simple models and familiar preconceptions of cause and effect may once have been useful, but taken at face value were a major obstacle to further understanding. The Universe is governed ultimately by probabilities. The implications of this uncertainty began to take root soon after the discovery of quantum mechanics, but it took several decades before other important concepts such as quantum entanglement were understood and demonstrated.

During this time, the central goal of physics remained as trying to explain as much as possible from some minimal subset of hypotheses. With the theory of general relativity and the Schrödinger equation, and later with the help of powerful computers, perhaps it would be possible to work out all the implications and probabilities.

Simplicity and complexity

Because of its broad scope, physics has traditionally diverged along two mutually opposite frontiers – the study of the infinitely small, and that of the immensely large. Looking inwards into matter, elementary particle physicists attempt to identify the innermost constituents of Nature – quarks, electrons, . . . – while their field-theoretical colleagues try to make sense of it all and explain how these particles interact to form substance and matter. Looking outwards, astronomers and astrophysicists chart the large-scale map of a Universe composed of stars and galaxies clustered on a dizzying array of scales, and cosmologists attempt to understand how all this came about.

The first section of the book – "Matter and the Universe" – deals with the composition of what we see around us. It begins with a chapter that explains how the cosmos itself has come under systematic study, complementing what has been learned by looking at its various components at different scales. This wider view reveals what is perhaps the biggest enigma of all – the Universe has to contain much more than we can see, a new Copernican revolution. The familiar matter and energy that we know and understand seems only to be the tip of a vast cosmic iceberg, the rest – "dark matter" and "dark energy" – being hidden from view. The visible tip of the cosmic iceberg is underpinned by a vast invisible plinth, complemented by mysterious forces that blur the familiar attraction of gravity. Despite all our efforts so far, we do not even know what, or even where, most of the Universe is!

Whatever and wherever it is, the Universe is enormous, but is ultimately made up of very small things. On the large scale, the Universe is described by relativistic gravity, and on the small scale by quantum physics. The sheer difference in scale between these two descriptions and the resultant polarity of their approaches kept them apart for many years. But the latter years of the twentieth century brought the realization that the Universe had been created in a Big Bang – an enormous but highly concentrated burst of energy where quantum physics had ruled and where gravity had played a major role. The Universe is the ultimate physics experiment. This realization heralded a new synthesis. A better knowledge of the Universe's microstructure brings a deeper understanding of the Big Bang and therefore its subsequent evolution and large-scale structure. The first chapters in this book cover this ongoing synthesis of the large and the small. The stubborn reconciliation of gravity with quantum physics remains a key objective in this work.

With such a synthesis, some ambitious physicists began to seek a "Theory of everything," an iconic set of succinct equations that had governed the Big Bang and everything thereafter. Such a theory would have to reconcile the quantum world with gravity. The theory of "superstrings" is often described as a candidate for such a theory. Author Michael Green does not fully share this view; however, the long-sought unification of gravity with quantum mechanics does seem to be viable in this approach. But such an ambitious venture has its price, namely the inclusion of many invisible extra dimensions that complement the four dimensions of conventional spacetime.

Despite concessions to probability, to extra dimensions, and to sheer calculational difficulties, the advances of the twentieth century went on to show that a bold reductionist approach is not the only solution, and in some cases is not even possible.

Pioneer attempts to understand physics through constituent behavior used the kinetic theory of gases, viewed as unstructured assemblies of microscopic elastic billiard balls. Confined to its stated range of validity, this modest theory was highly successful. With the realization that constituent motion ultimately has to be quantized, the subsequent picture of quantum statistical mechanics brought new understanding.

Looking at the Universe as a gas of galaxies may give some useful results, but its limitations are uncomfortably obvious. Everywhere around us we see structure – planetary systems, crystals, atoms, . . . – each level of which has its own characteristic behavior. New physics has revealed that matter can be made to exist in structured forms that are less familiar but nevertheless remarkable – superfluids, semiconductors, plasmas, liquid crystals, . . ., new types of matter whose appearance is often marked by phase transitions – abrupt onsets of new behavior. Many of these forms are not easily visible or even present in the Universe around us and can behave in curious ways. Many are due to microscopic quantum effects, which can nevertheless exist only in bulk matter (there is no such thing as a lone superconducting electron, and nobody has yet found a magnetic monopole). This new synthetic material is described in the second section – "Quantum matter."

Such bulk behavior can become relatively easy to identify once it has been discovered, but its explanation from first principles can be much less apparent. Ferromagnetism, known since antiquity, is a classic example. On a different timescale, about half a century elapsed between the discovery of superconductivity and superfluidity and their initial explanation in quantum terms. Quantum mechanics, developed in the early years of the twentieth century to explain the interactions of a few electrons with each other, showed how our confident familiarity with everyday Nature can be deceptive. Despite its apparent unfamiliarity, quantum mechanics helps us to understand and explain more aspects of the behavior of matter.

The third section – "Quanta in action" – includes chapters on quantum entanglement; on quanta, ciphers and computers; and on small-scale structures and nanoscience, providing good examples of how quantum physics can no longer be confined to a remote, cosily inaccessible realm and is becoming increasingly interwoven with everyday phenomena, enabling more phenomena to be explained, new ones to be discovered, novel materials engineered, and fresh approaches explored. The quantum world is no longer just a blurry backdrop visible only to the front row of the audience, and the realization that Nature can be controlled and manipulated at the quantum level has become a new driving force in physics and in technology.

The subtle interplay of quantum physics and measurement was for a long time a difficult conceptual obstacle, and even objections by such great minds as Niels Bohr and Albert Einstein were dismissed in some quarters as philosophical or pedantic. In his contribution on quantum entanglement, Anton Zeilinger explains how these questions were resolved and how the resulting deeper understanding is being exploited in new investigations, and even in potential applications, such as teleportation, quantum cryptography, and quantum computation. Such new methods could handle information as quantum bits, "qubits," while the deeper exploration of quantum mechanics continually tells us more about the enigma of reality.

One particularly important underlying quantum effect is Bose–Einstein condensation, in which atoms cooled to very low temperatures descend the quantum ladder and pile up on the energy floor. Like the questions which ultimately led to the discovery of quantum entanglement and related phenomena, such behavior was first predicted three-quarters of a century ago but has only recently been achieved, the technical barrier in this case having been the development of subtle techniques needed to cool atoms to within a fraction of a degree of absolute zero.

The chapters by William Phillips and Christopher Foot and by Claude Cohen-Tannoudji and Jean Dalibard describe how ultra-cold atoms have become a focus of attention for new physics at the start of a new century/millennium. This physics requires special skills, but does not require major resources and is well within the reach of university research laboratories. It is not Big Science. The resonance of interest in Bose–Einstein condensation is redolent of how the fashion for studying cathode rays at the end of the nineteenth century paved the way for much of the new physics of the twentieth century. As explained in the chapter by Subir Sachdev, Bose–Einstein condensation is the underlying mechanism in many other phenomena.

Theoretical physics is inexorably linked with mathematics, the natural language of Nature. When words have not yet been invented to describe many unfamiliar phenomena that can occur in Nature, mathematics provides the script (although this book contains a minimum of formalism). Riemannian geometry, for example, provided the ideal canvas on which to paint Einstein's ideas on relativity and gravity. Encouraged by this success, and others, such as the application of group theory, physicists hoped that further mathematical tools would turn up.

However, some developments began to suggest otherwise. Nature is complex as well as enigmatic, and this frontier of complexity provides a further and very new dimension for physics, complementing the traditional polarity of the very small and the very large, and possibly opening up new avenues for understanding the phenomena of the early Universe. Some of these insights into complexity come from the study of systems that are very familiar but nevertheless remain enigmatic (turbulent flow, grain dynamics). In such systems, small changes do not produce small effects. A seemingly insignificant footprint can provoke a mighty avalanche, but tracing such a catastrophe from first principles is difficult. While some modern physicists rely on high technology, modest experiments with piles of sand or mustard seeds still provide valuable insights.

In their continual quest for understanding, physicists make simplifying assumptions, stripping down problems to their bare essentials. A two-body problem is the easiest to analyze, and breaking down a complicated picture into the sum of interacting pairs of constituents can and does produce incisive results. But there is a danger that, if this analysis goes too far, the resulting component parts lose some of their connectivity. The exact original system cannot be recreated – only an approximation to it. The world cannot be forced to become simpler than it really is.

In his chapter on nonlinearity, Henry Abarbanel points out that a hundred years ago, before the advent of quantum theory, Poincaré discovered that just three fully interacting bodies could produce highly complicated results. As if afraid of the consequences, many physicists shunned this awkward revelation and preferred to investigate systems that, even if they were less familiar, were more predictable. But predictability is the ultimate criterion of understanding. As more systems came under investigation, calculations became more difficult and exact predictability increasingly a luxury.

Describing these nonlinear and often chaotic systems meanwhile calls for a reappraisal of the underlying objectives and the exploitation of radically new techniques. General examples that could link the physics of microscopic objects with more empirical laws underlying highly complex systems have been identified, providing valuable alternative viewpoints. Powerful computers take over when analytical mathematical treatment becomes impossible, and simulations provide an alternative, or possibly new, level of understanding. These implications of nonlinearity and complexity are elegantly summarized in the contributions by Henry Abarbanel and Antonio Politi. These chapters, together with that on collaborative physics and e-science by Tony Hey and Anne Trefethen, make up the fourth section of the book – "Calculation and computation."

As well as spanning the many orders of magnitude which separate the apparent diameter of a quark from that of the Universe, physicists now have to try to reconcile their traditional goal of seeking simplicity with the innate natural complexity which appears to surround us at all levels, and the ability of bodies, whether they be in crystals, galaxies, ferromagnets or biological cells, to "organize" themselves at very different scales into self-perpetuating structures. The insights gained from the physics of complexity have important implications in other disciplines, and could help explain how life itself functions and even how the human brain perceives and understands its environment. The natural signals inside the human nervous system are very different from synthetic pulses transmitted through circuits or glass fibers. Nikolaj Pavel's contribution on medical physics outlines how brain function is beginning to be explored, while Antonio Politi's on complex systems tries to understand our understanding, where physics techniques provide useful analogies.

Cyrus Safinya's intriguing chapter on biophysics shows how the behavior of complex biomolecules and biological function is ultimately underpinned by physics. Supramolecular biophysics contributes to the design of DNA carriers for gene therapy and for studying chromosome structure and function. It can also elucidate the structure and dynamics of nerve cells, and the mechanisms controlling DNA. Here is surely a subject full of physics potential for the twenty-first century.

Ingenuity

Experimental physics is firmly planted in ingenuity, and new discoveries can often be sparked by technological breakthroughs and innovative instrumentation. The advent of the telescope in the early seventeenth century revolutionized astronomy. Many of the developments at the hinge of the nineteenth and twentieth centuries were rooted in a recently acquired mastery of high-voltage and high-vacuum techniques. In the twentieth century, the liquefaction of helium opened the door to the cryogenic world of superconductivity and superfluidity.

There have been suggestions that Einstein's ideas of relativity could have been catalyzed by the increasing awareness in the late nineteenth and early twentieth centuries of the need to synchronize clocks. Local time was once very arbitrary, but mass transport needed accurate timetables valid over wide distances. The advent of radio communications substantially extended this requirement.

Later in the twentieth century, World War II brought major advances in nuclear physics, microwave techniques, and digital computers. This was initially science applied to the war effort, but with the war over, pure science reaped a huge reward from these advances. The scale of this applied science had also set a new scale for pure research. "Big Science" had arrived, requiring massive support and international collaboration. Space research is a good example, and the ability to carry out experiments beyond the stifling blanket of the Earth's atmosphere opens up a huge new window. Cosmology has now become an experimental science as well as a theoretical one.

Big Science has traditionally been involved with the physics frontiers of the very large, such as space research with its requirements for major instrumentation and satellites, and the very small, notably particle physics based on enormous high-energy accelerators. However, major efforts also attack the frontier of complexity. New international collaborations focus on the long-term goal of controlling thermonuclear fusion. On a smaller scale, applied physics laboratories such as Bell Labs and IBM Research have contributed an impressive array of pure-science breakthroughs. These developments have produced such fruits as semiconductors and transistors, with a major impact on industry and lifestyle.

The transistor was developed through an applied-physics effort by an industrial laboratory before the underlying science of semiconductors had fully been understood. However, pure research can also bring valuable spinoffs – a classic example being Röntgen's discovery of X-rays, which were used for medical imaging even before the atomic-physics origin of this radiation had become clear.

In another sphere, the advent of modern telecommunications and the ready availability of powerful computers has revolutionized research methods. No longer do scientists have to work alone in isolated laboratories, however large these might be. While the central laboratory remains the focus, some of the research effort can be "subcontracted" to teams dispersed across the globe. At CERN, the European particle-physics laboratory in Geneva, Switzerland, the World Wide Web was developed in the late 1980s to enable scientists to access research information remotely and share it with their colleagues via the Internet, without necessarily having to come to the laboratory. In the 1990s, the "Web" went on to take the world by storm. New "Grid" developments aim to do for raw data what the Web did for basic information.

In the chapter on collaborative physics and e-science, Tony Hey and Anne Trefethen outline how computers are increasingly being used in industry and commerce as well as science. The "virtual organizations" needed to handle the computing applications of tomorrow will one day become as commonplace as today's Internet. Such infrastructures will have to be very complex, but at the same time must be reliable and secure. Data-hungry physics applications are a driving force in the evolution of this e-science. The development of computation and computer techniques has been staggering. A few decades ago, few could have imagined the speed or the range of this impact. While this will continue, a new horizon could soon open up with the advent of true quantum computation, described by Artur Ekert in his contribution on quanta, ciphers and computers.

Physics and physicists play key roles in society. In his contribution on the physics of materials, Robert Cahn points out that transistors are now more widespread, and cheaper, than grains of rice. Invented only some sixty years ago, the transistor has become the quantum of modern electronics. Another example of a physics-based applications explosion is the laser, invented a decade after the transistor, but which now plays a key role in storing and retrieving digital data in increasingly compact forms. (The basic principles of this device are explained in the chapter by Phillips and Foot, which explores the deep analogy between Bose–Einstein condensates and lasers.) Lasers are not as ubiquitous as transistors, but nevertheless are widely used in home and office electronics equipment, and are extensively employed in medicine for microsurgery. In chemistry, lasers have opened up a new sector where they are used to "freeze-frame" the ultra-high-frequency kinetics of atomic or molecular mechanisms (see the contribution "Chemistry in a new light" by Jim Baggott in the companion volume *The New Chemistry*, edited by Nina Hall (Cambridge University Press, 2000)).

Lasers have also opened up new areas of physics and enable ultra-precision measurement to be made. The contribution by Claude Cohen-Tannoudji and Jean Dalibard describes the ingenious techniques used to cool atoms to very low energy levels and explore new quantum aspects of atomic behavior.

Less widespread than transistors and lasers, but also important, are powerful techniques such as neutron scattering, and X-ray analysis using beams of increasingly short wavelength. These tools were conceived inside physics laboratories, but quickly developed into valuable probes of matter for use in other areas of science and in engineering. Half a century ago, the unraveling of the molecular structure of DNA and of proteins by X-ray analysis was a milestone in biology and chemistry. Today large sources of neutrons and of X-rays (synchrotron radiation) have been built in many countries to serve large user communities. They provide vivid examples of the growing usefulness of physics.

This book cannot cover all such burgeoning applications fields, and concentrates instead on a few examples: biophysics, medical physics, and the physics of materials, which together make up the final section of the book – science in action. The earlier chapters which cover computational physics (Hey and Trefethen), nanoscience (Imry), and quantum cryptography (Ekert) provide other valuable examples of applications. Most of these areas are very new, but the history of medical physics can be traced back to Volta's eighteenth century demonstration that external electric current pulses applied to a frog's leg stimulate muscle contraction. Together, these examples illustrate how physics, even its extreme quantum description, has permeated modern life and will continue to do so.

The final chapter by Ugo Amaldi on physics and society was designed as an off-beat "after-dinner speech" for the book rather than a formal conclusion. It places the science in a contemporary setting, examines some current issues, and suggests what needs to be done to ensure the welfare of physics and physicists. Amaldi boldly predicts some unusual and interesting developments and spinoffs.

Multidisciplinary science and society

The diversity of all these new frontiers means that physics has also become highly multidisciplinary. Not that long ago, geniuses of the stature of Kelvin or Fermi could patrol many experimental and theoretical frontiers, contributing to several areas of the subject and correlating developments in apparently different spheres. A more recent example was Richard Feynman (1918–88). As well as making pioneer contributions to field theory, Feynman also produced key insights in the study of superfluidity, in quantum computation, and in nanoscience, making new objectives emerge from muddled thinking. Although he was a theorist, his suggestions went on to make major impacts in experimental science.

The sheer weight of accumulated knowledge means that physics has become polarized along distinct directions. There are dichotomies between big and small science and between basic and applied physics. There are contrasts between theory and experiment and between emergent and reductive approaches. Propeled to the distant frontier of a discipline, physicists run the risk of becoming isolated from society and even their scientific colleagues. One goal of this book is to provide a broad overview of the subject so that those working in one field can appreciate better what is happening elsewhere, even in their own university or research center.

The book has cast its net wide. It spans a wide spectrum of research at the frontiers of the very large, the very small, the very complex, and the most ingenious. However, the coverage of applications areas presented here is necessarily only a selection of the fields in which physics makes important contributions. There are more, and there will be even more. In July 1945, Vannevar Bush, Director of the US Office of Scientific Research and Development, submitted a report to President Truman. The document – "Science – The Endless Frontier" – went on to become extremely influential. The words used in 1945 have not lost their implication. The science underpinned by physics today is still an endless frontier.

There is another reason for appreciating modern physics. Because it is the basis of Nature, understanding this science is a vital component of today's civilization. It is no accident that almost all physics Nobel prizewinners and all the contributors to this book have worked or work in developed nations. There is a correlation between physics capability and national prosperity. Training new physicists will not immediately make nations more prosperous, but an intellectual core community is needed to ensure high academic standards and catalyze scientific and technological development. The Pakistani physicist Abdus Salam (1926–96), who shared the 1979 Nobel Prize, worked tirelessly to promote the cause of physics in Third World nations.

In exploring its frontiers, the increasing awareness of scale and complexity in modern physics brings a profound sense of humility at our own puny role in the nature of things and the inadequacy of our understanding. The implications of physics are fundamental but bewildering, ranging from the origins of the Universe to the latest applications of semiconductor technology. This impresses the layman but could initially awe the student. However, a deeper appreciation of the role and power of physics provides fresh opportunities for imagination.

The success of the first edition of *New Physics*, edited by Paul Davies and published in 1989, showed the value of an authoritative anthology of frontier science, with contributions from internationally recognized communicators who have all made distinguished contributions to the topics they write about. This book continues that tradition. Editorial intervention has been minimized, so the chapters retain individual styles and conventions. Inevitably, there is some overlap between chapters, but this has been cross-referenced. All chapters should be accessible to non-specialists.

We hope that you will enjoy reading, and thinking, about the newest *New Physics*.

Gordon Fraser, Divonne-les-Bains, July 2006

Gordon Fraser

Gordon Fraser studied physics and went on to a doctorate in the theory of elementary particles at Imperial College, London. After a brief research career, he moved to science writing. For 25 years he worked on publications at CERN, the European particle-physics laboratory in Geneva. He is author, co-author, and editor of several popular science books and has taught science communication as a visiting lecturer in several universities.

1 Matter and the Universe