Book Review

The Road to Reality: A Complete Guide to the Laws of the Universe

Reviewed by Brian Blank

The Road to Reality: A Complete Guide to the Laws of the Universe
Roger Penrose
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For the title of his latest epic, *The Road to Reality*, Roger Penrose has selected a metaphor that appears frequently in popular expositions of physics. It is no wonder that the phrase has become a favorite among physicists, for it suggests a single-minded pursuit of the ultimate destination: an understanding of all the underlying principles that govern the behavior of our universe. Perhaps that may seem to be an ambitious program. After all, it was not so very long ago that Eugene Wigner asserted, "The great success of physics is due to a restriction of its objectives." Since that sober assessment, however, stunning progress has changed the outlook of physics so greatly that several of its leading proponents have been emboldened to suggest that a complete grasp of the laws of nature lies just ahead of us.

As Penrose asserts, the voyage of discovery has lasted more than two and a half millennia and has been profoundly difficult. At the start of the journey, around 500 B.C.E., Heraclitus identified the major stumbling block: *Nature is wont to conceal herself*. Mathematical advances aside, the first significant steps on the road to reality were achieved in the period between 1543, the year Copernicus published his heliocentric theory of planetary motion, and 1687, the year Newtonian mechanics was introduced. This era, the first Scientific Revolution, culminated in a working awareness of the solar system, a basic framework for studying dynamics, and a mathematical formulation of one of Nature's interactions, gravity.

Many of the hallmarks of progress along the road to reality can already be discerned in the first Scientific Revolution. Because Nature so deftly hides her secrets, a crazy theory is often a prerequisite for making any headway. Copernicus, for example, defied not only established authority but also the common sense of every observer who, under the illusion of being at rest, watched the sun move across the sky. Other necessities for progress—mathematics for formulating and developing a theory and a physical apparatus for testing it—were also essential components of the revolution. The improved instruments for measurement devised by Tycho Brahe permitted Kepler to refute the orbits of Copernicus's system. Newton's calculus allowed him to extend Galilean dynamics and explain the laws that Kepler had observed. The road to reality had taken its now familiar course of revolution followed by successive approximation.

The nineteenth century witnessed the second Scientific Revolution. Between 1850 and 1865, fundamental notions such as energy and entropy were introduced. At first, many scientists deprecated energy as a mathematical abstraction. By the end of the century, however, energy was replacing force as the preferred attribute of reality around which to organize physical theories. Several new branches of physics—thermodynamics, statistical mechanics, the kinetic theory of gases—arose accordingly. The second revolution in physics culminated in a working awareness of our solar system's place in the Milky Way, the concept of a "disembodied" field, the mathematical description of a second fundamental interaction, namely electromagnetism, the discovery of an elementary particle (the electron), and, by virtue of the second law of thermodynamics, a stark new aspect of reality: the thermodynamic arrow of time.

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For all the successes of the second revolution, physics faced several challenges at the beginning of the twentieth century. The debate over the wave versus particle nature of light, which had erupted during the first revolution, was not definitively settled by the second, Maxwell's characterization of light as electromagnetic radiation notwithstanding. All experiments to detect a medium through which light propagated, the hypothetical luminiferous aether, failed. Newton's law of gravitation remained a useful scorecard of gravity, but it neither explained the mechanism by which gravity is effected nor permitted time to play any role in gravity's action. The new theories of the second revolution presented even more troublesome paradoxes, chief among which was the prediction of blackbody radiation having arbitrarily large energy. From an evolutionary point of view, our understanding of reality seems to have advanced not by a march down an orderly road but by an alternating sequence of leaps between the frying pan and the fire.

Historians of science often state that the twentieth century witnessed two revolutions in physics: quantum theory and general relativity. The first rescued physics from the ultraviolet catastrophe of blackbody radiation and resolved the dilemmas posed by the properties of light. By blurring the distinction between wave and particle, quantum theory presented counterintuitive insights into the nature of matter and energy. The second revolution, general relativity, combined space and time to provide a theory of gravity that is deeper than a mere bookkeeping formula. Both revolutions profoundly changed our conceptions of physical reality.

The twentieth century was, indeed, a productive one for physicists; two revolutions may not give them their due. A second elementary particle, the photon, was detected in 1923. By 1932 both the proton and the neutron had also been discovered. These nucleons led physicists to an additional two interactions: the strong and weak nuclear forces. Within a few decades, a large menagerie of subatomic particles had been assembled: positrons and muons in the 1930s, pions and kaons in the 1940s, Pauli's long-conjectured neutrino in the 1950s, and a great many others. The ever increasing particle zoo became ever more perplexing. Once, after having given a speculative lecture at Columbia, Wolfgang Pauli admitted, "This is a crazy theory." From the audience Niels Bohr called out, "Unfortunately, it is not crazy enough!" In 1963 Murray Gell-Mann and, independently, George Zweig proposed a theory of fractionally charged elementary particles (christened *quarks* by Gell-Mann) that proved to be just crazy enough. In the next decade and a half, the so-called *Standard Model* of elementary particles and their interactions arose. It is a theory that experimental physicists have repeatedly confirmed to exacting standards. Particles continue to be discovered—notably the top quark in 1995 and the τ-neutrino in 2000—but they fit into the theory the way the man-made synthetic elements fit into the periodic table.

During the same time span in which high energy physicists probed the smallest bits of reality, astronomers and astrophysicists revolutionized our understanding of the largest objects of reality, including our universe itself. By 1923 astronomers had confirmed the existence of galaxies beyond the Milky Way. Observations of distant celestial bodies coupled with general relativity gave rise to a new branch of physics, cosmology, that tells us much about how our universe came to be and how it will cease to be. Though elementary particle physics and cosmology deal with objects at diametrically opposite ends of reality, the two fields have come to be intricately intertwined. Knowledge gained from the study of subatomic processes is the basis for understanding the physics of stars and the synthesis of heavy elements in the universe. In return, the exotic constituents of the universe provide important tests of particle theory.

The whirlwind tour we have just concluded represents only a tiny fraction of what *The Road to Reality* covers in its 1,100 pages. Anyone who casually flips through a few of those pages will recognize immediately that more than length distinguishes *The Road to Reality* from other expositions that target a roughly similar audience. Here, uniquely so far as I am aware, we find an author presenting sophisticated concepts of physics by invoking sophisticated concepts of mathematics. Even an experienced mathematician who happens upon a page illustrated with diagrammatic tensor notation might shy away from Penrose's *Road*. As the author explains in his preface, "What I have to say cannot be reasonably conveyed without a certain amount of mathematical notation and the exploration of genuine mathematical concepts." Do not take this declaration to be a contemporary version of Copernicus's *Mathemata mathematicis scribuntur*. Penrose's idea is that mathematics should be written not only for mathematicians but also for anyone willing to learn. To that end, remedial lessons begin in the preface, where rational numbers are defined as equivalence classes.

The first sixteen chapters of *The Road to Reality* are primarily devoted to the mathematics needed to express modern physical theory. By the time page 383 is reached, the intrepid reader will have been introduced to a large number of topics in analysis, algebra, and geometry. Of these, the demands of analysis are comparatively modest: calculus, Fourier series, hyperfunctions, Riemann surfaces, and enough complex function theory to state the Riemann mapping theorem. The necessities from algebra include quaternions, Clifford and Grassmann algebras, linear algebra, transformation groups, and enough Lie theory to discuss the classical groups and their Lie algebras and representations. The topics from differential geometry are the most arduous: parallel transport, geodesics, curvature, the exterior derivative, calculus on manifolds, connections, and fibre bundles. All told, Penrose has condensed the outline of a quite respectable education in undergraduate mathematics into the first third of his book. When he states, "I am an optimist in matters of conveying understanding," we are inclined to believe him.

As a coping mechanism for the reader who turns off whenever a mathematical formula presents itself, Penrose suggests "skipping all the formulae and just reading the words." Such advice surely transcends well-founded optimism for there is scarcely a page on which mathematics and prose are not thoroughly interwoven. Readers who shun mathematics would do far better seeking out the many excellent works that target a more general audience and that can be assembled to cover similar ground. Even those who do not flee from mathematical symbols may prefer explanations of science in the style of Brian Greene or Stephen Hawking. Mathematicians who are interested in physics, however, should give Penrose's book more serious consideration. Some will choose to cut the book down to size by passing over the first sixteen chapters entirely. Others who want to brush up on a few topics will find that Penrose's synopses provide a useful background for the physics that lies ahead.

With 382 pages of mathematical preliminaries out of the way, Penrose turns his attention to the various scientific revolutions that transformed physics in the twentieth century. The second part of his book comprises 352 pages that are devoted to general relativity, quantum theory, elementary particle physics, and cosmology. The transition from mathematics to physics is nearly seamless. In part, that is because Penrose does not rigidly compartmentalize the two subjects. Quantum numbers are introduced in the chapter on the geometry of complex numbers, gauge connections appear in the chapter on fibre bundles, and, in the other direction, Hilbert spaces, unitary operators, and spherical harmonics are found in a chapter on quantum theory. Another reason for the smooth integration of mathematics and physics is that Penrose speaks with the voice of a mathematical physicist: even when topics from physics are not entirely familiar to us, the method and language of presentation are. For the selective reader, navigation between mathematics and physics is facilitated by the extensive collection of forward and backward references. The reader who has skipped over a bit of mathematics to speed ahead to the physics will find the backward references helpful. The forward references may strengthen the incentives of some readers to slog through seemingly abstract mathematics.

Those who reach the chapters on special relativity, general relativity, and quantum mechanics will find excellent treatments that are filled with physical insights and mathematical context. In particular, the four consecutive chapters that begin with the quantum particle and conclude with Paul Dirac's theoretical discovery of antiparticles are especially enlightening. In the last of these chapters, Penrose shows how the integration of special relativity and quantum theory gives rise to the prediction of antiparticles. Starting with the relativistic Hamiltonian of a quantum particle of rest mass μ, Penrose develops the Klein-Gordon equation $(\Box + (\mu/\hbar)^2)\,\psi = 0$ for the wavefunction ψ. He shows us how Dirac, by rediscovering Clifford algebras, factored the Klein-Gordon equation into what we now call the Dirac and anti-Dirac equations. Exposure to this mathematical background provides the reader with genuine insights into Dirac's prediction of the positron, the antiparticle of the electron, which was discovered only one year after its conjectured existence.

Dirac's theory of the electron is a natural point of departure for the Standard Model of elementary particles and their interactions, a subject that does not lend itself well to popular exposition. One of the difficulties is that the Standard Model is filled with jargon, much of which is whimsical rather than intuitive. Even more problematic for the novice is the overlapping of terms, as illustrated by the following sentence from *The Road to Reality*: "The family of hadrons includes those fermions known as 'baryons' and also those bosons referred to as 'mesons'." Hundreds of different particles—enough to make your head spin or your eyes glaze over, to quote Brian Greene—abound, all governed by a complicated theory of debatable mathematical consistency. In short, an author who attempts to explain the Standard Model to a general audience faces many pitfalls; Penrose does not sidestep all of them. Consider, for example, the discussion of hadrons in *The Road to Reality*. Hadrons are, by definition, the particles that interact through the strong nuclear force. On page 101, Penrose introduces them in this way: "…the modern viewpoint [is] that the 'strongly interacting' particles known as *hadrons* (protons, neutrons, π-mesons, etc.) are taken to be composed of *quarks*." It is a short excerpt that is laced with trouble for the newcomer:

- Commas should delimit the participial clause; as rendered, Penrose's statement implies that the set of hadrons does not contain the set of strongly interacting particles. This confusion is not entirely resolved 500 pages later when Penrose's next description of hadrons allows them to be a proper subset of the strongly interacting particles.

- Including the π-mesons in a list of familiar particles intended to anchor the concept of hadrons is counterproductive: the quoted extract is the only indexed entry for π-mesons. The problem propagates when, without explanation, Penrose uses the alternative terminology, *pions*, the next four times he mentions π-mesons (pages 436, 437, 494, and 628). The definition of *meson* finally appears on page 646, but it is not indexed.
- The subatomic particles represented by "etc." are not revealed until 500 pages later.
- The use of the phrase "are taken to be composed of" rather than the more concrete "are composed of" is baffling. The sentence has begun not with "the *fact* is" but with the equivocating "the modern viewpoint is". Why is further hedging necessary?
- The assertion of the quoted excerpt, repeated on page 645 as "All hadrons are taken to be composed of *quarks*," is contradicted when Penrose later states that each meson is composed of one quark and one antiquark. Additionally, *glueballs*, which are believed to have been detected at BNL, CERN, and DESY, are quarkless hadrons comprising only gluons.

The problems highlighted by the preceding discussion are neither isolated nor uniquely Penrose's: several well-regarded elementary treatments of the Standard Model, such as [3] and [10], are, in places, just as exasperating. Where Penrose bests other popularizers is that he gets the reader closer to the underlying mathematical structure. By discussing gauge connections and symmetry groups in a nontrivial way, he alone allows his readers to understand why the Standard Model is also called the $SU(3) \times SU(2) \times U(1)$ theory.

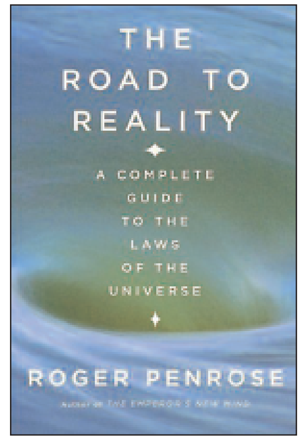
With the chapter called *The Big Bang and its thermodynamic legacy*, Penrose concludes the second part of *The Road to Reality* by sketching our present knowledge of cosmology. In outline, the Big Bang theory of an expanding universe originated when Alexander Friedmann (1922) and, independently, Georges Lemaître (1927), solved Einstein's equations of gravitation without adopting Einstein's initial hypothesis of a static universe. Edwin Hubble's discovery (1929) of the recession of galaxies provided early experimental evidence for the Friedmann-Lemaître model. Nevertheless, the Big Bang explanation for the expansion of the universe seemed to be just one more crazy theory—the name itself originated in the 1950s from a sarcastic barb that was uttered by a dissenting cosmologist. Beginning in 1964 when the cosmic microwave background radiation predicted by Big Bang cosmology was detected, an overwhelming body of observational evidence has confirmed the theory. Conventional treatments of cosmology flesh out this summary with a great deal of additional detail. Penrose, on the other hand, dispenses with these matters in a mere two paragraphs, which he finally presents more than one-third of the way into the chapter. Standard expositions of the Big Bang walk the reader through the stages of the cooling universe from Planck time to the present. Penrose does not. The notion of "freezing out" appears briefly in his chapter on the Standard Model but its role in the evolution of the early universe is not made clear. For that matter, neither nucleosynthesis nor star formation finds its way into *The Road to Reality*. There *is* a brief discussion of stellar evolution but it serves only to describe the creation of black holes. By and large, the chapter focuses on the thermodynamic puzzles of Big Bang cosmology that Penrose has raised and studied since the 1970s. While it is good to have an expert present mysteries of the universe that have occupied his thoughts for three decades, the downside is that readers will have to look elsewhere if they want to understand how the reality we now experience emerged from a plasma of elementary particles.

As I have suggested, *The Road to Reality* comprises three books in one. The third part, which is nearly as long as each of the first two, concerns the road ahead. It is here that Penrose fully lives up to his reputation as a recusant among physicists. According to an idea of cosmology that is now generally accepted, at some instant of time no later than 10^{-12} seconds "after the bang", the universe underwent an "inflationary" period of exponential growth in which its size increased by a factor of at least 10^{30}. The theory was conceived in 1979 by Alan Guth as an answer to the magnetic monopole problem that signaled a conflict between Big Bang cosmology and grand unified theories. At first, inflationary cosmology appeared to be yet another crazy theory. However, inflation resolved so many significant difficulties of conventional Big Bang theory that it gained serious consideration in short order. Inflation has also won over skeptics by being a predictive theory that has not been refuted by the observations that have been made since its formulation. Additionally, inflation, if correct, would indicate the presence of the long-sought hypothetical Higgs field at an earlier time of the universe. As Leon Lederman, one of the leading particle hunters, declared, "The astrophysicists have discovered a Higgs thing!" Against this cheery backdrop, Penrose will seem to be a killjoy when he demurs that "there are powerful reasons for doubting the very basis of inflationary cosmology."

The controversy over inflation might have been avoided, but it fits into the theme of the final portion of Penrose's book. His thesis is that there are too many inadequately explained phenomena for us to be near the end of the road to reality. Most pressing is the provisional nature of the Standard Model. Because this theory requires fundamental constants of nature as *input* parameters, it describes the reality of a different universe just as contentedly as it describes our own. That the values of the fundamental constants now seem arbitrary and not prescribed is, presumably, a defect of our present knowledge. Of even greater concern is the conflict between quantum theory and general relativity in those realms where they should both apply. Until some verifiable theory of quantum gravity appears, we must consider ourselves far from the road's end. Indeed, there is now a fork in the road that has caused an often contentious debate over the correct continuation. Penrose devotes a chapter to each of three possible paths to quantum gravity: string theory, loop variables (LQG), and his own twistor theory. (These approaches are also discussed, at a more elementary level, by Lee Smolin, a proponent of LQG, in *Three Roads to Quantum Gravity* [8]. Given that string theorist Brian Greene's recent book [1] has a section titled *Roads to Reality*, we infer that there is at least agreement about the metaphor that is to be used.)

Penrose may have taken off his gloves in the chapter on inflationary cosmology, but it is in the string theory chapter that bare-knuckle fisticuffs break out. In the first paragraph of the chapter, Penrose writes, "Very few [physicists] appear to anticipate that there will be fundamental changes in the framework of quantum mechanics. Instead, they argue for strange-sounding ideas like the need for extra dimensions to spacetime, or for point particles to be replaced by extended entities known as 'strings'." Five sections later, the rhetoric escalates: "To its most extreme detractors, [string theory] has achieved absolutely nothing, physically so far, and has little chance to play any significant role in the physics of the future." Although the reader may suspect that Penrose is not putting words in *other* detractors' mouths, he allows only that he is "less than positive about a good many aspects of the current string-theory programme". Unlike the theoretical objections to string theory that Penrose raises, many physicists object on principle: their tradition is to dismiss theories not tested by experiment as either philosophy or religion or mathematics. In his recent book on particle physics [10, p. 308], Nobel laureate Martinus Veltman expresses his justification for omitting string theory and supersymmetry with language that is as blunt as Penrose's: "The fact is that this book is about physics, and this implies that the theoretical ideas discussed must be supported by experimental facts. Neither supersymmetry nor string theory satisfy this criterion. They are figments of the theoretical mind. To quote Pauli: they are not even wrong."

Expounding the creation of the universe and its ultimate fate invariably turns an author's mind to philosophy, theology, or some other contemplative outlet. Penrose neither ponders why there is something rather than nothing nor engages in what science journalist Timothy Ferris terms God-mongering. Instead, *The Road to Reality* concludes with a chapter in which Penrose muses upon beauty and miracles, mathematically driven physics, the function of falsifiability in scientific theory, and the role of fashion in physical theory. In the last of these topics, Penrose addresses the stampede that is taking place along the string theory road to quantum gravity. Bandwagon effects, he worries, are drawing an ever increasing number of theorists down a path he suspects to be a dead end. Penrose is also troubled by the curious jawboning that marks the landscape. If you have already investigated string theory, then it is likely that you are acquainted with the slogan, "String theory is the only game in town." One well-known string theory textbook, quoted by Penrose, dismissively pronounces, "There are no alternatives…all good ideas are part of string theory." Similarly, the author of a new book on string theory declares [9, p.357], "As much as I would very much like to balance things by explaining the opposing side, I simply can't find that other side." Overwhelmingly outnumbered, Penrose can do no more than remind us that, "With ideas that are as far from the possibility of experimental confirmation or refutation as those in quantum gravity, we must be especially cautious in taking the popularity of an approach as any real indication of its validity." The mathematician who peers in, unable to take sides, will begin to appreciate the hard-liner's position: *This is what comes of debating philosophy*.



A very long book is almost certain to generate some annoyances. For me, the professionally compiled yet abysmal index of *The Road to Reality* proved to be an enduring irritant. The electron neutrino's rest mass $m(\nu_e)$ makes a good case in point. Determining the value of this parameter, and, in particular, establishing that it is nonzero, is of great current interest. Penrose introduces neutrino mass on pages 636 and 637 and then provides an upper bound for $m(\nu_e)$ on page 872. However, this second discussion has no index entry and the first is indexed only under the misspelled *nutrino*. Another source of frustration is the haphazard handling of the physicists behind the physics. Many of their given names are reduced to initials, and some physicists are not even accorded that much: James Cronin, Val Fitch, John Clive Ward, and George Zweig rate neither a first name, nor an initial, nor an index entry. Other physicists are *entirely* invisible. Thus, we learn about the Stern-Gerlach apparatus, but we do not encounter the two eponymous pioneers of quantum theory, Otto Stern and Walther Gerlach. Indeed, when a prominent physicist is mentioned, it is often only by chance. Eugene Wigner, for example, makes two tangential entrances, but not in the chapter that contains the circle of ideas once known as Wignerism.

Though these cited complaints are genuine, they do seem niggling when considered alongside the astonishing scope of Penrose's endeavor. The relatively few lapses that have been mentioned are not evidence of general carelessness. Given its length, breadth in both mathematics and physics, and its eight year gestation, *The Road to Reality* must be deemed extraordinarily accurate and coherent. If any nontrivial grievance is to be found, then I think we must look to an imbalance between the mathematical description of physical law and the presentation of observational support for it. Figments of the theoretical mind are part and parcel of mathematics, but when it comes to separating the crazy theories that represent physical reality from the crazy theories that are just plain crazy, we rely on empirical facts for conviction. Even Dirac, antielectron equation in hand, hesitated to predict antimatter. (As he later said, "The equation was smarter than I was.") Penrose's concentration on theory is perhaps best illustrated by his omission of CERN's Large Hadron Collider, which is scheduled to begin operations in 2007, from the chapter titled *Where lies the road to reality?* To obtain viewpoints drawn from the experimental side of physics, readers can supplement *The Road to Reality* with the excellent books ([4], [5]) of Leon Lederman and Don Lincoln, both of Fermilab. Reference [2] is an especially valuable resource containing articles written by many of the experimental and theoretical physicists who contributed to the Standard Model.

The Road to Reality was published in Great Britain and discussed by critics prior to the release of the American edition. Before Penrose's *Road* came into my hands, I was familiar with several reviews that damned it with faint praise. Typical of the bottom-line assessments is this one from Nobel laureate Frank Wilczek [11]: "There's much to admire and profit from in this remarkable book, but judged by the highest standards *The Road to Reality* is deeply flawed." With such criticism in mind, I approached my reviewing task apprehensively. As I progressed through the first few hundred pages, unconvinced by Penrose's conception, I found myself thinking nothing kinder than *The Road to Reality is paved with good intentions*. And yet, all my misgivings eventually yielded to the sheer quantity of Penrose's valuable insights and the unity with which he conveys the essential developments of twentieth century physics. In his review, Wilczek cites "serious blunders", drawing attention to three. These problems, perceptible only to sophisticates of physics, should be placed in perspective with a particular audience in mind. If Penrose brings his typical reader to the level of understanding the concepts that compose the disputed statements, then he has done a service in comparison to which the impact of his occasional miscues pales.

For mathematicians with a general interest in physics, Penrose's book will be self-recommending. Other mathematicians may find it useful to scan *The Road to Reality*, if only to glimpse the extent to which mathematical constructs infuse theoretical physics. There are a great many competing books that seek to explain the state of the art in fundamental physics. If you compare Penrose's work to any of the recent ones ([6], [7], [9], for example), then you will understand a reviewer's inclination to hold *The Road to Reality* up to the highest standards, for it is, indeed, *sui generis*. And that makes my bottom-line recommendation a cinch. For anybody who wants to learn up-to-date physics at a level between standard popularization and graduate text, *The Road to Reality* is the only book in town.

References

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