Arthur S. Eddington

The Nature of the Physical World

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The Nature of the Physical World
Gifford Lectures of 1927:
An Annotated Edition

Annotated and Introduced

By

H. G. Callaway

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NOTE TO THE TEXT

The present edition is based on the original text of Arthur S. Eddington's *The Nature of the Physical World*, which arose from the Gifford Lectures at Edinburgh in 1927.[1] Numerous reprints have since appeared in the U.K. in the U.S. and elsewhere in translation. The chief differences of the present edition of Eddington's text are that the spelling and punctuation are here Americanized throughout (Eddington's own punctuation and particulars are a bit irregular), and the text has been annotated to identify persons and sources of interest connected with Eddington's themes, and with special interest and emphasis on his philosophical views—particularly his philosophy of science and philosophy of religion. The annotations also include commentary both scientific and philosophical.

Since the author included no bibliography in the original edition, a bibliography for the volume has been assembled starting from Eddington's citations and including chief works of related interest both philosophical and scientific. The bibliography also includes background materials, both older and more recent, useful to readers in understanding and evaluating Eddington's contributions. The index to the present volume builds on the original index and expands it to cover the additions to this volume in analytical style.

My introductory essay, "A.S. Eddington, Physics and Philosophy," draws on the close reading implicit in the annotations and aims for an overview of central issues, but it also aims to bring the evaluation of Eddington's philosophical contributions up to date. The general idea of the present volume is that this should be a reading and study edition of use for students and professionals in the sciences and in the philosophy and history of science—

1. First published by the Cambridge University Press in 1928.

concerned with the early reception of Einstein and quantum mechanics in the English-speaking world; but it is also an edition of special use to those more directly concerned with Eddington's philosophy. Eddington's notes to his text are identified as such, and all other notes were added by the editor.

Arthur S. Eddington accomplished a great deal, in the decades following WWI, including seminal work in astrophysics. He helped make revolutionary advances in physics available to the English-speaking world. He also thereby contributed to the twentieth-century advance and standing of a Cambridge school in modern physics with world-wide weight and influence. Eddington is still read, though his forays into philosophy have not always been greeted with universal acclaim. This volume aims to assemble the critical perspectives and even out some of the rough spots—partly so that his contributions to physics and astrophysics may be better appreciated. From a more philosophical perspective, it is worth noting that Eddington's thought has entered into philosophical debates and discussions for nearly a hundred years.

Eddington’s Preface

This book is substantially the course of Gifford Lectures which I delivered in the University of Edinburgh in January to March 1927. It treats of the philosophical outcomes of the great changes of scientific thought which have recently come about. The theory of relativity and the quantum theory have led to strange new conceptions of the physical world; the progress of the principles of thermodynamics has wrought more gradual but no less profound change. The first eleven chapters are for the most part occupied with the new physical theories, with the reasons which have led to their adoption, and especially with the conceptions which seem to underlie them. The aim is to make clear the scientific view of the world as it stands at the present day, and, where it is incomplete, to judge the direction in which modern ideas appear to be tending. In the last four chapters I consider the position which this scientific view should occupy in relation to the wider aspects of human experience, including religion. The general spirit of the inquiry followed in the lectures is stated in the concluding paragraph of the Introduction.

I hope that the scientific chapters may be read with interest apart from the later applications in the book; but they are not written quite on the lines that would have been adopted had they been wholly independent. It would not serve my purpose to give an easy introduction to the rudiments of the relativity and quantum theories; it was essential to reach the later and more recondite developments in which the conceptions of greatest philosophical significance are to be found. Whilst much of the book should prove fairly easy reading, arguments of considerable difficulty have to be taken in their turn.

My principle aim has been to show that these new scientific developments provide new material for the philosopher. I have, however, gone beyond this and indicated how I myself think the material might be used. I realize that the philosophical views here put forward can only claim attention in so far as they are the direct outcome of a study and apprehension of modern scientific work. General ideas of the nature of things which I have formed apart from this particular stimulus from science are of little moment to anyone but myself. But although the two sources of ideas were fairly distinct in my mind when I began to prepare these lectures they have become inextricably combined in the effort to reach a coherent outlook and to defend it from public criticism. For that reason I would like to recall that the idealistic tinge in my conception of the physical world arose out of mathematical researches on the relativity theory. In so far as I had any earlier philosophical views, they were of an entirely different complexion.

From the beginning I have been doubtful whether it was desirable for a scientist to venture so far into extra-scientific territory. The primary justification for such an expedition is that it may afford a better view of his own scientific domain. In the oral lectures it did not seem a grave indiscretion to speak freely of the various suggestions I had to offer. But whether they should be recorded permanently and given a more finished appearance has been difficult to decide. I have much to fear from the expert philosophical critic, but I am filled with even more apprehension at the thought of readers who may look to see whether the book is "on the side of the angels" and judge its trustworthiness accordingly. During the year which has elapsed since the delivery of the lectures I have made many efforts to shape this and other parts of the book into something with which I might feel better content. I release it now with more diffidence than I have felt with regard to former books.

The conversational style of the lecture-room is generally considered rather unsuitable for a long book, but I decided not to modify it. A scientific writer, in foregoing the mathematical formulae which are his natural and clearest medium of expression, may perhaps claim some concession from the reader in return. Many parts of the subject are intrinsically so difficult that my only hope of being understood is to explain the points as I would were I face to face with an inquirer.

I may be necessary to remind the American reader that our nomenclature for large numbers differs from his, so that a billion here means a million million.

A. S. E.

August, 1928

A. S. EDDINGTON, PHYSICS AND PHILOSOPHY

> … we know that the theory of general relativity must be modified. Because the classical (i.e. non quantum-mechanical) version predicts points of infinite density—singularities—it prognosticates its own failure…
>
> —Stephen Hawking, *A Briefer History of Time*.

In his 1927 Gifford Lectures, delivered at the University of Edinburgh, and subsequently expanded to their published form, the work of Arthur Stanley Eddington (1882-1944) displays a number of distinctive elements. First and foremost, Eddington explains the new physics of special relativity, general relativity and quantum mechanics. This task dominates the present volume. The reader learns of the scientific achievements of Albert Einstein, and Hermann Minkowski, and further, the developments of the "old quantum theory" and the "new quantum theory," connected with the names of Max Planck, Einstein, Niels Bohr, Werner Heisenberg, Erwin Schrödinger, Paul Dirac, and others. Eddington deploys the prior Newtonian physics for background and contrast, and most of the present book is devoted to introducing readers to the great, and still unfolding story of the revolutions in physics which took place in the opening decades of the twentieth century.

Eddington, an English astronomer and physicist, did distinguished scientific work in astrophysics, and he was also the first major expositor of Einstein's work in the English language.[1] Partly

1. See, especially A.S. Eddington (1924) *The Mathematical Theory of Relativity*. Second ed. Cambridge: Cambridge University Press.

because *The Nature of the Physical World* (1928) did so much to introduce innovations in physics to the general, educated readers of the English-speaking world, the present book repays critical attention. In some degree, Eddington has entered into our ways of thought. His writings entered philosophical discussions and debates of his own time and have left an influence on subsequent philosophy. The emphasis in the present edition will be to understand and critically evaluate Eddington's philosophy. There will be much history of physics and astronomy along the way.

Eddington was concerned with more than physics, mathematics and astronomy. Particularly in his popular, expository books—the present volume is the most famous of them—he sketches a philosophy of science and of religion and makes suggestions for epistemology which have engaged the popular mind, and many in philosophy as well, over generations. His philosophical themes in the present book were developed further in subsequent writings, including *New Pathways of Science* (1935) and *The Philosophy of Physical Science* (1939) and they reach into his later scientific work. Part of what is going on in this more philosophical story turns on Eddington's critical attention to philosophical themes of the past—chiefly themes developed under the influence of Isaac Newton and Newtonian physics—from the early modern period down to the nineteenth century. He disputes common sense, nineteenth-century mechanistic philosophy and notions of "substance;" and he defends his own alternatives—chiefly cast in terms of abstract "structure."

Eddington also reveals in the present book something of his Quaker religious background, and this enters into the philosophical themes of the book—Eddington's philosophy of mind and religion. In his 1929 Swarthmore lecture given at Britain's Quaker Yearly Meeting, and published with the title *Science and the Unseen World* (1929), he declared that the significance of the world could not be uncovered in science; instead, "we have to build the spiritual world out of symbols taken from our own personality, as we build the scientific world out of the symbols of the mathematician."[2] He sponsors too, in the present book, his thesis of "selective subjectivism," which will be a subject of criticism below. That thesis, in turn, is closely related to Eddington's theme of "structure;" and scientific structuralisms have been highly esteemed.

1. Scientific career

Eddington was a much honored British astrophysicist of the first half of the twentieth century. He has been called "the most distinguished astrophysicist of his time"[3]—not without good reason. Following his education at Owens College, Manchester, and Trinity College, Cambridge, where he received high honors and demonstrated very considerable mathematical talent and ability, he became chief assistant at the Royal Observatory at Greenwich (1906-1913). At Greenwich, he gained practical experience in astronomy and studied stellar motions and the structure of the Milky Way. In his early book, *Stellar Movements and the Structure of the Universe* (1914) he suggested the hypothesis that the spiral nebulae, long known, though conflated with glowing clouds of gas and dust, are galaxies, "island universes," in the phrase of those times—stellar structures of the magnitude and character of the Milky Way.[4]

In 1913 Eddington was appointed Plumian Professor of Astronomy at Cambridge, and in 1914 he became Director of the Cambridge Observatory. By the end of his career, he was widely esteemed and had received honorary degrees from many universities. He was elected president of the Royal Astronomical Society (1921-1923), and subsequently elected President of the Physical Society (1930-1932), the Mathematical Association (1932), and the

2. Eddington (1929) *Science and the Unseen World*, reprinted in Volker Heine ed. (2013) *A.S. Eddington and the Unity of Knowledge*, p. 28.
3. See Subrahmanyan Chandrasekhar (1983) *Eddington*.
4. See Eddington, below, p. 169.

International Astronomical Union (1938-1944). Eddington was knighted in 1930 and received the Order of Merit in 1938. During the 1930s, his popular and more philosophical books made him a well known figure to the general public.[5]

When war broke out in 1914, Eddington declared himself a pacifist on grounds of religious conscience. This eventually caused him serious complications with the authorities, but did not inhibit development of his career. He claimed the status of a conscientious objector to war—at considerable personal and professional risk—but in contrast with many others objecting to the war, he was substantially protected, first by Cambridge University and later by the intervention of his Greenwich colleague, Frank W. Dyson, the Astronomer Royal of England.[6]

Though German publications were not generally available in Great Britain during the 1914-1918 war, Eddington was able to keep in touch with developments in Germany through the Netherlands, which remained neutral; and it is believed that he received a copy of Einstein's 1916 paper on general relativity from the Dutch physicist Willem de Sitter. De Sitter published on relativity, Einstein and astronomy in Great Britain, during the war, while Eddington was Secretary of the Royal Astronomical Society.[7]

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5. An account of Eddington's life is available in Allie Vibert Douglas (1956) *The Life of Arthur Stanley Eddington.* See also Matthew Stanley (2007) *Practical Mystic*: *Religion, Science and A.S. Eddington*, which focuses on the relationship between Eddington's scientific work and his Quaker religious background.
6. Frank Watson Dyson (1868-1939), son of a Baptist Minister and life-long non-conformist, was appointed Astronomer Royal of Scotland in 1905 and afterward Astronomer Royal of England (1910-1933). Dyson arranged for Eddington's participation in the 1919 eclipse expedition. See the account of Eddington's pacifism and exemptions from conscription in Stanley (2007) *Practical Mystic*, pp. 124-152.
7. See McCrea (1979) "Einstein: Relations with the Royal Astronomical Society," p. 253.

Einstein's famous paper,[8] and his new physics, would change the direction and character of Eddington's work in fundamental ways.

In 1918, Eddington published his *Report on the Relativity Theory of Gravitation*. This was followed by two further books devoted to relativity, culminating in *The Mathematical Theory of Relativity* (1923). In 1919 he led a famous expedition to the island of Príncipe off the west-African coast, and made observations credited with confirming Einstein's quantitative prediction of the gravitational curvature of the path of star-light in the vicinity of the sun during an eclipse. Eddington became a recognized expert on Einstein's new physics, and Einstein himself became a world-wide scientific and popular celebrity. Eddington later emphasized the influence of Einstein on his philosophical thought as well. It was only with his book of 1926, *The Internal Constitution of the Stars* and 1927*, Stars and Atoms,* that Eddington more fully returned to focus on prior astrophysical themes and studies—and to threads of his work started before his encounter with Einstein and general relativity. His astrophysical work was now to be informed by Einstein's physics. In his lecture, *The Expanding Universe* (1933) he came to terms with the work of Edwin Hubble.[9]

Eddington did astrophysical work on the Cepheid variable stars early on—stars having regular, periodic patterns of variation in their brightness. Since the intrinsic brightness or luminosity (apparent brightness, corrected for distance) of the classic Cepheid variable stars correlates empirically with their periods of variation, and because it was possible to directly determine the distances of the closer Cepheids, by parallax, this provided a means of determining the distances of very faint Cepheids and associated objects—from observational data on their variations.

The classical Cepheids exhibit a correlation between period and luminosity. The longer the period of variation in luminosity of the

8. Albert Einstein (1916) "The Foundation of the General Theory of Relativity."

9. Cf. Eddington's 1928 comments on Hubble below, p. 171n.

star, the greater its intrinsic brightness. Though it was later discovered that an important sub-class of Cepheids are not bound by this relationship, the Cepheids were of great interest because they provided a range of "standard candles," allowing the observational determination of astronomical distances to remote stars and galaxies.[10] Eddington's work on the topic brought him to the general problem of explaining stellar luminosity in terms of internal processes.

Direct observation of the interior processes of stars is not possible, but Eddington emphasized that it is possible to understand internal stellar processes based on two pillars of observational evidence—and established physical theory—, mass or gravitation and luminosity or output of radiation. Eddington starts from what is observable and uses the related results as crucial constraints on his development of theory. Both the mass and the luminosity of selected stars can be calculated from observational data.

The theory of stellar interiors must provide predictions open to falsification or confirmation, but the available and accepted accounts of gravitation and radiation, together with details of stellar observations, provide a "structure" of constraint upon Eddington's theoretical and indirect approach to internal stellar processes. The suspicion was afoot, even in the 1920s, that the enormous radiation output of stars depends on thermonuclear processes in the stellar interior, thought the relevant laws of nuclear physics were almost complete unknown at the time.[11] Familiar as he was with Einstein's $E = mc^2$, Eddington was favorable to the idea that hydrogen was being transmuted into heavier elements within the stars, in a process

10. Henrietta Leavitt (1868-1921), American astronomer at the Harvard Observatory, had discovered the empirical period-luminosity relationship of the Cepheid variables in 1912.

11. James Chadwick's discovery of the neutron, which facilitated probing of the atomic nucleus, would not come until 1932, four years subsequent to original publication of the present book; it was not until 1938 that the German-born, American physicist Hans Bethe (1906-2005) proposed the first detailed theory of stellar energy generation based on nuclear fusion.

involving conversion of matter into energy. But this point remained speculative in his 1926 book.

Eddington begins from the assumption that gas pressure, radiation and gravity typically establish a balance or equilibrium within the stars. Gravity, a function of mass, pulls everything toward the center, while gas and radiation pressure push outward. Eddington's developed theory works with three variables of pressure, density and temperature, linked together by the perfect gas law. This law states that given a particular quantity of gas, the product of its volume v and pressure p is proportional to the absolute temperature t; in the form of an equation, $pv = kt$, where k is an empirically estimated constant. The surface temperature of a star, in turn, is related to its luminosity.

Eddington defended the applicability of the idealized gas law to stellar interiors, against considerable tradition and resistance; and this hypothesis gives his theory genuine predictive power. The overall effect is to explain correlations between stellar mass and luminosity by means of the idealized gas law. The scope of this generalization is limited, however, by extremely dense stars, including the white dwarfs[12]—which involve a degenerate state of matter. At very high densities, the atoms of these stars are stripped of their electrons, and the increase of density proceeds to the nuclear level. Resistance to further gravitational contraction is then no longer covered by the classical physics of the ideal gas law, and instead partly depends on quantum mechanical phenomenon related to the Pauli exclusion principle.[13] Though much of the relevant nuclear physics was unknown at the time of his work, Eddington's

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12. Eddington (1926) *The Internal Constitution of Stars*, states, "I do not suppose that the white dwarfs behave like perfect gas." See p. 174.
13. Electrons are theorized to form a separate "gas" above the degenerate nuclei, and resist further compression by their exclusion from occupying the same quantum state. The Fermi-Dirac statistics together with special relativity allow for precise prediction of the mass-radiation correlations of white dwarfs. See Eddington's related discussion below, pp. 206-207.

theory of stellar interiors was successful and reasonably precise—and the basis for much subsequent work.

In a 1924 paper, the American astrophysicist, Walter S. Adams,[14] credited Eddington with predicting the displacement of the spectral lines of the white dwarf star, Sirius B, and thereby contributing to a new confirmation of Einstein's theory of gravitation. Adams cited the quantitative prediction in Eddington's 1924 paper, "On the Relations between Masses and Luminosities of the Stars,"[15] and confirmed the prediction by his own observations. The general idea is that the white dwarfs have such high density that their intense gravitation produces a measurable red-shift of their emitted radiation—as though they were moving away from the observer at a relativistic velocity.

Concluding his own paper, Adams wrote that "the results may be considered, … as affording direct evidence from stellar spectra for the validity of the third test of the theory of general relativity, and for the remarkable densities predicted by Eddington for the dwarf stars… ."[16] In his discussion of the white dwarfs, Eddington had favored high densities, though these where anomalous at the time. Only a very few white dwarfs were known. He had written that the question concerning their density "could probably be settled by measuring the Einstein shift of the spectrum, which should amount to about 20 km. per second, if the high density is correct."[17]

While Adams saw his own measurements of the red shift of Sirius B as confirming Einstein on gravitation, via Eddington's calculated prediction of the red shift, Eddington was more inclined to take relativity for granted and use it to predict measurable

14. Walter S. Adams (1876-1956) was Director of the Mount Wilson Observatory (1923-1946), and he is best known for his spectroscopic studies of stars. See Adams (1924) in the *Proceedings of the National Academy of Science*, vol. 11, pp. 382-332.
15. Eddington (1924) *Monthly Notices of the Royal Astronomical Society*, vol. 84, pp. 308-332.
16. Adams (1924), p. 387.
17. Eddington (1924), p. 322.

consequences of his hypothesis concerning the density of the white dwarfs. The episode demonstrates Eddington's high standing in his field and the close interrelations of theory and observation. It also demonstrates Eddington's physical insight in deftly avoiding over generalization of his theory based on the perfect gas law.[18]

An episode starting in the early 1930's connected with the publication of the second edition of Eddington's book, *The Internal Constitution of the Stars*, is closely connected with his long resistance to the idea of the final collapse of massive stars into black holes. When Eddington issued the second edition, there was some updating, but he failed to mention Ralph Flower's important 1926 paper on white dwarf equilibrium, based on the Pauli exclusion principle. But what developed out of the Flower paper was the proposal, by Chandrasekhar among others, that there is a limiting mass, beyond which no cold body (black dwarf, or burned-out white dwarf) could maintain itself against gravitational collapse—and the formation of what is now called a black hole. Just as increasingly dense white dwarfs would have their radiation output increasingly red-shifted, beyond a certain density, the radiation would be shifted completely off the spectrum, which is to say that light, and anything else, could not escape from it.

During the 1930s, Eddington stubbornly rejected the idea of the Chandrasekhar limit and final gravitation collapse. The thesis of the inevitable collapse of stars with a mass beyond the limit of about 1.4 solar masses was supported by many famous physicists and astronomers and widely regarded as an implication of the Einstein's gravitational curving of space-time—a thesis which Eddington himself had done so much to support. But Eddington was not convinced, and in sketching an alternative he held out the prospect

18. See Leon Mestel (2004) "Arthur Stanley Eddington: Pioneer of Stellar Structure Theory," for a somewhat technical, contemporary astronomer's appreciation of Eddington's theory of stellar interiors and a brief discussion of the connected work of Adams. See also W.H. McCrea (1979) which disputes the validity of the 1924 measurements.

of his own innovations in physics—connecting general relativity and quantum mechanics.

Eddington was not entirely alone in rejecting the Chandrasekhar limit during the 1930s, and his professional standing and prestige were so great that many supporters of Chandrasekhar were unwilling to take a public stand, though, in the accepted outcome of the debates, Eddington's arguments failed to sustain his position.[19] He appears to have incorrectly favored his own physical speculations against Chandrasekhar's rather firmer results in mathematical physics.[20]

Eddington's later scientific work, from 1928 until his death in 1944, was of a highly theoretical and speculative character. It is continuous with his earlier work on relativity—including, for example, his generalization of Hermann Weyl's theory of the electromagnetic and gravitational fields.[21] Eddington had attempted a geometrical theory of electromagnetism, "so that a yet more comprehensive geometry can be found, in which gravitational and electric fields both have a place."[22] This element of Eddington's thought lingers in the background of the present book. His emphasis on structure continued from early to late. In his 1921 paper, generalizing on Weyl, he wrote that "any conception of *structure* (as opposed to substance),"

> … must be analyzable into a complex of relations and relata, the relata having no structural significance except as the meeting point

19. For a detailed account of the issue, see Mestel (2004), pp. 70-71.
20. Chandrasekhar and Flower were awarded the 1983 Nobel Prize in physics for their related work.
21. The German-American mathematician, Hermann Weyl (1885-1955) had been a colleague of Einstein's at Zurich, before Einstein moved to Berlin in April 1914, and Weyl produced the first attempt at a "unified field theory" uniting electromagnetism and gravitation. For his generalization see Eddington (1921) in the *Proceedings of the Royal Society*.
22. Eddington (1920) *Space, Time and Gravitation*, p. 167. Eddington's early approach to a "unified field theory" will be found in chapter XI, of the 1920 book, pp. 167-179.

> of several relations, and the relations having no significance except as connecting and ordering the relata.[23]

This statement of the contrast between "substance" and structure is directly comparable to his treatment of the topics in the present book.[24] The point of Eddington's criticisms of the conception of "substance" is that he sees his own focus on relations, relata and structure as a needed improvement—one facilitating his own theoretical work. Employing his emphasis on "relation structure" in his later work, Eddington mounted a distinctive, theoretical approach to combining the physics of relativity and quantum mechanics. However, for many, the distance of this late work from experimental and observational results tends to render it excessively speculative.

In writing the present book, Eddington was following the latest developments in quantum mechanics closely and with considerable interest.[25] He was aware of the developments starting from the early contributions of Max Planck, Einstein and Niels Bohr, through the "new quantum theory" of Heisenberg, Schrödinger and Dirac—though there is no mention of Pauli.[26] Max Planck introduced the concept of the quantum (the idea of discrete "atoms" or units of physical action) in 1900, in explanation of black-body radiation; and Einstein's related work on the photoelectric effect, introducing the photon, appeared in 1905—the same year as his special theory of relativity. Bohr then developed his model of the atom, based in quantum mechanical concepts. In the mid-1920s, the pace of development in quantum mechanics intensified, including Heisenberg's

23. Eddington (1921), p. 121.
24. Regarding "structure" see Eddington, below, pp. 231-232ff.
25. See below Eddington's chapter devoted to "The New Quantum Theory," and p. 209, in particular: "My chief anxiety at the moment is lest another phase of reinterpretation [of QM] should be reached before the [Gifford] lecture can be delivered."
26. Wolfgang Pauli was awarded Nobel Prize for Physics in 1945 for his discovery (1925) of the Pauli exclusion principle.

matrix mechanics, Schrödinger's wave mechanics, Paul's exclusion principle, and culminating with Heisenberg's uncertainty principle and later, Dirac's prediction of the positron. Eddington provides below an engaging, and well informed account of the developments, up to the time of publication of the book, though he had been clearly more involved with Einstein and gravitation over the decade of the 1920s. He was sufficiently impressed by the uncertainty principle to reject the determinism of classical physics.[27]

Eddington came to believe, after publication of his Gifford lectures, that the time was ripe for a structural approach to the combination of relativity and quantum mechanics.[28] In the present book, his structural approach aims to encompasses gravity and electromagnetism, but is not extended to quantum mechanics. The aim of encompassing both general relativity and quantum mechanics in a structural approach, however, is the distinctive theme of his late and most speculative writings. His philosophical ideas brought him to the hypothesis that such a theory would make it possible to calculate the values of the physical constants (including the fine-structure constant, the ratio of the gravitational force to the electromagnetic force, the ratio of the masses of the proton to the electron, and even the total number of protons in the universe). This undertaking culminates in Eddington's *Fundamental Theory* (1946), published only after his death. His objectives in the final book are reflected, though, in earlier writings, including, *Relativity theory of Protons and Electrons* (1936) and *The Combination of Relativity Theory and Quantum Mechanics* (1943).

The specifics of Eddington's calculations of physical constants (those of particular interest are, at best, determined empirically)

27. See Eddington, below, p. 292.

28. According to the account in C.W. Kilmister (1994) *Eddington's Search for a Fundamental Theory*, this development was occasioned by Paul Dirac's work, relating SR and QM. See Kilmister (1994), pp. 90-94; and Dirac (1928) "The Quantum Theory of the Electron," *Proceedings of the Royal Society London*, A117, pp. 610-624.

have generally been greeted with much criticism, skepticism, and even parody.[29] It is worth noting, though, that the editor of Eddington's *Fundamental Theory*, the English mathematician, Edmund Whittaker (1873-1956) was an able and sympathetic expositor of Eddington's late work.[30] Overall, it is fair to say that Eddington's late work has been closely read for its suggestiveness and his characteristic flashes of physical insight. Eddington was a pioneer of subsequent physical thought. The precise relationship of general relativity to quantum theory remains to the present a central, open question of contemporary theoretical physics; and it is now thought to require a theory of "quantum gravity."[31] Though generally doubting the specifics of Eddington's calculations, theoretical physics continues to wonder and speculate about the constants.[32]

2. Selective influence of mind

In his concern with theory and the construction and reconstruction of theory, Eddington employs the idea of "world building" extensively.[33] An entire chapter of the present book is devoted to the theme; and in his accounts of world building, Eddington places a very considerable emphasis on the selective influence of the mind.

On one reading, Eddington's conception of world building may be understood as a formal, mathematical exercise, or preparation, making explicit the particular language and interpretation of vocabulary to be used in a formalized physical theory. However,

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29. For a contemporary criticism of Eddington's attempt to calculate physical constants, see John D. Barrow (2002) *The Constants of Nature*.
30. See e.g., Edmund Whittaker (1951) "Eddington's Principle in the Philosophy of Science," reprinted in Heine (2013); but see also the Kilmister (1994) *Eddington's Search for a Fundamental Theory*.
31. See e.g., Carlo Rovelli (2001) "Quantum spacetime: What do we know?" and Rovelli (2008) for a brief overview of contemporary theoretical alternatives.
32. See e.g., Steven Weinberg (1993) *The First Three Minuets*, p. 187.
33. See Chapter XI, below, pp. 231-246.

Eddington's "world building" does not explicitly (i.e., meta-linguistically) address the language of physics. It lacks the rigor of later philosophical structuralisms and of formal semantics. Still, Eddington saw himself as close to Bertrand Russell's theme of structure in *The Analysis of Matter* (1927).[34] Again, in some contrast, his talk of world building might be viewed as a useful metaphor, taken up to facilitate his proposals in the popular presentation of physics. In that light, it unhappily contrasts, by its vagueness, with the alternative of explicitly addressing theory, interpretation and model construction.

It is also possible to read Eddington literally, i.e., as an idealist, maintaining that the "world" of physics is literally a creation of the human mind.[35] No doubt, human beings have designed and developed our theories in physics and the required concepts. We do so in pursuit of statable and even for debatable purposes. But there is no clear and plausible sense in which this might reasonably be considered a literal matter of "building" or construction of the physical world. Least of all is such a conclusion supported by results of physics alone.

We have a task before us, according to Eddington: "We are going to build a World—a physical world which will give a shadow performance of the drama enacted in the world of experience."[36] The language of the "shadow performance," here is so distinctively

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34. See in particular, Bertrand Russell (1927), p. 226; and the discussion in Steven French (2003), p. 236.
35. See Eddington (1920) "The Meaning of Matter and the Laws of Nature According to the Theory of Relativity," *Mind*, 29, 114, p. 145: "…it is the *mind* which from the crude substratum constructs the familiar picture of a substantial world around us;" p. 153: "According to this view matter can scarcely be said to exist apart from mind." See also Eddington, below, e.g., p. 327, "…the world-stuff behind the pointer readings [of physics] is of nature continuous with the mind;" and p. 274, "The realistic matter and fields of force of former physical theory are altogether irrelevant—except in so far as the mind-stuff has itself spun these imaginings."
36. Eddington, below, p. 231.

Eddington's own that it is difficult *not* to take him at his word on the dependence of the physical world on the human mind. However that may be, there is a definite and distinctively nominalistic theme in Eddington's notions of world building and the selective influence of mind. This nominalistic theme is intimately related to Eddington's epistemology and his theory of mind. They are worth some examination in the present context.

Eddington maintains, in the present volume that "…the laws which we have hitherto regarded as the most typical natural laws are of the nature of truisms, and the ultimate controlling laws of the basal structure (if there are any) are likely to be of a different type from any yet conceived."[37] The interpretation that is most natural here is that for Eddington, "the mind" selects particular systems of "relations and relata," in the process of world building, so as to include particular laws of nature within the mathematical structure, so generated; and within the favored structure, the implicated laws are simply true by stipulation.[38]

However, Eddington's idea seems to conflict with attributing empirical status to the laws of nature; and this, no doubt, will strike many readers as strange. Einstein's introduction of the principle of relativity into physics, after all (given the empirical finding of the constancy of the velocity of light, independent of the choice of frames of reference), is plausibly regarded as requiring that the laws of physics turn out the same independent of the particularities of frames of reference. My point is to emphasize the empirical motivation of the selection of a mathematical system for representation of the laws of nature—a kind of point which Eddington often fails to emphasize sufficiently. In his talk of world building, he appears to confuse the "analytical" selection of conceptual materials for theory construction with an imposition of concepts and laws on a neutral or indifferent world.

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37. Eddington, below, p. 244.
38. Cf. Eddington, below, p. 148: "The whole thing is a vicious circle. The law of gravitation is—a put-up job."

There can be good judgment of better and worse in our related "world building," i.e., the selection of elements for theory construction. This is not to say that available evidence completely determines choice of theoretical system and related concepts. That would be an absurdly strong anti-nominalism—leaving no prospect of further or conflicting empirical evidence. Still, what is today merely theorized and postulated may tomorrow be tested and confirmed or rejected. Eddington seems to conflate with his term "world building" the mathematical formalization of existing theory, or theoretical constraint on proposed theory, with the postulation (or the mind's dictation) of constraints on theory and the future development of physical theory. This nominalism contributes significantly to the highly speculative character of Eddington's later thought.

According to Eddington, "the mind has by its selective power fitted the processes of Nature into a frame of law of a pattern largely of its own choosing; and in the discovery of this system of law the mind may be regarded as regaining from Nature that which the mind has put into Nature."[39] But this is to over-emphasize the role of theory and theorizing in relation to testing, experimentation and the accepted results of the scientific enterprize. Though scientists may reasonably select a prospective *direction* of the development of theory, new proposals are also bound by the past success of theory in accounting for empirical evidence. Even the most revolutionary theory has its conservative side. Surely, no one would have given Einstein's new physics a second thought, if it had not adequately taken in the massive evidence supporting prior Newtonian physics—and had it not added new predictions as well.

Science can freely choose a direction of development for theory, postulated law and concepts, only as hypothesis—or, rather, there is normally a diversity or pluralism of competing approaches; but the success of theory in testing depends on our *inability* to "put into

39. Eddington, below, p. 244.

nature," that which is not confirm in continued testing. (Both the proponents of Einstein's theory and those more skeptical can make the observations which confirmed Einstein's theory.) In physics, as elsewhere in science, many theories and proposals are vetted and detailed, but only a few are continually confirmed and called into established and accepted status.

Eddington will also be found below to emphasize values and the value of permanence in particular, in his arguments and in his conception of the selectivity of mind. "The element of permanence in the physical world," he writes, " … familiarly represented by the conception of substance, is essentially a contribution of the mind to the plan of building or selection."[40] But even here, the character of needed and reasonable replies is not essentially different. In his criticism of "substance," Eddington chiefly has in mind the notion of impenetrable, "billiard-ball" atoms, and he tends to ignore the correlated cognitive function of categorical system.

No one doubts that constellations of existing human values effect our relationships to nature and to other human beings, and this is not a matter to be settled without regard to those relationships. In particular, it seems completely unreasonable to suppose that arbitrary choice of values would be viable in practice or suit human life and the purposes which human values serve. On the contrary, arbitrary choice of values, or over-emphasis on particular values, is the typical object of criticism when we consider the all too frequent, bad turns of human history. Something of crucial importance is typically ignored if values are selected arbitrarily. For, what does "arbitrary" choice mean, when employed in criticism, if not choice without sufficient grounds and consideration?

This argument can be brought into contact with Eddington's emphasis on the scientific value of "permanence" in theory choice, or the value which mind places upon the permanent. After we have noticed the scientific preference for concepts and laws which better

40. Eddington, below, p. 242.

stand the tests of time and further evidence, then the question remains as to better and worse in the cognitive selectivity of consciousness or mind. The mere fact of selective attention does not imply anything about the cognitive value of particular selections, though in nominalistic style, Eddington tends to equate selectivity of attention with arbitrary imposition. No doubt, selective attention can be as arbitrary and unfounded as any one-sided human activity, but this does not show that all selectivity is arbitrary. Again, it does not show that preference for permanence can have no justification —as with the various conservation laws. Concern with permanence seems clearly an implication of the need and continued stress on confirmation by empirical tests; but this can not be plausibly understood as an imposition on, or dictation to nature.

3. Causation and indeterminacy

Writing on cause and effect, Eddington emphasizes the directionality of time:

> Cause and effect are closely bound up with time's arrow; the cause must precede the effect. The relativity of time has not obliterated this order. An event Here-Now can only cause events in the cone of absolute future; it can be caused by events in the cone of absolute past; … [41]

In contrast to spatial dimensions, on this account, time has not only a measurable extension, it also has a direction: "time's arrow"—pointing toward the future and away from the past. Part of the point of this short quoted passage, focused on the common-sense conception of cause and effect, is that the directionality of time is not disrupted by Einstein's account of the interrelation of space and time. Though judgments of simultaneity may differ, depending on the relations of differing frames of reference, still, as the point is usually put in terms of "light cones" (which define the sphere of

41. Eddington, below, p. 293.