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(*b*. Ramsgate, Kent, England, 15 February 1861; *d*. Cambridge, Massachusetts, 30 December 1947)

mathematics, mathematical logic, theoretical physics, philosophy.

Education, religion, and local government were the traditional interests of the family into with Whitehead was born, the son of a southern English schoolteacher turned Anglican clergyman. As a child Whitehead developed a strong sense of the enduring presence of the past, surrounded as the was by relics of England's history. The school to which he was sent in1875, Sherborne in Dorset, traced its origin to the eighth century. At Sherborne. Whitehead excelled in mathematics, grew to love the poetry of Wordsworth and Shelley, and in his last year acted as head of the school and captain of games. In the autumn of 1880 he entered Trinity College, Cambridge. Although during his whole undergraduate study all his courses were on pure or applied mathematics, he nevertheless developed a considerable knowledge of history, literature, and philosophy. His residence at Cambridge, first as scholar, then as fellow, and finally as senior lecturer in mathematics, lasted from 1880 to 1910. During the latter part of this period he used to give political speeches in the locality; these favored the Liberal party and often entailed his being struck by rotten eggs and oranges. In 1890 he married Evelyn Willoughby Wade, whose sense of beauty and adventure fundamentally influenced Whitehead's philosophical thought. Three children were born to them between 1891 and 1898: Thomas North, Jessie Marie, and Eric Alfred, who was killed in action with the Royal Flying Corps in 1918.

In 1910 Whitehead moved to London, where he held a variety of posts at University College and was professor at the Imperial College of Science and Technology. During this period, while active in assisting to frame new educational programs, he turned his reflective efforts toward formulating a philosophy of science to replace the prevailing materialistic mechanism, which in his view was unable to account for the revolutionary developments taking place in science.

In 1924, at the age of sixty-three, Whitehead became a professor of philosophy at Harvard University. There his previous years of reflection issued in a rapid succession of philosophical works of first importance, principally *Process and Reality: An Essay in Cosmology* (1929). He retired from active teaching only in June 1937, at the age of seventy-six. Whitehead died in his second Cambridge ten years later, still a British subject, but with a great affection for America. He had enjoyed the rare distinction of election to fellowships both in the Royal Society and in the British Academy. In 1945 he was also awarded the British Order of Merit.

Whitehead's life and work thus fall naturally into three periods which, although distinct, manifest a unity of development in his thought. At Cambridge University his writings dealt with mathematics and logic, although his thought already displayed those more general interests that would lead him to philosophy. In his second, or London, period, White-head devoted himself to rethinking the conceptual and experiential foundations of the physical sciences. He was stimulated in this work by participating in the discussions of the London Aristotelian Society. The writings of his third, or Harvard, period were distinctly philosophical, commencing with *Science and the Modern World* (1925), and culminating in *Process and Reality* (1929) and *Adventures of Ideas* (1933). These three works contain the essentials of his metaphysical thinking. Noteworthy among his several other books are *The Aims of Education* (1929) and *Religion in the Making* (1926), in which he combines a sensitivity to religious experience with a criticism of traditional religious concepts.

Although Whitehead's intellectual importance lies mainly in philosophy itself, he did significant work in mathematics, mathematical logic, theoretical physics, and philosophy of science.

Mathematics And Mathematical Logic . White-head's mathematical work falls into three general areas, the first two of which belong to his residence at Cambridge University, the third to his London period. The first area, algebra and geometry, contains his writings in pure mathematics, chief among which is his first book, *A Treatise on Universal Algebra* (1898). Other examples are papers on "The Geodesic Geometry of Surfaces in Non-Euclidean Space" (1898) and "Sets of Operations in Relation to Groups of Finite Order" (1899). The second area consists in work that would today be termed logic and foundations. It includes work on axiomatics (projective and descriptive geometry), cardinal numbers, and algebra of symbolic logic; it culminates in the three-volume *Principia Mathematica*, written with Bertrand Russell. The third area–less relevant from a mathematical point of view–contains the mathematical work that overlaps other fields of Whitehead's scientific activity, mainly his physics and his philosophy of mathematics. His paper "On Mathematical Concepts of the Material World" (1906) is typical of the former; his *Introduction to Mathematics* (1911) lies in the border area between mathematics and the philosophy of mathematics.

Algebra and Geometry. Whitehead's first book, *A Treatise on Universal Algebra*, seems at first glance entirely mathematical. Only in view of his subsequent development are several of his introductory remarks seen to have a philosophical import. This lengthy book, begun in 1891 and published in 1898, formed part of that nineteenth-century pioneering development sometimes referred to as the "liberation of algebra" (from restriction to quantities). Although the movement was not exclusively British, there was more than half a century of British tradition on the subject (George Peacock, Augustus De Morgan, and William Rowan Hamilton), to which Whitehead's mathematical work belonged.

Whitehead acknowledged that the ideas in the *Universal Algebra* were largely based on the work of Hermann Grassmann, Hamilton, and Boole. He even stated that his whole subsequent work on mathematical logic was derived from these sources, all of which are classical examples of structures that do not involve quantities.

After an initial discussion of general principles and of Boolean algebra, the *Universal Algebra* is devoted to applications of Grassmann's calculus of extension, which can be regarded as a generalization of Hamilton's quaternions and an extension of arithmetic. Major parts of the modern theory of matrices and determinants, of vector and tensor calculus, and of geometrical algebra are implied in the calculus of extension. Whitehead's elaboration of Grassmann's work consists mainly in applications to Euclidean and non-Euclidean geometry.

Although the *Universal Algebra* displayed great mathematical skill and erudition, it does not seem to have challenged mathematicians or to have contributed in a direct way to further development of the topics involved. It was never reprinted during Whitehead's lifetime. It is plausible to think that, by the time the mathematical world became aware of the many valuable items of the work, these had been incorporated elsewhere in more accessible contexts and more modern frameworks.

Logic and Foundations. Confining itself to the algebras of Boole and Grassmann, the *Universal Algebra* never became what it was intended to be, a comparative study of algebras as symbolic structures. Whitehead planned to make such a comparison in a second volume along with studies of quaternions, matrices, and the general theory of linear algebras. Between 1898 and 1903 he worked on this second volume. It never appeared, and neither did the second volume of Bertrand Russell's *Principles of mathematics* (1903). The two authors discovered that their projected second volumes "were practically on identical topics, "and decided to cooperate in a joint work. In doing so their vision expanded, and it was eight or nine years before their monumental *Principia Mathematica* appeared.

The *Principia Mathematica* consists of three volumes which appeared successively in 1910, 1912, and 1913. A fourth volume, on the logical foundations of geometry, was to have been written by Whitehead alone but was never completed. The *Principia* was mainly inspired by the writings of Gottlob Frege, Georg Cantor, and Giuseppe Peano. At the heart of the treatment of mathematical logic in the *Principia* lies an exposition of sentential logic so well done that it has hardly been improved upon since. Only one axiom (Axiom 5, the "associative principle") was later (1926) proved redundant by Paul Bernays. The development of predicate logic uses Russell's theory of types, as expounded in an introductory chapter in the first volume. The link with set theory is made by considering as a set all the objects satisfying some propositional function. Different types, or levels, of propositional functions yield different types, or levels, of sets, so that the paradoxes in the construction of a set theory are avoided. Subsequently several parts of classical mathematics are reconstructed within the system.

Although the thesis about the reduction of mathematics to logic is Russell's, as is the theory of types, Russell himself stressed that the book was truly a collaboration and that neither he nor Whitehead could have written it alone.[1] The second edition (1925), however, was entirely under Russell's supervision, and the new introduction and appendices were his, albeit with Whitehead's tacit approval.

Taken as a whole, the *Principia* fills a double role. First, it constitutes a formidable effort to prove, or at least make plausible, the philosophical thesis best described by Russell in his preface to *The Principles of Mathematics:* "That all pure mathematics deals exclusively with concepts definable in terms of a very small number of fundamental logical concepts, and that all its propositions are deducible from a very small number of fundamental logical principles." This thesis is commonly expressed by the assertion that logic furnishes a basis for all mathematics. Some time later this assertion induced the so-called logicist thesis, or logicism, developed by Wittgenstein–the belief that both logic and mathematics consist entirely of tautologies. There is no evidence that Whitehead ever agreed with this: on the contrary, his later philosophical work indicates a belief in ontological referents for mathematical expressions. The thesis that logic furnishes a basis for all mathematics was first maintained by Frege but later (1931) refuted by Kurt Gödel, who showed that any system containing arithmetic, including that of the *Principia,* is essentially incomplete.

The second role of the *Principia* is the enrichment of mathematics with an impressive system, based on a thoroughly developed mathematical logic and a set theory free of paradoxes, by which a substantial part of the body of mathematical knowledge becomes organized. The *Principia* is considered to be not only a historical masterpiece of mathematical architecture, but also of contemporary value insofar as it contains subtheories that are still very useful.

Other Mathematical Work. At about the time Whitehead was occupied with the axiomatization of geometric systems, he turned his attention to the mathematical investigation of various possible ways of conceiving the nature of the material world. His paper "On Mathematical Concepts of the Material World" (1906) is just such an effort to create a mathematical although qualitative model of the material world. This effort differs from applied mathematics insofar as it does not apply known mathematics to situations and processes outside mathematics but creates the mathematics *ad hoc* to suit the purpose; yet it resembles applied mathematics insofar as it applies logical-mathematical tools already available. The paper conceives the material world in terms of a set of relations, and of entities that form the "fields" of these relations. The axiomatic mathematical system is not meant to serve as a cosmology but solely to exhibit concepts not inconsistent with some, if not all, of the limited number of propositions believed to be true concerning sense perceptions. Yet the system does have a cosmological character insofar as it tries to comprehend the entire material world. Unlike theoretical physics the paper is entirely devoid of quantitative references. It is thus an interesting attempt to apply logical-mathematical concepts to ontological ones, and is an early indication of Whitehead's dissatisfaction with the Newtonian conception of space and time. In a qualitative way the paper deals with field theory and can be regarded as a forerunner of later work in physics.

The delightful little book *An Introduction to Mathematics* (1911) is another early example of Whitehead's drifting away from the fields of pure mathematics and logic, this time more in the direction of philosophy of mathematics. The book contains a fair amount of solid although mainly fundamental and elementary mathematics, lucidly set out and explained. The object of the book, however, "is not to teach mathematics, but to enable students from the very beginning of their course to know what the science is about, and why it is essarily the foundation of exact thought as applied to natural phenomena" (p. 2). In it Whitehead stresses the three notions of variable, form, and generality.

Theoretical Physics . Whitehead's contributions to relativity. gravitation, and "unified field" theory grew out of his preoccupations with the principles underlying our knowledge of nature. These philosophical considerations are presented chiefly in *An Enquiry Concerning the Principles of Natural Knowledge*(1919), *The Concept of Nature* (1920), and *The Principle of Relativity* (1922). A. S. Eddington, in his own book *The Nature of the Physical World* (Cambridge, 1929), comments: "Although this book may in most respects seem diametrically opposed to Dr. Whitehead's widely read philosophy of Nature, I think it would be truer to regard him as an ally who from the opposite side of the mountain is tunnelling to meet his less philospphically minded colleagues" (pp. 249–250).

In a chapter on motion in the *Principles of Natural Knowledge*, Whitehead derives the Lorentz transformation equations, now so familiar in Einstein's special theory of relativity. Whitehead's derivation, however, was based on his principle of kinematic symmetry,[2] and was carried through without reference to the concept of light signals. Consequently the velocity c in the equations is not necessarily that of light, although it so happens that in our "cosmic epoch," c is most clearly realized in nature as the velocity of light. There are three types of kinematics. which Whitehead termed "cosmic epoch," "elliptic," or "parabolic," according to whether c^2 is positive, negative, or infinite. Whitehead pointed out that the hyperbolic type of kinematics corresponds to the LarmorLorentz-Einstein theory of electromagnetic relativity and that the parabolic type reduces to the ordinary Newtonian relativity (Galilean transformation). He rejected the elliptic type as inapplicable to nature.

In *The Principle of Relativity* Whitehead challenged the conceptual foundations of both the special and general theories of Einstein by offering "an alternative rendering of the theory of relativity" (page v). One of Whitehead's fundamental hypotheses was that space-time must possess a uniform structure everywhere and at all times–a conclusion that Whitehead drew from a consideration of the character of our knowledge in general and of our knowledge of nature in particular. He argued that Einstein's view that space-time may exhibit a local curvature fails to provide an adequate theory of measurement:

Einstein, in my opinion, leaves the whole antecedent theory of measurement in confusion when it is confronted with the actual conditions of our perceptual knowledge. . . . Measurement on his theory lacks systematic uniformity and requires a knowledge of the actual contingent field before it is possible.[3]

Whitehead proposed an action-at-a-distance theory rather than a field theory. He relieved the physicist of the task of having to solve a set of nonlinear partial differential equations. J. L. Synge, who ignored any consideration of the philosophical foundations of the theory, has clearly presented the mathematical formulas of Whitehead's gravitational theory in modern notation.[4]

Using Synge's notation, the world lines of test particles and light rays in Whitehead's theory may be conveniently discussed by the Euler-Lagrange equations:

where $2L = -1$ for test particles; $2L = 0$ for light

rays;and . The Lagrangian L is defined:

where g_{mn} is a symmetrical tensor defined by

In equation (3) δ_{mn} is the Kronecker delta; G is the gravitational constant; c is a fundamental velocity; and m is the mass of a particle with a world line given by $x'_n = x'_n(s'_n)$, where s' is the Minkowskain are length such that $ds'^2 = -dx'_n dx'_n$; $y_m = x_m - x'_m$;

and . The parameter λ in equation (1)

is such that $d\lambda = (-g_{mn}dx_m dx_n)$. Latin suffixes have the range 1,2,3,4. Thus whitehead's theory of gravitation is described in terms of Minkowskian space-time with $x_4 = ict$ (where and c is the speed of light in a vacuum).[5] The basic physical laws of the Whitehead theory are invariant with respect to Lorentz transformations but not necessarily with respect to general coordinate transformations. Whitehead invoked neither the principle of equivalence nor the principle of covariance.

Clifford M. Will has challenged the viability of Whitehead's theory by arguing that it predicts "an anisotropy in the Newtonian gravitational constant G, as measured locally by means of Cavendish experiments."[6] Using Synge's notation, Will calculated Whitehead's prediction of twelve-hour siderear-time earth tides, which are produced by the galaxy, and found Whitehead' prediction in disagreement with the experimentally measured value of these geotidal effects. In Whitehead's theory the anisotropy in G is a result of the uniform structure of space-time demanded by the theory.

In order to understand the relation of the anisotropy to uniformity we must recognize that in Whitehead's theory gravitational forces are propagated along the geodesics of the uniform structure of space-time, while electromagnetic waves are deflected by the contingencies of the universe.[7] This restriction in the propagation of gravity produces the variation in the gravitatinal constant. While Whitehead's mathematical formulas imply this restriction, it is not demanded by his philosophy of nature. For Whitehead, gravitational forces share in the contingency of nature, and may therefore be affected, as electromagnetic waves are, by the contingencies of the universe.

In addition to the consideration of gravitation, in chapter 5 of *The Principle of Relativity* Whitehead extends his equations of motion to describe the motion of a particle in a combined gravitational and electromagnetic field. As Rayner points out,[8] this is not a "true" unified field theory since it does not interpret gravitational and electromagnetic phenomena in terms of a single primitive origin.

It is possible to demonstrate, as did Eddington[9] and synge,[10] that the predictions of Whitehead's theory and those of Einstein's general theory of relativity are equivalent with respect to the four tests of relativity: the deflection of a light ray, the red shift, the advance in the perihelion of a satellite, and radar time delay. The equivalence of the two theories with respect to these tests rests in the remarkable fact that both theories, when solved for a static, spherically symmetrical gravitational field, produce the Schwarzschild solution of the field equations.

In accordance with his usual practice, Whitehead assembled *Relativity* from lectures that he delivered at the Imperial College, the Royal Society of Edinburgh, and Bryn Mawr College. He did not publish in the journals of physical science nor enter into active discourse with members of the scientific community. His gravitational theory is not referred to in the formal treatments of relativity given by such authors as Bergmann, Einstein, and Pauli. The mathematical physicists who studied and extended Whitehead's physical theories in the 1950's had difficulty understanding his esoteric language and his philosophical ideas. While the two ends of Eddington's tunnel have not yet been joined under the mountain, considerable progress has been made by the careful exposition of Whitehead's philosophy of science by Robert M. Palter.[11]

In 1961 C. Brans and R. H. Dicke developed a modified relativstic theory of gravitation apparently compatible with Mach's principle.[12] It is significant that the Einstein, Whitehead, and Brans-Dicke theories represent distinct conceptual formulations, the predictions of which with regard to observational tests are all so close that it is not yet possible on this basis to make a choice among them. New experiments of high precision on the possible Machian time variation of G and on the precession of the spin axis of a gyroscope,[13] as well as theoretical considerations such as the "parametrized post-Newtonian" (PPN) formalism,[14] may be decisive, At present the Einstein theory is regarded as the most influential and elegant;

the Brans-Dicke theory has perhaps the most attractive cosmological consequences;[15] and the Whitehead theory, although clearly the simples, suffers from its obscurity.

Philosophy of Science . Whitehead once remarked that what worried him was "the muddle geometry had got into" in relation to the physical world.[16] Particularly in view of Einstein' theory of relativity, it was unclear what relation geometrical space had to experience. It was therefore necessary to find a basis in physical experience for the scientific concepts of space and time. These are, Whitehead thought, "the first outcome of the simplest generalisations from experience, and . . . not to be looked for at the tail end of a welter of differential equations."[17] The supposed divorce of abstract scientific concepts from actual experience had resulted in a "bifurcation of nature," a splitting into two disparate natures, of which one was a merely apprent world of sence experience, the other a conjectured, causal world perpetually behind a veil. Aside from extrinsic quantitative relations, the elements of this latter world were presumed to be intrinsically self-contained and unrelated to one another. Somehow this conjectured, monadically disjunctive nature, although itself beyond experience, was supposed to account causally for the unified nature of experience. Whitehead rejected this view as incoherent and as an unsatisfactory foundation for the sciences. According to Whitehead, "we must reject the distinction between nature as it really is and experiences of it which are purely psychological. Our experiences of the apparent world are nature itself."[18]

In his middle writings Whitehead examined how space and time are rooted in experience, and in general laid the foundations of a natural philosophy that would be the necessary presupposition of a reorganized speculative physics. He investigated the coherence of "Nature," understood as the object of perceptual knowledge; and he deliberately although perhaps knowledge; and he deliberately, nature as thus known from the synthesis of knower and known, which falls within the ambit of metaphysical analysis.

Two special characteristics of Whitehead's analysis are of particular importance: his identification of noninstantaneous events as the basic elements of perceived nature, and the intrinsically relational constitution of these events (as displayed in his doctrine of "significance"). Space and time (or space-time) are then shown to be derivative from the fundamental process by which events are interrelated. rather than a matrix within which events are independently situated. This view contrasts sharply with the prevalent notion that nature consists in an instantaneous collection of independent bodies situated in space-time. Such a view, Whitehead thought, cannot account for the perception of the continuity of existence, nor can it represent the ultimate scientific, fact, since change inevitably imports the past and the future into the immediate fact falsely supposed to be embodied in a durationless present instant.

Whitehead's philosophy of nature attempts to balance the view of nature-in-process with a theory of elements ingredient within nature ("objects"), which do not themselves share in nature's passage. Whitehead's boyhood sense of permanences in nature thus emerged both in his mathematical realism and in his philosophic recognition of unchanging characters perpetually being interwoven within the process of nature.

Method of Extensive Abstraction. "Extensive abstraction" is the term Whitehead gave to his method for tracing the roots within experience of the abstract notions of space and time, and of their elements.

In this theory it is experienced events, not physical bodies, that are related; their fundamental relation lies in their overlapping, or "extending over," one another. Later Whitehead recognized that this relation is itself derivative from something more fundamental.[19] The notions of "part," "whole," and "continuity" arise naturally from this relation of extending-over. These properties lead to defining an "abstractive set" as "any setf of events that possesses the two properties, (i) of any two members of the set one contains the other as a part, and (ii) there is no event which is a common part of every menber of the set."[20]Such a set of events must be infinite toward the small end, so that there is no least event in the set. Corresponding to the abstractive set of events there is an abstractive set of the intrinsic characters of the events. The latter set converges to an exactly defined locational character. For instance, the locational character of an abstractive set of concentric circles or squares converges to a nondimensional but located point. In analogous fashion, an abstractive set of rectangles, all of which have a common length but variable widths, defines a line segment. With the full development of this technique Whitehead was able to define serial times, and, in terms of them, space. He concluded that all order in space is merely the expression of order in time. “Position in space is merely the expression of diversity of relations to alternative time-systems.”[21]

In general Whitehead held that there are two basic aspects in nature. One is its passage or creative advance; the other its character as extended–that is, that its events extend over one another, thus giving nature its continuity. These two facts are the qualities from which time and space originate as abstractions.

The purpose of the method of extensive abstraction is to show the connection of the abstract with the concrete. Whitehead showed, for instance, how space is naturally related to the experience of events in nature, which have the immediately given property of extension. Whitehead’s procedure, however, is easily subject to misunderstanding. Most Whitehead scholars agree that Whitehead was trying neither to deduce a geometry from sense experience, nor to give a psychological description of the genesis of geometric concepts. Rather, he was using a mathematical model to clarify relations appearing in perception. Another mis-interpretation would be to assume that Whitehead took as the immediate data for sense awareness some kind of Humean sense instead of events themselves.

In his notes to the second edition of the *Principles of Natural Knowledge* Whitehead suggested certain improvements in his procedure. The final outcome of extensive abstraction is found in part 4 of *Process and Reality*, “The Theory of Extension,” in which Whitehead defines points, lines, volumes, and surfaces without presupposing any particular theory of parallelism, and defines a straight line without any reference to measurement.

Uniformity of Spatiotemporal Relations. In the Preface to *The Principle of Relativity* Whitehead states:

As the result of a consideration of the character of our knowledge in general, and of our knowledge of nature in particular. . . . I deduce that our experience requires and exhibits a basis of uniformity, and that in the case of nature this basis exhibits itself as the uniformity of spatio-temporal relations. This conclusion entirely cuts away the casual heterogeneity of these relations which is the essential of Einstein’s later theory.

The mathematical consequences of this conclusion for Whitehead’s theory of relativity have already been noted. It remains to indicate summarily the reasons that persuaded Whitehead to adopt this view.

Consonance with the general character of direct experience was one of the gauges by which Whitehead judged any physical theory, for he was intent on discovering the underlying structures of nature as observed. Further, he maintained the traditional division between geometry and physics: it is the role of geometry to reflect the relatedness of events: that of physics to describe the contingency of appearance. He also claimed that it is events, not material bodies, that are the terms of the concrete relations of nature. But since for Whitehead these relations were essentially constitutive of events, it might seem that no event can be known apart from knowledge of all those other events to which it is related. Thus, nothing can be known until everything is known–an impossible requirement for knowledge.

Whitehead met this objection by distinguishing between essential and contingent relations of events. One can know that an event or factor is related to others without knowing their precise character. But since in our knowledge on event discloses the particular individuals constituting the aggregate of events to which it is related, even contingently, this relatedness must embody an intrinsic uniformity apart from particular relationships to particular individuals. This intrinsic and necessary uniformity of the relatedness of events is precisely the uniformity of their spatiotemporal structure.

Whitehead provided an illustration of this in a discussion of equality.[22] Equality presupposes measurement, and measurement presupposes matching (not vice versa). It must follow that “measurement presupposes a structure yielding definite stretches which, in some sense inherent in the structure; match each other.”[23] This inherent matching is spatiotemporal uniformity.

It is well known that in his later philosophy Whitehead came to hold–contrary to his earlier belief–that nature is not continuous in fact, but “incurably atomic.” Continuity was recognized to belong to potentiality. not to actuality.[24] It has even been claimed that this later revision removes the basic difference between Einstein and Whitehead, so that the Whitehead of *Process and Reality* offers only an alternative interpretation of Einstein’s theory of relativity, not an alternative theory.[25] This claim, however, has not found wide support.

Despite some recent interest in it, Whitehead’s theory of relativity has been mainly ignored and otherwise not well understood. *The Principle of Relativity* has long been out of print, and it is impossible now to say whether it has a scientific future.

NOTES

1. Bertrand Russell. “Whitehead and Principia Mathematica.” *Mind*, n.s. **57** (1948), 137–138.

2. For a discussion and derivation. see C. B. Rayner. “Foundations and Applications of Whitehead’s Theory of Relativity.” University of London thesis. 1953: “The Application of the Whitehead Theory of Relativity to Non-static. Spherically Symmetrical Systems.” in *Proceedings of the Royal Society of London*, **222A** (1954), 509–526.

3.*The Principle of Relativity*. p. 83.

4. J. L. Synge, in *Proceedings of the Royal Society of London*. **211A** (1952), 303–319.

5. Whitehead’s requirement that space-time be homogeneous is not violated by a space-time of constant curvature. This extension of Whitehead’s theory has been carried out by G. Temple. “A Generalisation of Professor Whitehead’s Theory of Relativity,” in *Proceedings of the Physical Society of London*, **36** (1923), 176–193; and by C. B. Rayner, “Whitehead’s Law of Gravitation in a Space-Time of Constant Curvature,” in *Proceedings of the Physical Society of London*, **68B** (1955), 944–950.

6. Clifford M. Will, “Relativistic Gravity in the Solar System . . .” p. 141.

7. Misner, Thorne, and Wheeler, *Gravitation*. p. 430. Whitehead’s theory is termed a “two metric” theory of gravitation. The first metric defines the uniform structure of space-time: the second, the physically contingent universe.

8. Rayner. “Foundations and Applications . . .” p. 23.

9. Sir A. S. Eddington, “A Comparison of Whitehead’s and Einstein’s Formulae,” p. 192.

10. J. L. Synge, *The Relativity Theory of A. N. Whitehead* (1951). In Ch. 13 of *The Principle of Relativity* Whitehead obtains a red shift that disagrees with Einstein’s by a factor of 7/6. This is in disagreement with the terrestrial Mössbauer experiments (see R. V. Pound and G. A. Rebka, Jr., “Apparent Weight of Photons,” *Physical Review Letters*. 4 [1960]. 337–341.). Synge observes. however, that the discrepancy lies in Whitehead’s use of a classical rather than a quantum mechanical model of an atom and is not due to Whitehead’s gravitational theory. See also C. B Rayer, “The Effects of Rotation of the Central Body on Its Planetary Orbits. After the Whitehead Theory of Gravitation.” in *Proceedings of the Royal Society of London*, **232A** (1955), 135–148.

11. Robert M. Palter. *Whitehead’s Philosophy of Science*.

12. C. Brans and R. H. Dicke, in *Physical Review*, **124** (1961), 925–935.

13. L. I. Schiff, "Experimental Tests of Theories of Relativity," in *Physics Today*, **14** , no. 11 (November 1961), 42–48.

14. C. M. Will, op. cit.

15. R. H. Dicke, "Implications for Cosmology of Stellar and Galactic Evolution Rates," in *Review of Modern Physics*, **34** (1962), 110–122.

16. Lowe, *Understanding Whitehead*. p. 193.

17.*Principles of Natural Knowledge*. p. vi.

18.*The Principle of Relativity*. p. 62.

19.*Principles of Natural Knowledge*, p. 202.

20.*The Concept of Nature*, p. 79: *Principles of Natural Knowledge*, p. 104.

21.*The Principle of Relativity*, p. 8.

22.*Ibid*., ch. 3.

23.*Ibid*., p. 59.

24. Leclerc. "Whitehead and the Problem of Extension."

25. Seaman, "Whitehead and Relativity."

BIBLIOGRAPHY

I. Original Works. A chronological list of all Whitehead's writings may be found in P. A. Schilpp (see below). The following works are of most scientific importance: *A Treatise on Universal Algebra, With Applications* (Cambridge, 1898); "On Mathematical Concepts of the Material World." in *Philosophical Transactions of the Royal Society of London*, **205A** (1906), 465–525, also available in the Northrop and Gross anthology (see below): *Principia Mathematica*, 3 vols. (Cambridge, 1910–1913), written with Bertrand Russell: *An Introduction to Mathematics* (London, 1911); "Space, Time, and Relativity," in *Proceedings of the Aristotelian Society*, n.s. **16** (1915–1916), 104–129, also available in the Johnson anthology (see below); *An Enquiry Concerning the Principles of Natural Knowledge* (Cambridge, 1919): *The Concept of Nature* (Cambridge, 1920): *The Principle of Relativity, With Applications to Physical Science* (Cambridge, 1922), which is out-of-print but may be obtained from University Microfilms. Ann Arbor, Mich.: also, pt. 1. "General Principles," is reprinted in the Northrop and Gross anthology: *Science and the Modern World* (New York, 1925): *Process and Reality; An Essay in Cosmology* (New York: 1929). which is of scientific interest chiefly insofar as it gives Whitehead's final version of his theory of extensive abstraction: and *Essays in Science and Philosophy* (New York. 1947), a collection of earlier essays.

Two useful anthologies of Whitehead's writings are F. S. C. Northrop and Mason W. Gross, eds., *Alfred North Whitehead: An Anthology* (New York, 1961); and A. H. Johnson, ed., *Alfred North Whitehead: The Interpretation of Science. Selected Essays* (Indianapolis, 1961).

II. Secondary Literature. Paul Arthur Schilpp, ed., *The Philosophy of Alfred North Whitehead*, Library of Living Philosophers Series (New York, 1951). contains Whitehead's "Autobiographical Notes," a complete chronological list of Whitehead's writings, and essays pertinent to Whitehead's science by Lowe, Quine, and Northrop. Victor Lowe, *Understanding Whitehead* (Baltimore, 1962), is a valuable tool, especially pt. 2. "The Development of Whitehead's Philosophy," which is an enlargement of Lowe's essay in the Schilpp volume. Robert M. Palter, *Whitehead's Philosophy of Science* (Chicago, 1960), is a perceptive mathematical exposition of Whitehead's views on extension and on relativity. In 1971 appeared *Process Studies* (published at the School of Theology at Claremont, California), a journal devoting itself to exploring the thought of Whitehead and his intellectual associates. The fourth issue of vol. I (Winter 1971) contains a bibliography of secondary literature on Whitehead, to be periodically updated.

The following are cited as examples of the influence of Whitehead's thought on scientists or philosophers of science. In *Experience and Conceptual Activity* (Cambridge, Mass., 1965), J. M. Burgers, a physicist of some distinction. presents for scientists a case for a Whiteheadian rather than a physicalistic world view. Also, a strong Whiteheadian perspective dominates Milič Čapek. *The Philosophical Impact of Contemporary Physics* (New York, 1961).

Whitehead's later metaphysics, although consistent with and developed out of his reflections on science, forms another story altogether. For a more general introduction to his thought and to the literature, see the article on Whitehead in Paul Edwards, ed., *The Encyclopedia of Philosophy*, **VIII** (New York-London. 1967), 290–296.

On Whitehead's mathematics and logic, see Granville C. Henry. Jr., "Whitehead's Philosophical Response to the New Mathematics," in *Southern Journal of Philosophy*, **7** (1969–1970). 341–349; George L. Kline, ed., *Alfred North Whitehead: Essays on His Philosophy*, pt. **2** (Englewood Cliffs, N.J., 1963): J. J. C. Smart, *ysis*, **10** (1949–1950), 93–96, which is critical of the theory of types: Martin Shearn, "Whitehead and Russell's Theory of Types: A Reply," *ibid*., **11** (1950–1951) 45–48.

On Whitehead's theoretical physics, see Sir A. S. Edington, "A Comparison of Whitehead's and Einstein's Formulae," in *Nature*, **113** (1924), 192: Charles W. Misner, Kip S. Thorne, John Archibald Wheeler, *Gravitation* (San Francisco, 1973); C. B. Rayner, "Foundations and Applications of Whitehead's Theory of Relativity" (Ph.D. thesis, University of London, 1953); A, Schild. "Gravitational Theories of the Whitehead Type and the Principle of Equivalence," in *Proceedings of the International School of Physics*, "Enrico Fermi," course 20 (Italian Physical Society and Academic Press, 1963), 69–115; Francis Seaman, "Discussion: In Defense of Duhem," in *Philosophy of Science*, **32** (1965), 287–294, which argues that Whitehead's physical theory in *Process and Reality* illustrates the assumption of geometric, without physical, continuity; J. L. Synge, *The Relativity Theory of Alfred North Whitehead* (College Park, Md., 1951); Clifford M. Will, "Relativistic Gravity in the Solar System, **11** : Anisotropy in the Newtonian Gravitational Constant." in *Astrophysical Journal*, **169** (1971), 141–155; and "Gravitation Theory," in *Scientific American*, **231** , no. **5** (1974), 24–33. which compares competing theories.

On Whitehead's philosophy of science, see Ann P. Lowry, "Whitehead and the Nature of Mathematical Truth," in *Process Studies*, **1** (1971), 114–123; Thomas N. Hart, S. J., "Whitehead's Critique of Scientific Materialism," in *New Scholasticism*, **43** (1969), 229–251; Nathaniel Lawrence, "Whitehead's Method of Extensive Abstraction," in *Pgukisiophy of Science, 7 (1950), 142–163; Adikf Grünbaum, "Whitehead' Method of Extensive Abstraction," in British Journal for the Philosophy of Science*, **4** (1953), 215–226, which attacks the validity of Whitehead's method (see Lowe's reply in *Understanding Whitehead*, pp. 79–80): Caroline Whitebeck, "Simultaneity and Distance," in *Journal of Philosophy*, **66** (1969), 329–340: Wolfe Mays, "Whitehead and the Philosophy of Time," in *Studium generale*, **23** (1970), 509–524; Robert R. Llewellyn, "Whitehead and Newton on Space and Time Structure," in *Process Studies*, **3** (1973), 239–258; Ivor Leclerc, "Whitehead and the Problem of Extension," in *Journal of Philosophy*, **58** (1961), 559–565; Robert M. Palter, "Philosophic Principles and Scientific Theory," in *Philosophy of Science*, **23** (1956), 111–135, compares the theories of Einstein and Whitehead.

See also Francis Seaman, “Whitehead and Relativity,” in *Philosophy of Science*, **22** (1955), 222–226; A. P. Ushenco, “A Note on Whitehead and Relativity,” in *Journal of Philosophical*, **47** (1950), 100–102; Dean R. Fowler, “Whitehead’s Theory of Relativity,” in *Process Studies*, **5** (1975), which treats the philosophical foundations of Whitehead’s theory of relativity; and Richard J. Blackwell, “Whitehead and the Problem of Simultaneity,” in *Modern Schoolman*, **41** (1963–1964), 62–72. The extent to which applications of Whitehead’s philosophical scheme agree with modern quantum theory has been discussed by Abner Shimony, “Quantum Physics and the Philosophy of Whitehead,” in *Boston Studies in the Philosophy of Science*, **11** (New York, 1965), 307–330; and by J. M. Burgers, “Comments on Shimony’s Paper,” *ibid.*, pp. 331–342. Henry J. Folse, Jr., “The Copenhagen Interpretation of Quantum Theory and Whitehead’s Philosophy of Organism,” in *Tulane Studies in Philosophy*, **23** (1974), 32–47, challenges Shimony’s conclusions.

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