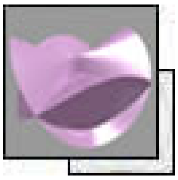
Relativity,Theory of



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Albert Einstein (1879-1955) is certainly the physicist of the 20th century most likely to conjure up the image of the "prototypical scientist" in the mind of both the scientist and the layperson. Such has been the admiration for him that he has obtained by now mythical status. For example, who has not heard of the famous formula $E = mc^2$? Einstein's fame rests not only on the slightly comical and heart-warming face seen in his more famous photographs (long dishevelled hair, large moustache, with a gaze, at once penetrating and distracted, and a countenance which inspires sympathy) but above all for the novelty of the "theory of relativity" which has engendered the belief that Einstein is one of the most ingenious physicists of the Modern era. Even though Einstein was awarded the 1905 Nobel Prize in physics (in the same year that he published his work on the theory of special relativity) for the theory of the photoelectric effect (interpreted as the result of discrete light quanta, or photons, whose energy is proportional to their frequency), not for the theory of special relativity, Einstein's name is basically associated with this last theory. The theory of relativity is considered to be one of the greatest scientific theories of recent times as it allowed for the development of an entire cosmology [2], revolutionized the concepts of time [3], space, and matter [4], even from the philosophical point of view, and, together with quantum mechanics [5], it forms the basis of all of physics as we know it today. However, the theory of relativity has also led to widespread effects on both the way of thinking and collective imagination of the 20th century, through unwarranted alterations or faulty interpretations of its. One has laid the blame (and, according to some, the merit) on the discovery of the special theory of relativity for the rise of a kind of philosophical relativism which negates the existence of eternal, immutable truths or absolutes (I am surprised by the fact that this is listed as one of the reasons why Einstein is the most important person of the 20th century in *Time* magazine). There are also the science-fiction extrapolations such as "time travels", or those inspired by its paradoxes (of which the "twin paradox" is well known), and this is perhaps the reason why special relativity is the most popular of all theories.

Relativity was developed in two stages corresponding to two different theories, different even in the epistemological sense: the "theory of special relativity" and the "theory of general relativity." The latter, however, is not a simple extension of the former: In fact, the development of the two theories followed two different "philosophies" or methodologies which were a result of the development and maturing of Einstein's thought during the course of his life. In what follows I will not describe the technical aspects of "relativity" (I refer the reader to numerous specialized and popular texts: see the Bibliography). I will instead trace the main lines of thought from an epistemological point of view. I will look first at the theory of special relativity and later at the general theory. I will conclude with a few considerations of the scientific-philosophical problems involved.

I. The Theory of Special Relativity

1. The Physical Approach. The theory of special relativity (1905) arose from a need which we could call "experimental": it was necessary to give a consistent and satisfactory explanation of the result of the famous Michelson-Morley experiment (1881 and 1887). With such an experiment, one repeatedly tried to detect the addition of the velocity of light coming from the sun with the velocity of the earth (cf. Pais, 1982). According to "classical" kinematics, the two velocities should be added if the earth moved towards a light source, and subtracted if it moved away. This would have allowed one to measure the velocity of the earth moving in absolute space, as conceived by Newton; that is, with respect to the "ether" which fills it (as it was supposed) and through which light travels. But the experiment had revealed, within a small margin of experimental error, that the velocity of light was always the same, and equal to 3 x 10 8 m/sec, independently of the velocity of the earth.

In order to find an explanation for this situation, Einstein used a very precise "methodology" on the basis of which the concepts of Newtonian mechanics had to be revised (see Mechanics [6]). The "philosophy" behind special relativity is considered to be the basis of the "operationism," a methodology proposed by Bridgman (1882-1961). According to Bridgman, a physical theory must only use those quantities which can be experimentally observed and measured. "Let us examine what Einstein did in his special theory. In the first place, he recognized that the meaning of a term is to be sought in the operations employed in making application of the term. If the term is one of which is applicable to concrete physical situations, as "length" or "simultaneity," then the meaning is to be sought in the operations by which the length of concrete physical objects is determined, or in the operations by which one determines whether two concrete physical events are simultaneous or not. This is well brought out by the following quotation form Einstein himself in connection with a discussion on simultaneity of two lighting strokes: 'The concept does not exist for the physicist until he has the possibility of discovering whether or not it is fulfilled in an actual case. We thus require a definition of simultaneity such that this definition supplies us with the means by which, in the present case, he decide by experiment whether both lighting strokes occurred simultaneously'." (P.W. Bridgman, *Einstein's Theories and the Operational Point of View*, in Schilpp, 1949, p. 335).

In addition to the operationist one of Bridgman, there is another fundamental epistemological assumption in the theory of relativity. It is to take as starting principles of a theory just those facts which seem not to be contradicted by observation. Hence, the fact that the velocity of light *in vacuo* does not add with other velocities (be they the velocity of the source which emits the light or the velocity of the observer which receives it, where both velocities are measured with respect to the "ether" in which light supposedly travels) becomes one of the pillars on which the entire theory of relativity is built upon. This is the principle of the "invariance of the velocity of light," and since it is the "constants of constants" it is generally denoted as *c*. The other guiding principle is the "principle of relativity" which had already been formulated by Galileo (1564-1642) and which Einstein would extend besides mechanics to other laws of physics, including electromagnetic laws. Starting from these two principles and using elementary mathematics, Einstein was able to deduce easily the kinematic transformation laws of space-time which Voigt, Lorentz and Fitzgerald had already discovered, without fully understanding them from a conceptual point of view. In so doing he was able to get rid of mechanistic remnants such as the hypothesis that the ether is some sort of elastic medium which filled Newton's (1642-1727) "absolute space" and through which light supposedly propagated. As Einstein himself has explained in his *Autobiographical Notes:* "According to the rules of connection, used in classical physics, of the spatial co-ordinates and the time of events in the transition from one inertial system to another the two assumptions of (1) the constancy of the light velocity, (2) the independence of the laws (thus specially also of the law of constancy of the light velocity), are mutually incompatible (despite the fact that both taken separately are base o experience). The insight that is fundamental for the special theory is this: the assumptions (1) and (2) are compatible if relations of a new type ('Lorentz transformations') are postulated for the conversion of co-ordinates and the times of events. [...] This is by no means nearly a conventional step, but implies certain hypotheses concerning the actual behavior of moving measuring rods and clocks, when can be experimentally validated or disproved" (pp. 56-57).

The consequences of these two simple principles were earthshattering and at first hard to believe. (a) We have, from the kinematic point of view, the dissolution of the Newtonian concept of "absolute" space and time as independent containers of corporeal objects and fields which move inside them: space and time are measured in different ways according to the velocity with which rods and clocks move, undergoing a "length contraction" and a "time dilation." Consequently, even velocities, if close to that of light, do not add according to Galilean-Newtonian kinematics; they however obey the rule that the resulting velocity can never exceed that of light. b) The consequences from the dynamical point of view are even more surprising. They include the famous "equivalence" of mass and energy expressed by the most well-known formula of relativity: $E = mc^2$. According to this formula, the mass of a certain quantity of matter can be, under the right conditions, transformed into energy (and vice versa). This forms the basis of the generation of nuclear energy, whose efficiency has been correctly interpreted in theoretical models of energy production in stars.

2. The Geometrical Approach. Special relativity underwent a sort of re-conceptualization when Minkowski (1864-1909), who had been one of Einstein's "excellent teachers" (cf. *Autobiographical Notes,* p. 15), proposed a representation of space-time in four dimensions ("Minkowski space") where time becomes the fourth dimension in addition to the three spatial ones. "Minkowski's important contribution to the theory lies in the following: Before Minkowski's investigation it was necessary to carry out a Lorentz-transformation on a law in order to test its invariance under such transformations, he, on the other hand, succeeded introducing a formalism such that the mathematical form of the law itself guarantees its invariance under Lorentz-transformations. By creating a four-dimensional tensor-calculus he achieved the same thing for the four-dimensional space which the ordinary vector-calculus achieves for the three spatial dimensions" (*ibidem*, p. 59). Once they were rewritten in the Minkowski formalism, Maxwell's equations of electrodynamics, which had remained unmodified by relativity (as they were correct from the start, unlike Newtonian mechanics which had to be relativistically modified), become compact, symmetric, and elegant, making even more "evident" the unification of electricity and magnetism brought about by J. Clerk Maxwell (1831-1879).

All of a sudden, physics was transformed into geometry. The intuitive perception of motion and its dynamic qualities seemed to crystallize into an ideal geometrical static structure of a Platonic, Cartesian and Spinozian flavor. It was perhaps a slightly cold vision, however elegant and symmetric it may have been. From that point on, the role of mathematics in physics, and particularly that of geometry, would in a certain sense dominate the older way of doing science and lay the ground-work for the general theory of relativity.

II. The Theory of General Relativity

1. From Operationism to the Criterion of "Inner Perfection." Einstein officially published his work on general relativity in 1916, but already had his first intuitions back in 1908. General relativity arose, consequently, in a perspective which was much different from that of the operationist point of view adopted in special relativity. Newton's theory of gravitation was adequate enough to explain experimental data. Even certain anomalies in astronomical observations, such as the precession of the perihelion of Mercury, were not too worrisome and could be explained within the frame of Newtonian mechanics. However, Einstein's new epistemological framework did not please Bridgman, the founder of operationism: "Einstein did not carry over into his general relativity theory the lessons and insights which he himself has taught us in his special theory" (Bridgman, *op. cit.*, in Schilpp, 1949, p. 335), but one should say that he brought others which were not less ingenious; he sought a theory which satisfied, among other things, the epistemological criterion of simplicity, elegance, and unification. His problem had become that of finding an even more unified explanation of all of physics, beginning by pointing out a number of weak methodological points (that is, points that had an unsatisfactory solution, also philosophically speaking), and then criticizing constructively the scientific scenario of his day, "Before I enter upon a critique [...] of physics," Einstein says, "something of a broadly general nature will first have to be said concerning the points of view according to which it is possible to criticize physical theories at all. The first point of view is obvious. The theory must not contradict empirical facts. [...] The second point of view is not concerned with the relation to the material of observation but with the premises of the theory itself, with what may briefly but vaguely be characterized as the 'naturalness' or 'logical simplicity' of the premises (of the basic concepts and of the relations between these which are taken as a basis). [...] The second point of view may briefly be characterized as concerning itself with the 'inner perfection' of the theory, whereas the first point of view refers to the "external confirmation" (*Autobiographical Notes*, pp. 21-23).

With the advent of general relativity and quantum mechanics, mathematics would become more important, but less intuitive and technically more elaborate (it required advanced tools such as differential geometry which after the discovery of relativity developed significantly, and functional analysis, needed to define the Hilbert spaces used in quantum mechanics); physics becomes more distant from direct experience [7] and common sense. "The more the basic concepts and axioms distance themselves form what is directly observable, so that the confrontation of the implications of theory by the facts becomes constantly more difficult and more drawn out" (*ibidem*, p. 27), the more the epistemological criterion of "inner perfection" becomes important. One had already confronted the problem of the search for "invariants," that is, observer independent quantities, and the one of universal dimensionless "constants," and "symmetries" of natural laws [8], which form a sort of objective *datum* at the basis of the universe and a guide in our knowledge of it. What was still unsatisfactory in special relativity was the fact that the laws of dynamics are valid for only a restricted class of observers (that is, the "inertial" observers of Newtonian mechanics); a well formulated physical theory should express laws in the same form, independent of the observer (covariance). It was the idea of the "principle of relativity" which guided the development of special relativity and which now had to be more deeply exploited.

2. From Mach's Principle to the Principle of Equivalence. To carry out this project, Einstein drew inspiration from Mach and his considerations of the relationship between inertia and gravitation: "Mach conjectures that in a truly rational theory inertia would have to depend upon the interaction of the masses, precisely as was true for Newton's other forces" (*Autobiographical Notes*, p. 29; see also Sciama, 1969). According to Einstein, Mach's criticism is essentially sound. Beginning from an appropriately revised version of Mach's ideas, he obtained a formulation of the "principle of equivalence" between inertial and gravitational mass, or else between the gravitational field and "apparent forces" which arise in non-inertial systems. "That the special theory of relativity is only the first step of a necessary development became completely clear to me only in my efforts to represent gravitation in the framework of this theory. [...] Now it came to me: the fact of the equality of inert and heavy mass, i.e., the fact of the independence of the gravitational acceleration of the nature of the falling substance, may be expressed as follows: In a gravitational field (of small spatial extension) things behave as they do in a space free of gravitation, if one introduces in it, in place of an 'inertial system,' a reference system which is accelerated relative to an inertial system" (*Autobiographical Notes*, pp. 63-65).

3. From Minkowski's Flat Space to Riemann's Curved Space. At this point one needed a fitting mathematical tool to introduce the principle of equivalence in the four-dimensional space-time so as to generalize Minkowski's space in a new structure capable of including gravity. "The fact of equality of inert and heavy mass thus leads quite naturally to the recognition that the basic demand of the special theory of relativity (invariance of the laws under Lorentz-transformations) is too narrow, i.e., that an invariance of the laws must be postulated also relative to *non-linear* transformations of co-ordinates in the four-dimensional continuum" (*ibidem*, p. 67). This step leads to introduce a curved space-time based on Riemann's non-Euclidean geometry.

I will not enter into further technical details, but simply emphasize that in this way the element of "non-linearity" comes into play in the equations because of the curvature of non-Euclidean space-time. Using two-dimensional surfaces as a way of visualizing four-dimensional space-time, we can say that curved space-time is not like a plane but rather like the surface of a sphere (closed space) or a saddle (open space). General relativity is the first field theory to use "non-linear" equations of the same kind as those which, a few decades later, would revolutionize the entire epistemological status [9] of the sciences, with the appearance of deterministic chaos (see Indeterminism [10]) and complexity.

III. The Search for Unification

The criterion of inner perfection of the theory, understood as a criterion of "simplicity" could not be other than a criterion of "unification." If Kepler, Galileo, and Newton had unified "celestial" mechanics and "terrestrial" mechanics, and Maxwell unified electricity and magnetism, a consequence of special relativity had been, among other things, that of making electromagnetism compatible with mechanics by correcting the latter. But now general relativity had unified gravity and the dynamics of motion with the geometry of space-time and, to do so, proposed a solution which seemed to be the simplest. There were no longer mechanical principles on the one hand, and laws of gravitation (as for Newton) or laws of the electromagnetism (as for Maxwell) on the other. Now we dealt with a single system of equations for both the field and the motion. All theories up to now required, in addition to the field equations, special equations for the motion of material bodies under the influence of the fields; in general relativity, instead, the law of motion need not (and must not) be assumed independently since it is already implicitly contained within the law of gravitational field (*ibidem*).

Epistemology of unification would push subsequent research towards the inclusion of the electromagnetic field in a more generalized theory, a project which Einstein did not succeed in completing. After

Einstein's death (1955), the objective of unification remained latent for some time in physics. However, it experienced a re-awakening a short later, representing now the heritage left by the discoverer of "relativity" to all physicists of the end of the 20th century. The interest in unified theories of gravitation and electromagnetism in a space-time with more than four dimensions following the model of Kaluza-Klein, to whom Einstein devoted considerable attention, or in a space with affine connection and a non-symmetric metric tensor, which Einstein considered the most natural generalization of the equations of gravitation and believed that they had "the fair probability of being found valid, if the way to an exhaustive description of physical reality on the basis of the continuum turns out to be possible at all" (*Autobiographical Notes*, p. 93), are now at the center of the most recent research. The main problem of unification has been that of a "conceptual," and not just technical unification, between relativity and quantum mechanics. The attempt of Paul A.M. Dirac (1902-1984) at combining the two theories using a purely technical approach has led to a quantum field theory with impressive predictive power. But one ended up perhaps with a merely mathematical theory similar, in some sense, to the ancient Ptolemaic system of the planets, which made good predictions but gave little physical understanding of the real world. Today, we are still seeking a unified theory, but the epistemological background is changing. If, on the one hand, one is pursuing the road of unification opened up by relativity and quantum field theory (being the latter now occupied with the not so easy attempt to quantize gravity), on the other hand, one has run into the problem of "non-linearity" (by now inevitable in general relativity which was the first theory to introduce non-linearities in the fields). Non-linearity caused the appearance of problems such as instability, deterministic chaos, and complexity; and we do not yet know what the outcome of such research will be. Mathematics itself, which is the most important tool of modern physics, is being studied in its foundation along the lines of Cantor, Russell, Whitehead and Gödel. Not a few physicists, mathematicians, and philosophers of science, are comparing the new problems with the ancient ones found by Greek and medieval thought, which seem to arise again in a new, interesting, and inescapable way.

IV. Scientific-philosophical questions

From its birth, the theory of relativity has raised a number of conceptual problems which necessarily carried with them deep philosophical implications.

1. Space and Time. Special relativity had overturned, before all, the Newtonian concept of absolute space and time [3]. At first glance, this "relativization" of length (Lorentz contraction of length), time (dilation of time), and the concept of simultaneity (relativity of simultaneity) seemed to lead one to think of a philosophical subjectivism, according to which concepts of space and time are transferred from the objective realm of external reality (realism [11]) to the subject which observes it (idealism [12]). But a short later, with the advent of the theory of general relativity, one realized, on the contrary, that "relativity," had transferred space and time from their role as empty, external containers of the object, as Newton would have had it, or as conceptual categories internal of the subject (as Kant would have had it), to the role of the order relations determined by the bodies themselves (distribution of energy-mass, or matter-field) and by their motion. In general relativity, the properties of the metric, connection, and curvature of space and time are determined by bodies and their interactions and not vice-versa, and this led to an even greater realism than that of Newtonian physics. This is closer to the conception of space and time of Aristotle than that of Descartes and Kant.

2. Relativity and Objectivity. "Relativity," therefore, notwithstanding the name which can lead one astray, had nothing to do with philosophical relativism: on the contrary, it was a theory of "invariants," that is of laws which assume the same form for all observers (covariance): the Minkowski space-time formulation had already enabled one to show this result for inertial observers within the context of special relativity; Einstein, who was not content with this, later extended the independence of physical laws to "all" observers in his theory of general relativity. As he explicitly stated, "Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of 'physical reality'." (*Autobiographical Notes*, p. 82).

3. Matter and Energy. The other conceptual revolution was related to the equivalence of mass and energy which seemed to overturn the traditional conception of matter as something with consistency. One discovered that matter did not have this consistency because, under certain conditions, it could be even annihilated, disappearing into the impalpable flux of energy. And this ambiguity arose from one's confusing "materiality" with "impenetrability," attributing therefore a sort of immateriality to the energy of radiation, which is penetrable. In reality, "materiality" could have been considered as something common to both particles and fields, both having mass-energy and being therefore capable of determining the metric of space-time; the "impenetrability" was instead related, in the framework of quantum mechanics, to Pauli's principle and therefore to the properties of fermionic fields and their particles; whereas "compenetrability" was a characteristic of bosonic fields such as the electromagnetic field.

This transformation did not even have to lead to a certain "overcoming" of the concept of matter or its ontological consistency. Actually, Einstein's equation does not negate the ontological consistency of matter; nor does it remove its philosophical conclusions, generally of a metaphysical order, regarding its ontological dependence, or its relationship with what philosophy calls "spirit [13]." One establishes only that the material substrate, i.e., the sensible object of empirical science, is no longer only matter or energy as independent realities, but their common presence.

4. Causality. From the philosophical point of view, another important consequence of relativity is related to the concept of causality. The fact that information or energy cannot travel exceeding the speed of light according to special relativity, leads to the incompatibility of this theory with the idea that a cause can produce an instantaneous effect on a target, when the "source" of causality is located at a non-zero distance away from the target. This is so because a causal signal cannot travel faster than the speed of light. This requires the elimination of the instantaneous action at a distance from physical theories. In the realm of non-separable systems of quantum mechanics, this way of understanding causality has lead to many paradoxes and problems (for example, the Einstein-Podolsky-Rosen paradox) for which various solutions have been proposed (see Quantum Mechanics [5]). These solutions try to tackle in various ways the problem of non-locality and the relationship between the "whole" and its "parts." The latter will appear later in the physics of complex systems.

5. "Geometrical" and "Dynamical" Physics. In light of the new problems suggested by the science of non-linearity and complexity, and by the comparison between the epistemological status of physics and biology as it is being developed today, attention seems to be shifted towards methodological questions which lie at the basis of science and towards new ways of mathematization. There are today two major tendencies: the first tends to "reduce physics to geometry": the geometry of space-time is abundantly amplified in the number of its dimensions, which are susceptible to many different interpretations and physical meanings; the other tends to diversify the role of space and time in a "dynamical" perspective in which effects such as the high sensitivity to initial conditions, instability, chaos, the asymmetry (arrow) of time and thermodynamic irreversibility of non-equilibrium systems (typical of biological systems), come into play. Certainly, the theory of relativity and field theories based on relativity reflect the first tendency, due to their complete space-time reversibility. It is not easy to foresee how a possible future, unified and non-linear field theory, can take into account the new aspects of complexity. However, even in the context of a geometric view of space-time, there exists an invariant with absolute temporal character, such as "proper time": let it be the cosmological time of the expanding universe or the proper time related to the motion of any material body in the universe. It is only in terms of this "proper time" that thermodynamic irreversibility and chaos can be introduced, thereby re-establishing the dynamic character of the theory. If Einstein had admired the static and rigidly deterministic geometrization which brought him closer to Descartes' and Spinoza's vision, nevertheless it would be the cosmological theory formulated in the context of general relativity by Lemaître and Friedmann to convince him of the dynamic element of the universe, which becomes evident in the universe's expansion (see Cosmology [2]).

6. Local and Global Physics. To conclude this essay I can now add that present-day scientists are seeking to overcome the classical method of reductionism [14], which appears to be insufficient to advance scientific knowledge of nature. For the physicist, this seems to entail not limiting oneself to theories governed by linear equations, according to which the sum of two solutions is also a solution, and consequently, the "whole" is obtained as the sum of its "parts." General relativity has been the first theory to require that the simplest invariant law be non-linear and inhomogeneous in its field variables and derivatives. Nevertheless, it is still a local theory, in some sense, since it makes use of differential geometry, and therefore the structure of the vector space which it utilizes is necessarily local, that is, based on the fact that in the neighborhood of a point, every space can be approximated by a linear space, just as a curve can be approximated by its tangent or a surface by its tangential plane. And this limitation allows one to formulate the principle of equivalence only in a small spatial region and not on a large scale, as Mach would have liked. But this is not so much a limitation of Einsteinian relativity as a characteristic of all mathematical theories based on differential and integral calculus which is by nature reductionist. But, up to now, we do not yet have an alternative mathematical theory, and we do not yet know if in future we will be able to formulate one.

Read also: Cosmology [2]
Matter [4]
Mechanics [6]
Realism [11]
Time [3]

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