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Einstein, Science and Philosophy

Friedel Weinert

> Albert Einstein (...) is a Kantian and a Greek
> empirical rationalist rather than a Humean
> British positivisic empiricist
> [Northrop 1949, 390]

I. Problem-Situations

1 On September 26, 1905 Albert Einstein's paper 'On the Electrodynamics of Moving Bodies' appeared in the *Annalen der Physik*. It is generally agreed that it is one of the most important scientific papers ever written. But was it a revolutionary paper? Einstein generalizes the Galilean relativity principle to include electro-magnetic phenomena; he postulates the velocity of light in vacuum as an upper speed limit on all phenomena. He uses the Lorentz transformations for the calculation of spatial and temporal measurements in the transition from one reference frame to another. There is much to be said for the view that Einstein's Special theory of relativity completes classical physics, especially the work of James C. Maxwell. [Holton 2000] Einstein himself did not see his theory as a 'revolutionary act'. But Einstein's work did introduce a philosophical revolution in our fundamental notions. This means that general notions, like mass, energy, time, space, causation, determinism, which are used in human attempts to construct coherent schemes of nature, have undergone radical changes as a result of scientific discoveries, such as those associated with the Special and General theory of relativity (STR, GTR) and Quantum Mechanics (QM). According to Max Born the revision of old concepts has to happen under the constraints of new experience. [Born 1949, 75] We can consider them as physico-philosophical notions because they are not tied to any particular physical theory and have often been the subject of philosophical reflection from the Greeks to the present day. Hans Reichenbach characterized Einstein as a philosopher by implication but also speaks of the 'philosophical consequences' of Einstein's work. [Reichenbach 1949, 310] (cf. [Howard 2004]) That is, Einstein was willing to consider the status of the physico-philosophical notions in the light of his scientific discoveries. It may be more

appropriate to characterize Einstein's philosophical innovations as *consequences* of his scientific work. Implications can be hidden in the logic of a situation. But Einstein and many other physicists of his generation were fully aware of the philosophical dimensions of their scientific work. I prefer therefore to speak of the philosophical *consequences* of Einstein's work. In order to appreciate what is meant by philosophical consequences, we should distinguish them from the deductive consequences of physical theories. A *deductive* consequence follows from the principles and internal logic of the theory. It is a deductive consequence of the premises of STR that reference frames do not share a universal time axis. A *philosophical* consequence of a physical theory concerns its conceptual features. Certain conceptual positions are compatible or incompatible with the theory but they are not directly testable and are subject to interpretations. For instance a notion of absolute time is incompatible with the theory of relativity. But physicists and philosophers have argued, alternatively, that the theory of relativity can be made compatible with a static or a dynamic view of time. The philosophical consequences of the theory of relativity extend far beyond the familiar reshaping of the notions of space and time. What made Einstein a great physicist was his ability to question unquestioned assumptions in the tradition of physical theorizing. What made him an even greater physicist was his ability to recognize the limits of his own work. This talent led him from the Special to the General theory of relativity and beyond to attempts to construct a unified field theory. What made him a decent philosopher was his willingness to pursue the philosophical consequences of his physical discoveries, *e.g.*, regarding the physico-philosophical notions.

2 Einstein followed the logic of the problem situation, which his physical discoveries had created, into the field of philosophy. A *problem situation* indicates that at any time, t, in the history of science there exist perceived problems, which attract a number of tentative solutions [Popper 1963, 198–200]; for instance the great puzzle of the 17th century was to know why planets stay in their orbits around the sun; some of these tentative solutions will be eliminated; for a certain period of time, $t+t'$, usually one theory survives and is regarded in the scientific community as the most adequate theory in the light of the available evidence. If the available evidence is inconclusive with regard to competing theories, it may still be possible, as we shall see, to appeal to other constraints to achieve a distribution of credibility over the competitors. These tentative solutions include philosophical presuppositions, which may change under the impact of scientific discoveries. For instance, classical physics presupposes a unique time axis for all reference frames; a presupposition, which became questionable with the emergence of the STR. To regard Einstein as a philosopher is to consider his position on a number of philosophical issues. Einstein philosophizes within the constraints of science, in particular his science. His questions are familiar to every philosopher of science: How do theories relate to the external world? What is the nature of reality? What is the nature of time and space? What is the status of scientific theories? What does quantum mechanics tell us about reality? Given the principle of relativity, what is to be regarded as the real?

II. Facts and Concepts

3 As Einstein philosophizes within the ambit of the theory of relativity, he sets these philosophical questions within a concrete scientific problem situation. His answers derive their significance from this problem situation. The problem situation is the kinematics of reference frames, given the results of classical mechanics and electromagnetism. Historically, his first concern was the notion of time. When the Special theory of relativity was generalized to the General theory, his second philosophical worry became the notion of space—or more precisely space-time, for Einstein had accepted Minkowski's four-dimensional representation of the relativity theory. But with hindsight we can reorder his philosophical concerns into a logically more coherent picture.

4 Einstein's fundamental philosophical position arises from the age-old puzzle of how a body of concepts is related to collection of facts. More generally, how do abstract scientific theories relate to concrete empirical data? How do scientific theories represent empirical reality? Such questions of representation go beyond the immediate concern of scientists who could contend themselves with the solution of particular technical problems. However such questions lie in the nature of scientific theorizing, as the Greek astronomer Ptolemy already knew. Once a theoretical account, like geocentrism, is available the question arises: to which extent is it an accurate account of the real world? As we shall see, Einstein's solution to this question, with respect to the theory of relativity, can be cast in terms of scientific constraints. Einstein's philosophical worry derived from his dissatisfaction with Newtonian physics as a fundamental theory. When Einstein aired his worry, for instance in his Obituary of Ernst Mach (1916), he warned against the Kantian tendency to regard certain concepts as thought necessities. Once certain concepts have been formed, often on the basis of experience, there is a danger that they will quickly take on an independent existence. People are tempted to regard them as necessary presuppositions, without which science cannot be done. For instance, for two thousand years astronomers regarded the circle as the only permissible orbit of planets. Concepts, however, just like theories, are always subject to revisions. Einstein complained that

> Concepts, which have proved useful in the ordering of things, easily acquire such a degree of authority over us that we forget their earthly origin. We take them as unchangeable givens. They come to bear the stamp of 'thought necessities', of the 'a priori given'. ([Einstein 1916, 102]; translated by the author)

5 What Einstein had in mind were the notions of space and time. Isaac Newton had regarded it as necessary to introduce the notions of absolute space and time into his mechanics in order to make sense of his laws of motion. Newton's laws of motion make reference to temporal and spatial notions: state of rest, rectilinear uniform motion. A reference frame must be defined relative to which the movement of a body is 'uniform' or follows a 'straight' line. There are known rotational inaccuracies in the movement of the earth around the sun. A straight line drawn on the surface of the earth is 'straight' for a surveyor on earth but 'curved' for an observer in space. Newton mistrusted physical regularities observed on earth because they may contain systematic distortions. He required that the notions of space and time, for use in mechanics, must be freed from all reference to material motions. Newton stipulated that spatial and temporal notions must be *absolute*—independent of physical events and *universal*—all observers, whatever their location or velocity in the universe, must agree on their

temporal and spatial measurements. Few classical physicists had questioned Newton's reasoning, with the notable exception of Gottfried W. Leibniz, Ernst Mach and James Maxwell. So these notions had become part and parcel of classical physics. They had congealed to philosophical presuppositions, to thought necessities, to unquestioned assumptions. The Special theory arrived at a different result. Temporal and spatial measurements became relativized to particular reference frames. This was a necessary consequence of embracing the principle of relativity and taking the velocity of light as a fundamental postulate of the theory. Through his own work Einstein witnessed how such fundamental physico-philosophical notions as time and space required conceptual revision. This made him forever suspicious about the sway that such notions could hold over people's minds. Einstein aims at a careful balance between concepts and facts.

6 Although the fundamental notions—energy, event, mass, space, time—are logically speaking free inventions of the human mind, they must strike empirical roots. [Einstein 1920, 141] As Einstein's scientific theories unfolded, several philosophical consequences suggested themselves. This process can clearly be observed in the notion of time.

III. Philosophy of Being or Becoming?

7 The Special theory of relativity leads to a relativization of time to particular reference frames. Observers, attached to different reference frames, which are in relative uniform motion with respect to each other, will measure the flow of time differently. In the present context the ancient philosophical question 'What is time?'—which famously puzzled Saint Augustine—reduces to the question 'What is physical time?' Physical time is simply what clocks in motion tell us. Einstein time is clock time. Clock time is to be understood in a broad sense. We use mechanical clocks to measure time intervals. Other regular processes—sound pulses, atomic oscillations—could be used for the same purpose. The problem is that such processes, too, are subject to relativization. Atomic oscillations yield to gravitational forces. The wavelengths of light and sound depend on the movement of the source, as evidenced in the Doppler Effect. In the world of special relativity there is only one signal, which escapes this restriction. Light retains the same velocity, *c*, in all directions and irrespective of whether it is emitted from a moving or stationary source. These well-established facts led to a questioning of the traditional notion of absolute and universal time. Well-known physicists like A. Eddington [1920], K. Gödel [1949] and H. Weyl [1921] have claimed that the Special theory of relativity leads to a static view of time. The argument runs as follows: the Special theory shows that simultaneity cannot be absolute, as Newton assumed, since this presupposes a propagation of all causal influence at infinite speeds. But Einstein's light postulate shows that light propagates at finite velocity. It is a limit velocity so that no material process can travel as fast as light. This has drastic consequences. Observers in different reference frames, which travel at relative constant speed with respect to each other, will not agree on the simultaneous happening of some event, E. Einstein presented a well-known thought experiment: Let bolts of lightning strike the front and rear end of a moving train. Do they hit the ends of the train simultaneously or not? It is the motion of the observer, which determines the answer. For stationary observers on the platform of a station, the events are simultaneous. For observers on the train they do not hit the opposite ends of the train simultaneously. The reason resides in the finite propagation

of light. The train passengers rush toward the light signal from the front and run away from the rear signal. The same is true of the reading of clock times in different reference frames, which move with constant velocity with respect to each other. The observers will not agree on their respective clock times. Their clocks tick differently, depending on the state of motion. If there is no cosmic notion of time (as Newton assumed), to which all observers can appeal, time must pass at different rates for each observer, depending on the speed of the reference frame. Time cannot be an objective property of the universe. It depends on the perception of observers. The passage of time seems to be an illusion, as Eddington, Gödel and Weyl concluded. By contrast, the physical universe is static, a block universe. Einstein did at times adopt such a philosophy of being.

> For us believing physicists, the distinction between past, present, and future is only an illusion, even if a stubborn one. (Quoted in [Hoffmann 1972, 257–8]) From a "happening" in three-dimensional space, physics becomes, as it were, an "existence" in the four-dimensional "world". [Einstein 1920, Appendix II, 122; Appendix V, 150]

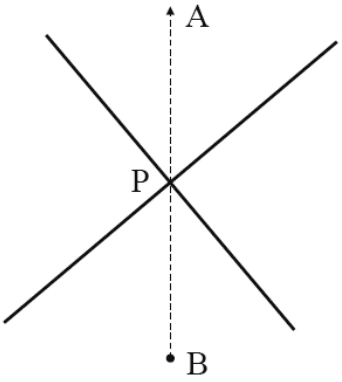
8 The argument infers the unreality of time from the results of the relativity theory: numerous reference frames are seen in constant motion with respect to each other; each reference frame carries clocks, rigid rods and perhaps an observer; the motion of the reference frames determines different clock times, which any resident observers will record; therefore the observers cannot agree on the simultaneity of two events and there is no absolute simultaneity as in Newton's mechanics; as observers cannot agree on the simultaneity of events across different reference frames, it seems that there are as many times as there are reference frames; the passage of time seems to be a human illusion in the sense that there is no objective, observer-independent *Now*. But there are also numerous passages in Einstein's work, which express a more dynamic view of time. Rather than speaking of space-time, as Minkowski did, Einstein often prefers the expression, 'time-space'. [Einstein & Infeld 1938, 199–208] [Einstein 1922a, 29] And he points out that time and space do not have the same status in Minkowski's four-dimensional world.

> The non-divisibility of the four-dimensional continuum of events does not at all (...) involve the equivalence of the space co-ordinates with the time co-ordinate. [Einstein 1922a, 30]

9 In his theory of space-time, Einstein aligns his thinking to the relationist position, espoused by Leibniz and Mach. According to the relational view, time and space are nothing but the order of actual and possible events. Space is the coexistence of such events and time is the order of succession of such coexisting events. In his deliberations of the General theory of relativity, Einstein leaves the reader in no doubt that he regards the total mass-energy distribution in the universe as the source of the space-time metric. 'The gravitational field determines the metrical laws of the space-time continuum.' [Einstein 1922a, 59; 1922b, 20–4] What could be said in favour of such a dynamic view? Consider first what would happen, if all references to observers were dropped. All observers can be replaced by clocks and rods. The clocks in different reference systems will be affected by the respective relative motions of the systems. No observer will conclude that there must be a mysterious transience of time—a moving *Now*, signalling the march of time from past to future. Without conscious observers, there is no need for the introduction of a tensed view of time, according to which objects change their temporal properties—their dates—by moving from past to present

to future. The tensed view falls foul of McTaggart's objections and is incompatible with the findings of the Special theory of relativity. [Savitt 2000] In particular the tensed view of time requires a privileged *Now*, which cannot be squared with the principle of relativity. Does this leave us with a tenseless view of time, as McTaggart claimed, according to which there is only a static 'before-after' relation between events? Events are juxtaposed like beads on a string (B-series). The physical world just *is*, it is a block universe. The passing of time is a human illusion. There is an alternative between these extreme positions (of the tensed view *versus* the block universe). The tenseless view is mistaken in equating tenselessness with changelessness. [Grünbaum 1973, 325] [Smart 1963, 138-40] The physical occurrence of events does not exclude change. Change occurs in the transition between events, even if these events are ordered in four-dimensional Minkowski space-time. Consider, for instance, the famous twin paradox. One of the two twins is a space traveller who returns to earth after a visit to a distant star only to find that his twin brother, who remained on earth, has aged more than he has. This can be explained within the STR by a consideration of the effect of motion on the world lines of the two twins: the world line of the earth-bound twin turns out to be longer than the world line of the travelling twin [Lockwood 2005, 46–51] because the traveller's clock, including his biological clock, is subject to time dilation effects. If we were to take the heart beats of the twins as our clocks, these electromagnetic signals, which the twins exchange during the journey, will be subject to the relativistic Doppler Effect with the result that the number of signals the twins receive respectively will not be equal. A physical change occurs. The relational view already emphasized that time was the order of succession of events. In the STR the relational notion of the 'order of successive events' becomes restricted to the light cone structure of Minkowski spacetime. The crucial notion of the finite propagation of light in STR limits the connectibility of reference frames to time-like connected events. It is interesting to note that several early commentators on the Special theory already proposed a dynamic interpretations of space-time, according to which worldliness propagate through space-time and acquire a history. [Cunningham 1915, § 60] [Schlick 1917, 181] [Reichenbach 1958, 183] The crucial point is that traditionally the STR only considers purely kinematic aspects of the propagation of worldlines and the relations between reference frames. But these kinematic relations have entropic aspects, as revealed in the asymmetric behaviour of electromagnetic radiation. It is these entropic aspects of worldliness, which give the relationist the purchase to consider a dynamic view of spacetime. This fits in well with a specific argument from entropy, which Einstein employed against Kurt Gödel's idealistic interpretation of the Special theory of relativity [Gödel 1949]. Einstein considers the question of the temporal direction of events. Imagine we send a signal from *B* to *A* through *P*. This is an irreversible process. On thermodynamic grounds he asserts that a *time-like* world line from *B* to *A* through *P* in a light cone takes the form of an arrow making *B* happen *before P* and *A after P* (see Figure I).

Figure I: *Einstein's consideration of the (local) direction of time in response to Gödel's idealistic interpretation of the Special theory of relativity. A time-like world line exists between A and B, which lies within, not outside the light cone*.



10 This secures the 'one-sided (asymmetrical) character of time (...), *i.e.*, there exists no free choice for the direction of the arrow.' [Einstein 1949a, 687] This is true at least if points A, B and P are sufficiently close in cosmological terms. But the asymmetrical character of time is here based on a fundamental *earlier-later* or *before-after* relation between physical events without reference to an observer. There is an event, B, at which the signal is emitted. And there is a later event, A, at which the signal is received. This whole event is irreversible. There is an entropy gradient between the state of events at B and A. The assessment of this differential entropy between the two locations does not depend on a particular reference frame. According to a fundamental result of the Special theory of relativity the entropy of a system is frame-independent. [Einstein 1907, § 15] Thus all time-like connected frames will agree on the order of the succession of events, even if there is disagreement about the simultaneity of these events. It may be objected that this entropic theory of time could not form the basis for a general dynamic theory of time. As is well known the second law of thermodynamics is a statistical principle; there is an extremely low probability of a reversal of events in our observable space-time regions. Although it is unlikely in the life-time of the universe, the second law permits a spontaneous reheating of a glass of cold water by a rearrangement of the molecules. But the arrow of time is supposed to be one-directional. This objection need not worry the relationist in the present context, because the concern here is to establish the possibility of a *dynamic* interpretation of space-time not on a global but local scale. Locally, the entropy gradient points in the direction from B to A. All time-like connected observers agree. For the relationist this establishes, within local space-time regions, an order of the succession of events and thereby physical time for time-like related frames. Reichenbach expressed such a view in his hypothesis of the branch structure:

> The paradox of the statistical direction (of time) was solved, in a continuation of Boltzmann's ideas, by the recognition of the sectional nature of time direction: a large isolated system can indeed define a time direction in a section of its whole temporal development, if this section is rich in branch systems governed by the laws of statistical isotropy. [Reichenbach 1956, 207] (cf. [Davies 1974, § 3.4])

11 Although Einstein endorsed, from time to time, the unreality of time, his whole theory of time-space is relational. It points towards a philosophy of becoming since physical time is constituted by the asymmetric, invariant order of physical events in space-time.

There are several statements in Einstein's work which suggest this relational reading of his space-time concept:

> I wished to show that space-time is not necessarily something to which one can ascribe a separate existence, independently of the actual objects of physical reality. [Einstein 1920, vi]
>
> There can be no space nor any part of space without gravitational potentials; for these confer upon space its metrical qualities, without which it cannot be imagined at all. The existence of the gravitational field is inseparably bound up with the existence of space. [Einstein 1922b, 21]

12 It is not the job of the philosopher to put Einstein's philosophical thinking into a straight-jacket. The philosopher must evaluate whether the philosophical consequences, which the physicist claims to follow from the physical discoveries, do indeed follow. (As we have seen prominent physicists like Eddington, Gödel and Weyl explicitly claimed that the block universe was a philosophical consequence of the STR, whilst Einstein wavered in his support for a static universe.) This is a question of conceptual evaluation, not empirical testing. We have indicated that a dynamic interpretation of space-time is possible and compatible with the STR. It is possible if we consider the entropic aspects of space-time events and align the STR to relationist thinking. There are similar philosophical presuppositions and consequences at work in Einstein's views on quantum mechanics.

IV. Quantum Mechanics

13 Above we characterized the philosophical consequences of scientific theories—they do not follow deductively but are nevertheless conceptual consequences of these theories. As such they are not 'justifiable by scientific methods.' [Frank 1949b, 355] Einstein revolutionized our philosophical notion of time by relativizing both time and simultaneity to particular inertial reference frames. He thereby uprooted a prior philosophical commitment to absolute time. Scientific revolutions or innovations often upset earlier philosophical presuppositions. Such presuppositions seem to be unavoidable in science. But in his discussions of quantum mechanics, for example, Einstein was guided by a traditional notion of causality. In his lifelong opposition to the Copenhagen interpretation of quantum mechanics he disregarded the lesson about thought necessities, which the theory of relativity had taught him. According to Einstein, quantum mechanics was incomplete because it only permitted statistical statements about ensembles of atoms. Quantum mechanics was unable to make precise spatio-temporal predictions about the trajectories of individual atoms. Heisenberg's indeterminacy principle, whose validity Einstein fully endorses, prevents deterministic spatio-temporal determinations of atomic trajectories. The ability to make such predictions was for Einstein one of the fundamental requirements of science. Only differential equations, he said, would satisfy the demand of the physicist for causality. [Einstein 1927, 255] Note that Einstein associates the notion of causality with the availability of differential equations and therefore predictive determinism. It is a functional view of causality, because it reduces the causal relation between two parameters to a functional relation between the rate of change with respect to time of one parameter, say velocity, v, and the application of a force, F. (See [Frank 1932] [Weinert 2004, ch. 5.1]) This demand for deterministic causality is a reflection of Laplacean determinism, which the quantum theory was hoping to overcome. When

Einstein warns that a probabilistic view of quantum mechanics will lead to its incompleteness, on the grounds that it does not allow for precise space-time trajectories of atomic particles, he clings to one of the most venerable presuppositions of classical physics. In his criticism of Newtonian mechanics, Einstein bemoans the inability to jettison fundamental notions like absolute space and time. But in his view of quantum mechanics he himself relies on a presupposition inherited from classical physics, e.g. the belief in strict determinism.

14 It has often been debated whether Einstein's fundamental worry about quantum mechanics derived from fear of 'action-at-a-distance', rather than his belief in strict causality. (See [Howard 1993] [Fine, 1986] [Cushing & McMullin, 1989]) In quantum mechanics two particles, issued from a common source with particular spin alignments, may be so far separated in space-time that no known causal interaction can take place between them. Yet a measurement of the spin property of one particle will instantly change the spin direction of the other particle even over cosmic distances. Einstein found such 'action-at-a-distance' unpalatable. The Born interpretation offered him a way out of the dilemma. According to the Born rule, which Einstein embraced [Einstein 1940, 923-4], the square of the wave function, $|\Psi|^2$, only delivers statistical statements about the probability of events, not the determination of actual events in space and time.

15 Einstein accepted the quantum theory as a heuristic device because the Born rule told him that it only delivered an incomplete description of reality. An incomplete description may not satisfy the 'causal' demand for differential equations. This incompleteness charge gave him the freedom to believe that a complete description of atomic reality could be found. Einstein yearned for a complete and direct description of reality. [Einstein 1940, 924] By this he means a direct representation of the actual space-time events, rather than a probability distribution of possible outcomes of measurements. Such a complete description of actual events in space-time will avoid non-local effects. For it will be subject to the 'strict laws for temporal dependence.' [Einstein 1940, 923] [Einstein 1948, 323] In physics the 'strict laws for temporal dependence' are typically expressed in differential equations. The incompleteness charge against QM gave him the freedom to believe that a complete description of reality would recover the differential equations, which described the temporal evolution of real physical systems in space-time. The Schrödinger equation is of course a differential equation, which spells out the time evolution of a quantum system. However, this does not satisfy Einstein, because the Schrödinger equation describes time evolution in an abstract Hilbert space.

16 Einstein's insistence on a complete description of real events and his functional view of causality leads me to agree with Fine [Fine 1986, 97–103] that Einstein's concern with nonlocality was not primary. It was a consequence of a deeper concern with strict causality. Einstein actually maintains that a renunciation of the principle of locality would render empirically testable laws impossible. And locality is expressed in differential equations in real space-time. [Einstein 1927, 261] Since the discovery of Bell's inequalities in the 1960s much effort has gone into distinguishing various senses of 'locality.' If we speak, with Einstein, of the 'mutually independent existence of spatially distant things', we formulate a principle of spatial *separability*. (See [Einstein 1948] transl. in [Howard 1993, 238]) In view of the results of quantum mechanics, we must distinguish this principle of separability from the principle of *locality*. This

principle has been formulated in a number of ways. Einstein locality means that no ‘faster-than-light-signals’ should be permitted to propagate between spatially separated quantum systems. But locality can also mean that a spin measurement performed on one system, which is spatially separated from another system in the sense of satisfying Einstein locality, cannot influence the spin state of the other system. This type of locality Einstein calls the ‘principle of local action’.

17 However various types of entanglement have been observed between quantum systems, which display degrees of correlations of their spin properties even though they are spatially separated in the sense of Einstein locality. Einstein’s principle of local action is violated in quantum mechanics. [Cushing & McMullin 1989] [Howard 2004, § 5] Schrödinger dubbed this now familiar type of correlation ‘entanglement of our predictions or of our knowledge’ concerning the quantum states of a photon pair. [Schrödinger 1935, 827] Recently, the programme of decoherence has identified environmental entanglement, i.e. the irreversible loss of interference terms to the environment in the creation of classical states. Quantum mechanics was Einstein’s *bête noire*. His opposition never faltered. Today it is generally regarded as untenable. Quantum systems manifest degrees of entanglement over large distances. Einstein’s ‘spooky action-at-a distance’ is a laboratory reality.

18 We see in Einstein’s work both the role of presuppositions (causality in QM) and the effect of scientific discoveries on fundamental notions (time, space, mass). Less well-known is that Einstein makes some significant contributions to our understanding of scientific theories. In particular his views harbour a possible solution to the vexing question of the representational power of scientific theories.

V. The Representational Nature of Scientific Theories

19 To Einstein, scientific constructs (laws, models, and theories) are free inventions of the human mind. No amount of inductive generalizations can lead from empirical phenomena to the complicated equations of the theory of relativity. But science is not fiction. Science assumes the existence of an external world. Scientific theories are statements about the external world. ‘Physics is the attempt at the conceptual construction of a model of the *real world*, as well as its lawful structure.’ (Quoted in [Fine 1986, 97], italics in original) Einstein therefore depicts scientific knowledge as a synthesis of reason and experience, which raises the question of the representational nature of scientific constructs.

20 Einstein makes a famous distinction between *constructive* theories and *principle* theories. [Einstein 1919; Miller, 1998, 125] The role of a constructive theory is to propose models, which assign an underlying structure to the observable phenomena. The kinetic theory of gases models gas molecules *as if* they were billiard balls. Early atom models modelled atoms *as if* they were tiny planetary systems. The role of a principle theory is to propose fundamental principles: the laws of thermodynamics, the principles of relativity, of covariance and invariance, and the constancy of light. These principles constitute constraints on the construction of models and theories. They forbid the occurrence of physical events, like superluminary velocities or perpetual motion machines.

21 All scientific theories give rise to a philosophical question: how do scientific theories relate to the external world? Ernst Mach’s answer is cast in terms of phenomenalism;

Duhem's answer in terms of holism; Poincaré's answer in terms of conventionalism. Einstein's answer was influenced by these authors but it was also particularly pragmatic, *e.g.*, it was shaped by his work on relativity. Firstly, Einstein was primarily concerned with what he called principle theories, like the theory of relativity. Here the role of constraints comes to the fore. Einstein often declares the world of experience as the final arbiter of the validity of scientific theories. In Popperian fashion he regarded all scientific theories as falsifiable. But empirical evidence, in the theory of relativity, is only one form of constraint. Scientific theories present hypothetical 'pictures' of the external world. But Einstein was no naïve realist. A scientific theory constructs a coherent and logically rigid account of the available empirical data. Logical consistency was Einstein's second constraint on theories since he believed in the mathematical simplicity of nature. [Einstein 1933, 274] The coherence of a theory may always come under threat with new empirical discoveries. There is nothing final about the representation of a scientific theory of the external world. Theories are free inventions, yet they must retain roots in the empirical world. Does this mean that there is always a plethora of competing theoretical accounts, which nevertheless are compatible with the available evidence? If this were the case scientific theories would face the serious problem of underdetermination. That is, there would always be a number of theories, which are able to explain the empirical evidence, although they fundamentally disagree about their theoretical structure. For instance the Copernican model of the solar system (1543) explains the same observational evidence as the Ptolemaic account although the Copernican model is based on the principle of heliocentrism, while the Ptolemaic account embraces the principle of geocentrism. In this situation Einstein recommends pragmatically to distinguish a logical from a practical point of view. From the logical point of view, Einstein grants that there are always numerous theoretical accounts, which could in principle account for the available evidence. For there seems to be no limit to the number of competing constructions, which, at least in principle, could claim to give a coherent and simple account of the available phenomena. This is due to the fact that theories are the result of human ingenuity. Yet in practice, the number of available theories is always limited. Einstein did not believe that many competing representations of the empirical world could be sustained. He goes even further: he believes that there is one correct theory. The structure of the external world has the power to eliminate many rival accounts. The surviving theory displays such a degree of *rigidity* that any modification in it will lead to its falsehood. 'Rigidity here means that the theory is either true or false but not modifiable.' [Einstein 1950b, 350; 1936] (cf. [Hentschel 1992], [Scheibe 1992] and [Weinberg 1993]) Einstein illustrates the lack of underdetermination, from the practical perspective of the working physicist, by the analogy of solving a crossword puzzle. Although we are free to insert any word into the columns and rows of a word puzzle, this freedom is very restricted. Only one word will 'fit', only one word will solve 'the puzzle in all its forms.' [Einstein 1936, § 1] The structure of the external world practically determines the form of the theoretical system. [Einstein 1918b; 1933]

22 Going beyond Einstein it will also be useful to split the space of possible theories or models into *alternative and rival* accounts. Alternative accounts, like the Schrödinger and Heisenberg pictures in quantum mechanics are mathematically equivalent; covariant formulations of physical laws in the General theory of relativity are form-invariant. They pose no problem in terms of underdetermination. Rival accounts like Lorentz's and Einstein's models of the kinematics of reference systems are based on

incompatible theoretical principles. Lorentz's account of time dilation and length contraction postulates an absolute rest frame, whilst Einstein's motivation was to abandon all need for absolute reference frames. Rival accounts therefore pose a problem from the point of view of underdetermination. In the practice of science, however, there is little underdetermination. How can this be explained? If we look at Einstein's philosophical writings about physics, we notice his insistence on constraints such as unification and the logical simplicity of a theory; he also holds that evidence is the final arbiter of a theory's fate. Einstein locality, logical simplicity and unification are *methodological* constraints, since they are principles of the methods of science. Compatibility with available and new evidence is an *empirical* constraint. In the present context the methodological constraints are of lesser importance than some of the other constraints, which are associated with the theory of relativity. Looking at Einstein's way of doing physics, we notice his employment of a number of *theoretical* constraints, since they derive more particularly from the theories of relativity. In particular, as we shall see, the light postulate, relativity principles, covariance and invariance principles. We can characterize constraints as restrictive conditions of an empirical or theoretical kind, which descriptive and explanatory accounts must satisfy to count as viable candidates for the scientific description and explanation of the natural world. With respect to the theory of relativity, Einstein holds that the interplay of specific constraints—like covariance, invariance, relativity—creates a *fit* of the theory or model with the evidence extracted from the external world. Any modification, he holds, would destroy the coherence of the theory of relativity. [Einstein 1918b; 1919; 1933] This provides a clue to a solution of the puzzle of how theories manage to represent the world. A theory 'represents' a section of the empirical world, if it satisfies a certain number of constraints. The representation is illustrated in terms of fit, as in the analogy of the crossword puzzle. But 'fit' should be understood in terms of satisfaction of constraints. [Weinert 2006] The representation is not an image, nor need it be perfect or absolute.

> In order that thinking might not degenerate into 'metaphysics', or into empty talk it is only necessary that enough propositions of the conceptual system be firmly enough connected with sensory experiences and that the conceptual system, in view of its task of ordering and surveying sense-experience, should show as much unity and parsimony as possible. [Einstein 1944, 289]

23 We have thus assigned to pure reason and experience their places in a theoretical system of physics. The structure of the systems is the work of reason; the empirical contents and their mutual relations must find their representation in the conclusions of the theory. In the possibility of such a representation lies the sole value and justification of the whole system, and especially of the concepts and fundamental principles which underlie it. [Einstein 1933, 272]

24 As it changes with the changing nature of constraints, fit comes in degrees. In the simplest case, a model represents the topologic structure of a system; e.g. a heliocentric scale model of the solar system represents the spatial arrangement of the planets around the sun. The models used in the theory of relativity are more sophisticated structural models, which combine a topologic with an algebraic structure. The algebraic structure of the model expresses the mathematical relations between the components of the model. Consider, for instance, Einstein's thought experiment, which involves two discs whose circumference and diameter are to be measured. [Einstein 1920, 80; 1922a, 58–9] Let the discs be arranged in such a manner that disc *B* rotates

uniformly about a common axis with disc *A*. This is its topologic aspect. But the main interest lies in the algebraic structure, *e.g.*, how the parameters on the two discs will be measured. To carry out the measurements, measuring rods are placed along the radius and tangentially to the edge of the disc. *A* does not rotate so that the ratio of circumference to diameter is equal to π. From the point of view of *A* the ratio C/D on *B* will be greater than π. Due to length contraction of the tangential rods the circumference will appear greater on *B* than on *A*. Now place two similar clocks on *B*, one at the centre, C_1 and one at the periphery, C_2. Judged from *A*, C_2 will go slower than C_1. We may assume that no faulty instruments are involved. These respective measurements are objective. Observers on the respective discs will regard their respective measurements as accurate. Mathematically, the thought experiment stresses the effect of motion on the measurement of the parameters. Note that the algebraic structure implied by Euclidean geometry fails and must be replaced by a structure provided by Riemannian geometry.

25 Let the empirical facts, methodological principles and theoretical postulates constitute a constraint space. The theory of relativity satisfies a number of empirical and theoretical constraints, which improve its fit to the external world. The empirical facts comprise Einstein famous predictions: the red shift of light as a function of gravitational field strengths and the bending of light rays in the vicinity of strong gravitational fields. He also explains the perihelion advance of Mercury and other planets. In the theory of relativity the most important theoretical constraints are the following:

1) The postulation of the constancy of the speed of light

26 It had been known since Roemer's first determination of the speed of light in 1675 that light propagates at a finite velocity of approximately 300 000 km/s. Einstein turned this value into a theoretical postulate such that the speed of light becomes the limit velocity, which no material particle can reach. In the language of the Minkowski representation of space-time this means that from any event, *E*, light signals converge from the past and diverge into the future at a constant speed, forming past and future cones. All inertial observers will see the angle of convergence and divergence inclined at 45° to the vertical. The light cones do not tilt. And all observers measure the same velocity for *c*, irrespective of the direction and their state of motion with respect to the light source.

2) Principles of Relativity

27 Einstein began his 1905 paper on the Special theory of relativity by a consideration of standard attempts to explain Faraday's induction current. He complained that according to the then current view an asymmetry of explanation for an observationally indistinguishable phenomenon occurred. If the coil is in motion with respect to the magnet at rest (in the ether), the charges in the coil experience a magnetic force, which pushes the electrons around the coil, inducing a current. If the magnet is in motion with respect to a coil at rest, the magnetic force is no longer the cause of the current, for no magnetic force applies to charges at rest. The magnet now produces an electric field in the coil, resulting in the current. To avoid this asymmetry of explanation—an asymmetry not present in the phenomena—Einstein postulated the physical

equivalence of reference frames. In its general form the principle of relativity states that all coordinate systems, which represent physical systems in (uniform or non-uniform) motion with respect to each other, must be equivalent from the physical point of view. [Einstein 1920, 59, 97–8] In other words, the laws which govern the changes that happen to physical systems in motion with respect to each other are independent of the particular coordinate system, to which these changes are referred. So it is not admissible that an induced current is explained differently, depending on whether the magnet or the coil is in motion.

3) Invariance and Symmetries

28 We can understand reference frames (in the STR) as idealized physical systems whose space-time coordinates are given by rigid rods and idealized clocks. They are subject to various symmetry operations, like rotation or translation in space and time. The Special theory obeys the Lorentz-transformations, because the Galilean transformations fail as we approach the speed of light. The Galilean transformations, for instance, result in different values for the speed of light, if we change from a stationary to a moving reference frame. The Lorentz-transformations deal with space-time transformations of a global kind; that is, they are constant throughout the space-time region. They form a symmetry group. (The General theory requires a larger symmetry group.) Symmetry constraints emphasize physical aspects: the symmetry operations return some values of parameters as invariant (like the space-time interval) and leave others as variant (like the clock readings in different reference frames, in constant motion with respect to each other). Symmetries result from transformations that leave all relevant structure intact. We are familiar with such symmetry transformations in daily life. We easily change the clock as we travel between different time zones. But the tennis games we play at home and abroad are the same as far as the physical parameters are concerned.

4) Covariance

29 Covariance is *prima facie* a mathematical constraint. The modern use is quite different from the way Einstein uses the notion of covariance. Einstein associates covariance with the transformation rules of the theory of relativity.

30 He imposes on the laws of physics the condition that they must be covariant **a)** with respect to the Lorentz transformations (in the Special theory of relativity) [Einstein 1949c, 8; 1950, 346] and **b)** to general transformations of the coordinate systems (in the General theory). [Einstein 1920, 54–63; 1950, 347] The theory of relativity will only permit laws of physics, which will remain covariant with respect to these coordinate transformations. [Einstein 1930, 145–6] This means that the laws must retain their form ('Gestalt') 'for coordinate systems of any kind of states of motion.' [Einstein 1940, 922] They must be formulated in such a manner that their expressions are equivalent in coordinate systems of any state of motion. [Einstein 1916; 1920, 42–3, 153; 1922a, 8–9; 1940, 922; 1949a, 69] A change from coordinate system, K, to coordinate system, K', by permissible transformations, must not change the form of the physical laws. This leads to the characterization of covariance as *form* invariance. [Weinert 2007a] Einstein often illustrates covariance with respect to the space-time interval ds^2. [Einstein 1922a, 28] In

Minkowski space-time, the space-time interval ds^2 is expressed as an invariant expression in what remains essentially a quasi-Euclidean space:

$$ds^2 = \sum_{\nu=1}^{3} (\Delta x_\nu)^2 - c^2 \Delta t^2 = 0 \qquad (1)$$

31 2.6 If the expression satisfies covariance it must remain form-invariant under the substitution of a different coordinate system, *i.e.*,

$ds^2 = 0 = ds'^2$:

$$ds^2 = \sum_{\nu=1}^{3} (\Delta x_\nu)^2 - c^2 \Delta t^2 = 0 = ds'^2 \sum_{\nu=1}^{3} (\Delta x'_\nu)^2 - c^2 \Delta t'^2 = \qquad (2)$$

32 The equation for the space-time interval, *ds*, remains form-invariant if *K* is substituted by another quasi-Euclidean inertial frame, *K*', as indicated by the coordinates $\Delta x'_\nu$. For Einstein a fit must exist between the theory of relativity and the material world. We explicated fit in terms of the satisfaction of constraints, associated with the theory of relativity. If their amount and their interconnections can be increased, then many scientific theories will fail to satisfy the constraints. It will usually leave us with only one plausible survivor. For instance, after the development of the Special theory, Einstein increased the constraints on an admissible relativity theory. Inertial reference frames should not be privileged over non-inertial frames. This extension of the relativity principle and the demand of covariance lead to the General theory of relativity. This theory was able to explain the perihelion advance of Mercury, where Newtonian mechanics had failed. It would be exaggerated to claim that there is such a tight fit between the theory and the world, that there is a one-to-one mapping of the theoretical with the empirical elements. Einstein, in fact, rejected naïve realism. [Einstein 1944, 280–1] Due to the need for approximations and idealizations there will always be theoretical structure, for which there is no direct empirical evidence. For instance, the evidence does not tell us whether space-time exists, devoid of all matter. But Einstein holds that one theory always satisfies the constraints better than its rivals. It does not follow from this argument that the survivor—let us say the theory of relativity—will be true. It does follow that the process of elimination will leave us with the most adequate theoretical account presently available. New experimental or observational evidence may force us to abandon this survivor. The desire for unification and logical simplicity may persuade us to develop alternative theoretical accounts. Einstein’s attempt to extend the principle of relativity from its restriction in the Special theory to inertial reference frames to non-inertial reference frame in the General theory is a case in point. Although Einstein does claim that there is one correct theory, he cannot mean this in an absolute sense. His insistence on the eternal revisability of scientific theories, including constraints, speaks against this interpretation. What he must mean is that there is always one theory, at any one point, which best fits the available evidence. This one theory copes best with all the constraints, which logic and evidence erect; but there is nothing final about such a theory; it will always remain falsifiable.

VI. What is Einstein’s philosophical allegiance?

33 He has been appropriated by neo-Kantians, realists, positivists and holists alike. Each camp can claim textual evidence for its preferred interpretation [Frank 1949] [Holton 1965; 1973] [Howard, 1990; 1993; 2004]. In a number of papers, Don Howard has promoted the view that Einstein agreed with Duhem’s underdetermination thesis, and generally adopted a holist view of theory confirmation, *e.g.* only a theory as a whole body of statements faces the verdict of experimental evidence. [Howard 1990; 1993] This view implies the denial of crucial experiments, and a certain latitude of choice of conceptual elements with respect to the empirical evidence. It is akin to conventionalist ideas associated with Poincaré. According to this interpretation there exist logically incompatible theories, which nevertheless are equally compatible with the evidence. The question is whether Einstein’s way of doing physics is compatible with this strong holist interpretation.

34 If we look at the development of the theory of relativity, we notice that there are several problems with this holist interpretation. Einstein’s insistence that at any one point in the history of science only one rival theory is the most adequate theory (alone capable of satisfying all the constraints) suggests that confirmation holism does not necessarily imply the existence of equally good competitors, *e.g.* observationally indistinguishable but ontologically divergent theories. In particular, Einstein’s work on relativity shows that other than empirical constraints are at hand to distribute credibility unevenly over the space of possible theories. Einstein actually employs these constraints, as we have seen, to argue in favour of the relativity theory. In his discussion of the rotating disc thought experiment, Einstein explicitly avoids saving Euclidean geometry ‘come what may’, although this is a conventionalist stratagem.

35 We should also note that neither Duhem nor Quine were the complete holists they are made out to be. Discussions of holism usually highlight the radical underdetermination of an entire theory by empirical evidence. [Howard 1993] It is often overlooked that both Duhem and Quine accepted the coherence of scientific theories as a constraint, as much as Einstein did. According to this aspect, theories are structured conceptual systems, which entertain many mathematical and conceptual interrelations between them. This aspect makes the deducibility of empirical laws from more fundamental laws possible. Duhem, for instance, appeals to an analogy of science with an organism,

> in which one part cannot be made to function except when the parts that are most remote from it are called into play, some more than others, but all to some degree. [Duhem 1954, 187–8] [Weinert 1995]

36 The coherence aspect corresponds to Einstein’s insistence on the rigidity of scientific theories, for which he uses the analogy of the crossword puzzle (Section V). This rigidity shows that changes in one part of the theory will affect other parts of the theory, so that the ‘latitude of choice’ is more restricted than holism is ready to admit. The presence of constraints and the concern for ‘fit’ point in the direction of a stronger form of realism. Einstein is fond of the view that theoretical constructions are not inductive generalizations from experience but free inventions of the human mind. Nevertheless there must be a ‘fit’ between the theoretical expressions and the external world. This fit is achieved in the theory of relativity, we suggested, through the introduction of constraints. The increase in constraints—extension of the relativity principle to non-inertial motion, the introduction of the principle of equivalence and

the form-invariance of laws (covariance principle)—takes Einstein from the STR to the GTR. If there is indeed a 'fit' between what the theory says and what the material world presents, the question of realism returns.

37 Consider, for instance, Einstein's view of Poincaré's conventionalism about geometry. Einstein reflected on the status of geometry in the light of the GTR. [Einstein 1921; 1922b] He distinguishes an axiomatic and a practical geometry. He agrees with Poincaré that the laws of axiomatic geometry are based on conventional choices, say in favour of Euclidean geometry and its axioms. But Einstein sees an important difference between an axiomatic and a practical geometry: the former makes no reference to the world of experience, whilst the latter does.

> The question whether the practical geometry of the universe is Euclidean or not, has a clear meaning, and its answer can only be furnished by experience. [Einstein 1922b, 23]

38 According to Einstein this view of geometry was an essential prerequisite for the development of the GTR.

> The question whether the structure of [the four-dimensional] continuum [of space-time] is Euclidian, or in accordance with Riemann's general scheme, or otherwise, is, according to the view which is here being advocated, properly speaking a physical question which must be answered by experience, and not a question of mere convention to be selected on practical grounds. [Einstein 1922b, 39]

39 What counterbalances the strong holist interpretation of Einstein's views is Einstein's repeated insistence that out of many rival theories there is one with the most adequate fit and that practical geometry allows fewer conventional elements than Poincaré is ready to concede. From the point of view of Einstein's problem situation, his philosophical attitude was characterized during his lifetime as a form of *critical realism*. Einstein certainly approved of this way, in which Lenzen and Northrop characterized his epistemological position (See [Lenzen 1949] [Northrop 1949] [Einstein 1949b, 683]). It simply regards scientific theories as hypothetical constructs, free inventions of the human mind. But there is also an external world, irrespective of human awareness. To be scientific, theories are required to represent reality. They represent reality by satisfying both empirical and theoretical constraints. A theory is not a mirror image of the world. It is a mathematical representation, which provides coherence of the empirical data and shows their interconnections. Theories are hypothetical, approximate constructions, which in a process of fitting and refitting, deliver a coherent picture of the external world. In human efforts to understand the world, experience and reason go hand in hand. In modern terms, Einstein's relativity theory may be characterized as leading to a form of structural realism. [Weinert 2007b] The relativity theories are principle theories, which employ general coordinate systems to explain the behaviour of physical systems in uniform or accelerated motion with respect to each other. Such coordinate systems are well-suited to represent physical systems, since they can be regarded as structural models of the target systems. Physical systems typically display structures, consisting of relata and relations. As the models of the relativity theories are able to represent both the topologic and algebraic aspects inherent in physical systems, they can be said to represent the structure of physical systems. Einstein declares that 'the concepts of physics refer to a real external world, *i.e.*, ideas are posited of things that claim a 'real existence' independent of the perceiving subject (bodies, fields etc.)' [Einstein 1948, 321, transl. Howard, 1993, 238] These representational claims cover both the relata (fields, material particles,

reference frames) and the relations (the mathematical relations between the relata). Given that scientific theories manage to represent aspects of the external world, what picture of reality does the relativity theory espouse?

VII. What is Reality?

40 The structural realist makes the assumption that there is a structured external material world. Theories which ‘fit’ a domain of this external world present us with a view of physical reality. Such views have changed with the progression of physical theories. There was a time when physicists liked to think of the world as a massive clockwork. Particles populated the universe. Only their primary qualities mattered. They were at rest or in constant regular motion. Einstein suspected that this classical picture was mistaken. It required Newton’s absolute space and time and action at a distance. For Einstein, physicists like Heinrich Hertz, Michael Faraday and James Maxwell made significant steps in the revision of the physical worldview when they introduced fields as fundamental physical entities. Einstein regarded the theory of relativity as a field theory, which dispenses with action at a distance. But Einstein was never able to overcome the fundamental dualism in the physical worldview between particles and fields. This may be the reason why we find in Einstein’s work two concepts of physical reality. In his relativistic thinking about the nature of reality, Einstein became one of the first physicists to realize the significance of symmetries and invariance in science as a new criterion of what the physicist should regard as objective and physically real.

41 The starting point is the principle of relativity. In the STR it states that all reference systems, which represent physical systems in motion with respect to each other, must be equivalent from the physical point of view. But we have already observed that in the transition from one reference system to another some properties change. The classic examples are temporal and spatial measurements, as well as mass determinations. From the phenomenon of time dilation and the relativity of simultaneity some physicists concluded that time cannot be a physical property of the universe. Some transitions to other reference systems do not, however, affect the physical properties. The classic example is the velocity of light in vacuum. The Special theory of relativity postulates that the value of ‘*c*’ will be the same in all time-like connected reference systems, which move at constant speed with respect to each other. Some physical properties are immune to changes in reference systems, while others are not. The velocity of light is the same in all directions and irrespective of whether it is emitted from a moving or stationary source. But the wavelengths of light depend on the movement of the source (Doppler Effect). Symmetry principles, like the geometric symmetries of the STR, show the invariant aspects of the equations, which apply to Minkowski space-time. While in classical physics, many properties, like time, mass, space, energy were regarded as ‘absolute’, in the Special theory of relativity, many properties became relational. Relational means that they cannot be considered in abstraction from the coordinate values in particular reference frames. So the question arises, ‘What is real?’ For it seems that if two observers disagree about the length of an object or the simultaneous occurrence of an event, they cannot both be right. An object, so it appears to us, cannot have two different lengths at the same time.

42 But we need to take into consideration the lessons of relativity.

43 The answer to the question of reality is embedded in the mathematics of the Special theory of relativity. Minkowski's four-dimensional interpretation of space-time provided Einstein with a new criterion for the physically real. Physics, he says, deals with 'events' in space and time. [Einstein 1949c] Temporal and spatial measurements varied from reference frame to reference frame. They could not be physically real. But the space-time interval, *ds*, remained invariant for every observer. It was therefore to be regarded as real. [Einstein 1920 App. II, 1922a, 23–31; 1936, 34-41] [Scheibe 1981] In general, what a scientific theory tells us to regard as 'real' is what remains invariant in transitions between different reference frames. These transitions are governed by transformation groups. In the STR the Lorentz transformations take us from one reference system to another. They state how the spatial and temporal coordinates of one reference systems translate into another. As we change between various reference systems, say, from stationary to constantly moving systems, the laws of physics express invariant properties of physical systems, like the space-time interval of equation (1). Einstein at first considered inertial systems and later accelerated systems. The laws of physics must retain their form (remain covariant) under the substitution of coordinate systems through all transformations. [Norton 1989; 1993] What remains invariant is to be regarded as the physically real.

44 More specifically Einstein advanced his 'point-coincidence argument'. Einstein explicitly claims that the laws of physics are statements about space-time coincidences. In fact only such statements can 'claim physical existence'. [Einstein 1918a, 241; 1920, 95] [Norton 1992, 298] As a material point moves through space-time its reference frame is marked by a large number of co-ordinate values x_1, x_2, x_3, x_4. This is true of any material point in motion. It is only where the space-time coordinates of the frames intersect that they 'have a particular system of coordinate values x_1, x_2, x_3, x_4 in common'. [Einstein 1916a, 86; 1920, 95] In terms of observers, attached to different reference systems, it is at such points of encounters that they can agree on the temporal and spatial measurements. Many physicists concluded as a philosophical consequence of the relativity theory that only the invariant can be the physically real. [Eddington 1920] [Weyl 1921] [Born 1953] [Dirac 1958] [Wigner 1967, Part I] [Planck 1975]

45 However, as Born pointed out frame-dependent properties may also lay claim to reality. [Born 1953] [Weinert 2004, ch. 2.8] Clock and meter readings in particular reference frames are not perceptual illusions of observers. These measurements have perspectival reality since they are relational. They are relational in the sense that they must be derived from the coordinate values of particular reference frames. Born compared the perspectival realities to projections, which are defined in a number of 'equivalent systems of reference'.

> In every physical theory there is a rule which connects projections of the same object on different systems of reference, called a law of transformation, and all these transformations have the property of forming a group, i.e. the sequence of two consecutive transformations is a transformation of the same kind. Invariants are quantities having the same value for any system of reference, hence they are independent of the transformations. [Born 1953, 144]

46 The Lorentz transformations show, Born adds, that quantities

> like distances in rigid systems, time intervals shown by clocks in different positions, masses of bodies, are now found to be projections, components of invariant quantities not directly accessible. [Born 1953, 144]

47 This leads to a modified view of physical reality, which is still compatible with the Minkowski presentation of the theory of relativity. It admits both frame-dependent and frame-independent realities. The invariant is not the only reality but it is the focus of physics. What now becomes of the criterion that only the invariant is to be regarded as real? It derives from the fact that physics is not interested in perspectival realities. Physics is interested in the underlying structures, which relate the different perspectives. Relativistic physics is interested in the structure of space-time. This structure can be described mathematically, as Minkowski has done. It will tell us that the space-time interval, ds, is invariant across the reference systems. The particular perspectives then result from attaching clocks and rods to the world lines, which crisscross space-time. Once the symmetries tell us what remains invariant across reference frames, it is not difficult to derive the perspectival aspects, which attach to different reference frames, as a function of velocity. The theory of relativity led Einstein to an invariance view of reality. But his opposition to the Copenhagen interpretation of QM led him to a more classical separability view of reality: spatially separated system, A and B, which obey Einstein locality, possess physical properties, which are not immediately affected by external influences on either of the systems. [Einstein 1948]

VIII. Philosophy and Science

48 Philosophical consequences do not flow from scientific theories with logical compulsion. Nevertheless, certain kinds of philosophical positions are more akin to scientific findings than others. For instance, a belief in Newton's absolute space and time and the invariance of mass has become incompatible with the findings of STR. An adherence to Euclidean geometry has become incompatible with the GTR. Einstein's belief in deterministic causality and the principle of local action has become questionable in the light of QM. He once accused philosophers of dragging concepts into the den of the *a priori*.

> Philosophers had a harmful effect upon the progress of scientific thinking in removing certain fundamental concepts from the domain of empiricism, where they are under our control, to the intangible heights of the *a priori*. [Einstein 1922a, 2, italics in original]

49 Sometimes, however, the very foundations of science become shaky. This happened twice in Einstein's lifetime: relativity and quantum theory. Then the physicist himself is forced to become a philosopher through a 'critical contemplation of the theoretical foundations'. The philosopher-scientist is a familiar figure in the history of science (Newton, Leibniz, Darwin, Bohr, Born, Duhem, Planck, Poincaré). Max Born gave expression to the role of the philosopher-scientist when he wrote that

> History has shown that science has played a leading part in the development of human thought. [Born 1949, 75]

50 This philosophical turn of scientists is due to a basic epistemological situation in the sciences, of which Einstein was very aware: the need to map symbolic systems (theories, models, equations) onto an independently existing reality. This mapping has to satisfy criteria of 'fit'. If the scientific discoveries are sufficiently profound, conceptual consequences become unavoidable because they touch on our most profound physico-philosophical notions (determinism, nature, time etc.). A need arises

to rethink these fundamental notions; Einstein and other philosopher-scientists did not shirk from this task. A philosopher-scientist is someone who in Einstein's words considers the career of 'certain fundamental concepts' within the problem situation, in which they arise. The problem situation may be the kinematics of reference systems or the evolutionary theory. The physico-philosophical concepts need to be reassessed in the light of scientific discoveries, because they acted as unquestioned assumptions prior to the new discovery. In Einstein's case these were concepts like mass, space and time, the nature of physical reality and of scientific theories. In such reassessments the scientist turns to more conceptual issues, which are no longer deductive consequences of the theory. As Einstein realized, when the foundations of science become problematic, the man of science becomes a philosopher. [Einstein 1936, § 1] The philosophical legacy of Einstein's scientific work is immense. It ranges from metaphysics to the philosophy of physics. The theory of relativity demonstrates clearly how difficult the relationship between facts and concepts has become. We cannot simply cling to the concepts, irrespective of what experiment and observation tell us. This was Einstein's charge against Newton and Lorentz. Ironically it also reflects his own difficulties with quantum mechanics, since he relies on notions like determinism and separability. Nor can we simply inductively generalize from the facts, neglecting the concepts. Therefore Einstein believed in the importance of theoretical thinking and the power of constraints. As Einstein realized himself, science makes philosophical presuppositions. The scientist needs philosophical ideas, simply because amongst the experimental and mathematical tools in the toolbox of the scientist there are conceptual tools, like the fundamental notions. Philosophical presuppositions can both guide and misguide the scientist. When the philosophical presuppositions change as a result of scientific discoveries, science does not dictate to philosophy the answers. But it constrains the philosophical consequences, which follow.

51 The philosophical consequences include such questions as to which extent the Special theory is compatible with objective becoming or static being. Then there was the question of determinism in the interpretations of quantum mechanics, and the question of causal relations between entangled quantum systems. There is the issue of the representational nature of theories, more precisely the question of fit, which we interpreted as the requirement for the satisfaction of certain constraints. Finally, the philosophical notion of physical reality must be in harmony with the scientific findings. The 'point-coincidence argument' therefore led physicists to the invariance criterion of physical reality but Einstein's notion of 'local action' (no-action-at-a-distance) has not found the approval of quantum physicists. Einstein's work has shown that there is a genuine interaction between science and philosophy. Every true theorist is a 'tamed metaphysicist'. [Einstein 1936 17; 1950b, 342] We have seen how Einstein's physical problem situation lead to philosophical consequences. A consideration of Einstein's career as a physicist-philosopher illustrates Reichenbach's observation that the 'evolution of philosophical ideas is guided by the evolution of physical theories'. [Reichenbach 1949, 301]

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ABSTRACTS

The aim of this paper is to provide a readable account of the immense philosophical legacy of Einstein's scientific work. Einstein was not a systematic philosopher but his physical thought had philosophical consequences. In his willingness to pursue the philosophical consequences of his scientific work, Einstein followed in the footsteps of physicists like Newton, Mach, Planck and Poincaré. Einstein derived these consequences from the problem-situations, into which his work as a physicist had led him. These philosophical consequences range from metaphysics to the philosophy of physics. To a certain extent they can be regarded as answers to philosophical questions. Of particular interest is his view of the representational nature of scientific theories, in which the notion of constraints plays a significant role. An analysis of the role of constraints in Einstein's 'philosophy of science' has often been neglected in the literature.

Cet article a pour objectif de présenter un compte-rendu accessible de l'immense héritage philosophique de l'œuvre scientifique d'Einstein. Einstein n'était pas un philosophe de métier, mais son raisonnement en sciences physiques portait en soi des conséquences philosophiques qu'il était prêt à explorer. En explorant les conséquences philosophiques de ses travaux scientifiques Einstein s'inscrit dans la démarche de physiciens tels que Newton, Mach, Planck et Poincaré. Einstein déduisait les conséquences philosophiques de la problématique que son travail de physicien faisait surgir. Ces conséquences philosophiques vont de la métaphysique à la philosophie de la physique. Dans une certaine mesure, ces conséquences philosophiques peuvent être considérées comme étant des réponses à des questions philosophiques. On peut noter en particulier, ses vues sur l'aspect représentationnel des théories scientifiques et son insistance, à leur sujet, sur la notion de contraintes. Les travaux sur Einstein ont souvent négligé l'étude des contraintes en philosophie des sciences.

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