# THE MODERN SYNTHESIS: EINSTEIN AND KANT

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**Abstract.** The paper discusses the Kantian legacy in modern views about scientific theories. The aim of this paper is to show how Einstein's philosophy of science, which was inspired by his physics, offers a specialized version of the Kantian synthesis of Empiricism and Rationalism. In modern physical theories (relativity and quantum theory) Kant's *a priori* conditions become 'constraints', as shown in Einstein's use of principle theories. Einstein's use of principle theories shows how constraints are used to steer the mapping of the rational onto the empirical elements of scientific theories.

## I. Introduction

> When Kant said, 'Our intellect does not draw its laws from nature but imposes its laws upon nature', he was right. But in thinking that these laws are necessarily true or that we necessarily succeed in imposing them upon nature, he was wrong. (K. Popper: *Conjectures and Refutations* 1963, 48)

The debate about Kant's legacy in modern philosophy of science – after the emergence of relativity and quantum theory – has a long history. Neo-Kantians, like Cassirer, saw the Kantian synthetic a priori principles as in need of revision but not rejection. For Cassirer 'Kant rightly insists that the general concept, the „category" of causality, must be specified in a definite sense, in order to be usable and applicable empirically. However, we can no longer seek this specification in the same direction that Kant did.' (Cassirer 1956, p. 166, cf. pp. 74-5, 162-3) By contrast, the logical empiricists tended to see the Kantian principles as refuted by modern scientific discoveries. For instance, Reichenbach praises Helmholtz for having 'clearly stated that Kant's theory of space is untenable in view of recent mathematical developments.' (Reichenbach 1958, p. 36) But Reichenbach also distinguished two senses of *a priori*, which Kant tried to merge: in one sense it refers to apodictic necessity and universality and in another sense to the constitutive character of certain principles. (Reichenbach 1992, pp. 146-55) He judges that 'the first sense of a priori cannot be maintained in the face of the theory of relativity while the second is retained with even more depth and solidity.' (Reichenbach 1992, p. 148) Similar statements are echoed in Heisenberg's reflections on physics and philosophy. (Heisenberg 1958, Ch. V, pp. 90-1) Reichenbach concludes that 'science is preoccupied with the choice of general principles that are *as specific as possible*.' (Reichenbach 1922, p. 156, italics in original) Friedman has recently taken up this theme and interpreted the *a priori* in the constitutive sense as a relativized *a priori*. 'Kant's analysis is therefore correct for Newtonian physics, as a historically given theory. In special relativity, however, we change – under pressure of new findings – precisely the background space-time structure.' (Friedman 1999, p. 61) Such views have gained much currency since M. Foucault, throughout his work and in different contexts, spoke of a historical *a priori*.

Although both Cassirer and Reichenbach demand a 'specialization' of the framework principles, it remains to be seen *how* this task is to be carried out. The aim of this paper is to show how Einstein's philosophy of science, which was inspired by his physics, offers a specialized version of the Kantian synthesis of Empiricism and Rationalism. In modern physical theories (relativity and quantum theory) Kant's *a priori* conditions become 'constraints', as shown in Einstein's use of principle theories. Einstein's use of principle theories shows how constraints are used to steer the mapping of the rational onto the empirical elements of scientific theories. The long arm of Kant's Copernican turn makes itself felt in Einstein's modern synthesis between experience and reason.

## II. Kant's Copernican Turn

Although Kant's revolution in metaphysics was inspired by the work of Copernicus, Kant does not claim that the Copernican model constitutes a revolution in astronomy. In both his *Critique* and his *Streit der Fakultäten* (1798), he clearly speaks of the Copernican 'hypothesis'. (Kant 1798, A139-40) In the Introduction to the 2nd edition of the *Critique of Pure Reason* (1787) Kant is mostly interested in the Copernican turn (*Wende*) – it consists in the Copernican change of perspective. This change of reference frame from a stationary to a moving Earth inspires Kant to attempt a similar turn in metaphysics.

> Failing of satisfactory progress in explaining the movements of the heavenly bodies on the supposition that they all revolved around the spectator, he [Copernicus] tried whether he might not have better success if he made the spectator to revolve around the stars and the stars to remain at rest. (Kant 1787, Preface BXVII; cf. Miles 2006; Gardner 1999, pp. 37-44; Palmquist 1993, Ch. II, III.1)

Kant is interested in this shift of perspective because he hopes to overcome some severe limitations of British Empiricism and Continental Rationalism, respectively. Empiricism, stung by Hume's inductive scepticism, cannot explain the universality and necessity of scientific knowledge. Rationalism, exonerated by Descartes from the need for severe testability, cannot curtail the flight of reason into unbridled metaphysical speculations. Kant's ingenious insight was to see that both Empiricism and Rationalism offered partial solutions to the question of objective knowledge. Kant sought to secure scientific knowledge through a synthesis of Empiricism and Rationalism. This synthesis is meant to produce the necessity, objectivity and universality of scientific knowledge (in particular as embodied in Newtonian mechanics), which neither Empiricism nor Rationalism can achieve. In Kant's approach the synthesis is based on transcendental principles, to which any possible science of nature must conform. These principles of pure reason render a coherent access to the empirical world possible; they are presuppositions of objective experience. In modern parlance, they act as constraints on the knowable.

As constraints are of great significance in modern science, let us briefly review how Kant hopes to achieve the synthesis of Empiricism and Rationalism and what constraining role the *a priori* principles play in this synthesis.

Unlike the empiricists, Kant does not attempt to derive all knowledge of the external world from sense impressions. Unlike the rationalists, Kant does not attempt to derive empirical knowledge either from Cartesian 'clear and distinct ideas' or Leibnizian logical principles. Kant asks a transcendental question: 'What are the conditions of the possibility of objective experience of the external world?'[1]

Kant thinks that the human mind has a mental structure, which all humans share irrespective of what happens in individual minds. In order to

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[1] Note that Popper also saw in Kant's philosophy the first attempt at a 'critical synthesis' of empiricism and rationalism, see K. Popper ($^2$1994, p. 17) but Popper does not further reflect on how this synthesis is to be achieved in modern scientific theories.

secure objective knowledge, this mental architectonic (Palmquist 1993, p. 21) must make use of synthetic *a priori* principles. They secure the transformations of perceptions into the systematic, lawlike connections of objective experience. (Kant 1786, A XIII) Furthermore the Kantian conditions are not subject to modifications by empirical discoveries, since they are presuppositions of such discoveries. If the structure of the human mind has a Kantian architectonic, then a question of fit arises. The rational must fit the empirical for an objective view of the external world to be possible. The notion of 'fit' is to be analyzed by the use of constraints, in either the Kantian or the Einsteinian sense. The internal conditions, which Kant imposes on the perceptual material, are supposed to put limitations on the conditions of fit: the conditions of the possibility of objective experience as such are at the same time the conditions of the possibility of the objects of experience. (Kant 1787, B197) The Kantian conditions are tailor-made to ensure that the perceptual world conforms to the presuppositional structure of the human mind. How is it possible for the external world to disprove any of the internal conditions imposed on the mind? How can science discover that its presuppositions are mistaken on the Kantian view? Kant relies on his distinction between formal and material nature or pure natural science and empirical science. He holds that the synthetic *a priori* principles provide the necessary conditions for the possibility of objective experience, but in order to experience individual objects of experience and their relations, it is necessary to employ empirical science. (Kant 1787, Preface; cf. Morrison 1989; Mittelstaedt 2003, pp. 209-12; Friedman 1992, §4.2; Körner 1955, p. 78) There is no direct route from the rational to the empirical. Although Kant does not think that the presuppositional structure determines the empirical content of scientific thinking – the principles are constitutive of the objects of experience (Friedman 1999, pp. 60-1) – his views imply that the empirical world cannot in a straightforward way either confirm or disconfirm the presuppositions. For instance, Kant regarded the axioms of Euclidean geometry as constituting synthetic *a priori* knowledge. On this assumption there can be no physically possible world, accessible to human cognition, in which Euclid's axioms are violated. Euclidean geometry describes the world that human beings can experience. Kant 'thought that Euclidean geometry applied to physical objects, to sense-given things in space.' (Strawson 1966, p. 284; Bennett 1966, §§4, 9; Brittan 1978, Ch. 2) Furthermore, any empirical discoveries must conform to the category of causality, which is inherent in the mind. Empirical investigation may show that what we took to be the empirical cause of a particular event turned out not to be the cause of that event. But whatever causal relations we discover between particular events, they must conform to the category of causality.

The synthesis between the empirical data and the rational principles is achieved through constraining the empirical sense data by way of abstract principles. The objectivity of scientific knowledge is achieved through this dynamic structure. In essence the presuppositional structure of the mind consists of the Axioms of Intuition and the Categories. Kant regards space and time as pure forms of intuition, which leads to an objective-idealist view of space and time. Outside of our sensory experience space and time do not exist. The twelve Categories, arranged in four sets of three – Quantity, Quality, Relation and Modality – constitute the second pillar of the presuppositional structure of the mind. What is of interest in the present context is how they are to fit the phenomenal data which are delivered to our senses by the perception of the external noumenal world. Kant believes that a condition of fit is that the Categories have to be schematized. The schematism stands between the abstract categories of thought and the concrete perceptual experiences, it mediates between them. Kant's thesis of schematism is far from clear; it will be sufficient for present purposes to quote a reconstruction of Kant's problem of category-application:

> A schema is a kind of counterpart to a concept, and it involves imagination. Since imagination produces intuitions, which for humans are necessarily temporal, schemas – even schemas of atemporal concepts – are all somehow temporal. (Bennett 1966, p. 150)

> Since something must provide the meeting point between pure concepts and empirical intuition, and nothing else could do so, pure intuition must do so. (…) time is the most general unifying condition of intuitions and concepts (…) the pure logical concept of substance (…) becomes when schematized 'permanence of the real in time'. And the pure logical concept of causality (…) becomes the concept of 'the real upon which, whenever posited, something else always follows'. (Gardner 1999, pp. 166-70; Friedman 1992, pp. 8, 39; Körner 1955, pp. 70-5)

Even if Kant's solution is obscure, his theory of schematism demonstrates his awareness that some mechanism needed to be found such that the mental forms could be mapped onto perceptual data to transform appearance into experience and to constitute objective knowledge.

Although Kant's synthesis had its root in British Empiricism and Continental Rationalism it is not strictly dependent on these two doctrines. As later developments showed the synthesis can be generalized to speak of the merging of rational and empirical constituents, of reason and experience, as the two building blocks of scientific knowledge. This merger is most striking in scientific theories, which Einstein called ‘principle theories’; they provide frameworks for the interpretation of nature. (DiSalle 2006, p. 119) Kant showed his appreciation of this framework idea in his characterization of Galileo’s mathematization of nature:

> Reason, in order to be taught by nature, must approach nature with its principles in one hand, (…), and, in the other hand, the experiments thought out in accordance with these principles (…).

He expresses the synthesis idea in the famous quote:

> Thoughts without content are empty, intuitions without concepts are blind.’ (Kant 1787, BXIII-XIV, B75 respectively)

But we must be aware that this synthesis in modern physical theories departs drastically from the Kantian form. The modern way of constructing the synthesis is the most interesting part of Kant’s legacy. It heavily relies on a general notion of constraint, as becomes clear in Einstein’s theory of relativity. Analogously to Kant’s *a priori* conditions, we define constraints here as restrictive conditions, which either govern the admissibility of certain parameters into scientific theories or models or the admissibility of certain solutions to scientific equations. As will be discussed, the role of such constraints shows its true significance in relativity and quantum theory. The basic epistemological idea is Kantian: there is an external world, which exists independently of the human mind (for Kant this was the noumenal world); science postulates theoretical constructs (hypotheses, laws, models, principles and theories), which it tries to map onto sections of the external world (for Kant the constructs belong to the architectonic of the mind); the aim is to achieve a sufficient amount of ‘fit’ between the theoretical constructs and the empirical data. In order to achieve this fit a certain number of conditions must be satisfied. In modern physical theories such restrictive conditions or ‘constraints’ must be subject to empirical testing and possible revision, while Kant’s *a priori* conditions are not meant to be testable. Furthermore, they form a ‘constraint space’, which allows the formulation of alternative theories, which still satisfy the constraints. This latter feature of the constraint space becomes noticeable in quantum mechanics. By contrast, Kant aims to provide ‘metaphysical foundations’ to classical mechanics. (Friedman 1992, p. 136) Kant’s *a priori* conditions narrow the space of possible alternatives to a class of theories, which stay within his synthetic *a priori* conditions. Within this transcendental constraint space, any scientific advances must proceed in a manner that is consistent with those principles. They lay down the conditions, under which it is possible to gain knowledge of the objects of experience. In the modern view, the most obvious constraint is that the theoretical constructs must be testable by the empirical data. Often the logical simplicity of the scientific constructs is imposed as a further constraint. But as we shall see from an analysis of the theory of relativity and quantum mechanics, regarded here as principle theories, more *specific* constraints have emerged in modern physical theories.

In modern philosophy of science the equivalent to Kant's schemata is to make a scientific theory represent the external world via a number of models.[2] Models represent the general in terms of the particular, e.g. general features of nature in terms of quasi-specific parameters. Typical examples in the Special theory of relativity are the reference frames. Just as Kant's schemata are not images but 'a monogram of pure imagination a priori', (Kant 1787, A142; cf. Weinert 2006) the models are not pictorial representations; when models represent physical systems, they do so under the condition of abstraction and idealization. But this still requires us to say what it means for a theory to represent via models, and what it means for a model to 'fit' the empirical data. Kant believed that the framing of our perceptions by the categories and the pure forms of intuition guaranteed the necessity, objectivity and universality of classical physical knowledge of the natural world. If Kant's programme of a synthesis between the empirical and the rational is indeed his legacy to a modern understanding of science, we should expect to find this synthesis in some paradigmatic modern scientific theories. We should also expect to find the concerns, which are associated with such a synthesis: the distinction between the rational and the empirical elements in scientific thinking; how to map them onto each other to ensure the objectivity of knowledge; how to revise Kant's particular answers to these questions in view of newer scientific knowledge. The next sections will first discuss how a typical representative of modern science, e.g. Albert Einstein, assesses the question of a synthesis in his philosophical writings. And then we consider the work of constraints in modern physical theories (relativity and quantum theory) in order to put some flesh on the bones of the epistemological programme.

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[2] According to Palmquist (1993, Ch.I. 2, 3) Kant employs (geometric) models as metaphors.

## III. The Modern Synthesis between Reason and Experience

**1.** The modern solution to the question of representation changes some parameters. On the side of the rational, the constraints become externalized and subject to modifications; there are several types of constraint to be imposed on scientific constructs, like theories, models and laws. On the empirical side, Kant's sensory experience of objects becomes replaced by experimental and observational measurement data, taken from physical systems. However one achievement of Kant's Copernican turn is retained. Kant emphasized the priority of the rational element in the acquisition of objective knowledge. Many scientists since Kant have accepted the priority of theory. So it is still an urgent question how a theoretical construct, like a scientific model or theory, can make objective statements about an independently existing natural world, e.g. the question of representation. Scientists are eminently aware of the need to find a synthetic match between the rational and the empirical. Einstein, for instance, invokes the relativized *a priori* when he states:

> The theoretical attitude here advocated is distinct from that of Kant only by the fact that we do not conceive of the „categories" as unalterable (conditioned by the nature of the understanding) but as (in the logical sense) free conventions. They appear to be *a priori* only insofar as thinking without the positing of categories and of concepts in general would be as impossible as is breathing in a vacuum. (Einstein 1949a, p. 674, italics in original)

When Einstein wrote these words he stood in a long line of scientists, going back to the French physiologist Claude Bernard, the English evolutionist Charles Darwin, and the German-speaking physicists Heinrich Hertz, Ernst Nernst, Ludwig Boltzmann and Hermann von Helmholtz. (Scheibe 2006, pp. 307ff; Weinert 2004, Ch. 2.5) C. Bernard wrote in 1865 that it is not possible to make an experiment without a preconceived idea. Justus von Liebig, the pioneer of organic chemistry, took a similar line in 1863:

> An experiment not preceded by theory, i.e. by an idea, bears the same relation to scientific research as a child's rattle does to music. (Quoted in Hacking 1983, p. 153)

Clearly, scientists wish to find a solution to the question of representation in the practice of physical theories. But what we observe after Kant is a reconfiguration of the *a priori* categories and conditions to various types of constraints, which function at best as relativized conditional *a prioris* and which operate on various levels of scientific activity.

**2.** Einstein entertained a very Kantian view of the matter. To associate Einstein with Kantian philosophy may sound at first surprising, if not plainly mistaken. Although Einstein's physics is best viewed as the culmination of the classical tradition, his work has fundamentally changed some of the basic tenets of Kant's philosophy of nature. For instance, according to Kant we represent to ourselves only one time and one space. (Kant 1787, A32, A189, A25) But for Einstein, 'there are as many times and places as there are reference systems.' (Pauli 1981, p. 137) Nor was Einstein particularly impressed with the Kantian solution to the problems of space. Kant's 'denial of the objectivity of space can (…) hardly be taken seriously.' (Einstein 1920, p. 137)

Even though Einstein rejected many of the particular solutions, which Kant adopted, as they were inspired by classical physics, there is good reason to think that Einstein shared Kant's epistemological concern about the synthesis between the rational and the empirical. Einstein rejects Kant's preoccupation with thought necessities and fixed categorical frameworks. Classical space and time cannot be regarded as necessary preconditions of the possibility of experience. Mathematicians conceived of non-Euclidean geometries; and thought experiments about the behaviour of rotating systems demonstrate that non-Euclidean worlds can be modelled and measured. In such worlds the ratio of circumference to diameter of a circle is no longer equal to π for all observers. Scientific theories are, like the axioms of geometry, free inventions of the human mind. Nevertheless, there is a distinctly Kantian flavour in Einstein's position on the nature of scientific knowledge. It lies in the middle way between the 'aristocratic illusion of pure thinking' and the 'plebeian illusion of pure sense perception', amounting to a synthesis of reason and experience, which was the hallmark of Kant's critical philosophy. In Einstein's view of scientific knowledge, reason and experience must form a union, governed by principles. The rational element even enjoys a certain logical priority over the empirical element because of the priority of theory over inductive generalizations. In this sense, 'every theory is speculative.'[3] Einstein considers that the rationalist dream of comprehending external reality through the power of pure thinking can, to a certain extent, be achieved. But this trust in mathematical rationalism is only one

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[3] (Einstein 1950, p. 349) Einstein endorses the Kantian view, which he expresses in the statement: „'The real is not given to us, but put to us (*aufgegeben*) (by way of a riddle)." This obviously means: There is such a thing as a conceptual construction for the grasping of the inter-personal, the authority of which lies purely in its validation. This conceptual construction refers precisely to the „real" (by definition), and every further question concerning the „nature of the real" appears empty.' (Einstein, 1949a, p. 680)

side of the coin. For scientific theories to be objective, it is necessary to anchor them in the empirical world. In a Kantian fashion reason must seek a union with experience.

> We have thus assigned to pure reason and experience their places in a theoretical system of physics. The structure of the system 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 1954, p. 272)

Einstein praises Kant for having made a 'step towards the solution of Hume's dilemma' although the particular form of Kant's solution is untenable.

> Whatever in knowledge is of empirical origin is never certain (Hume). If, therefore, we have definitely assured knowledge, it must be grounded in reason itself. (Einstein 1944, p. 285)

Einstein is however aware that the Kantian synthesis poses an epistemological problem, e.g. how the rational is to 'fit' the empirical. His solution, in its most general terms, is remarkable in its Kantian flavour:

> 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, p. 289)

Einstein often stated that experience is the final arbiter of the validity of scientific theories but he also stressed the importance of the value of logical simplicity. He thus arrived (as quoted) at logical simplicity and empirical confirmability as the two features of a good scientific theory. An analysis of the Special theory of relativity reveals, however, that Einstein requires more specific constraints on scientific theories than compatibility with empirical data and mathematical simplicity to ensure a 'fit' between the rational and the empirical. These constraints act, as we shall see, as relatively *a priori* conditions, not on the possibility of experience, but on the possibility of constructing adequate theories and models of the physical world. But there is a major difference between Einstein and Kant. On the one hand, Einstein's trust in mathematical rationalism makes him confident that among all the possible theoretical constructions, the correct one can be found. (Einstein 1954, p. 226) On the other hand this does not mean that such a theory can pretend to possess the universality and necessity, which Kant tried to establish for his categories of thought. For Einstein all scientific knowledge is conjectural and this includes the constraints, which are imposed on the rational constructs. Nevertheless he insists that at any particular stage in the history of science, out of a number of competing accounts, one will be regarded as cognitively most adequate because it best copes with all the constraints which scientific constructs have to satisfy. Awareness of his own role in the history of physics imparted to Einstein the view that there is nothing final about scientific theories. Newton's mechanics was the ruling paradigm in physics until Einstein questioned its fundamental assumption of absolute reference frames. Soon after 1905 Einstein began to see the limits of the Special theory of relativity. This theory treats inertial reference frames as privileged for the formulation of the laws of physics. The space-time continuum is still 'quasi-Euclidean': the reference frames are in uniform motion with respect to each other and are related by the Lorentz transformations. The motion affects the behaviour of clocks (time dilation) and rods (length contraction) but no physical processes affect the structure of Minkowski space-time. In his GTR Einstein sought to overcome this restriction by abandoning the preference for inertial reference frames. Space-time becomes fully dynamic in the sense that it affects the trajectory of world-lines and the presence of mass-energy fields affects the structure of space-time.

From this general epistemological commitment to the synthesis between reason and experience, Einstein shows how this union is to be achieved in modern physical theories, like the theory of relativity. Einstein's solution is based on his distinction between *constructive* and *principle* theories. (Einstein 1954, pp. 227-32) Constructive theories employ relatively simple formalisms, which are meant to represent the hypothetical structure of a physical system. The role of a constructive theory is to propose hypothetical (or *as-if*) models, which assign an underlying mechanism to the observable phenomena. The hypothetical mechanism is meant to explain the observable phenomena. The kinetic theory of gases models the behaviour of gas molecules *as if* they were billiard balls. Early atom models modelled atoms *as if* they were tiny planetary systems. A constructive theory, in order for its models to represent the observable phenomena, introduces in its formalism a number of idealizations and abstractions. The models represent the phenomena *as if* they only consisted of the components, which the model introduces. Nevertheless, for the representation to succeed the models must retain a degree of approximation to the systems modelled. Constructive theories encourage causal-dynamical explanations, since they assign to the observable phenomena an underlying mechanism.

Einstein was mostly concerned with theories of principles. Principle theories employ very general features of natural systems, from which mathematical criteria follow, which natural events and their models must obey. The role of a principle theory is to work on the basis of well-confirmed fundamental physical principles: the laws of thermodynamics, the principles of relativity, of covariance and invariance, and the constancy of light. These principles forbid the occurrence of certain physical events, like superluminal velocities or perpetual motion machines. They constitute relativized constraints on the construction of models and theories and the representation of phenomena. Principle theories seek to represent physical systems, via structural models, under the constraint of these principles. 'Principle theories provide a framework for asking empirical questions about physical interactions in general.' They act in a quasi-Kantian role as conditional *a priori* constraints on the description of physical systems. Principle theories encourage structural explanations since they encourage questions like 'what is the structure of the world like if certain principles are to hold in it?' (DiSalle 2006, pp. 119, 153; Hagar 2008)

The Kantian problem-situation presents itself to Einstein in the following way: If there is an independently existing natural world, a view to which Einstein was committed, and if the scientific constructs are free inventions of the human mind, a view to which Einstein adhered, then reason and experience must form a synthesis. This synthesis enables scientific theories, models and laws to make objective claims about the independently existing empirical world. In order to achieve this representation Einstein relies on a number of specific constraints.

## IV. The Role of Constraints

As noted above, constraints can be understood as restrictive conditions, which symbolic constructs must satisfy in order to qualify as admissible scientific statements about the natural world. In his philosophical writings Einstein usually stresses 'empirical confirmation' and 'logical simplicity' as the two most important constraints on scientific theorizing. In his criticism of quantum mechanics he considers 'causality' and 'locality' as important constraints. We can regard these constraints as contributing to a presuppositional constraint space, in which physical laws, models and theories must be embedded. By imposing constraints on the phenomena and the scientific constructs Einstein hopes to achieve the required 'fit' between the rational and the empirical. Fit is a metaphor for the satisfaction of constraints.

Although Einstein speaks of ‘empirical confirmation’ he is much closer to Popper’s idea of falsification than to the idea of inductive confirmation. For, as we have seen, Einstein stresses the priority of theory. No amount of evidence amounts to the equations of the theory of relativity. But the equations of the theory of relativity can be subject to empirical testing. Such tests have confirmed the phenomena of time dilation, the red shift of light in gravitational fields and the deflection of light near strong gravitational bodies.

But beyond such constraints as ‘empirical confirmation’, ‘causality’ etc., which, according to Einstein, any scientific theory must satisfy, there is a specific set of conditional *a priori* constraints, which constitute principle theories in physics, like the theory of relativity.

- Einstein postulates the constancy of the *velocity of light* as a constraint, to which the empirical phenomena must conform. In the Special theory no material processes are permitted to exceed or even reach the velocity of light. In terms of Minkowski space-time light rays constitute the null-like world lines, which define the limits of causal propagation. This constraint has the further consequence that ‘mass’ is no longer an invariant parameter in relativistic mechanics.
- *Relativity Principles*. No reference frame must serve as a preferred basis for the description of natural events since no absolute reference frames are detectable. Reference frames are treated as indistinguishable from a physical point of view. For this reason Einstein abandoned Newton’s absolute and universal notions of spatial and temporal reference frames as well as 19th century ether theories. Then he discovered that even his Special theory gave an unjustifiable preference to inertial systems and Euclidean geometry. The General theory extends the principle of relativity to all kinds of motion – inertial and non-inertial – now described in general coordinates. ‘Gaussian co-ordinates are essentially equivalent for the formulation of the general laws of nature.’ (Einstein 1920, pp. 97-8; Friedman 1992, Ch. IV.5) In its general form the principle states that all coordinate systems, which represent physical systems in motion with respect to each other, must be equivalent from the physical point of view. Generally, relativity principles stipulate the physical equivalence of frames or the indistinguishability of their state of motion.
- *Symmetries*. Whether we consider inertial frames or arbitrary coordinate systems, there must be transformation rules between them. In the Special theory of relativity the transformation rules are expressed in the Poincaré group; in the General theory there are more general transformation

groups, which no longer favour inertial frames. In the transition between reference frames and coordinate systems it is required that the symmetry operations return some values of parameters as invariant (like the space-time interval, $ds^2$) and leave others as frame-dependent (like the clock readings in different reference frames, in constant motion with respect to each other). Such symmetries result from transformations that leave all relevant structure intact.

- ♦ *Covariance Principle*. Covariance is *prima facie* a mathematical constraint on the formulation of the laws of nature. According to Einstein the laws of nature must remain 'invariant with respect to arbitrary coordinate transformations?' (Weyl 1924, p. 197) A mere change of coordinates will not affect the structure encoded in physical laws, which govern the behaviour of physical systems. Einstein understands covariance as 'form invariance'. The physical laws must remain form-invariant as coordinate systems undergo symmetry operations. This means that the laws must retain their form ('Gestalt') 'for coordinate systems of any kind of states of motion.' (Einstein 1940, p. 922; 1949b, 69) They must be formulated in such a manner that their expressions are equivalent in coordinate systems of any state of motion. (Einstein 1920, pp. 42-3, 153; 1940, p. 922) Einstein imposes on the laws of physics the condition that they must be covariant **a)** with respect to the Lorentz transformations (Lorentz covariance in the Special theory of relativity) (Einstein 1949c, p. 8; 1950, p. 346) and **b)** to general transformations of the coordinate systems (general covariance in the General theory). (Einstein 1920, pp. 54-83; cf. Weinert 2007) Although Einstein treated the covariance principle as an extension of the general relativity principle, 'form invariance' is too weak a requirement to guarantee the 'physical equivalence' of coordinate systems. Covariant formulations also admit of various degrees of invariance. The modern view of covariance is that the laws must remain invariant whether they are considered from different coordinate systems or described in different mathematical languages, for instance in a coordinate-free language. Different mathematical formulations may be used to formulate the laws of nature and covariance requires that this re-description be equivalent. Covariance can be understood as the requirement that equivalent expressions of the laws of nature must refer to the same objective state of affairs.

Einstein often illustrates covariance with respect to the space-time interval $ds^2$. In Minkowski space-time, the space-time interval $ds^2$ is an invariant in what remains essentially a quasi-Euclidean space, e.g. for the propagation of light:

$$ds^2 = \sum_{n=1}^{3} (\Delta x_n)^2 - c^2 \Delta t^2 = 0 \quad (1).$$

If the expression satisfies covariance it must remain form-invariant if a primed coordinate system is used instead of an unprimed one:

$$ds^2 = \sum_{n=1}^{3} \left(\Delta x_n\right)^2 - c^2 \Delta t^2 = 0 = d's^2 = \sum_{n=1}^{3} \left(\Delta x'_n\right)^2 - c^2 \Delta t'^2 \quad (2).$$

Einstein speaks of covariance as a restrictive principle, but all the physico-mathematical principles discussed act as restrictive constraints in the theory of relativity:

> The laws of physics are invariant with respect to the Lorentz-transformations (for the transition from one inertial system to any other arbitrarily chosen system of inertia). This is a restricting principle for natural laws, comparable to the restricting principle of the non-existence of the *perpetuum mobile* which underlies thermodynamics. (Einstein 1949b, p. 57; 1922, p. 28)

**1.** Whether a theory is a constructive or a principle theory, it must be subject to testability. Einstein believed that scientific theories were ‘free invention of the human mind’. Logically, this situation should give rise to a multitude of equivalent physical theories. But Einstein believed that in practice his principle theories provided the best *fit* between the theory and the world of experience. (Einstein 1918; Einstein 1933, p. 272; Einstein 1954, pp. 290-93; Einstein 1944, p. 280) But only a naïve realist would claim that there is such a tight fit between the theory and the world that a one-to-one mapping exists between the theoretical and the empirical elements. Due to the need for approximations and idealizations there will always be mathematical structure, for which there is no direct empirical evidence, as for instance in the need for complex numbers $\sqrt{-1}$ in physical theories. But Einstein’s view is that, given the constraints needed, one theory – the theory of relativity – *at any one time* always satisfies the constraints better than its rivals. It does not follow from this argument that the theory of relativity should be regarded as true. Rather a process of elimination, aided by the imposition of constraints, will leave us with the most adequate theoretical account presently available. New experimental or observational evidence may force us to abandon the successful theory. The desire for unification and logical simplicity may persuade us to develop alternative theoretical accounts. The need for new fundamental principles may have a similar effect. Einstein's extension of the principle of relativity from its restriction to inertial reference frames in the Special theory to non-inertial coordinate systems in the General theory is a case in point.

The procedure to bring about a synthesis between reason and experience is to secure a 'fit' between the rational constructs and the empirical data. Einstein's solution is that this fit is achieved through the satisfaction of various empirical and theoretical constraints: as the theory of relativity demonstrates, the models and laws of this theory must be embedded in an appropriate constraint space. These constraints, however, must themselves be subject to forms of testability to ensure that purely metaphysical constraints do not halt the progress of scientific theories. The representation of the empirical by the rational would be impeded if the constraints were treated as fixed Kantian *a priori* conditions. (Einstein 1916, pp. 101-4; cf. Weinert 2006) The insistence on testability of the principles is a significant departure from the Kantian tradition. Lorentz invariance is testable; one of its earliest tests occurred in the Michelson-Morley experiment. Many other tests have recently been performed and there are suggestions that slight deviations from Lorentz invariance may occur on the Planck scale. But the further implication of the policy of keeping the constraints open to some form of testability can be seen if we reconsider Einstein's views on quantum mechanics in the light of the conditional nature of the principles.

**2.** *Quantum Mechanics*. Einstein's opposition to the Copenhagen interpretation of quantum mechanics is well known. Einstein demanded that constraints like locality and causality should be imposed on quantum mechanics. By locality Einstein means that no 'faster-than-light-signals' should be permitted to propagate between spatially separated quantum systems. Causality in Einstein's work is understood as the spatio-temporal determination of atomic trajectories. (Einstein 1927) He saw these constraints exemplified in the use of differential equations, which trace the temporal evolution of a physical system and its well-determined parameters. But the development of quantum mechanics has seen the need for other constraints to obtain the synthesis between experience and reason in the field of atomic systems. A brief look at quantum mechanics shows two developments:

**a)** Constraints must remain subject not only to testability but to the possibility of drastic revision, not just extension, if the 'fit' between the rational and the empirical is to succeed. Famous experiments in the history of quantum mechanics have revealed non-classical properties of quantum mechanical systems. Such experiments demonstrate, for instance, the existence of entangled quantum systems, which violate Einstein locality and the Bell inequalities. They therefore require a different mathematical representation: the superposition principle to deal with entangled systems, the Pauli Exclusion Principle to deal with fermions, the distinction between operators and observables and that between the unitary evolution of the wave equation and its stochastic reduction in the measurement process to deal with observational results.

**b)** Einstein fully accepted the fundamental mathematical postulates of quantum mechanics: the Schrödinger wave equation, $\Psi$, the Heisenberg indeterminacy principle, the Born rule and others. But how this mathematical model was interpreted in the Copenhagen interpretation as a representation of quantum 'reality' did not satisfy Einstein. In terms of the above distinction he must have regarded quantum mechanics as a constructive theory: an interpretation of the empirical phenomena in terms of hypothetically postulated mechanisms. Einstein found himself in agreement with most physicists on the empirical constraints, due to numerous well-confirmed experiments on, say, entangled systems, and on the mathematical constraints. There is no disagreement about methodological constraints, like consistency and testability. Einstein's objections to quantum mechanics reflect the disagreement about the 'completeness' of quantum mechanics. The deterministic evolution of quantum states, described in the Schrödinger equation, is confined to an abstract Hilbert space and the measurement of such systems leads to observable statistical averages. According to the Born rule, the square of the wave function, $\left|\Psi\right|^2$ , only delivers statistical information about the probability of events, not the trajectory of actual events in space-time. Einstein accepted the quantum theory as a heuristic device because the Born rule allowed him to conclude that it only delivered an incomplete description of reality. Even if the existence of entangled systems and the violation of the Bell inequalities are accepted as facts, there is still dissent about how to interpret the facts. Such disagreements occur over the role, if any, of non-local hidden variables and the dynamics, if any, involved in the 'collapse' of the wave function and the epistemological status of the state vector, $\left|\Psi\right\rangle$.

But unlike Einstein, most physicists probably regard quantum mechanics as a principle theory, although it deviates considerably from the principles Einstein had in mind. First, it provides a structural explanation, as illustrated in Bohr's model of the hydrogen atom (1913). Furthermore the theory works on the basis of 'well-confirmed fundamental physical principles': the Franck-Hertz experiment (1914) confirmed Bohr's postulate of energy quantization; the Stern-Gerlach experiments (1921-23) confirmed the quantization of angular momentum and eventually led to the concept of spin; the famous Aspect experiment (1982) tested the Bell inequalities, using variable analyzers, in favour of the predictions of quantum mechanics; finally modern *which-way* experiments (1991-2003) confirm the degree of entanglement of quantum systems.

These confirmations show that quantum physicists only carried out Einstein's recommendations: that scientific theories had to be logically coherent and 'simple' and empirically testable. However, the principle of locality and the principle of causality had to be abandoned. Compared to Kant's *a priori* conditions the principles, which form the pillars of principle theories, become 'relativized' in a dual sense: some principles, like Einstein locality, can only be imported into quantum mechanics at the price of a conflict with the Special theory of relativity; revised principles needed to take their place, which are still subject to testability. But the situation in quantum mechanics is such that it allows the co-existence of consistent, alternative theories – like Bohmian mechanics or dynamic collapse theories – within the same constraint space. Hence the constraint space cannot always be as narrow as Kant and Einstein envisaged.

One of the major differences between the older philosophical tradition and newer ones is the insight that science deals with physical systems, rather than individual happenings. (Scheibe 1997, Ch. II; Scheibe 2006, pp. 330-1; Weinert 2004, Ch. 2.4, 2.5) Such physical systems display physical structures, which can be represented by the algebraic and topologic aspects of the many kinds of models employed in science, as will be discussed presently. If the synthesis between mathematical and physical structures is to be achieved, it must be achieved through a structural kind of realism. The relativity theory and quantum mechanics show that there is a great emphasis on structures and systems in science. In fact, the importance of structures in science throws new light on the requirement of 'fit'.

## V. The importance of structure

As shown by Einstein's theory of relativity, the notion of fit should be interpreted as the satisfaction of constraints. From Einstein's distinction between constructive and principle theories it can be inferred that scientific theories represent the natural world via various kinds of models. Models are ideal vehicles for the representation of the structure of physical systems. By structure we understand a system, consisting of relata and relations.

Such a system only exists when the relata are related through quantifiable relations, e.g. the laws of physics, symmetries and other mathematical postulates. The job of scientific models is to represent such physical structures. 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 encodes the mathematical relations between the relata of the model. (Cf. Weinert 1999) There is a strong concern for structure in the theory of relativity – in the Special theory this concern is revealed through the importance of the inertial reference frames, in the General theory through the importance of abstract coordinate systems. In the Special theory the inertial reference frames constitute the relata and the Lorentz-invariant equations of motion constitute the relations. But, as we observed, the relations are subject to further constraints: relativity and symmetry principles and the covariance requirement. In the General theory the inertial reference frames lose their importance and abstract coordinate systems take their place; the relations are provided by generally-covariant equations. The idealized structures in science (expressed through a range of models) are meant to represent the structures of the physical world. 'Physics is the attempt at the conceptual construction of a model of the *real world*, as well as its lawful structure.' (Einstein, quoted in Fine 1986, p. 97, italics in original; cf. Einstein 1948, p. 321; Einstein 1949b, p. 81; Einstein 1918) In quantum theory the theoretical structure (postulates) aims at a representation of the behaviour of atomic systems as it reveals itself in numerous experiments. The history of quantum mechanics shows the need for new representational devices as a response to experimental data. When Stern and Gerlach, for instance, carried out their famous experiments (1921-25) on space quantization of the magnetic moments of the silver atoms in an inhomogeneous magnetic field, it soon transpired that the observed behaviour of the atomic beam – the splitting of the beam into two traces when the silver atoms were in the ground state ($n = 0; l = 0; m_l = 0$) – required the introduction of a fourth quantum number, *s*, for intrinsic angular spin.

In terms of a structural account of reality, the inertial reference frames, coordinate systems and the state vector, $|\Psi\rangle$, constitute the relata, which are related to each other through the relations. These relations are represented by the equations and other constraints, which hold between these different relata. Einstein's attitude to the Copenhagen interpretation of quantum mechanics may well have inspired his view, at least in part, that the relations had to take the form of ‘structure laws’. Einstein conceived of the theory of relativity as a field theory. According to Einstein and Infeld, the equations of the theory of relativity and electrodynamics can be characterized as *structure laws*. (Einstein/Infeld 1938, pp. 236-45) In these authors’ view structure laws apply to various fields. Structure laws express the changes which happen to electromagnetic and gravitational fields. These structure laws are local in the sense that they exclude action-at-a-distance. They respect Einstein locality. ‘They connect events, which happen now and here with events which will happen a little later in the immediate vicinity.’ (Einstein/Infeld 1938, p. 236) Note that the equations specify the type of relata, which they bind into a system. The Maxwell equations determine mathematical correlations between events in the electromagnetic field; the gravitational equations express mathematical correlations between events in the gravitational field. The Born rule determines the probability of observable quantum events. ‘Quantum physics deals only with aggregates, and its laws are for crowds and not for individuals.’ (Einstein/Infeld 1938, p. 289) Einstein holds that structure laws have the form ‘required of all physical laws.’ (Einstein/Infeld 1938, pp. 238, 243) We can therefore say that structure laws determine how the components (or relata) of physical systems are mathematically related to each other. The relations and the relata therefore form a system. Apart from space-time events, the relata may refer to objects like planets (as in Kepler’s laws), electromagnetic or gravitational fields or quantum systems. Fit as the satisfaction of constraints in a structural realist, rather than a naïve realist sense means that the models employed in the relativity theory and quantum mechanics are only required to represent the structural features of the system modelled, e.g. the relata and relations under conditions of approximation and idealization. But the structure laws, if they are to represent quantum mechanical relations, can no longer be local laws (in the sense of Einstein locality), because of the existence of entanglement. Einstein conceded that underdetermination was a logical possibility but held that from the practical point of view of a working physicist there was always one superior theory at any one time. In Einstein’s synthesis this means that one theory, at that time, coped better with the constraints (empirical and theoretical) than rival theories: it fits better into the constraint space. In structural realism, as it emerges in the Special theory of relativity, the representational claims cover more than the empirical substructures. The theoretical structures are meant to represent the physical structures. The importance of reference frames in the Special theory of relativity meant that Einstein arrived at his own version of structural realism, in which both the relata and the relations of physical systems are granted independent reality, to which the models refer. Einstein held 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, p. 321, translated in Howard 1993, p. 238) The job of the theory is to describe and explain this physical structure by the introduction of appropriate models, which represent, with degrees of abstraction and idealization, the system of relata and relations. Einstein’s version of structural realism seems to require that both the relata and the relations have some representational force.

## Conclusion

The long arm of Kant’s Copernican revolution resonates in modern physical theories, because Kant had correctly identified the problem situation. Kant saw the problem of objective scientific knowledge as the problem of finding a synthesis between the principles of the rational mind and the store of phenomenal data, taken from an independently existing noumenal world. In modern physical theories, the synthesis takes a different form. The thesis of this paper has been that the freely chosen scientific constructs (rational element) manage to represent structural features of the natural world (empirical element), because these constructs are subject to powerful constraints. These constraints became particularly prominent in the theory of relativity, and later in quantum mechanics. The constraint space of these theories makes them extremely important from a philosophical point of view. The constraints are neither seen as mind-dependent nor as synthetic *a priori*. A look at Einstein’s constructive work – the theory of relativity – and his polemical work – his opposition to the Copenhagen interpretation of quantum mechanics – illustrates that constraints must remain testable in some sense, even though the theoretical constraints act in a quasi-Kantian capacity. But they are revisable and, as quantum mechanics shows, they may form a constraint space, a framework, which allows room for consistent alternative theories.

In terms of the synthesis between the rational and the empirical, Kant assumes the tightest fit between the presuppositional structure of the mind and the phenomenal world. Einstein sees a certain amount of latitude between the theoretical and empirical elements but his principle of covariance serves to reign in this latitude with respect to the physical laws, which govern inertial reference frames in the Special theory and general coordinate systems in the General theory of relativity. Einstein agrees that in science there may be incompatible theoretical models coping with the same empirical evidence. But by constructing his theory of relativity as a principle theory, with its characteristic constraints, he hopes to reach the most adequate model available at a particular moment in time by a process of elimination. It is in quantum mechanics that the latitude is greatest due to the abstract nature of the mathematical apparatus and the gap between the experimental results and their theoretical understanding. Nevertheless the concern for a synthesis between reason and experience is imposed by the constraint space of quantum mechanics. It would be a mistake to interpret this concern for fit in a naïve realist sense of a one-to-one mapping of the theoretical and empirical constituents. As we have seen, Einstein himself rejected such a 'plebeian illusion of naïve realism' according to which 'things „are" as they are perceived by us through our senses.' (Einstein 1944, p. 281)

Einstein never tired of reminding his readers that the rational mind can put order on the empirical data. He considered that the 'eternal mystery of the world is its comprehensibility.' It is not surprising that the mysterious comprehensibility reminded him of Kant. 'It is one of the great realizations of Immanuel Kant that the setting up of a real external world would be senseless without this comprehensibility.' (Einstein 1936, p. 292)

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