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ARTICLE

Einstein and the Laws of Physics

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ABSTRACT: The purpose of this paper is to highlight the importance of constraints in the theory of relativity and, in particular, what philosophical work they do for Einstein's views on the laws of physics. Einstein presents a view of local "structure laws" which he characterizes as the most appropriate form of physical laws. Einstein was committed to a view of science, which presents a synthesis between rational and empirical elements as its hallmark. If scientific constructs are free inventions of the human mind, as Einstein, held, the question arises how such rational constructs, including the symbolic formulation of the laws of physics, can represent physical reality. Representation in turn raises the question of realism. Einstein uses a number of constraints in the theory of relativity to show that by imposing constraints on the rational elements a certain "fit" between theory and reality can be achieved. Fit is to be understood as satisfaction of constraint. His emphasis on reference frames in the STR and more general coordinate systems in the GTR, as well as his emphasis on the symmetries of the theory of relativity suggests that Einstein's realism is akin to a certain form of structural realism. His version of structural realism follows from the theory of relativity and is independent of any current philosophical debates about structural realism.

KEYWORDS: Einstein, covariance, invariance, laws of nature, laws of physics, realism, relativity, structural realism, symmetries

1 Introduction

> "The great power possessed by the general principle of relativity lies in the comprehensive limitation which is imposed on the laws of nature (...)" (Einstein 1920, p. 99).

Physics is the description and explanation of the kinematic and dynamic behavior of physical systems. Einstein agreed with this characterization when he wrote:

"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, p. 97; italics in original; Einstein 1948, p. 321). In his writings, Einstein often speaks of the laws of nature. When he does so, it is always in connection with the way the laws of nature are symbolically formulated in physics. In accordance with philosophical custom we should distinguish between the *laws of nature* and the *laws of physics*. The laws of nature are the regularities, which exist in nature, irrespective of human awareness. The laws of physics are symbolic expressions of the laws of nature (Einstein 1949a, p. 68; Weinert 1993; Weinert 1995). In Einstein's understanding the laws of physics refer to the laws of nature. This basic distinction between the lawful regularities, which exist in nature, and their symbolic formulations in the language of mathematics, reflects Einstein's realist attitude of his later years. Einstein was a realist in the sense that he believed in the existence of an external world (Einstein 1922, p. 2; Einstein 1948, p. 321; Einstein/Infeld 1938, p. 296; Einstein 1949a, p. 81). This external world consists of objectively given objects and fields and their lawlike regularities (Einstein 1948, § 2). Einstein also says that physics deals with space-time events (Einstein 1949b, p. 6). But he also believed that scientific theories, including the laws of physics, were at all times subject to possible modifications. The empirical world provides the raw material, the rational mind imposes a structure on the empirical material. Not any structure will do, for the empirical world will resist the imposition of order that does not fit. How is this fit to be achieved? How can physics capture the "lawful structure" in nature? In a nutshell, Einstein's answer is: For the laws of physics to be expressions of the lawful regularities in nature, they have to satisfy certain constraints. These constraints must be imposed on the laws of physics, as the symbolic expressions of the laws of nature. The constraints are needed to ensure an acceptable degree of fit between the laws of physics and the laws of nature. The connection between scientific constraints and Einstein's views on physical theories and laws has not been explored in the literature. The purpose of this paper is to highlight this connection between physics and philosophy. In this process it will be possible to construct an account of the laws of physics out of the toolkit of Einstein's physics. To spell out this connection, we have to consider (a) Einstein's employment of constraints in the theory of relativity (Sections 2 and 3); (b) Einstein's view on structure laws, which lead to a structural view of laws (Subsection 4); (c) Einstein's version of realism (Section 5).

2 Physical Constraints

2.1 Einstein's Constraints

In his work Einstein appeals to a number of constraints. Constraints can be understood as restrictive conditions, which symbolic constructs must satisfy in order to qualify as admissible scientific statements about the natural world. If theories are free inventions of the human mind, as Einstein insists, there is a need for constraints to make them relevant to the external world. A *methodolog-*

ical constraint is the appeal to logical simplicity and unification in the choice of scientific theories. An *empirical* constraint is the demand that a scientific statement must conform to well-confirmed facts about the physical world. The empirical facts comprise Einstein's famous predictions: the redshift 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. A *theoretical* constraint is the demand that a scientific statement must be compatible with well-established mathematical theorems and physical principles. Einstein introduces relativity, symmetry and covariance principles as theoretical constraints. For a discussion of Einstein's views on the laws of physics, the methodological constraints are less important than the constraints associated with the theory of relativity. The insistence on constraints, which the physical laws must satisfy, is due to the enhanced importance of inertial frames in the Special theory of relativity. Inertial frames can be understood as idealized systems, which in the Special theory of relativity are constructed from measuring rods and synchronized clocks. Many physical properties, which were erstwhile regarded as absolute, become perspectival in this theory. Perspectival means that particular values of parameters can only be determined by taking the coordinate values of individual inertial frames into account. These coordinate values are read off synchronized clocks and rigid rods. These elements are allowed to vary from inertial frame to inertial frame. They lead, as we shall see, to a perspectival notion of reality. The prime examples are temporal and spatial measurements. These result in different coordinate systems, which describe the motion of the reference frames through space-time. The inertial frames are also related through the Lorentz transformation rules, which leave certain elements invariant. The prime example is the velocity of light. Also the general laws, "on which the edifice of theoretical physics is based, claim to be valid for every natural event" (Einstein 1918b, p. 109). We have, on the one hand, a large number of frames, between which only some properties remain invariant. On the other hand, the general laws of physics claim validity for every inertial and non-inertial system. To satisfy these demands, constraints come to hand. As the theory of relativity developed, Einstein imposed three constraints on the laws of physics; first relativity and symmetry principles, later his covariance principles.

2.2 Relativity Principles

In his famous 1905 paper Einstein used an explanatory asymmetry in classical accounts of induced currents to motivate his relativity principle. He complained that the then current view offered two different explanations for an observationally indistinguishable phenomenon. If a conductor is in motion with respect to a magnet at rest (in the ether), the electrons in the conductor experience a Lorentz force, which pushes them around the conductor, inducing a current. If the magnet is in motion with respect to the conductor at rest, the Lorentz force is no longer the cause of the current, for no Lorentz force applies to charges at rest. The time-dependent magnetic field now produces an electric field inside and outside the conductor, resulting in the same current. To avoid this kind of asymmetry of explanation – an asymmetry not present in the phenomena – Einstein required the physical equivalence of all inertial frames and the Lorentz invariance of Maxwell's equations. No inertial frame must serve as a preferred basis for the description of natural events. For this reason Einstein abandoned Newton's absolute space and time and 19^{th} century ether theories. Later he found that even his Special theory (STR) conferred an unjustifiable preference on inertial frames and Euclidean geometry. The General theory (GTR) extends the principle of relativity to all – inertial and non-inertial – systems. In its general form the principle states that all frames must be equivalent from the physical point of view. This extension is required if the theory of relativity is to include accelerated frames.

Generally, relativity principles stipulate the physical equivalence of frames or the indistinguishability of their state of motion. In particular, Einstein referred equivalence to the laws of motion. The laws which govern the changes that happen to physical systems in motion with respect to each other are independent of the particular system, to which these changes are referred (Einstein 1905, § I.2). In the General theory, the inertial frame no longer plays any particular part, having been replaced by general coordinate systems. The general principle of relativity reads: "All Gaussian co-ordinates are essentially equivalent for the formulation of the general laws of nature" (Einstein 1920, pp. 97–98; Einstein/Grossmann 1914, p. 216; Friedman 1983, Ch. IV.5; Earman 1974, p. 273).

As was pointed out, an inertial frame can be understood as an idealized system, in which only certain parameters are of interest, in particular parameters, which concern the state of motion of the system. In his 1905 paper Einstein defined inertial frames by a network of measuring rods and synchronized clocks. Within a particular inertial frame they are all at rest with respect to each other. To construct an inertial frame – "a mechanical scaffold" (Einstein/Infeld 1938, p. 156) – we need a system of finite rigid rods to indicate the three spatial dimensions. We then attach a number of synchronized clocks to the rods of the "scaffold". According to the Special theory of relativity, the clocks and rods will behave in distinct ways, depending on the state of motion of the frame. Rods will undergo length contraction and clocks will register time dilation effects in a frame that moves at high speed with respect to a stationary frame. This relativistic behavior of the clocks and rods will give us the spatial and temporal coordinates of a particular inertial frame (at rest or in motion).

In the GTR inertial frames are replaced by general coordinate systems because this theory is based on non-Euclidean geometry and accepts the non-uniform motion of the frames. Einstein illustrates the assignment of coordinates with a rotating disc thought experiment. We want to measure the ratio of circumference to diameter, C/D, on two discs, which are arranged in such a way that one disc is at rest and the other rotates uniformly with respect to it. In a Euclidean world we would predict that $C/D = \pi$ on both discs. But relativity demands that we introduce two frames. In the system at rest, K, $C/D = \pi$. But measured from this system, K, the ratio in the rotating system, K', will measure $C/D > \pi$. This inequality is due to the length contraction of the tangential rods placed along the circumference of *K'*. There is therefore a need for more general coordinate systems to discuss the behavior of clocks and rods in accelerated systems or gravitational fields. Because the rigid measuring rods and synchronized clocks can no longer be used in gravitational fields, arbitrary coordinate systems take the place of the inertial frames of the STR (Norton 1993, p. 836). Coordinate systems can be characterized as the "smooth, invertible assignment of four numbers to events in space-time neighborhoods" (Norton 1993, § 6.3; Earman 1974, p. 270; Landau/ Lifschitz 1975, p. 230; Lyre 2004, pp. 131–132; Stachel 1989, p. 65, p. 86). The use of more general coordinate systems will play a role in considerations of covariance. In a letter to Ehrenfest, dated December 26, 1915, Einstein declares that "the inertial frame signifies nothing real" (quoted in Stachel 1989, pp. 86–87). As in the STR the inertial frames were used to take temporal and spatial measurements, Einstein concluded that in the GTR space and time had lost "the last vestiges of reality" (Einstein 1916, § 3; Einstein 1949a, p. 67).

2.3 Invariance and Symmetries

Whether we consider inertial frames or arbitrary coordinate systems, there must be transformation rules between them. In the STR the transformation rules are expressed in the Poincaré group; in the GTR there are more general transformation groups, which no longer favor inertial frames. As they allow only dynamic objects, Einstein's desire to move beyond Minkowski space-time, with its fixed pseudo-Euclidean background, is satisfied. Every gravitational field represents a change of the spatio-temporal metric, which is determined by the functions g_{ik}. These functions determine the metric properties in curved coordinate systems. Einstein was one of the first physicists to appreciate the importance of symmetry principles in physics.

The symmetry principles of the relativity theory are related to invariance. Compared with the many types of symmetries, which are recognized today (global, local, external, internal, continuous and discrete symmetries, see Castellini 2003, Ch. 26.6; Kosso 2000; Martin 2003), Einstein only deals with space-time symmetries of a global (STR) or local (GTR) kind. The Lorentz transformations are global transformations: they are constant throughout space and time.

The Lorentz rules show how to transform coordinates x and t into x' and t'. However, in Minkowski space-time, the space-time interval, ds^2, remains the same in transitions between two inertial frames and is expressed by the invariant line element:

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2 \, . \tag{1}$$

Equation (1) captures Einstein's desire to call his theory "theory of invariants" rather than "relativity theory". The point about symmetries is that in a transition between inertial frames they return certain invariant parameters. But clock readings change between inertial frames in constant motion with respect to each other.

What about the laws of nature? If the laws of nature are to be the same in all coordinate systems, they must govern the invariants of the transformation groups.

That is, the laws of physics must express the invariant features as coordinate systems undergo space-time transformations. 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, p. 241; Einstein 1920, p. 95). As a material point moves through space-time its trajectory is marked by a large number of co-ordinate values x_1, x_2, x_3, x_4. It can equally well be described in terms of 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 coincide that they "have a particular system of coordinate values x_1, x_2, x_3, x_4 in common" (Einstein 1916, p. 86; Einstein 1920, p. 95). In terms of observers, attached to different coordinate systems, it is at such points of intersection that they can agree on the temporal and spatial measurements. This is Einstein's point-coincidence argument. As we shall see, Einstein regards the equivalence of different coordinate systems – $\mathrm{d}x, \mathrm{d}x'$ – as an argument for general covariance (Einstein 1916, § 3; see Norton 1993, § 3.5; Stachel 1989, p. 87). From this argument, many physicists, including Einstein, concluded as a philosophical consequence of the symmetries of the relativity theory that only the invariant can be regarded as the physically real. This may be dubbed the "invariance view of reality" (Weinert 2004b, Ch. 2.8).

2.4 Perspectival Reality

Is it true that only the "invariant is real"? What happens, say in the STR, to the clock and meter readings in particular inertial frames? Should we conclude that these events are "unreal" in the respective inertial frames? This would be unwise because the situation does not depend on perceptual relativity. Different systems in motion with respect to each other measure different values for rod lengths and clock times. These measurements do not depend on what observers perceive. Rather for the observers in the respective systems, these measurements have *perspectival* reality. Observers in time-like related frames, moving at a constant velocity with respect to each other, can observe that their clocks ticks at different rates and their measuring rods do not measure the same lengths. The ticking rate of the clocks and the behavior of measuring rods show that perspectivalism is not observer-dependent but frame-dependent. It depends on the behavior of rods and clocks in particular frames. For instance, in the famous Maryland experiment (1975–76), atomic clocks were put on 15-hour-flights. When they were compared to earth-bound, synchronized clocks, it was found that the air-born clocks had experienced time dilation – they had slowed down by 53ns. The perspectival realities of physics are the result of a combination of frame-dependent and frame-independent parameters of inertial frames. For the different inertial frames are held together by four-dimensional Minkowski space-time.

If we adopt perspectival realities, what becomes of the physicist's criterion that *only* the invariant is to be regarded as real? The adoption of perspectival, frame-dependent realities does not contradict the invariance criterion of reality. The Minkowski space-time structure has both invariant and perspectival aspects. In Minkowski space-time, the non-tilting light cones, emanating from every space-time event, are invariant for every observer. The space-time interval, ds, is invariant across inertially moving frames. The particular perspectives then result from attaching clocks and rods to the "scaffolds". That is, they result from the particular "slicing" of space-time by the world lines of inertial systems in relative, constant motions with respect to each other. The symmetries tell us what remains invariant across inertial frames, and what is variable. Once we know that the laws remain invariant across different inertial frames, we can derive the perspectival aspects, which attach to different inertial frames, as a function of velocity. Such a modified view of physical reality can be derived from the Minkowski presentation of the theory of relativity. Max Born compared the perspectival realities to projections, which must be connected by transformation rules to determine what remains invariant. The projections are reflections of frame-dependent properties. But there are also frame-independent properties, which are invariant 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, p. 144).

The Lorentz transformations show, Born adds, that perspectival 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, p. 144). We can therefore see that perspectivalism and invariance are two faces of symmetries (Weinert 2004a).

2.5 Active and Passive Transformations

The relativity principles state that all inertial and non-inertial frames are to be treated as equivalent from a *physical* point of view. The invariance principle states that symmetry transformations performed on inertial frames must return some values of parameters as invariant. But how can we make sure, asks Weyl, that the laws of nature remain "invariant with respect to arbitrary coordinate transformations?" (Weyl 1924, p. 197). To see the need for a further constraint, at which Weyl hints, consider the distinction between *active* and *passive* transformations. The active interpretation of the transformation rules means that the inertial frames themselves experience a physical change – a translation or rotation, which leaves certain invariants. The passive interpretation means that we keep the physical system fixed and merely change the coordinate system, from which the system is described. Intuitively, we would agree that a mere change of coordinates will not affect the lawful regularities, which govern the behavior of the system. The laws must retain their form whether they are considered from different coordinate systems or described in different mathematical languages. This intuition reflects Einstein's demand that the laws of physics remain "covariant" with respect to different coordinate systems of the theory of relativity.

3 Mathematical Constraints

3.1 Covariance

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.

He 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 1949b, p. 8; Einstein 1950b, p. 346) and **(b)** to general transformations of the coordinate systems (general covariance in the General theory; Einstein 1920, pp. 54–63; Einstein 1950b, p. 347). The theory of relativity will only permit laws of physics, which will remain covariant with respect to these coordinate transformations (Einstein 1930, pp. 145–146). This means that the laws must retain their form ("Gestalt") "for coordinate systems of any kind of states of motion" (Einstein 1940, p. 922). They must be formulated in such a manner that their expressions are equivalent in coordinate systems of any state of motion (Einstein 1916; Einstein 1920, pp. 42–43, 153; Einstein 1922, pp. 8–9; Einstein 1940, p. 922; Einstein 1949a, p. 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.

Einstein often illustrates covariance with respect to the space-time interval $\mathrm{d}s^2$ (Einstein 1922, p. 28, p. 61), e.g. the form invariance of the expression

$$\mathrm{d}s^2 = \mathrm{d}s'^2 \, . \tag{2}$$

Expression 2 remains form-invariant under a substitution of coordinate system, K, into another quasi-Euclidean coordinate system, K', as indicated by the coordinates $\mathrm{d}x, \mathrm{d}x'$ etc. An essential insight of the General theory was that Minkowski space-time still remains quasi-Euclidean, since it does not take into account the presence of gravitational fields. The equivalence principle allowed Einstein to make the step to a general principle of relativity. When gravitational fields are introduced, the space-time interval, $\mathrm{d}s^2$, assumes the more general form

$$\mathrm{d}s^2 = g_{ik}\mathrm{d}x^i\mathrm{d}x^k = 0 \, , \tag{3}$$

where the g_{ik} are functions of the spatial coordinates x^1, x^2, x^3 and the temporal coordinate x^0.

It is now this more general relation, which must remain covariant with respect to "arbitrary continuous transformations of the coordinates" (Einstein 1950b, p. 350; Einstein 1920, p. 154). It is however possible to recover Eq. (1). In an inertial system with spatial Cartesian coordinates $x^{1,2,3} = x, y, z$ and temporal coordinate

$x^0 = ct$, the functions g_{ik} become $g_{00} = -1, g_{11} = g_{22} = g_{33} = +1$ and $g_{ik} = 0$ for $i \neq k$.
Einstein takes the equivalence of all coordinate systems as a reason to require a general covariance principle for the formulation of the laws of nature. Here equivalence does not mean physical equivalence of frames but equivalence of theoretical expressions. For we have seen that the laws must retain their *form* if we substitute the space-time variables of K for those of K'. But if in K the speed of light is c, and K is transformed into K' such that the value of c is not returned, then the law has not retained its form. The general laws of nature are to be expressed by equations, which hold good for all systems of coordinates, that is, are covariant with respect to any *substitutions* whatsoever (generally covariant; Einstein 1916, p. 83; quoted in Stachel 1989, p. 87; see also Einstein 1930, p. 146; Einstein/Grossmann 1914, pp. 215–256).
The criterion of substitution serves as a more general characterization of covariance; it applies also to models of space-time theories. Such models can be represented in the general form $\langle M, O_i \rangle$, where M represents the differentiable manifold of space-time points (the topology of space-time in local neighborhoods) and the O_i's represent various geometric objects, like the spatio-temporal metrics, which differ between STR and GTR.

Definition 1 *The laws of a theory T are covariant for a set of coordinate systems CS, if and only if for any particular coordinate system cs ($cs \in CS$) and any particular dynamic model m = (M, O_1, $O_2 \ldots O_n$), which is a member of the set of dynamically possible models M_T^D, the laws of T hold when the cs-coordinate components of the geometric object field O_i' (on the manifold M) are substituted into these laws.*[1]

Under the substitution criterion the laws retain the same form in all particular coordinate systems, *cs*, in the set *CS*. The substitution criterion explains why covariance has often been thought of as "empty of physical content" (Weinberg 1972, p. 92; Kretschmann 1917). It seems to be merely a mathematical operation. Einstein however insisted, as we shall see below, that covariance "had heuristic value". We can shed some further light on this question by asking, "What does form invariance mean?" Recall that Einstein regards the equivalence of different coordinate systems – $\mathrm{d}x, \mathrm{d}x'$ – as an argument for general covariance. If we look at the various expressions used in the examples, we see that they do not retain their symbolic forms. They may not even retain their syntactic form as we can transform from Cartesian to polar coordinates. The following idea suggests itself: covariance expresses the requirement that different symbolic expressions of the laws of nature express the same propositional content. The propositional content expresses an objective fact about the real world, which remains unaffected by the choice of different symbolic formulations (the linguistic expressions "Morning Star" and "Evening Star" share the same referent: the celestial object Venus).

[1] Adapted from Definition 3 of Earman (1974), p. 278; see also Friedman (1983), p. 51; Norton (1989), p. 1241; Lyre (2004), pp. 129–132.

A change in symbolic form should not change the objective relations, which the laws express. Form invariance therefore means that the space-time relations, expressed in different theoretical expressions, remain objective, i.e. they retain their propositional content (see Kosso 2003; Scheibe 1981; Scheibe 1991; Earman 1974, p. 287). As Einstein often stressed we are free to choose our symbolic expressions or coordinate systems, whether they are physical theories, laws or axioms of geometry.

If covariant equations share the same referent so that they remain equivalent under the criterion of substitution, what can we say about the referent of the laws of physics? Einstein's notion of structure laws will help us clarify this issue. But let us first consider some complications.

3.2 Complications

Einstein himself was not always clear about the precise status of the covariance principle. Confusingly, Einstein associates general covariance both with invariance under non-linear transformations and the general principle of relativity. For instance, he characterizes the principle of relativity as a covariance principle: the laws of nature are statements about space-time coincidences; they find their natural expression only in covariant equations (Einstein 1918a, p. 241).[2]. When he turns to the General theory he considers that from a formal point of view the "admission of non-linear coordinate transformations" is a "mighty enlargement of the idea of invariance, i.e. the principle of relativity" (Einstein 1949b, p. 10; see also Einstein 1920, pp. 97–98; Einstein 1922, p. 60).[3]

In these formulations Einstein runs together several constraints on laws, which more recent scholarship has kept apart (Norton 1989; Norton 1992; Norton 1993; Norton 2003; Friedman 1983; Scheibe 1981; Scheibe 1991; Stachel 1989; Stachel 1993). Einstein thought of relativity principles as requiring the physical equivalence of all frames. Wigner described the Lorentz transformations as geometric symmetry transformations, which carry one inertial frame into another. A Lorentz transformation of a inertial frame K into K' returns some invariant properties. In Minkowski four-dimensional space-time the Lorentz transformations become rotations of the coordinate axes, from t to t' and from x to x' through some angle, α. The tangent of α indicates the speed of the x'-t'-system with respect to the x-t-system. But if covariance is understood as form invariance, then it should be distinguished from both relativity principles and symmetry invariance.

[2] On can see why Einstein is tempted to treat the general relativity principle as a covariance principle: where space-time events coincide, the coordinate values coincide too, so the substitution from K to K' is covariant. The covariant expressions are equivalent, just as the frames K and K' are treated as physically equivalent (see Norton 1992, p. 298).

[3] One can see why Einstein is tempted to associate transformations with (form) invariance: the substitution under arbitrary transformations does not change the form of the law; and according to the principle of relativity inertial frames are equivalent from a physical point of view; across these frames the laws are invariant, but this is symmetry invariance, not form invariance.

(A) Although Einstein treated the covariance principle as an extension of the general relativity principle, it does not guarantee the relativity of all kinds of motion. The "sameness of form" is too weak to guarantee "physical equivalence" of systems in motion. (Friedman 1983, p. 206–208; Landau/Lifschitz 1975, § 82; Dieks 2006, p. 183, p. 186). Covariant formulations of space-time theories may retain privileged inertial frames. Newtonian mechanics can be reformulated in terms of neo-Newtonian space-time theory; its symmetry group is the Galilei group. In neo-Newtonian space-time the notion of absolute space has become superfluous but it still requires the notion of absolute time, absolute simultaneity planes and Euclidean inertial frames. Covariant formulations of the STR abandon the notion of absolute time but retain relative quasi-Euclidean simultaneity planes. As Einstein recognized, the STR still displays a preference for inertial reference frames. Space-time itself is a rigid background, which acts on the inertial systems but nothing acts on the structure of space-time.
(B) Covariance is not a symmetry principle in the sense of the Lorentz transformations, which transform the reference system under consideration, while retaining some invariant parameters. It is true that covariance produces *form* invariance and therefore equivalence between theoretical expressions. But it is symmetry of the mathematical formulations, a redescription, not a transformation of the inertial frames (as idealized systems) under space-time transformations. Covariant formulations of space-time theories exist, which admit of different degrees of invariance. Consider, for instance, geometric formulations of Newtonian and neo-Newtonian space-time, respectively:

$$\left\langle \mathbb{R}^3, t, h, A, \nabla \right\rangle \tag{4}$$

($\mathbb{R}^3$ is the Euclidean manifold, t and h stand for temporal and spatial metrics, A defines the special reference frame of absolute space and ∇ defines the affine connection); in neo-Newtonian space-time absolute space is shown to be superfluous because of the Galilean relativity principle:

$$\left\langle \mathbb{R}^3, t, h, \nabla \right\rangle \ . \tag{5}$$

In Newtonian space-time it is possible to define "sameness of place at different times", indicating the postulation of absolute space; this is no longer possible in neo-Newtonian space-time. Formulations (4) and (5) are covariant, but in (5) the invariance of "place at different times" is lost (see also Earman 1974, pp. 276–277; Norton 1993, § 5.4; Scheibe 1981, pp. 457–458).
To distinguish form invariance (covariance) from symmetry invariance we could just say that it is the difference between a formal (passive transformation) and a physical aspect (active transformation; Norton 1993, § 2.3, § 6). But there is more to covariance than the demand for the equivalence of theoretical expressions. The expressions must be objective: they must have the same referent. This complicates matters, since covariance, introduced as a mathematical constraint, acquires physical significance in an indirect way (Lyre 2004, pp. 131–132; Norton 1989, § 4.3; Norton 2003; Norton 1992).

Einstein was very aware that the covariance constraint involved a link of the laws with the world of experience. In his defense against Kretschmann's objection that covariance was physically vacuous (Kretschmann 1917) he points out that the principle of covariance has heuristic value. It points us in the direction of the most logically coherent theory, to the simplest system of laws. For nature is the realization of mathematical simplicity (Einstein 1918a, p. 242; Einstein 1933, pp. 116–117; Einstein 1949a, p. 68; see also the discussion of covariance in Misner/Thorne/Wheeler 1973, §§ 3.3–3.4, §§ 12.4–12.5). This is of course the expression of a metaphysical belief. Later Einstein sees more clearly the link between covariance and objectivity. First to ensure "simplicity" there is the need for covariance:

> "The theory of relativity arose out of efforts to improve, with reference to logical economy, the foundation of physics as it existed at the turn of the century. The so-called special or restricted relativity theory is based on the fact that Maxwell's equations (and thus the law of propagation of light in empty space) are converted into equations of the same form, when they undergo Lorentz transformation" (Einstein 1940, p. 922).

This ensures that the laws continue to hold under (Lorentz) substitutions, that they are objective statements about the external world. But form invariance is not a sufficient condition to restrict the contents of the laws. The formal property must be enhanced.

> "This formal property of the Maxwell equations is supplemented by our fairly secure empirical knowledge that the laws of physics are the same with respect to all inertial systems" (Einstein 1940, p. 922; Earman 1974, p. 272).

Here Einstein clearly refers to the empirical issue of objectivity, i.e. he links covariant equations to symmetry invariance. The inertial frames can be subjected to Lorentz transformations; in crossing over from K to K' the laws retain their form; the transformations and the resulting invariances can be observed. Lorentz invariance is testable, which indirectly confirms form invariance (see Kostelecký 2004; Bluhm 2004; Kraus et al. 2002). Although the mathematical expressions are free to change, they must change within the constraints of what the lawful regularities in nature allow us to express. In this sense covariant equations have empirical significance.

3.3 Modern Considerations

Covariance is not tied to transformations between inertial frames; it is quite general. On the modern understanding, the laws of nature can be expressed in different mathematical languages. We can express geometric properties in Cartesian and polar coordinates. Modern space-time theories are expressed in terms of sets of geometric models of the form $\langle M, O_i ... O_n\rangle$. We can express the equation of motion of the geodesics in coordinate-dependent language as

$$\frac{d^2 x_i}{du^2} = 0 \ , \tag{6}$$

where Eq. (6) is expressed in terms of a coordinate system $\langle x_i\rangle$ in flat space-time. In coordinate-free language, the equivalent equation is:

$$D_{T_\sigma} T_\sigma = 0 \ . \tag{7}$$

where D_{T_σ} is a derivative operator or affine connection and T_σ is a tangent vector field (Friedman 1983, pp. 38–9).
The modern view of covariance is **(a)** that laws can be expressed in different – coordinate-dependent and coordinate-independent – ways or **(b)** that covariance can be understood generally as the equivalence of formalisms.
Ad (a) M. Friedman (Friedman 1983, pp. 50–54) first considers covariance in coordinate-dependent formulations, which Einstein had at his disposal. Introduce a system of differential equations in $\mathbb{R}^4$:

$$D\left(\Phi^\alpha, \Theta^\beta\right) = 0 \ , \tag{8}$$

where $\Phi^\alpha, \Theta^\beta$ are objects on the manifold.
A system of equations is said to be *covariant* under the *coordinate transformation* from $\langle x_i\rangle$ to a second coordinate system $\langle y_j\rangle$ just in case the same class of models of the form $\langle M, \Phi, \Theta\rangle$ is picked out relative to $\langle y_j\rangle$. That is,

$$D_{\langle x_i\rangle}\left(\Phi^\alpha_{\langle x_i\rangle}, \Theta^\beta_{\langle x_i\rangle}\right) = 0 \tag{9}$$

if and only if

$$D_{\langle y_j\rangle}\left(\Phi^\alpha_{\langle y_j\rangle}, \Theta^\beta_{\langle y_j\rangle}\right) = 0 \tag{10}$$

Then he turns to a coordinate-free characterization of covariance. The coordinate transformations are replaced by manifold transformations h[4]: “one-one, suitably continuous and differentiable mappings of a neighborhood of M into M”. This changes the geometrical objects from Θ to $h\Theta$, rather than the components of the geometrical object from $\Theta^\alpha_{\langle x_i\rangle}$ to $\Theta^\alpha_{\langle y_j\rangle}$. Take again a system of differential equations (8) in $\mathbb{R}^4$. Relative to $\langle x_i\rangle$ it picks out a class of models $\langle M, \Phi, \Theta\rangle$. The system of equations is “said to be *covariant* under the *manifold transformation* h just in case $\langle M, h\Phi, h\Theta\rangle$ is also a model, relative to $\langle x_i\rangle$, for each $\langle M, \Phi, \Theta\rangle$”. That is,

$$D_{x_i}\left(\Phi^\alpha_{\langle x_i\rangle}, \Theta^\beta_{\langle x_i\rangle}\right) = 0 \tag{11}$$

if and only if

$$D_{x_i}\left(h\Phi^\alpha_{\langle x_i\rangle}, h\Theta^\beta_{\langle x_i\rangle}\right) = 0 \tag{12}$$

[4] Such smooth mappings are known as diffeomorphisms.

for all Φ, Θ on M (see also Norton 1989, §§ 2.4–2.5).
Ad (b) E. Scheibe tries to come to grips with the notion of covariance by first introducing the notion of "species of structures", which refers to the mathematical objects of the formalism (topological spaces, differentiable manifolds, Hilbert spaces); secondly by introducing the concept of equivalence of species of structures, i.e. covariant versions of a theory must be equivalent to the original one. The aim is to "present covariance not as any kind of invariance but rather as a concept of equivalence between two formulations of a physical theory that are already invariant, one of which, however, has a higher 'degree' of invariance than the other" (Scheibe 1981, p. 311; Scheibe 1991). Scheibe's notion of the equivalence of theoretical expressions, which we have used above, captures Einstein's criterion of substitution. Instead of insisting on "form invariance", it also expresses the objectivity assumption, which we associated with covariant expressions of the laws of physics.

4 Laws of Physics

We have encountered several constraints on the laws of physics: covariance, invariance and relativity principles. Under Einstein's realist assumptions, the laws of physics are at least approximate expressions of the laws of nature, if they satisfy these constraints.

4.1 Einstein's Structure Laws

When Einstein says that the laws of physics express the lawful regularities in nature, what exactly does he mean? Einstein does not directly address this question. But an answer is embedded in the constraints, which Einstein imposes on the laws. The laws of relativistic physics generally express the behavior of physical systems. In the STR they can be represented as idealized inertial systems. A consideration of the STR strongly suggests that science deals with physical systems, not individual happenings. Science is interested in physical events represented as the interaction of idealized systems. But physical systems are manifestations of structure. Physical systems display structure: they consist of relata and relations, the constituents of a system and how they are related. The relations between the constituents are often expressed in the laws of physics. The laws play an essential part in determining the behavior of physical systems. The idealized systems model only certain structural aspects of the natural system. For instance, the inertial frames of the STR concentrate on kinematic relations. So we should expect the laws of physics to express structural properties of physical systems. The laws express the (invariant) relations between the constituents of the structure. In his philosophical writings Einstein usually emphasizes the importance of a tight fit between the laws and experience: the world of experience practically determines the theoretical system (Einstein 1918b, p. 109). He also appeals to notions like simplicity. In the development of the theory of relativity he imposes further constraints on the laws of physics. They must satisfy the light postulate, relativity principles and the covariance principles. The constraints Einstein imposes on the laws of physics are necessary to keep a relatively close fit between the rational and the empirical, between the symbolic expressions and what they express (Einstein 1918b, p. 109; Einstein 1919, p. 131; Einstein 1950b, p. 350; Miller 1998, Ch. 2). In this way Einstein hopes to satisfy the objectivity criterion, which is attached to the laws of physics.

What does "fit" mean? Our consideration of constraints suggests that "fit" should be explicated in terms of constraints. A scientific model or law "fits" its domain, if it satisfies a number of constraints.[5] The most obvious requirement is that the theoretical system should be compatible with the empirical constraints. But as the development of the theory of relativity has shown, Einstein felt compelled to introduce further constraints, in particular, the constraints associated with the theory of relativity. We can think of the idea of "fit" – understood as satisfaction of constraints – as an extension of the "best matching" of graphs to empirical data. A set of data may satisfy, say, a quadratic equation. If we go beyond empirical constraints, as the theory of relativity does, we say that a scientific theory "fits" an empirical domain if it satisfies a number of constraints. Einstein's view was that the one theory, which best copes with all the constraints – the restrictive conditions imposed on scientific constructs – was the theory of relativity. By contrast, Lorentz's account of time dilation and length contraction postulates an absolute rest frame and therefore violates the constraint of relativity. This view will be important in our consideration of Einstein's realism (Section 5).

According to Einstein and Infeld, the equations of the theory of relativity and electrodynamics can be characterized as *structure laws* (Einstein/Infeld 1938, pp. 236–245). In the authors' view structure laws apply to 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 connect events, which happen now and here with events which will happen a little later in the immediate vicinity" (Einstein/Infeld 1938, p. 236). 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 equations of quantum mechanics determine the probability wave. "Quantum physics deals only with aggregates, and its laws are for crowds and not for individuals" (Einstein/Infeld 1938, p. 289). Einstein submits that structure laws have the form "required of all physical laws" (Einstein/Infeld 1938, p. 238, p. 243). Einstein derives his view of structure laws from the problem situation, into which the theory of relativity had led him. Wigner was similarly aware of the importance of structure "in the events around us,"

[5] This proposal assumes that the constraints are fairly robust and valid for a certain domain, as proved to be the case in the theory of relativity. A complication arises, if the "wrong" constraints are imposed, as for instance in Aristotelian views of motion in geocentric theories of the solar system or in 19^{th} century ether theories of electromagnetism. The wrong constraints will either hinder or decrease the representational fit of the laws and models. A sufficient condition for fit may well be that the constraints must be independently justifiable and testable (see Weinert 2006).

> "that is correlations between the events of which we take cognizance. It is this structure, these correlations, which science wishes to discover, or at least the precise and sharply defined correlations" (Wigner 1967, p. 28).

Wigner emphasizes that the correlations between events can be mathematically determined; it is the mathematical determination, which provides the structure of the correlation. Generalizing the Einstein-Infeld-Wigner view we can therefore say that structure laws express how the components (or relata) of physical systems are mathematically related to each other. Apart from space-time events, the relata may refer to objects like planets (as in Kepler's laws), electromagnetic or gravitational fields or the wave function, ψ (as in the Schrödinger equation). 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, p. 321, transl. Howard 1993, p. 238).

Through the insistence on constraints, imposed on scientific constructions to improve their "fit" with reality, and the views on structure laws Einstein's work hints at a *structural view of laws*. His views on structure laws agree quite closely with similar views expressed by Karl Popper.[6]

4.2 A Structural View of Laws

Popper's view on laws of nature was influenced by his falsification criterion. If we conjecture that a certain statement 'a' expresses a natural law, Popper writes,

> "we conjecture that 'a' expresses a structural property of the world; a property which prevents the occurrence of certain logically possible singular events" (Popper 1959, p. 432).

According to Popper, natural laws express certain structural properties about the physical world, and forbid others. The laws forbid perpetual motion machines and superluminary velocities. Popper puts particular emphasis on the prohibitive nature of the laws because of his concern with falsification procedures. Theoretical statements in science are for Popper falsifiable conjectures. For Popper a universal law asserts impossibility. The converse of Popper's view is that laws not only forbid, they also enable physical events. As Einstein put it, the laws express the structure of physical systems, like electromagnetic and gravitational fields, as well as probability waves. The structural aspects of natural systems, quite generally are expressed in the laws of physics. This philosophical conception of laws is

[6] This is not the only philosophical agreement between Einstein and Popper. Einstein also agrees with Popper that inductive generalizations will not lead to the field equations of the theory of relativity. Theory has priority over observational data. In his "Autobiographical Notes" Einstein observes about the discovery of the equations of the gravitational field: "No ever so inclusive collection of empirical facts can ever lead to the setting up of such complicated equations. A theory can be tested by experience, but there is no way from experience to the setting up of a theory" (Einstein 1949a, p. 89).

interesting because it remains close to how practicing physicists like Einstein use symbolic law expressions. A structural view of physical laws states that laws express structural features of physical systems. They express how the relata – the components of the system structure – are related to each other in a lawlike manner – the relations. Physical systems do not exist isolated in the world. They form part of larger, interrelated networks of systems and regularities. This interrelatedness is inherent in the logic of inertial frames. The transformation groups of the theory of relativity capture precisely what happens as we move between inertial frames or more generally coordinate systems. This extension of the structure from smaller to larger systems has occurred in the transition from the STR to the GTR in several steps: first, the structure of an inertial frame is described; this consists of the use of rigid rods and synchronized clocks, how their readings change as we go from unprimed to primed frames, according to the Lorentz transformations, and how certain parameters remain invariant; later the structure of this inertial system is embedded in larger coordinate systems, covering both inertial and non-inertial motion. The job of science is to formulate laws, which will express such structural features. A structural view of the laws of physics emphasizes three points (Weinert 1993; Weinert 1995, pp. 48–52).

- Laws do not refer to individual objects, or to particular properties of objects: in Einstein's words, "they connect space-time events"; more generally they connect the relata.
- Laws refer to structures. They express structural properties of physical systems: in Einstein's words, "the equations determine physical fields"; more generally, they express mathematical relations between the relata of the systems.
- The structures of physical systems consist of relations and relata. In the theory of relativity they are symbolized either as idealized inertial frames or more generally as arbitrary coordinate systems. They are related through the transformation groups. "In all inertial CS the same laws are valid and the transition from one CS to another is given by the Lorentz transformations" (Einstein/Infeld 1938, p. 189; Einstein 1920, p. 150).

As Einstein emphasized, the laws of physics have important epistemological components. Quite generally, they can be corrected and improved upon, as Einstein's work demonstrates. More specifically, we have learned from Einstein that in order to improve the fit between laws of physics and laws of nature, a number of constraints must be imposed on the symbolic expressions of laws. How do these constraints look from the point of view of a structural view of laws?
(1) Einstein imposed his relativity principles as a *first* constraint on the laws of physics. The structure laws must describe the changes that happen to a physical system, K, just as well as from the point of view of any system, K', that is physically equivalent to it.

> "If two coordinate systems are in uniform parallel translational motion relative to each other, the laws according to which the states of a

> physical system change do not depend on which of the two systems these changes are related to" (Einstein 1905, § I.2; translated in Brown 2005, p. 74).

The operation must lead to quantitatively identical results, because the systems are physically indistinguishable. If this does not happen we are entitled to conclude that our theoretical generalizations about the natural world are mistaken. If we express the general laws on the basis of Galilean inertial frames and Euclidean geometry, we may experience a misfit between our theories and the world, as in the case of the rotating discs. How can this misfit be avoided? Einstein demanded more general coordinate systems. The mathematical *form,* which the laws of physics assume in these coordinate systems, must still express the structure of corresponding sections of an independently given physical world. The claim is that the laws of physics will accurately represent regularities in nature if they satisfy the constraints imposed on them. For the general coordinate systems, Einstein demanded the satisfaction of the covariance constraint besides the other constraints and the adoption of Riemannian geometry. If they satisfy the constraints, their mathematical *form* will reveal important structural features about the natural world.[7] For instance a quadratic equation of motion tells us that physical systems in motion obey this form, and not others. The constraints will increase the fit between our theories and the world. The first constraint makes sense from a structural view of laws: it cannot be the case that the structural relations change with respect to a change of the inertial frame. Einstein said so himself in his 1905 paper when he complained that induced currents should not lead to different explanations depending on whether the conductor or the magnet was in motion. If there are any perspectival warps, due to particular coordinate values, they do not prevent us, as we have seen, from recovering the invariant structural relations.

(2) The second constraint was symmetry invariance. If laws of physics express the physical properties of natural systems, in symbolic form, and how these systems are related to each other, then symmetries express constraints on the laws. Wigner held that "there is a structure in the laws of nature, which we call the laws of invariance" (Wigner 1967, p. 29). Symmetries become structural constraints, for they determine the invariant parts of the structure, as inertial frames and coordinate systems are subjected to transformations. Although there are many forms of symmetries, here we only need attend to the geometric global or local space-time symmetries. The space-time laws must obey the symmetry constraints, in order to guarantee the invariances of the space-time structure. Einstein uses this procedure to show:

(a) The Galilean transformation rules are invalid in non-classical domains, for they give the wrong values for the measurement of c from the point of view of two equivalent inertial systems. Consider two observers, one in a system at rest, K, one in constant motion with respect to the first in frame K' who want to measure the speed of light. They need to adopt the

[7] For a similar line of argument regarding causal equations, see Woodward (2003), p. 335.

Lorentz transformations to determine that they have measured the same value respectively.

(b) If non-inertial frames are to be regarded as equivalent to inertial ones, as the general principle of relativity demands, this has consequences for geometry. If the ratio of C/D in a system, K', rotating uniformly with respect to a system at rest, K, is greater than π from the point of view of K, we can no longer retain Euclidean geometry for space-time (Einstein 1920, pp. 80–81; Einstein 1922, pp. 58–59; Einstein 1930; Saunders 2003, § 16.4).

(3) Einstein's final constraint was covariance. In the words of Hermann Weyl, "two systems of reference are equally admissible if in both of them all universal geometric and physical laws of nature have the same algebraic expression" (quoted in Brading/Castellani 2003, p. 21). On the one hand covariance gives us the freedom to express the laws in a number of theoretically equivalent coordinate systems. On the other hand the covariance principle imposes a constraint on the admissible forms of laws. Form invariance suggests that through the equivalence of expressions the laws of physics convey structural information about the natural world. Many equations of motion take a quadratic form. Although we can use Eqs. (6) or (7) to express the equation of motion in space-time, both expressions give us structural information concerning a particle's inertial motion. This structural information must be gleaned from the symbolic expressions but it resides in what they express. It resides in their referent or propositional content. Covariance in these terms is the constraint that the symbolic formulations of the laws of physics must retain the same physical referents. It is therefore vital that equations of motion for a restricted domain can be shown to be limiting cases of a larger domain, as the correspondence principle demands. This procedure is applied in the transition from Eq. (2) to Eq. (3). It can also be shown that coordinate-dependent formulations of laws mathematically correspond to coordinate-free formulations (Friedman 1983, Ch. II.1). It is the "sameness of reference" of covariant equations, which makes them objective. In fact, as Rosenthal-Schneider noted long ago "general covariance is not a sufficient condition for the admissibility of an equation as an expression of a law of nature, but combined with simplicity and compatibility with experience it has great heuristic value" (Rosenthal-Schneider 1949, p. 138, Fn. 18; cf. Norton 2003). Covariance therefore points, indirectly, to the question of realism.

5 Einstein and Realism

Running through the discussion of Einstein and the laws of physics is the question of Einstein's realism. It is generally agreed that Einstein's position shifted from an early sympathy for positivism to a later commitment to realism (Holton 1965; Fine 1986; Scheibe 1992, p. 119; but see Howard 1990; Howard 1993). But which form of realism? Many different versions of realism have been proposed in philosophy (Psillos 1999; Falkenburg 2007). The discussion so far suggests that

Einstein embraced some form of critical realism. This position 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 a number of empirical and theoretical constraints. The critical realist need not claim that the theories and its laws are true mirror reflections of the world and its regularities. There only needs to be the objectivity assumption that laws of physics are good approximations and idealizations of nature's regularities. The laws express invariant, not perspectival aspects. But if the laws are projected into particular inertial systems, perspectival aspects of the kinematics of reference frames result. Physical laws are symbolic, idealized representations of nature's laws. Einstein's critical realism is to be understood in a broad sense of a synthesis of the rational and the empirical, not in the specific sense in which this term was used by some philosophers in the 1920s (see Hentschel 1990, Ch. 4). Nevertheless some philosophers have recently stressed that it is more accurate to see Einstein as a holist. For the purpose of assessing this view, it is appropriate to distinguish two versions of holism: **(a)** a weaker version holds that a scientific theory is like a coherent conceptual web and that it is not possible for empirical evidence to target specific elements in this theory; Einstein had sympathies for this view (Howard 1990; Howard 1993). There is also a stronger version **(b)** according to which there exist logically incompatible theories, which nevertheless are equally compatible with the evidence. Such a holist attitude towards scientific theories leads to a softer form of realism in the sense of empirical adequacy (Fine 1986; Howard 1990; Howard 1993; Howard 2004; Lyre 2004, pp. 49–55). Einstein accepts that, from a logical point of view, arbitrarily many "equivalent systems of theoretical physics are possible". Yet, he insists that from a practical point of view, history has shown that one system usually proves to be superior (Einstein 1918b). Einstein employs the analogy of a crossword puzzle to make his point. The liberty of conceptual choice, which the physicist enjoys, is that of "a man engaged in solving a well designed word puzzle. He may, it is true, propose any word as the solution; but there is only one word which really solves the puzzle in all its forms" (Einstein 1936, p. 21; Scheibe 1992, p. 130). Given Einstein's insistence on the "rigidity" or coherence of physical theories, despite the freedom to invent theoretical concepts, it is doubtful that Einstein was sympathetic to the stronger version of holism.

A problem with the holist interpretation (b) is that it neglects the importance of constraints in Einstein's work. 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 compatibility is achieved, we suggested, through the introduction of constraints. If there is indeed a fit between what the theory says and what the material world presents, the question of realism returns. 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 best fit. Einstein did not believe that many alternative representations of the empirical world could be sustained. He goes even further: he believes that there is one "correct" theory at any particular moment in time. This must be the theory which best satisfies the constraints. The structure of the external world has the power to eliminate many rival accounts. The remaining theory could of course be underdetermined by evidence, as the weak version of holism claims. However, the surviving theory displays such a degree of *rigidity* that any modification in it will lead to its falsehood (Einstein 1919, p. 232; Einstein 1936; Einstein 1950b, p. 350; Hentschel 1992; Scheibe 1992; Weinberg 1993). The idea of coherence or rigidity has implications even for the weak version of holism (Weinert 1998). It speaks against the weak holist view that core components of scientific theories cannot be targeted because of the general underdetermination of theories by experience. Einstein illustrates the lack of underdetermination, from the practical perspective of the working physicist, by the analogy of solving a crossword puzzle. In a similar way the structure of the external world, as an empirical constraint, combined with theoretical constraints, has the power to determine, practically, the form of the theoretical system. In Einstein's science this process is reflected in the transitions from Newtonian mechanics to the STR, and from the STR to the GTR. In these transitions important core elements of the theories – like the transformation rules, the addition-of-velocities theorem, and the mathematical form of physical laws – are targeted and submitted to tests.

It was noted above, in connection with Einstein's structure laws, that physical systems are manifestations of structure. Einstein shared the view of many physicists that physics deals with systems rather than individual happenings. Given the concern with structure in Einstein's physics – the inertial frames, the coordinate systems, the invariance principles, the structure laws – it is not far-fetched to ask to which extent Einstein's realism is compatible with some form of structural realism. This question is independent of the current debate in philosophy about the virtues of epistemic *versus* ontic structural realism, respectively. Rather the claim is that Einstein's physics leads to a structural view of reality. Judged from Einstein's statements it seems clear that he regarded both relata and relations as (idealized) expressions of properties in the physical world.

The considerations in this paper suggest that a structural realist reading of physical laws is compatible with Einstein's science. According to such a structural view of laws, the laws of physics capture structural aspects of natural systems. That is, they symbolically express the structure of a class of natural systems by showing how their relata are mathematically related to each other. Einstein clearly believes in the existence of a lawlike, structured reality, a physical world consisting of a network of systems, which can be described and explained by physical theories. The constructs of physical theories (axioms, constraints, coordinate systems, laws, models, theorems) express the structure of natural systems in mathematical form. Einstein seems to have believed in the reality of classical objects, fields and the structure of space-time, insofar as it is determined by the matter-energy contents of the universe. If Einstein's science led him, philosophically, to a version of structural realism, it holds that the physical world consists of structures, where these structures are understood as consisting of relata and mathematical relations. The relata are the inertial frames but also classical objects, fields and models of space-time. The relations are the "structure laws" but also the symmetry principles, which come to prominence in the theory of relativity. Einstein's emphasis is on how this ontological structure can be adequately expressed in physical theories. Despite Einstein's insistence on the rigidity of physical theories like the STR and GTR (e.g. their coherence), it would be a mistake to see Einstein as a naïve realist for whom theories are mirror images of reality. This view would neglect the rationalist component in his philosophical views. Einstein himself regarded the "overcoming of naïve realism" as an important step towards the recognition that a synthesis of the rational and empirical was the best characterization of science (Einstein 1944). As a physicist Einstein believes in the existence of a lawful structure of the real world. As a critical realist Einstein stresses the conjectural nature of the constructs of the real world, which nevertheless must be adequately mapped onto the systems in the physical world. As a (reconstructed) structural realist, Einstein holds that the rational constructs are abstract, idealized mappings, which capture the structural elements of physical systems, like the kinematic relations between inertial reference frames. In this sense Minkowski space-time model gives us structural knowledge of the real world of space-time events, e.g. it gives us invariant and perspectival aspects of these events. But any scientific model, any symbolic representation of physical regularities is always subject to modifications. When Einstein claims that only one "correct" theory survives, he means that this theory best fits the given constraints at any one time. The evolution of Einstein's thought, from the STR to the GTR, shows that the domain of validity of a theory can get narrowed as the constraint space enlarges.

We have associated Einstein's views on laws with his own version of structural realism to show that his science is compatible with a stronger realist position that goes beyond the demand for empirical adequacy. The structural realist interpretation serves as a corrective reminder that not only Einstein's words but also his science supports a structural version of realism.

6 Conclusion

A consideration of Einstein's physics, with its particular toolkit of geometry, constraints and coordinate systems can be fruitfully employed in philosophical discussions of the theory of relativity. First, constraints serve as an important tool, quite generally, to ensure the fit between symbolic representations and natural systems. Second, the constraints show how the laws of physics give rise to a structural interpretation of the laws of nature. It makes statements about the laws of nature via considerations of the laws of physics, rather than metaphysics. Third, a consideration of constraints has implications for Einstein's realism. In particular a consideration of the laws of physics and invariance principles suggests that the theory of relativity seems to be compatible with some form of structural realism, in the sense that it is concerned with structural aspects of the natural world.[8] We can agree with Reichenbach that "the evolution of philosophical ideas is guided by the evolution of physical theories" (Reichenbach 1949, p. 301). In this sense Einstein was truly a physicist-philosopher.

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[8] For more general arguments regarding the compatibility of the theory of relativity with structural realism, see Stachel (2002) and Lyre (2004) , Ch. 5. For a discussion of the connection between invariance and reality see Weinert (2004a).

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