Invariance, Symmetries and Structural Realism

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Abstract

The paper discusses the invariance view of reality: a view inspired by the relativity and quantum theory. It is an attempt to show that both versions of Structural Realism (epistemological and ontological) are already embedded in the invariance view but in each case the invariance view introduces important modifications. From the invariance view we naturally arrive at a consideration of symmetries and structures. It is often claimed that there is a strong connection between invariance and reality, established by symmetries. The invariance view seems to render frame-invariant properties real, while frame-specific properties are illusory. But on a perspectival, yet observer-free view of frame-specific realities they too must be regarded as real although supervenient on frame-invariant realities. Invariance and perspectivalism are thus two faces of symmetries. Symmetries also elucidate structures. Because of this recognition, the invariance view is more comprehensive than Structural Realism. Referring to broken symmetries and coherence considerations, the paper concludes that at least some symmetries are ontological, not just epistemological constraints.

I. Introduction. The recognition that there is a connection between invariance and reality harks back to the Greeks. The Greeks made the fundamental discovery that underneath the flux of phenomena some invariant entity resides, like substance, which serves to unite the apparent flux. Modern philosophy of science has tended to give such purely metaphysical questions first an epistemological twist. Under the British Empiricists and Continental Rationalists, the Greek preoccupation with metaphysics turned into the issue of what the human mind can know about reality. At the beginning of the 20th century, the question received another shift towards scientific theories. What do scientific theories tell us about the structure of reality? The Special theory of relativity (1905) and the Quantum theory (1911-1925) played a significant role in this latest shift.

The theory of relativity rejected both the idea of an absolute, privileged reference system (like the ether), in which all bodies were 'truly' at rest or in motion, and the idea of invariant spatial and temporal measurements. These now became relative to particular reference frames, as do energy and mass. Quantum theory, in the standard Copenhagen interpretation, made the particle-wave duality dependent on experimental arrangements in double-slit experiments. The collapse of the wave function from the potentiality of permitted values to the actuality of measured values further chipped away at traditional views about material reality. With the rise of relativity and quantum theory the question of the invariant properties of reality occurred with renewed urgency.

This is not just a purely philosophical question. It is a philosophical consequence of scientific theorizing. And so it is not surprising to find numerous scientists contemplating the age-old philosophical question regarding to connection between invariance and reality.[1] They basically suspect that a link exists between frame-invariant parameters and what we should regard as physically real. I will call this the **invariance view** of reality: the invariant is regarded as a candidate for the real. Certain properties change from framework to framework, others remain invariant. The physicist wants to be able to track

[1] Dirac, *The Principles of Quantum Mechanics* (^{4}1958), vii, §8. Planck, too, regarded the constant in our worldviews as the real; see *Vorträge* (1975), 49, 66, 77, 291; see also Poincaré, *Science* (1902), Pt. IV, Ch. X; Cassirer, 'Zur Einsteinschen Relativitätstheorie' (1920), 12ff, 28ff, 34ff. The thesis is a common theme in many publications: Born, *Natural Philosophy* (1949), 104ff, 125; Born, 'Physical Reality' (1953), 143-9; Costa de Beauregard, 'Time in Relativity Theory' (1966); Wigner, *Symmetries* (1967), Feynman, *Six Not So Easy Pieces* (1997), 29-30; Weinert, *Scientist as Philosopher* (2004), Ch. 2.8

what does and what does not change under appropriate transformations. The mathematical tool to do this can be found in group theory and symmetry principles. The invariance view of reality is therefore more abstract and formal than the classical view of reality. The invariance view also sheds light on key issues in the currently fashionable thesis of Structural Realism. This paper will argue that the invariance view is more comprehensive: it naturally answers questions about the structure of reality and draws our attention to symmetry principles in pursuit of the philosophical question of reality.

II. The Invariance View of Reality. The Special Theory of Relativity generalizes the Galilean relativity principle and adopts the finite velocity of light as a postulate. The results are: time dilation, length contraction and relative simultaneity. The equivalence of inertial reference frames has many far-reaching consequences: energy, mass, momentum, spatial and temporal measurements become *relational* parameters. Relational means that particular values of certain parameters can only be determined by taking the coordinate values of individual reference frames into account. If, for instance, observers in different reference frames, moving inertially with respect to each other, take different temporal measurements from their respective clocks, then time cannot be a feature of the physical universe. At least many relativists, as they were once called, arrived at this conclusion. According to Pauli (1981, 14-5) 'there are as many times and spaces as there are Galilean reference systems.' Quantum mechanics, too, was forced to treat many parameters as relational, as a direct consequence of the indeterminacy principle. For, on the Copenhagen interpretation, quantum systems possess no definite physical properties until questioned about them in a measurement process. Wave and particle aspects are relational to the measurement frame. And the degree of momentum of a quantum system can only be known at the expense of a renunciation of spatial knowledge; equally for energy and time.

If the relativity and the quantum theory regard many parameters as relational, then they are not invariant across different reference frames. But neither theory stops there. The corollary of the relativity principle and the quantum postulates is that certain properties remain invariant across all reference frames. The invariance view tends to regard the invariants as physically real. The invariance view is closely connected with *symmetry principles*. For if reference frames are related to each other by transformation groups, which keep certain parameters symmetric, then there are elements of structure, which remain invariant. This is just what symmetry principles affirm. Symmetry principles are of fundamental importance in modern science. They state that certain, specifiable changes can be made to reference systems, without affecting the structure of the physical phenomena. For instance, experimental results are invariant under spatial, temporal and rotational symmetries. Symmetries result from specified group transformations that leave all relevant structure intact.[2]

In 1916 Einstein required that the general laws of nature are to be expressed in equations, which are valid for all coordinate systems. In the GTR general coordinate systems replace the inertial reference frames of the STR. Coordinate systems can be made subject to continuous transformations, like rotation and reflection. Such transformations or symmetry operations allow transitions between various coordinate systems. The group of invertible transformations is the covariance group of the theory. Einstein characterizes covariance as form invariance. 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, 8; 1950b, 346) and **b)** to general transformations of the coordinate systems (general covariance in the General theory). (Einstein 1920, 54-63; 1950b, 347) The theory of relativity will only permit laws of physics, which will remain covariant with respect to these coordinate transformations. (Einstein 1930, 145-6) This means that the laws must retain their form ('Gestalt') 'for coordinate systems of any kind of states of motion.' (Einstein 1940, 922) They must be formulated in such a manner that their expressions are equivalent in coordinate systems of any state of motion. (Einstein 1916; 1920, 42-3, 153; 1922, 8-9; 1940, 922; 1949a, 69) A change from an unprimed coordinate system, *K*, to a primed coordinate system, *K'*, by permissible transformations, must not change the form of the physical laws.

[2] Van Fraassen, *Laws and Symmetry* (1989), 243; see also Rosen, *Symmetry in Science* (1995) Ch. I: Symmetry is immunity to possible change; Martin, 'Continuous Symmetries' (2003)

These transformations between coordinate systems occur against the background of invariant parameters. This invariant is taken to be physically significant. ‘The factual or physically significant quantities of a theory of space and time are the invariants of its covariance group.'[3] Although the covariance principle introduces a certain gauge freedom in the symbolic representation of the laws of nature, covariant formulations of the laws of physics are constrained by the relations between the relata in the structure of physical systems. Einstein’s demand that the laws of physics remain covariant – form invariant – means that the covariant expressions must refer to the same referent. The referent – the physical relations between the physical relata in the structure of natural systems – remains invariant across covariant symbolic formulations of the laws of physics.

The invariance view of reality seems to commit us to the view that frame-variant properties, like temporal measurement, are not real; only frame-invariant properties are real. This is in fact the conclusion, which many authors have drawn.

> Thus *A. Eddington*: 'All the appearances are accounted for if the real object is four-dimensional, and the observers are merely measuring different three-dimensional appearances and sections; and it seems impossible to doubt that this is the true explanation.'[4]
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> Equally *T. Maudlin*: 'the objective features of the world must be represented by invariant quantities.' Why? Because frame-dependent quantities 'change from reference to reference frame' and are, in part, artefacts of convention.[5]
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> And *M. Lange*: 'If two frames from which the universe can be accurately described disagree on a certain matter, then that matter cannot be an objective fact.'[6]

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[3] Norton, ‘Philosophy of Space and Time’ (1996), 21-2; Friedman, *Foundations* (1983); Scheibe, 'Invariance and Covariance' (1981), 311-31, 'A Most General Principle of Invariance' (1994), 510: covariance as invariance under coordinate transformations; Weinert, ‘Einstein and the Laws of Physics’ (2007)
[4] Eddington, *Space, Time, Gravitation*, (1920), 181
[5] Maudlin, *Quantum Non-Locality and Relativity* ([2]2002), 34
[6] Lange, *Philosophy of Physics* (2002), 207; cf. Belashov, 'Relativistic objects' (1999), 659, 'Relativity' (2000).

> Finally, P. *Kosso*: 'The real is perspective-independent: symmetries amount to the discovery of reality in the appearance by understanding what is permanent in terms of what changes.'[7]

How serious is this demotion of frame-variant properties to mere appearances? Nozick, (2001, 329, note 11) points out frame-specific temporal and spatial measurements in the Special theory of relativity are not invariant, yet they are objective. Nozick's point is that frame-dependent features can be both objective and perspectival. We can relate two aspects of the invariance view to two different versions of Structural Realism, depending on whether we reason from theories to the world or from the world to theories.

- *The Invariant is the Real.* This is the epistemological part of the invariance view. It is the claim that invariant parts of theories correspond to structural elements of physical reality. It is a realist claim about scientific theories regarding the structure of reality. In terms of the recent discussion of Structural Realism (Rickles et al. 2006) the epistemological part of the invariance view should be recognizable as equivalent to one version of Structural Realism - Epistemological Structural Realism (*ESR*). For *ESR* claims that we acquire structural or mathematical knowledge of the physical world but that the underlying reality as such remains veiled.[8] Our structural claims about the physical world are to be regarded as candidates for continuity in our knowledge claims, although this may not reflect an ontological continuity. All we know is structure – the relata are simply placeholders for the relations. Although *ESR* tells us that there is structural continuity in our knowledge claims – as reflected in the mathematical formalism - it does not commit itself as to whether these structural features are represented in the ontologies of our theories. In this respect the epistemological part of the invariance view goes further. It claims that there is a structural continuity between reference frames, which it expresses typically in terms of space-time symmetries. But significantly, it adds that what remains invariant

[7] Kosso, 'Symmetry' (2003)
[8] B. d'Espagnat, *La Realité Voilé* ([2] 1981) ; Worrall, 'Structural Realism' (1989), Chakavortty, 'Structuralist Conception' (2003)

across different reference frames is a *candidate* for the real. Consequently what science comprehends are the ontological structures of the world, even though in an approximate and idealized fashion. This modification will lead to a consideration of the status of symmetries (Section IV).

- *The Real is the Invariant.* This is the ontological part of the invariance view. It is the claim that invariant parts of reality correspond to invariant parts of theories. It is a metaphysical presupposition in scientific theories about the structure of reality. This ontological part of the invariance view should be recognizable as equivalent to another version of Structural Realism - Ontological Structural Realism (*OSR*). This is the view that not only our knowledge of the physical world is restricted to structural knowledge, but that the physical world itself has a structural ontology. All there is, is structure. Proponents of OSR cannot agree on whether only to grant the relations reality or both the relations and the relata in equal measure. (See Rickles et al. 2006) But again the ontological component of the invariance view goes further. It distinguishes between *frame-specific* and *frame-invariant* parts of reality and derives this distinction from symmetry principles. It regards not only the relations but also the relata as real (at least in the STR).

Many of the claims associated with the two versions of Structural Realism are anticipated in the invariance view and its emphasis on symmetries, and can be reassessed from this standpoint.

According to the above-quoted interpretations of the invariance view the real cannot be frame-specific. In one sense modern science seems to support this interpretation of the physical world. According to the founding fathers of modern science colour is a perceived, secondary quality. A modern version of this view removes the reference to the observer and holds that colour is not invariant across different reference frames, because of the Doppler effect. (Cf. van Fraassen 1989, 275) That is, the change in frequency of electromagnetic radiation is a function of the relative velocity between emitter and receiver. So colour is not real in the physical sense. Equally for time and space. Temporal and spatial measurements in moving reference frames undergo time dilation and length contraction, respectively, because of the invariance of the speed of light and the topological invariance of light cones. So, once again, they cannot be real in a physical sense. Physicists like Eddington and Weyl explicitly denied the reality of time as a result of the Special theory of relativity.

Many of the inferences from the frame-dependence of properties to their physical unreality gain their plausibility from the insertion of observers into the picture. Many textbook formulations of relativity theory explain the theory by attaching a human observer to each reference frame. Observers have perceptions and perceptions are notoriously subject to illusions. So it becomes very tempting to treat the frame-variant properties as illusory, unreal.

But in another sense there is something odd about this interpretation of the invariance view of reality. All human observers can be replaced by clocks and measuring rods. Consider a particle attached to a reference frame moving with a velocity of 0.8c along its positive *x*-axis. The particle releases a photon, a light pulse, at an angle of 90° in the positive *y*-direction. Now consider a second, stationary reference frame, in which the angle of the photon release is measured. At what angle, in the stationary frame, will the light pulse leave the moving reference frame of the particle? The answer is: at 36.9°. We should note that an 'observer' in quantum and relativity theory need not be a human observer. 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.

Such examples lead to what may be called a *reality paradox* on the invariance view. The effects seem to be real in each reference frame: the measurements in each reference frame are accurate. The presence of observers is only essential for the reading of measurements.. Yet they are not invariant under symmetry considerations. So on the above interpretation of the invariance view, they should not be considered as real. Whether we consider the forward radiation of fast-moving particles or the time dilation of atomic clocks, we face a dilemma. Even under the replacement of observers by instruments, the measurements tell us that the frame-specific effects are real. Yet the standard interpretation of the invariance view suggests that they should be regarded as illusory.

ESR cannot avoid the paradox because it is only concerned with epistemological continuity of form, not content. It does not guarantee ontological continuity.

OSR does not help to solve the paradox because its claim - all there is, is structure - does not tell us which aspects of this structure are frame-variant or frame-invariant, respectively. For all we know, all ontological structure may be temporally or spatially variant, failing to satisfy symmetry demands. There is nothing in *OSR* to exclude this possibility. But if we take *OSR* claims seriously, this is precisely what we wish to know. Which structures, amongst equivalent reference frames, remain invariant? To say that only structures exist, does not guarantee, paradoxically, that they are real in any physically significant sense.

The clocks and rods urge us to admit *frame-specific* realities. But does this admission not fly in the face of the invariance view? One way out of the reality paradox may be an appeal to *perspectivalism*: many of the relational parameters, like mass, energy, time, are real within a specific reference frame only. However, perspectivalism must not be made an observer-dependent notion. Observers impose the double burden of relativism or idealism. We know that we can replace all observers by rods, light signals and atomic oscillations and the reference frames will still register *relational* parameters. Significantly, perspectivalism must incorporate the relativistic insight that these reference frames are connected to each other by symmetry transformations. The laws of physics do not apply to specific reference frames. Reference frames are connected by space-time symmetries, which implies that there must be invariant properties.

Let us see how such a perspectival view of invariance would deal with the issues at hand. Consider again the photon angle in the forward radiation of fast moving particles. What is invariant here is what governs these phenomena. It is equation (1), relating the angles in the two reference frames[9]:

[9] Sexl/Schmidt, *Raum-Zeit-Relativität* (1978), 106; Bohm, *Special Theory of Relativity* (1965), 77-80; Wigner, *Symmetries and Reflections* (1967), 53-7. The parameter ε represents the angle as seen in the laboratory, the ε' represents the angle in the photon system.

$$\tan \varepsilon = \frac{\sin \varepsilon' \sqrt{1 - {v^2}/{c^2}}}{\cos \varepsilon' + {v}/{c}} \qquad (1)$$

The equation expresses the underlying structure. What the moving particle 'sees' and what the lab instrument 'observes' are only perspectival aspects. They are real from their perspectival points of view. As all reference to observers can be extirpated from the consideration of reference-frames, can we avoid the paradox of reality? We can relate perspectivalism to *supervenience*, understood as a physical relation. For instance, as Oersted observed, an electric current in a wire produces a magnetic field; and as Faraday discovered, a magnetic flux induces an electric current. Oersted's magnetic field and Faraday's current are examples of supervenient properties in a purely physical sense. Supervenience requires the co-variation of a physical base (the underlying structure) with a supervenient domain (the frame-specific realities) and a dependence relation. The frame-specific realities are supervenient on the frame-independent realities, in the sense that a variation of coordinates changes the measurement of temporal and spatial lengths, whilst the space-time interval 'ds' remains invariant across all coordinate systems. The frame-specific appearances are physically dependent on the frame-invariant structures. Yet they are real, but not in an observer-dependent sense. Perspectivalism is not observer-dependent but frame-dependent. The perspectival realities of physics are the result of a combination of particular reference frames with frame-invariant underlying structures. Equation (1) expresses the invariant of forward radiation - or the structure, which we regard as physically real, in a non-perspectival sense. Faraday's law of magnetic flux expresses the underlying structure of the physical base, which leads to the flow of current. In the case of the Lorentz contraction, it is the underlying space-time structure, which we regard, under this criterion, as physically real because it is invariant under external symmetries. But it looks as if we had simply shifted the problem from perspectival realities to the question of the existence of invariant structure. According to Structural Realism structure consists of relata and relations, although in many versions of

Structural Realism, the relata are regarded as mere placeholders, whilst the relations are primary. The invariance view reveals that there is more to structure than relata and relations. There exists in fact a close affinity between structures and systems. Let us first see what symmetries tell us about structure (Section III) and then consider the reality of structures (Section IV).

III. Symmetries & Structure. A structure consists of relata and relations, both of which can be frame-specific or frame-invariant. It is existing relations, which hold the relata together and bind them into specific structures. The physical manifestation of a structure is a natural system. A system, like the solar system, consists of relata (the planetary bodies and the sun) and relations (Kepler's or Newton's laws). The relations prescribe the elliptical orbits of the relata. Frame-specific realities may not be physically interesting, for two reasons:

1. In some cases, a change of reference frame can make these apparent realities disappear: as the asymmetry in the observable phenomena, depending on whether the magnet or the conductor is moving, as Einstein pointed out at the beginning of his 1905 paper. It is also the basis for Einstein's argument against the reality of gravitation in his famous thought experiment, which establishes the equivalence between inertial and gravitational mass.
2. In other cases, the frame-specific parameters do not disappear but vary in value with a change of reference system. The time registered by two clocks in relative inertial motion to each other, does not disappear, as we change reference system, nor does it stay the same. These are therefore supervenient, perspectival realities.

Physics is interested in frame-invariant realities, because the frame-specific realities can be obtained from them by transformation rules and symmetry principles. Frame-invariance therefore helps the unification process. How can we get hold of frame-invariant realities if all our experience of reality seems perspectival? It is the symmetries, which will help us pin them down. Symmetries result from the application of transformation groups of the theory of relativity, which will leave all relevant parameters unchanged. Relevant parameters are those, which prove to be immune to the possible changes expressed in symmetry operations, applied to coordinate systems.

Symmetries can be distinguished according to different properties.[10] Rotation, reflection, spatial and temporal translations and space-time symmetries are typical *geometric* symmetries. They take events, things and properties as their objects. A better name may be *external* (global) symmetries. External symmetries result from the application of space-time transformation groups. They are external to their reference objects because they govern the invariance of their objects with respect to an 'external' change of space-time reference systems. So according to the Galileo transformations, an event that happens at a location x, can equally be transported to a location x', because the two locations are related by the equation $x' = x - vt$. Whatever event takes place at location x, its physical nature will not change as a result of its transport to x'. In the relativistic case the Lorentz transformations apply.

Gauge symmetries like the charge-parity symmetry in certain particle interactions are representatives of the newer *dynamic* symmetries. They take electromagnetic, gravitational, weak and strong interactions between elementary particles as their objects. A better name may be *internal* (local) symmetries. Internal symmetries are combined into gauge groups. They govern the internal symmetry of ‘physical interactions', as for instance in the transformation of the electric and magnetic field vectors of charges as we go from stationary to moving systems. Local gauge symmetries obtain in quantum mechanics. For instance, the wave function of a charged particle, Ψ, can undergo a phase shift:

$$\Psi' = \Psi e^{i\Delta} \quad (2),$$

which will not affect the equation of motion, nor the square of the wave function:

$$\left|\Psi'\right|^2 = \left|\Psi\right|^2 \quad (3).$$

[10] Wigner, *Symmetries and Reflections* (1967); Morrison, ‘Symmetries as Meta-Laws’ (1995); Rosen, *Symmetry in Science* (1995), 72-6; Earman, *World Enough* (1989), 173; Mainzer, *Symmetries* (1996), 277, 341f, 357, 414, 420 calls dynamic symmetries ‘gauge groups’; *Encyclopaedia of Physics* (Article 'Symmetry Laws'); Cao, *Conceptual Development* (1997), Ch. 9

The famous violation of parity in weak interactions is a further example of how invariance under a group of local transformations (gauge symmetry) can be obtained. They are not invariant under charge reversal, *C*, or space inversion, *P*, but they are invariant under their combined operation, *CP*, and under time reversal, *T*. We will use the CPT symmetry as an argument for the ontological significance of symmetries.

Considerations of symmetries tell us that the traditional characterization of structure as 'relata + relations' cannot be restricted to lawlike physical relations between events and objects. Amongst the relations we have to count symmetries. The relata (fields, objects, properties, reference frames) are governed by their relations (laws of nature, symmetry principles). That makes the relations structural principles: for the relata to be governed by the relations means for the relations to put constraints on the relata - structural constraints since they determine the type of relata, which are allowed to enter the relations. The relations will act as constraints on the placeholders: they will only allow specific types of placeholders into the relations. But the relations themselves are governed by symmetry principles. Amongst the relations, we find conservation laws, and these follow from symmetry principles, according to Noether's theorem.[11] They are higher-order principles. If the symmetries preserve structure, then they are constraints on structure. In the first instance, we may regard the structure as consisting of relations and relata, but symmetries are higher-order constraints on relata and relations. As higher-order principles the symmetries give us - barring some further considerations below - the invariant structures, in which physics is interested. We can, in Leibnizian fashion, adopt a *relational* approach to structure.[12] Such an approach emphasises that structure is born of

[11] According to Noether's theorem symmetries and conservation laws are related. The laws of conservation are consequences of the space-time symmetry operations. Conservation of momentum results from invariance with respect to spatial translations, conservation of energy from invariance with respect to temporal translation, conservation of angular momentum from invariance with respect to spatial rotation and conservation of the centre of mass from invariance with respect to uniform motions. See Mainzer, *Symmetries of Nature* (1996), 350; Feynman, *6 Not So Easy Pieces* (1997), 29-30; Rosen, *Symmetries* (1995), 150-3, Wigner, *Symmetries* (1967), 18ff

[12] As St. French shows in his 'Eddington's Structuralist Conception of Objects' (2003), Arthur Eddington adopted such a relational approach to structure in the early 20th century; cf. French/Ladyman, 'Remodelling Structural Realism' (2003)

a union of relata and relations. As soon as we place two atoms into an empty universe, we have a triad of relata, relations and symmetries. The triad is embedded in the natural world, which consists of interrelated systems.

Given appropriate constraints, structures tend to be frame-invariant. But structure also has frame-variant perspectival manifestations. The relations between relata themselves may not be structure-preserving, as for instance the distance between two objects may change, while the Euclidean distance, r^2, remains the same. From the viewpoint adopted here, the philosophical debate on Structural Realism has neglected two important aspects: the role of symmetries in the determination of both perspectival and invariant features. We can see that *perspectivalism and invariance are two faces of symmetries.* Symmetries offer a deeper insight into the nature of reality, because they automatically yield frame-specific (perspectival) and frame-invariant properties of physical reality. A consideration of symmetries therefore anticipates many features of Structural Realism.

As we have seen, Structural Realism comes in competing versions, which appear as two different faces of the invariance view. As the *epistemological* thesis that the invariant is the real the invariance view makes a theoretical claim about the structure of reality. Such claims to reality have been typical of scientific theories from geocentrism to string theory. Above we called the *ontological* thesis that the real is the invariant a metaphysical presupposition. But even metaphysical presuppositions can change as a result of scientific discoveries, as the transition from absolute to relative simultaneity demonstrates. (Weinert 2004, Ch. 4) According to the relational view of structure, relata and relations interrelate in such a way that it can be misleading to claim that structures are prior to relata (as some versions of *OSR* do). Events, objects and properties are needed as inputs to structures. The question is whether certain structures are invariant. This is determined by symmetry principles. But invariant structures also need the input of relata. Relativity theory tended to feed 4-dimensional events into the structures, while quantum theory took invariant properties of quantum systems (e.g. spin) as inputs. Modern theories of quantum gravity reach for a deeper level. In string theory the fundamental objects appear as strings or membranes, in loop quantum theory as fundamental loops. Philosophy cannot prejudge the fundamental ontology, which theoretical physics is unearthing, by declaring that all is structure. To elucidate the nature of structure, we should now consider how the invariance view offers possibilities of testing invariance through the perspectival nature of our observations and experiments.

IV. Symmetries & Invariance. To say that an equation represents a mathematical structure does not per se help to decide between *ESP* and *OSR*. Equations are just structural principles, which may either tell us something about the structure of our knowledge, as *ESR* claims, or the structure of the physical world, as *OSR* claims. There is no need to *postulate* that structures are real. The symmetries already give us frame-invariant and frame-variant structures. But this just shifts the argument to the question whether symmetries reflect real or only epistemological structures. Some have argued that symmetry principles must be construed as constraints on epistemological structures. (Morrison 1995; van Fraassen 1989, Pt. III, Ch. 10) If symmetries are merely constraints on epistemological structure, then symmetries add nothing of empirical content to the elements, on which they operate. And it is certainly foolish to regard every piece of mathematical structure as reflecting some reality.

Consider nothing more than the Galilean fall law:

$$\Delta y = v_o t - \tfrac{1}{2} g t^2 \qquad (4)$$

and assume that the height Δy = 240m, the velocity, v_o = 40m/s and $g \approx$ 10m/s^2, which after some rearrangement and unit cancellation, yields:

$$t^2 - 8t - 48 = 0$$
$$(t-12)(t+4) = 0$$

so that either t_1 = 12s or t_2 = ¬ 4s; but t_2 is not regarded as a physical solution so that the time of flight, t_1, is 12 seconds.

On the other hand, we have already seen that symmetries, by virtue of being higher order principles, are interrelated with the relata and the relations. The system of relata and relations are not regarded as purely epistemological objects in physics but as grounded in the real world. In other words there is the strong warranted belief that the natural world exists independently of its observers. If the natural systems in the physical world display various kinds of structure, then scientific theories must represent this structure through various models. But if symmetries are interrelated with the relata and the relations, it is reasonable to expect that they are more than constraints on epistemological structures; they are grounded, via this interrelation, in the physical world. It is through this route that the principle of covariance gains empirical significance. This grounding must be based on observational and experimental phenomena to prevent that every symmetry, by default, becomes an ontological chunk of the world. As symmetries are *prima facie* epistemological objects, we are operating within the epistemological arm of the invariance view: the invariant is (a candidate for) the real. If we can argue that symmetries must be more than constraints on epistemological structure, we may conclude that the world consists of ontological structures.

There are at least two arguments in favour of treating symmetries as more than constraints on epistemological structure. We may restrict our attention here to symmetries whose candidate status for the real has some empirical credibility. That is, we restrict attention to symmetries, which can be connected to experimental and observational data. So we can bracket the appearance of symmetries in theories, which themselves have no empirical backing at this stage. For instance, string theory postulates new symmetries, so-called *dualities*: the winding modes for a circular universe of radius *R* are the same as the vibration modes for a circular universe of radius *1/R* and vice versa. These two universes are physically indistinguishable. Whilst these are considered to be important *epistemological* constraints on different versions of string theory, they cannot be regarded as *ontological* constraints, since string theory is (still) thoroughly empirically underdetermined.

1) One argument in favour of the view that certain symmetries are part and parcel of the furniture of the world comes from the observation of *broken* symmetries. The argument is based on a classic falsificationist move. Every lab-based experiment confirms that external symmetries hold good in a finite number of spatio-temporal locations. Yet it is not possible to confirm that *all* phenomena in nature are subject to symmetry principles.

The reason is the asymmetry of verification and falsification. But we can learn something about the structure of nature from the experimentally confirmed phenomenon of *broken* symmetries. The most famous example is the violation of parity symmetry in weak interactions.[13] C. S. Wu (1957) discovered parity non-conservation in beta decay of CO^{60}. Soon afterwards parity non-conservation was observed in meson decay (Garwin 1957) and hyperon decay (Crawford 1957). Generally, electromagnetic interactions display parity invariance or invariance under space reflection. Weak interactions, however, display a preference for chirality: right- or left-handedness. Parity invariance is violated in weak interactions. Wu took up a suggestion by Lee and Yang to measure the angular distribution of electrons in beta decay (of polarized CO^{60}): $CO^{60} \rightarrow Ni^{60} + e^{\neg} + \nu_e$

Let θ be the angle between the orientation of the parent nuclei and the momentum of electrons. Wu and her coworkers observed an asymmetry in the distribution of electron momentum parallel and anti-parallel to the nucleus spin. The asymmetry of beta particle emission was dependent on the direction of the magnet field, *H*. The asymmetry showed that parity was not conserved in beta decay. 'If an asymmetry in the distribution between θ and 180° - θ (…) is observed', they write, 'it provides unequivocal proof that parity is not conserved in beta decay. The asymmetry effect has been observed in the case of oriented CO^{60} ' (Wu 1957, 1413).

To illustrate the violation of parity in weak interactions, consider the π^+ meson decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu .$$

Wu's experiment showed that in weak decay processes particles are emitted with left-handedness, anti-particles with right-handedness. (Figure Ia,b)

[13] C. S. Wu, 'Parity Conservation' (1957); H. R. Quinn/M.S. Witherell, 'The Asymmetry between Matter and Anti-Matter' (2003); Feynman, *Six Not So Easy Pieces* (1997), Ch. 2.4-2.9; Weinberg, *Dreams of Final Theory* (1993); Morrison, 'The Overthrow of Parity' (1957)

Figure Ia: Meson decay: the π^+ decays into the μ^+ (anti-muon) and ν_μ (muon neutrino), which are only emitted with left-handedness. Because of conservation laws, their spins are opposite but both particles have left-handed chirality. Parity is violated, since the mirror image (*top right* in Fig. Ib) does not occur; only left-handed leptons participate in weak interactions.

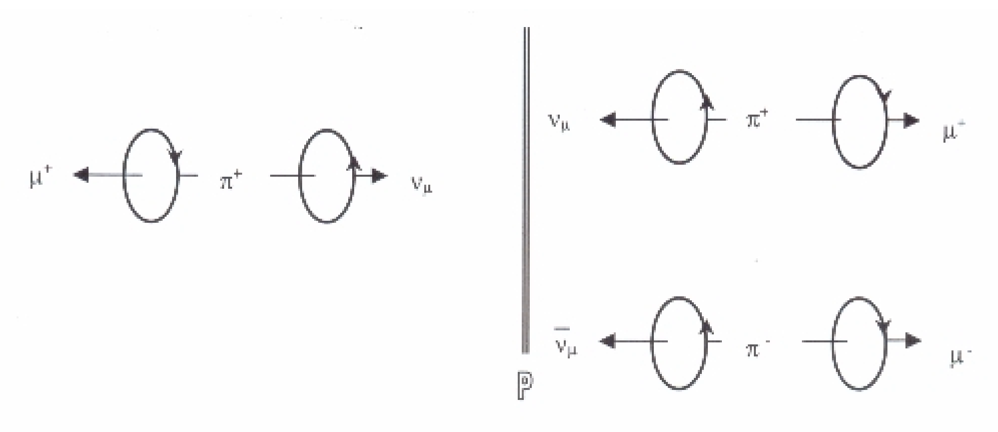

Figure Ib: When charge is reversed, parity is restored, (*bottom right*, Fig. Ib). The meson π^- decays into an anti-muon neutrino and a muon , μ^-. Meson decay is invariant under the simultaneous change of parity and charge: CP invariance.

The violation of parity symmetry in weak interactions is therefore a strong indication of the existence of CP-invariance in nature, and by inference to the existence of unbroken parity symmetry in all strong interactions. In 1965 it was found that such decay processes are not invariant under reversal of temporal order. The combination of C, P, and T, however, restored invariance. The so-called CPT theorem shows that a quantum field theory must obey CPT symmetry if it obeys Lorentz symmetry.

Turning now to external symmetries, time dilation experiments, like the famous Maryland experiment (1975-76), have shown so far no violation of time translation effects in the Special theory of relativity. The experiment confirms that no temporal symmetry exists for systems in inertial motion with respect to each other. The Lorentz transformations measure the quantifiable effects, which the kinematic state of one system experiences compared to the kinematic state of another inertial system. They therefore show which of the physical changes that can happen to the system remain invariant and which ones change in a transition to another reference frame. Just like parity symmetry, Lorentz invariance is testable; one of its earliest test 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. If the breaking of Lorentz symmetry was in fact observable, it would, like CP violations in weak interactions, be an indication that Lorentz invariance is an ontological aspect of space-time at macroscopic levels, rather than a mere epistemological constraint. (Bluhm 2004; Kostelecký 2004; Lämmerzahl 2005)

2) The second argument is that symmetries reflect the fundamental interrelatedness of nature. This argument is derived from coherence considerations. There are numerous reasons to believe that the universe consists of interrelated systems. These systems consist of structures, constituted by relata and relations. At least since the 19th century, with its discoveries of atomic structure, entropy, electro-magnetism, and natural selection, we think of nature as a system of interrelated subsystems. So we must think of theories as representing this interrelatedness via appropriate models. The symmetries play an important part in this interrelatedness and its unification.

But why should we assume that if the system of relata and relations is confirmed, the symmetry principles, which govern these structures are also confirmed? If invariants are physically meaningful, it will be surprising if symmetries are merely analytic tools. The symmetries tell us more than what the objects and laws tell us. They tell us, which quantifiable changes affect the systems and which do not. So they tell us that the empirical world is one of interrelated subsystems; the interrelation is subject to quantifiable constraints. For if symmetries are immunities to change, this change is not just an epistemological change to our knowledge claims. The change happens to physical systems. Some physical changes leave parts of the system invariant. Broken symmetries, like the violation of parity invariance in weak interactions or cosmological tests of Lorentz invariance demonstrate that the immunity is sometimes lifted. But in each case we can track the changes that happen to physical systems through our investigations. Some changes affect the frame-variant parts of the structures, as in time dilation. Others affect what was taken to be the frame-invariant parts, as in broken symmetries. Those who think of symmetries as no more than epistemological constraints, make the mistake of thinking that the empirical confirmation of a theory cannot reach the symmetry principles. But the tight connection between relata, relations and symmetry principles means that the invariants are more than epistemological constraints. The invariants are the survivors of the permissible physical changes, which can affect the system. Science provides no justification for the arbitrary distinction between relata and relations as belonging to reality and *external* and *dynamic* symmetries as belonging to epistemology.

VI. Conclusion. These arguments from broken symmetries and coherence support the argument that the world consists of structures. We arrived at this conclusion by following the route of the invariance view, rather than *OSR*. We propose that the invariance view is a better representation of how knowledge claims map onto the world, because it gives us criteria for candidates of the real. While Structural Realism argues from philosophy to science and the world, the invariance view argues in the opposite direction, from science and the world to philosophy. It has the additional advantage that it brings the importance of symmetries to the fore. It also shows, at least for the Special theory of relativity, that structures require the presence of relata (reference frames and coordinate systems in the theory of relativity). If an ontological version of Structural Realism is correct, it must regard the reality of structures as embracing both the relata and the relations.

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