Pergamon

Stud. Hist. Phil. Sci., Vol. 29, No. 3, pp. 409–424, 1998
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Printed in Great Britain
0039–3681/98 $19.00+0.00

What is Structural Realism?

*James Ladyman**

> [T]he structure of this physical world consistently moved farther and farther away from the world of sense and lost its former anthropomorphic character …. Thus the physical world has become progressively more and more abstract; purely formal mathematical operations play a growing part (Planck, 1996, p. 41).

1. Introduction

In the debate about scientific realism, arguably the two most compelling arguments around are the 'no miracles' argument, and the 'pessimistic meta-induction'. Unfortunately these pull in opposite directions (towards realism and antirealism respectively). In an attempt to break this impasse, and have 'the best of both worlds', John Worrall introduced *structural realism* (although he attributes its original formulation to Poincaré) (Worrall, 1989). Using the case of the transition in nineteenth-century optics from Fresnel's elastic solid ether theory to Maxwell's theory of the electromagnetic field, Worrall argues that:

> There was an important element of continuity in the shift from Fresnel to Maxwell—and this was much more than a simple question of carrying over the successful empirical content into the new theory. At the same time it was rather less than a carrying over of the full theoretical content or full theoretical mechanisms (even in 'approximate' form). … There was continuity or accumulation in the shift, but the continuity is one of form or structure, not of content (1989, p. 117).

According to Worrall, we should not accept full-blown scientific realism, which asserts that the *nature* of things is correctly described by the metaphysical and physical content of our best theories. Rather we should adopt the structural realist emphasis on the mathematical or *structural* content of our theories. Since there is (says Worrall) retention of structure across theory change, structural realism both (a) avoids the force of the pessimistic meta-induction (by not committing us to

* Department of Philosophy, University of Bristol, 9 Woodland Road, Bristol BS8 1TB, U.K.
Received 5 February 1997; in revised form 11 July 1997; in revised form 11 July 1997

PII: S0039-3681(98)00014-4

belief in the theory's description of the furniture of the world), and (b) does not make the success of science (especially the novel predictions of mature physical theories) seem miraculous (by committing us to the claim that the theory's *structure*, over and above its empirical content, describes the world).

This paper addresses the interpretation and further elaboration of structural realism. Although structural realism has attracted considerable attention, and similar views seem to be advocated by Michael Redhead and Elie Zahar among others, Worrall's proposal needs to be developed if it is to provide a substantive alternative to traditional scientific realism.[1] In particular, there is a fundamental question about the nature of structural realism that should be answered: is it metaphysics or epistemology? Worrall's paper is ambiguous in this respect. At times his proposal seems to be that we put an epistemic constraint on realism to the effect that we should only commit ourselves to believing in the structural content of a theory, while remaining agnostic about the rest. This is suggested by Poincaré who talks of the redundant theories of the past capturing the 'true relations' between the 'real objects which Nature will hide for ever from our eyes' (Poincaré, 1905, p. 161). What this might mean is explored below.

On the other hand, Worrall's position is not explicitly an epistemic one, and other comments suggest a departure from the metaphysics of standard scientific realism. For example, he says:

> On the structural realist view what Newton *really* discovered are the relationships between phenomena expressed in the mathematical equations of his theory (1989, p. 122; my emphasis).

If the continuity in scientific change is of 'form or structure', then perhaps it is being suggested that we should abandon commitment to even the putative the reference of theories to objects and properties, and account for the success of science in other terms. Redhead says:

> [R]ealism about what? Is it the entities, the abstract structural relations, the fundamental laws or what? My own view is that the best candidate for what is 'true' about a physical theory is the abstract structural aspect (1996, p.2).

Others who have contributed to structural realism have also implied a significant departure from traditional realist metaphysics. According to Zahar, science can never tell us more than the structure of the noumenal world; the nature of the entities and properties of which it consists is inaccessible to us. This seems to concur with structural realist sentiments expressed by Howard Stein:

> [O]ur science comes closest to comprehending 'the real', not in its account of 'substances' and their kinds, but in its account of the 'Forms' which phenomena 'imitate' (for 'Forms' read 'theoretical structures', for 'imitate', 'are represented by') (Stein, 1989, p. 57).

[1]Redhead (1996, p. 3); Zahar (1994).

Below I will argue that structural realism gains no advantage over traditional scientific realism if it is understood as merely an epistemological refinement of it, and that instead it ought to be developed as a metaphysical position. I explain why the semantic approach to scientific theories offers the natural framework for this, and what a metaphysical structural realism must involve if it is to do justice to the intuition behind the no-miracles argument.

2. Epistemological Structural Realism

This section explores how we can understand the claim that we should believe in the *structural* content of theories as an epistemic constraint. It will be argued that the most obvious way of doing so leads to a position that is both familiar (from the writings of Russell and of Grover Maxwell) and incapable of solving the problem of ontological discontinuity. Another epistemological structural realism, an interpretation due to Stathis Psillos, will also be considered and found to be inadequate. However, it is argued that structural realism might yet offer the best of both worlds if it is understood in metaphysical terms.

2.1. Russell, Maxwell and Ramsey Structure

A position called structural realism, that amounts to an epistemological gloss on traditional scientific realism, was, as Worrall mentioned, detailed and advocated by Maxwell (1962, 1970a, b, 1972). Maxwell wanted to defend a robust scientific realism, but he wanted this to be compatible with what he called 'concept empiricism' about the meaning of theoretical terms, and he also wanted to explain how we can have epistemic access to unobservable entities. The problem as Maxwell saw it was that theories talk about all sorts of entities and processes with which we are not *acquainted*. How, he wondered, can we then know about and refer to them and their properties? The answer that Maxwell gave, following Russell's emphasis on structure and relations in his later philosophy (see, for example, Russell, 1927), was that we can know about them by *description*, that is we can know them *via* their *structural* properties. In fact, he argues, this is the limit of our knowledge of them, and the meanings of theoretical terms are to be understood purely structurally.

The way that Maxwell (and others such as David Lewis, 1970) explicate this notion that the structure of the theory exhausts the cognitive content of its theoretical terms, is to consider the Ramsey sentence of the theory. As is well known, Ramsey's method allows the elimination of theoretical terms from a theory, and their replacement with a collection of existentially-quantified bound predicate variables (or names, in Lewis). If one replaces the conjunction of assertions of a first-order theory with its Ramsey sentence, the observational consequences of the theory are carried over, but direct reference to unobservables is eliminated.

If we formalise a theory in a first order language: $\varnothing(O_1, \ldots, O_n; T_1, \ldots, T_m)$, then the corresponding Ramsey sentence is $\exists t_1, \ldots, \exists t_m \varnothing(O_1, \ldots, O_n; t_1, \ldots, t_m)$. Thus the Ramsey sentence only asserts that there are *some* objects, properties and

relations that have certain logical features, satisfying certain implicit definitions. It is a higher-order description, but ultimately connects the theoretical content of the theory with observable behaviour. However, it is a mistake to think that the Ramsey sentence allows us to eliminate theoretical entities, for it still states that these exist. It is just that they are referred to not directly, with theoretical terms, but by *description* or by *logical form*, that is *via* variables, connectives, quantifiers and predicate terms whose direct referents are (allegedly) known by *acquaintance*. Thus Maxwell (and Russell) claimed that knowledge of the unobservable realm is of its *structural* rather than *intrinsic* properties, or, as is sometimes said, is limited to knowledge of its *second order* properties.[2] It is arguable that this is the purest structuralism possible, for the notion of structure employed refers to the higher-order properties of a theory, those that are only expressible in purely formal terms.

This is an epistemological structural realism meant to vindicate and not to revise the ontological commitments of scientific realism. On this view the objective world is composed of unobservable objects between which certain properties and relations obtain; but we can only *know* the properties and relations of these properties and relations, that is the *structure* of the objective world.

There are serious difficulties with this view, which were originally raised by Newman (1928) and which have been recently discussed by Demopoulos and Friedman (1985). The basic problem is that structure is not sufficient to uniquely pick out any relations in the world. Suppose that the world consists of a set of objects whose structure is W with respect to some relation R, about which nothing else is known. *Any* collection of things can be organised to have structure W provided there is the right number of them. As Demopoulos and Friedman point out, this is because if $\exists$ is consistent, and if all its purely observational consequences are true, then the truth of the corresponding Ramsey sentence follows as a theorem of second-order logic or set theory (provided the initial domain has the right cardinality, and if it does not then consistency implies that there exists one that does). The *formal* structure of a relation can easily be obtained with any collection of objects provided there are enough of them, so having the formal structure cannot single out a unique referent for this relation—in order to do so we must stipulate that we are talking about the *intended* relation, which is to go beyond the structural description. 'Thus on this view, only cardinality questions are open to discovery! ' (*ibid.*, p. 188); everything else will be known *a priori*.

This leads Demopoulos and Friedman to conclude that reducing a theory to its Ramsey sentence is equivalent to reducing it to its empirical consequences, and thus that:

> Russell's realism collapses into a version of phenomenalism or strict empiricism after all: *all* theories with the same observational consequences will be equally true (p. 635).

[2]Eddington also defended the view that knowledge of the unobservable is structural but added, unlike Russell, that it was *a priori*. Eddington seemed to think that the canonical form of structure was group-theoretic, though not for the same reasons as those influenced by phenomenology like Weyl (see Solomon, 1989). Weyl's views are discussed briefly below.

This conclusion can be reached by a different path. It has been proved, by Jane English (1973), that any two Ramsey sentences that are incompatible with one another cannot have all their observational consequences in common. In other words, if we treat a theory just as its Ramsey sentence then the notion of theoretical equivalence collapses onto that of empirical equivalence. Therefore, equating the structure of a theory to what is embodied in its Ramsey sentence cannot do justice to Worrall's intention in proposing structural realism, since he is quite clear that commitment to the structure of a theory goes beyond commitment to its strictly empirical level.

In any case, it is hard to see how Maxwell's epistemology and semantics could help deal with the problem of theory change that structural realism is intended to solve. After all, as Maxwell himself pointed out, his structural realism does not dispense with reference to theoretical entities, but makes that reference a function of the (place of the theoretical terms in the) overall structure of the theory, as manifested in the Ramsey sentence. The problem of ontological discontinuity is left untouched by simply adopting Ramsification. In fact, it seems even worse if contextualism about the meaning of theoretical terms is adopted to this extent. Hence, this epistemic reading of structural realism is of no help with the problem of theory change.

2.2. The Problem of Theory Change

The most powerful element of Worrall's highly suggestive paper is the demand for a view that can accommodate *both* the key arguments in the realism debate. Of course, many have argued that traditional realism can be defended against the supposed problem of theory change.[3] Let us suppose, however, that the realist accepts that theory change presents them with serious difficulties, and, in particular, that they admit that parts of current theories may well not refer. Realists may claim to be able to modify scientific realism in the light of this. If they were to sanction belief only in those parts of theories that have been or will be retained in cases of radical theory change, then realism would not be undermined by the pessimistic meta-induction.

What is needed for this strategy is a principled way of distinguishing those parts of theories that will be retained from those that may be abandoned, so that a non-*ad hoc* differentiated attitude towards theories can be advocated. Realists would then not believe in all of the theories currently accepted, in the hope of avoiding ontological commitments that will be relinquished by their future counterparts.[4] Perhaps then we should interpret structural realism as offering a way of differen-

[3]Discussion of radical theory change centres around Laudan (1981). Notable attempts to defend referential continuity and traditional realism in the face of historical problems are Hardin and Rosenberg (1982), Psillos (1992, 1994, 1996), and Kitcher (1993). (For a response to Psillos see Ladyman, forthcoming.) It is worth noting that we do not need to construct a meta-induction, as Laudan does, to use theory change against traditional realism. Instead we can treat the cases of the ether and caloric as counterexamples to the (version of the no-miracles) argument that theories could not be novelly predictively successful if their central theoretical terms did not refer.

[4]This is how Papineau sees the issue (1996, p. 12), as well as Psillos (1996).

tiating ontological commitment so that we can be sure of achieving referential success. Papineau and Psillos argue, quite rightly I think, that structural realism cannot do this.

Psillos (1995) claims that structural realism presupposes distinctions between the *form* and *content* of a theory, or between our ability to know the *structure* and our ability to know the *nature* of the world. The (sensible) realist will not accept these distinctions, according to Psillos. He argues that one success of the scientific revolution was the banishing of mysterious 'forms' and 'substances' that might not be fully describable in structural terms, and the consequent concentration of the mechanical philosophers on quantitative descriptions of the properties of things. For Psillos, properties in mature science are defined by the laws in which they feature: the nature of something consists in its basic properties, and in the equations expressing the laws these obey.

Similarly, Ernan McMullin says:

> What are electrons? Just what the theory of electrons says they are, no more, no less, always allowing for the likelihood that the theory is open to further refinement (McMullin, 1984, p. 15).

We have a theory of electrons that describes their behaviour in terms of the laws, interactions, and so on, to which they are subject. This description, which may be termed a structural one, gives us the last word on electrons, says the realist. This is what Psillos means when he says that:

> [T]he nature and the structure of a physical entity form a continuum (1995, p. 15).

Thus, for Psillos, structural realism cannot be distinguished from traditional realism without a dubious distinction between *structure* and *nature*.[5]

So it seems the realist can claim that structural realism is no different from scientific realism in so far as it advises a structural understanding of theoretical entities, because 'restriction of belief to structural claims is in fact no restriction at all' (Papineau, 1996, p. 12). Thus construed, it gains no advantage over traditional realism with the problem of theory change because it fails to make any distinction between parts of theories that we should and shouldn't believe. Realists may well think that all their knowledge of the unobservable is structural, whether they explicate this in the Ramsey way or not, but this will not help them with ontological discontinuity.

In fact, I will argue later that traditional realism is committed to more than purely structural knowledge. In any case, suppose that Worrall is correct in his claim that there is retention of mathematical structure across theory change which is in other respects radical. I do not think this too controversial a claim, for there are many examples other than the structural continuity between Fresnel's wave optics and Maxwell's theory of the electromagnetic field. Friedman's (1983) presentation of the structure of Newtonian and relativistic spacetime theories shows

[5]This is just the complaint of Braithwaite against Eddington's structuralism (Braithwaite, 1940, p. 463).

that there is more continuity between them than is obvious. The use of the correspondence principle in the development of quantum mechanics gives us many examples of structural continuity. For instance, the Hamiltonian operators used in quantum mechanics for systems such as a simple harmonic oscillator or a particle subject to a Coulomb potential are of the same form as their classical counterparts (the difference being that they feature the appropriate Hermitian operators instead of the variables that classically represent the values of the quantities of position and momentum).[6] There is also the very important analogy between quantum operator commutation relations and classical Poisson brackets developed by Dirac. Again there is a common mathematical form. It seems that Worrall is indeed on to something when he points out the continuity in the mathematics of very different theories. If Psillos' reading of structural realism does not allow us to take advantage of Worrall's insight, then we should look for a different interpretation of structural realism.

The traditional realist may also be heartened by the claim that there is structural or mathematical continuity in the history of science, hoping that where there is continuity of structure this can be construed as continuity of ontology. However, there are many cases of theory change where although relations are preserved, the relata and even their logical type is not. For example, it is widely held that the equation (known as Ehrenfest's theorem) $\mathbf{F}(\langle\mathbf{r}\rangle) = m d^2\langle\mathbf{r}\rangle/dt^2$ exhibits continuity between classical and quantum mechanics; it certainly has a similar form to the equation $\mathbf{F} = m\mathbf{a}$. But the quantum equation has as its arguments the expectation values of Hermitian operators, whereas the classical equation features continuous real variables. Another case is the transition from classical to special relativistic mechanics where mass is transformed to relativistic mass, and thus goes from being a simple property of objects to being a relation between the simple property of rest mass, the two-place relation of the speed of light, and the three-place relation of relative velocity. The suggestion that the extension of these classical theories is the same as that of their successors is implausible in the extreme. Worrall's paper suggests that we accept the fact of radical ontological replacement and thus that we abandon our commitment to the ontology of scientific theories (standardly construed).

3. Towards a Metaphysical Structural Realism

3.1. The Semantic Approach and Structural Realism

To be an alternative to both traditional realism and instrumentalism, structural realism must incorporate epistemic commitment to more than the empirical content of a scientific theory, namely to the 'structure' of the theory, while stopping short of realists' commitment to the full ontology postulated by the theory. Hence, the debate about how to characterise theories and their structure is of central concern

[6]Zahar (1994) appeals to the Correspondence Principle in his defence of a neo-Kantian species of structural realism.

for the structural realist. I have argued that conceiving the structure of a theory in terms of its Ramsey sentence cannot be appropriate for structural realism. Implicit in that discussion was the so-called 'syntactic' or 'received' conception of theories. The alternative 'semantic' or 'model-theoretic' approach to theories, which is to be preferred on independent grounds, is particularly appropriate for the structural realist.[7] This is because the semantic approach itself contains an emphasis on *structures*. That is, theories are to be thought of as presenting structures or models that may be used to represent systems, rather than as partially-interpreted axiomatic systems. Theories are not collections of propositions or statements, but are 'extra-linguistic entities which may be described or characterised by a number of different linguistic formulations' (Suppe, 1974, p. 221).

In the context of the syntactic approach, within which a theory is taken to be a set of sentences, realism amounts to the commitment to standard (correspondence) referential semantics, and to truth, for the whole theory. How should we understand questions about the relationship between theoretical objects and the world in terms of the semantic conception of theories? Ronald Giere addresses this issue in his writings on the semantic approach. Unlike van Fraassen, he seems to accept that the semantic approach transforms the terms of the scientific realism debate. In particular, Giere argues that it is unreasonable to expect all theoretical representation in science to fit the mould in which philosophers cast linguistic representation; Tarskian semantics is not appropriate for a consideration of the representative role of spacetime structure or Hilbert space.[8] One reason for this is that Giere's 'constructive realism' stops short of asserting that real systems resemble models in all respects. Instead, he claims that models are at best similar to real systems in many or most aspects.

So, Giere's version of the semantic approach relies on a notion of *similarity* in specified respects and to specified degrees, and of course it is a notorious complaint that similarity is a uselessly vague concept; everything is similar to everything else in some respect or other. It may therefore be better to use the notion of *partial isomorphism* to represent the relationships between theoretical structures and models of the phenomena.[9] However, this is not the crucial issue here, for, even if we reject the claim that models are similar to anything in the world, Giere is right that once the semantic approach is adopted the crucial issue is whether or not theoretical models tell us about *modalities*.[10]

Recall that the motivation for the realist element in the structural realist programme is the no-miracles argument. We demand some explanation of the success

[7]That the semantic approach to scientific theories is preferable is obviously controversial, but I take it for granted in the following. For a defence and articulation of the semantic approach see French and Ladyman (forthcoming).

[8]See Giere (1995).

[9]This is introduced in French and Ladyman (forthcoming), and applied to the history of superconductivity in French and Ladyman (1997).

[10]He argues that they do and states that (his) '[c]onstructive realism is thus a model-theoretic analogue of the view advocated by Grover Maxwell' (Giere, 1985, p. 83). Therefore, he says, constructive realism is a species of structural realism (*ibid.*).

of science—in particular, of the novel predictive success of theories. Consider van Fraassen's explanation for the success of science: theories are born into a jungle red in tooth and claw, that is, a fiercely competitive environment, and hence they have to be successful to survive. This is as if we were to explain consciousness by saying that selection pressures are such that organisms that do not develop sophisticated representational systems will not survive as well as those that do. This does not explain how it is that any particular organism has the capacity for consciousness. To answer that question we need a theory that explains how particular physical constitutions and functionality can give rise to consciousness. The equivalent question for scientific theories is: how is it possible for a particular theory to make novel predictions that are then vindicated? Think of Eddington's detection of light from a star behind the sun, the example that so impressed Popper. How can general relativity have predicted this correctly on van Fraassen's account? It is examples like this that seem miraculous without some realist ingredient in one's philosophy of science. Yet this need not be the same as asking how is this possible if the theory is not *true* (or approximately true).

In an everyday context our ability to predict relations between phenomena is grounded in our acceptance of the existence of objects and their properties. In the case of the unobservable world, realism about unobservable objects attempts to provide a similar grounding for our predictive success. But, if we reject traditional scientific realism yet wish to avoid scepticism (if structural realism is to be any kind of realism at all), we must provide some account of the world as unobserved by us. If structural realism is motivated by the no-miracles argument then it must explain how the relations in a model can correctly predict some previously unknown modal relations among phenomena in the world. This is a question that van Fraassen cannot answer at all, for he says that 'the locus of possibility is the model, not a reality behind the phenomena' (van Fraassen, 1980, p. 202). Although agnostic about scientific realism, he is atheistic about modality and believes in no objective causality or necessity in reality.[11]

Of course the traditional realist has such an explanation: theories that are approximately true express laws of nature that describe how the unobservable entities and processes described by the theories *must* behave. However, this account is undermined not merely by cases of radical ontological discontinuity, but also by the work of Cartwright and others which has emphasised the manifest falsity and ideal nature of theoretical models in science. Cartwright argues that the (so-called) laws that constrain abstract models, such as the law of universal gravitation or Schrödinger's equation, if understood as factual descriptions of how things in the world behave, are either false or irrelevant to the empirical domains to which they are supposed to apply. This is because the conditions under which they are

[11]There is therefore a tension in van Fraassen's position, for he thinks that unobservable entities *may* exist, but that laws and natural kinds definitely do not. Yet if, for example, electrons do indeed exist but do not form a natural kind subject to laws of interaction and so on, then we are wrong about a very important aspect of them, making it hard to see on what grounds we can say that *they* exist rather than some other things entirely.

supposed to obtain are counterfactual, and also because they are applied in the models to idealised or abstract entities.[12]

Cartwright takes this to show that theoretical models are not genuinely representational at all; rather, they are to be understood as tools for the construction of phenomenological models which are representational.[13] However, from the perspective of the semantic approach we do not expect the high-theoretical structure to be a law-like description of the world, rather we envisage a complex hierarchy of models or structures employed by the theory. As has been argued elsewhere, *contra* Cartwright *et al.*, abstract theoretical structure plays an important role in the development of low-level models of the phenomena, and some of the most profound novel predictions of science are directly obtained from highly theoretical models.[14] What is more, the highly abstract structures of modern physical theories do furnish us with explanations of a sort, what Hughes has called 'structural explanations' (Hughes, 1989). Hence, the most theoretical parts of a theory, the abstract mathematical structures it employs at the greatest level of generality, must have some grip on reality. It is clear that the 'grip on reality' in question must go beyond a correct description of the actual phenomena to the representation of modal relations between them.

3.2. Structure

According to Zahar (1994, p. 14) the continuity in science is in the *intension* not the *extension* of its concepts. Perhaps, if we are to believe that the mathematical structure of theories is what is important, then as Zahar suggests, we need a different semantics for theories: one that addresses the representative role of mathematics directly. The advantage of adopting such a view is that we would then be content with the continuity of mathematical structure that is found even between theories that differ radically if taken realistically, and so would not be confounded by theory change.[15] This would seem to entail a corresponding shift from a metaphysics of objects, properties, and relations, to one that takes structure as primitive.

To return to the claim that traditional realism is itself operating with a structuralist conception of its objects; this is quite misleading. Although theoretical terms are indeed understood in terms of the laws, equations and so on in which they feature, traditional realism *does* involve acceptance of more than the structural properties of theoretical entities. Theories are construed in terms of metaphysical commitments that are underdetermined by the evidence for them.

Underdetermination has been thought to show both that theory choice in science is not rational, and that we are unjustified in believing that the world is just how our best theories say it is. These are related but can be distinguished. Hence, recent work has sought to show that the existence of empirically equivalent theories does

[12]Cartwright (1983, 1989).
[13]Cartwright *et al.* (1996).
[14]French and Ladyman (1997).
[15]For example, Saunders (1993) has shown that the method of epicycles may be regarded as a Fourier approximation to an elliptical representation of planetary orbits.

not undermine the rationality of choosing one theory over another at a particular stage in the development of a science. It is pointed out that the empirical equivalence of two theories need not imply their evidential equivalence. This issue may be orthogonal to that of whether underdetermination undermines ontological commitment to a theory. For example, if, like Larry Laudan, one is a pragmatist and not a scientific realist, then one may well think that theory choice is thoroughly rational given pragmatic constraints, but that nonetheless ontological commitment to the theories thus chosen is unjustified given the possibility of empirically equivalent theories with alternative ontologies (Laudan, 1981). Furthermore, Roger Jones (1991) has argued that where we have a theory admitting alternative formulations each of which suggests a different metaphysics (his example is Newtonian mechanics and its 'action at a distance', 'variational', 'field-theoretic', and even 'curved spacetime' formulations), we cannot be realists about such a theory because we do not know which version to believe about how the world really is.

Even if we are able to decide on a canonical formulation of our theory, there is the further problem of metaphysical underdetermination with respect to, for example, whether the entities postulated by a theory are individuals or not.[16] There is, of course, much dispute about whether or not quantum particles, or spacetime points, are individuals. Realists would perhaps say that deciding these issues is a matter for the special sciences involved, and that these problems do not have to be solved for us to be realists.[17] But the recent history of the philosophy of physics shows us the impossibility of simply 'reading one's metaphysics off one's physics'. One example is the debate about nonlocality in the context of the Bohm–EPR experiment, which showed that whether the world is nonlocal is in a sense underdetermined, and may be proved or disproved according to the choice of assumptions about possessed values, determinism and so on.[18] In the case of individuality, it has been shown in the work of Steven French and Michael Redhead (French and Redhead, 1988; French, 1989), that electrons may be interpreted as either individuals or nonindividuals.[19]

We need to recognise the failure of our best theories to determine even the most

[16]Recent work by Decio Krause (1992) suggests that standard model theory presupposes that the basic objects of first-order predication are individuals because the axioms of ZF set theory ensure that the elements of sets are distinguishable individuals.

[17]Peter Forrest (1994) argues that we need not have solved the metaphysical disputes about the nature of the entities involved to accept scientific realism. In this he claims to follow the practice of the working scientist of talking as neutrally as possible about, say, particles. But of course the 'working scientist' must be allowed to believe in scientific realism on any plausible, even non-realist, view. The neutrality of that discourse is prephilosophical and in particular premetaphysical, and provides merely temporary solace before the metaphysical nature of the entities involved becomes a scientific issue.

[18]See Redhead (1987), for example.

[19]It is worth remarking that Paul Teller (see, for example, Teller, 1989) has proposed the introduction of 'non-supervenient relations', that is relations that do not supervene on the monadic properties of any individuals, in order to understand quantum entanglement. On this view, facts about relations must be understood as irreducible to facts about the non-relational properties of individuals. The non-supervenient relations are in fact there to partially salvage a classical ontology, with quantum entities as individuals (see French, 1989). However, this is an interesting shift away from an ontology that takes objects as primary, for a relation that does not supervene must be understood as having reality of itself, and to this extent Teller's proposal amounts to realism about structure.

fundamental ontological characteristic of the purported entities they feature. It is an *ersatz* form of realism that recommends belief in the existence of entities that have such ambiguous metaphysical status. What is required is a shift to a different ontological basis altogether, one for which questions of individuality simply do not arise. Perhaps we should view the individuals and nonindividuals packages, like particle and field pictures, as different *representations* of the same structure. There is an analogy here with the debate about substantivalism in general relativity. Recently it has been suggested that this issue also calls for a different fundamental ontology within which to assess the reality of spacetime. Robert DiSalle (1994) has suggested that the *structure* of spacetime be accepted as existent without being supervenient on the existence of spacetime points. This is a restatement of the position developed by Stein in his famous exchange with Grünbaum, according to which spacetime is neither a substance, nor a set of relations between substances, but a structure in its own right.

So we should seek to elaborate structural realism in such a way that it can diffuse the problems of traditional realism, with respect to both theory change and underdetermination. This means taking structure to be primitive and ontologically subsistent. I want briefly to turn to the use of group theory in modern science to suggest further how we can explicate structural realism.

Weyl's approach to relativity theory is essentially group-theoretic. That is, in common with his approach in geometry, he takes the objects of the theory to be characterised by invariance under particular groups of transformations. Similarly, in the case of quantum mechanics, he asserts that:

> All quantum numbers, with the exception of the so-called principle quantum number, are indices characterising representations of groups (1931, p. xxi).

The central point of philosophical relevance is that the mathematical notion of invariance is taken by Weyl to characterise the notion of *objectivity*.[20] It is this that liberates physics from the parochial confines of a particular coordinate system. For Weyl, appearances are open only to intuition (in the Kantian sense of subjective perception) and therefore agreement is obtained by giving objective status only to those relations that are invariant under particular transformations. What is particularly striking is the way that Weyl uses the insights gathered from his work on transformations and invariants in relativity theory to make his crucial contribution to the development of quantum mechanics.[21] The point is that the choice of the

[20]Weyl's views have recently been revived by Sunny Auyang (1996) in an explicitly neoKantian project which attempts to solve the problem of objectivity in quantum mechanics. Auyang seeks to extract the 'primitive conceptual structure' in physical theories and she too finds it in what she calls the 'representation–transformation–invariant structure'. This is essentially group-theoretic structure. Auyang, like Born and Weyl, thinks that this is what separates an objective state of affairs from its various representations, or manifestations to observers under different perceptual conditions, and such invariant structure under transformations.

[21]Weyl's fundamental role in the history of quantum mechanics is strangely absent from most histories of the subject. Some of the contributors to Deppert *et al*. (1988) seek to redress this. In particular see the papers by Julian Schwinger, George Mackey, and David Speiser. It is surprising that even the recent very detailed and scholarly study of the relationship between Heisenberg's and Schrödinger's

momentum space representation of Schrödinger amounts to the choice of a coordinate system. Weyl saw immediately that the proto-theories of Schrödinger and Heisenberg had fundamental mathematical similarities. He therefore took them to be in all important respects different versions of the same theory:

> [T]he essence of the new Heisenberg–Schrödinger–Dirac quantum mechanics is to be found in the fact that there is associated with each physical system a set of quantities, constituting a non-commutative algebra in the technical mathematical sense, the elements of which are the physical quantities themselves (Weyl, 1931, p. viii).

Thus Weyl here anticipates von Neumann's unification of the theories in his classic text on quantum mechanics, and indeed Dirac in his book on the theory cites Weyl as the only previous author to employ the same 'symbolic method' for the presentation of the theory as he does himself. This method according to Dirac 'deals directly in an abstract way with the quantities of fundamental importance (the invariants etc. of the transformations)' and therefore it goes 'more deeply into the nature of things' (Dirac, 1930, p. viii). Dirac uses vectors, and not rays in Hilbert space like Weyl and von Neumann, in his treatment of quantum mechanics, but both he and Weyl recognised that the mathematical status of the two rival theories of quantum mechanics as alternative *representations* of the same mathematical structure, makes preference for either eliminable once a unified framework is available.[22]

The idea then is that we have various representations which may be transformed or translated into one another, and then we have an invariant state under such transformations which represents the objective state of affairs. Representations are extraneous to physical states but they allow our empirical knowledge of them. Objects are picked out by individuating invariants with respect to the transformations relevant to the context. Thus, on this view, elementary particles are just sets of quantities that are invariant under the symmetry groups of particle physics.

Consider the following remark by Howard Stein:

> But if one examines carefully how phenomena are 'represented' by the quantum theory … then … interpretation in terms of 'entities' and 'attributes' can be seen to be highly dubious …. I think the live problems concern the relation of the Forms… to phenomena, rather than the relation of (putative) attributes to (putative) entities … (1989, p. 59).

The suggestion is that the forms in question are given by the invariance structure of theories. This notion of structure may give us one way of explicating structural realism, although this is a matter for further study.

mechanics, and their successor von Neumann's quantum mechanics, completely omits Weyl from the story (Müller, 1997).

[22]Although it may not have been until the empirical success resulting from Dirac's relativistic theory of the electron, based as it was on the underlying group structure, that it was widely acknowledged by physicists that the abstract structure of a group is of greater significance than particular representations of it. Indeed, in the early days of quantum mechanics Weyl reports that some talked of eliminating the 'group pest' (Weyl, 1931, p. x).

4. Conclusion

Ernan McMullin has said:

> [I]maginability must not be made the test for ontology. The realist claim is that the scientist is discovering the structures of the world; it is not required in addition that these structures be imaginable in the categories of the macroworld (1984, p. 14).

The demand for an individuals-based ontology may be criticised on the grounds that it is the demand that the structure of the mind-independent world be imaginable in terms of the categories of the world of experience. Traditional realism should be replaced by an account that allows for a global relation between models and the world, which can support the predictive success of theories, but which does not supervene on the successful reference of theoretical terms to individual entities, or the truth of sentences involving them. It is interesting to note that Benacerraf (1965) argued that objects to be properly called such must be individuals, and that, therefore, a structuralist construal of abstract objects like numbers must fail, because an object with only a structural character could be identified with any object in the appropriate place in any exemplary structure. If he is right about this then structural realism amounts to the claim that theories tell us not about the *objects* and *properties* of which the world is made, but directly about *structure* and *relations*.

Acknowledgements—For detailed comments on an ancestor of this paper I am very grateful to Steven French, Katherine Hawley, Robin Hendry, David Papineau, Stathis Psillos, and an anonymous reader for this journal. Thanks also to Decio Krause, Mike McGuire, Mauricio Suárez, Paul Tappenden, John Worrall and Elie Zahar.

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