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SCIENCE, METAPHYSICS AND STRUCTURAL REALISM

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1. Introduction

Scientific realism is the view that we ought to believe that our best current scientific theories are approximately true and that their central theoretical terms successfully refer. Hence, if the theories employ terms that purport to refer to unobservable entities such as electrons, or gravitational waves, then, realists say, we ought to believe that there really are such entities having the properties and exhibiting the behaviour attributed to them. For many philosophers scientific realism is obvious and uncontroversial. Certainly, for example, in debates about physicalism, reductionism and supervenience in the philosophy of mind, it is normally assumed by all parties that there are atoms, molecules, ions and so on; the question is whether that is all there is, or whether there are emergent, or causally autonomous entities and properties over and above the physical stuff. Scientific explanations throughout the physical but also the life sciences make essential reference to unobservable entities such as electromagnetic waves, nitrogen molecules and gravitational fields. Furthermore, there is a powerful argument in favour of scientific realism, namely the no-miracles argument; the overall empirical success of scientific methods would be a miracle if our best scientific theories were not approximately true. Hence, one might be forgiven for thinking that there is no question that scientific realism is correct.

However, there are many reasons for some degree of scepticism about scientific knowledge. Some are perhaps *merely* philosophical, but some are internal to science itself. The familiar underdetermination argument is one of the former; since we can only test the empirical consequences of a theory, how do we know that the one we have is correct rather than some incompatible rival, which is nonetheless empirically equivalent to it? Antirealists of an empiricist stripe go on to argue that we should confine ourselves to believing what theories tell us about the observable phenomena and suspend judgement about the unobservable world. On the other hand, there is also a powerful empirical argument, based on the history of science, which threatens scientific realism and which seems to give us a reason not just for an agnostic scepticism but for 'atheistic' scepticism. The argument in question is known as the pessimistic meta-induction and it has the following structure:

(i) There have been many empirically successful theories in the history of science which have subsequently been rejected and whose theoretical terms do not refer according to our best current theories.
(ii) Our best current theories are no different in kind from those discarded theories and so we have no reason to think they will not ultimately be replaced as well.
(iii) By induction we have positive reason to expect that our best current theories will be replaced by new theories according to which some of the central theoretical terms of our best current theories do not refer.

Therefore, we should not believe in the approximate truth or the successful reference of the theoretical terms of our best current theories.

The most common realist response to this argument is to restrict realism to theories with some further properties (usually, maturity, and *novel* predictive success) so as to cut down the inductive base employed in (i). Now giving an account of novel predictive success that satisfies constraints on theories of confirmation such as objectivity and impersonality, and which also conforms to paradigm scientific judgements about the confirmation of specific theories in the history of science is not a trivial task.[1] However, assuming that such an account can be given there are still a couple of cases of mature theories which enjoyed novel

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[1] See Leplin (1997) for a recent detailed attempt to address this problem, and Ladyman (1999) for a critique of it.

predictive success by anyone's standards, namely the ether theory of light and the caloric theory of heat. If their central theoretical terms do not refer, the realist's claim that approximate truth explains empirical success will no longer be enough to establish realism, because we will need some other explanation for success of the caloric and ether theories. If this will do for these theories then it ought to do for others where we happened to have retained the central theoretical terms, and then we do not need the realist's preferred explanation that such theories are true and successfully refer to unobservable entities.

There are two basic (not necessarily mutually exclusive) responses to this:

(a) Develop an account of reference according to which the abandoned theoretical terms are regarded as referring after all.
(b) Restrict realism to those parts of theories which play an essential role in the derivation of subsequently observed (novel) predictions, and then argue that the terms of past theories which are now regarded as non-referring were non-essential so there is no reason to deny that the essential terms in current theories will be retained.

The former is usually pursued in the context of a causal theory of reference, according to which someone can successfully refer to an entity, despite being quite wrong about many of its properties. Hence, it is argued that the term 'ether', which was widely deployed in the nineteenth century in the context of the wave theory of light, referred all along to the electromagnetic field. In general, the problem with (a) is that it tends to make successful reference to easy.[2] Strategy (b) is used by Stathis Psillos (1999) who argues that the term 'caloric' was not a central term in the caloric theory of heat. I have taken issue with this account elsewhere (Ladyman (2002)). Whether or not my critique is convincing, it seems fair to say that the danger with strategy (b) is that it may rely on hindsight in such a way as to make the pronouncements as to which terms are central and which are not depend on which have subsequently been abandoned. This would make (b) an ad hoc solution to the problem of

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[2] See Hardin and Rosenberg (1982), Laudan (1984), Kitcher (1993) chapter 5, Psillos (1999) chapters 5&6, and Ladyman (2002), chapter 8.

abandoned theoretical terms.

Structural realism was revived by John Worrall (1989) as a more radical attempt to defend a form of realism about science in the face of the pessimistic meta-induction. He argued that while the ontology of scientific theories may change, there is often retention of theoretical structure even after significant revolutions. For example, the equations of classical mechanics can be recovered as a limiting case of the equations of special relativity, and the equations of Fresnel's wave theory of optics are retained in Maxwell's theory of the electromagnetic field, even though Fresnel's elastic solid ether was abandoned. Hence, a form of realism that is only committed to the *structure* of theories would not be undermined by theory change. There are many possible interpretations of structural realism. Perhaps the most minimal is just to treat it as a defence of the cumulative nature of science in the face of Kuhnian worries about revolutions. However, it is clear that Worrall intended to go further than this since he explicitly referred to the need for some form of realism to account for novel predictive success in science.

Recent work has revealed that many different forms of structuralism and structural realism can be found in the work of some of the greatest philosophers of science. Barry Gower's (2000) historical survey of structural realism discusses how structuralism figures in the thought of Cassirer, Schlick, Carnap and Russell. Worrall approvingly cited Poincaré as a structural realist (and Ellie Zahar (1994) and Gower seem to agree with this reading of him), however, Mary Domski (1999) has argued convincingly that Poincaré was not any kind of realist in the modern sense of the term. His structuralism was combined with his neo-Kantian views about the nature of arithmetic and group theory, and with his conventionalism about the geometry of space and time. Hence, she argues, he is better thought of as a structural empiricist or a structural neo-Kantian. Meanwhile, Stathis Psillos (1999) has explored the connections between structuralism and the Ramsey sentence approach to scientific theory as it figured in the development of Carnap's philosophy from logical positivism to ontologically relativist empiricism.

One way of thinking about structural realism is as an epistemological modification of scientific realism to the effect that we only believe what scientific theories tell us about the relations entered into by unobservable objects, and suspend judgement as to the nature of the latter. Hence, it is sometimes said that scientific theories tell us only about the form or structure of the unobservable world and not its nature. Russell and later Carnap took this one step further and argued that we cannot even know the relations; rather all we can know is *their* properties and relations. On this extreme form of structuralism science only tells us about purely logical features of the world. Elsewhere (1998) I discussed Russell's view and argued that in general epistemological forms of structural realism do not significantly improve the prospects of standard scientific realism, and hence that structural realism should be thought of as metaphysically rather than epistemically revisionary.

Worrall's only motivation for introducing structural realism was the need to respond to the pessimistic meta-induction. However, there is another motivation that figures prominently in the history of structuralism about scientific knowledge, namely to offer an ontology that is appropriate to the 'new physics' of quantum mechanics and general relativity. For example, although in his discussion of Cassirer's work, Gower confines himself to an epistemological reading of structural realism, Steven French and I (forthcoming) have argued that Cassirer was more radical than this, and that like Weyl, he was concerned to replace an individual based ontology with one more suited to twentieth century science. Relatedly, Steven French has recently examined the role of group theory in the development of quantum mechanics (1999, 2000), and explored the idea of the group-theoretic 'constitution' of objects as sets of invariants under symmetry transformations which was can be found in the writings of Cassirer, Weyl, Born and Schrödinger. I shall not explore that idea further here but explain how modern physics challenges deep-rooted metaphysical intuitions, and then suggest how structural realism might be developed in response to it.

2. Identity and Individuality in Modern Physics

The debate about whether quantum particles are individuals or not began with the beginnings of quantum statistics. It became clear early on that there was a fundamental difference between the way classical statistical mechanics and the new quantum theory dealt with the permutation of indistinguishable elementary particles.[3] The crucial point is illustrated by the following example. Imagine that there are two particles (1 and 2), and two states (A and B), and each of the particles must be in one state or the other. Classically there are four possible configurations for the system:

> Both 1 and 2 in A; both 1 and 2 in B; 1 in A and 2 in B; 1 in B and 2 in A.

Hence, if these are regarded as equipossible, each will be assigned a probability of 1/4. The situation is quite different in quantum mechanics; there are only three possible states:

> Both 1 And 2 in A; both 1 and 2 in B; one of 1 and 2 in A and the other in B.

Hence, if these are regarded as equipossible, each will be assigned a probability of 1/3. In quantum statistics then what would be regarded as two possible states of affairs classically is treated as one possible state of affairs. This is formalised by the so-called 'indistinguishability postulate'[4]:

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[3] Both classical and quantum elementary particles of a given type are regarded as indistinguishable in the sense that they will all have the same mass, size and shape (if any), charge and so on; but they may in principle be distinguished by their spatiotemporal or other state dependent properties. We may think of the former properties as 'essential', in the sense that they are characteristic of the natural kind to which a particular particle belongs, as opposed to the 'accidental' properties which are those that a particle just happens to have, such as its velocity or position at a particular time. (Note that this distinction between 'essential' and 'accidental' properties does not correspond to that between 'permanent' and 'temporary' properties; an electron might happen accidentally to have the same position throughout the history of the universe.) Some authors talk of "identical particles" (for example, van Fraassen 1991) but they mean by this just what I shall mean by indistinguishable particles; the particles are not strictly identical of course since they may even be qualitatively identical because they are in the same state, and yet still numerically (or quantitatively) distinct.

[4] See Greenberg and Messiah (1964).

If P is the operator corresponding to the interchange of the particles 1 and 2 in a two particle quantum state, that is,
$\mathbf{P}\Psi_{12} = \Psi_{21}$ and $\mathbf{P}\Psi_{21} = \Psi_{12}$,
then $\langle \mathbf{P}\Psi_{12} \mid \mathbf{Q} \mid \mathbf{P}\Psi_{12} \rangle = \langle \Psi_{12} \mid \mathbf{Q} \mid \Psi_{12} \rangle$, $\forall \mathbf{Q}$, $\forall \Psi_{12}$

Here Q is any observable whatever. So, according to the formalism of quantum mechanics, the permutation of indistinguishable particles in some state is not observable, and states which differ only with respect to the permutation of particles of the same kind are treated as the same state labelled differently.

Early in the history of quantum mechanics this led some physicists to argue that quantum particles are not individuals. To understand what is a stake here we must separate the related concepts of distinguishability and individuality.[5] A principle of distinguishability or discernibility is what allows the judgement that two things are different from one another. There are two obvious possibilities; A is different from B either if it has a different spatio-temporal location, or if it has a different set of properties. Ordinary everyday objects, such as leaves and snowflakes, never, it seems, possess all the same properties; they are distinguishable by both their spatiotemporal properties and their intrinsic properties.[6] The particles of classical physics of a given type were thought to share all their intrinsic properties, but, in classical physics it is assumed that particles have well defined trajectories in space and time and therefore they are distinguishable at least by their spatiotemporal properties. Hence, for everyday objects and for classical particles, the principle of the

[5] The distinction is due to the scholastic philosopher Suarez.

[6] Intrinsic properties are normally defined to be those which an object possess independently of everything else that exists; roughly those that it would still have if it were the only thing in the universe (but see Lewis 1983). Hence, the mass and charge of (classical) elementary particles, and the shape and size of a person are intrinsic properties. Extrinsic properties are just those that are not intrinsic; weight, being the brother of and cost are extrinsic properties. Another usage common in the foundations of quantum mechanics (see for example, Jauch 1966, p. 275) treats the intrinsic properties of a system as those that do not depend on the state of the system, and the extrinsic properties as those that do. This seems to equate intrinsic with essential; in any case I shall adopt the former definitions as this would seem to beg the question of whether spatiotemporal properties are intrinsic or extrinsic since they are obviously state dependent.

identity of Indiscernibles (PII) is true, and it is plausible to argue (with Leibniz) that individuality and distinguishability amount to the same thing.

However, conceptually and metaphysically we can separate distinguishability – how it is that we can tell that one thing is the same or different from another – and individuality – in virtue of what it is that two things are different from one another, and one thing is identical with itself and not with anything else. There are three main candidates in the philosophical tradition for a principle of individuation for physical objects:

(1) Transcendent individuality (this is similar to Post's term 'transcendental individuality' adopted by French and Redhead 1988); the individuality of something is a feature of it over and above all its (usual) properties. Different ways of cashing this out include Locke's substantial substratum, the notion of a 'bare particular'; and the notion of haecceity or thisness due to Duns Scotus.
(2) Spatio-temporal location or trajectory
(3) Some set of properties; this may be all properties as in the 'bundle' theory of Russell, or some restricted set.

Until the advent of quantum mechanics most philosophers in the modern era thought it was clear that PII is true, even if only contingently so, and objects are individuals in virtue of their possession of a set of properties not possessed by an other object. The most obvious candidates for these properties are the spatiotemporal properties of the individual. It was assumed that a principle of impenetrability, according to which no two particles could occupy the same spatiotemporal location, was true of classical particles. Hence, classical particles were thought to be distinct individuals in virtue of each one having a unique trajectory in spacetime distinct from every other one. After the advent of quantum mechanics the status of PII has been the subject of debate, and the possibility of some principle of individuation that appeals to some feature of particles other than their qualitative properties has been taken seriously.

For one thing in the formalism of quantum mechanics particles are not always assigned well defined trajectories in spacetime. Furthermore, two or more particles in an entangled state at a given time may possess exactly the same monadic and relational properties that are expressible by the formalism of the theory. Consider the singlet state of a pair of electrons for example:

$$\Psi_{12} = 1/\sqrt{2} \{ | \uparrow\rangle_1 | \downarrow\rangle_2 + | \downarrow\rangle_1 | \uparrow\rangle_2 \}$$

(Here the electrons are labelled 1 and 2, and the spin components of + and – along an arbitrary axis are represented by up and down arrows respectively.) Clearly, according to this state description there is no property of particle 1 that cannot also be predicated of particle 2.

Hence, quantum particles appear sometimes to possess all the same intrinsic *and* extrinsic properties. If two electrons really are two distinct individuals, and it is true that they share all the same properties, then there must be some principle of individuation that transcends everything that can be expressed by the formalism in virtue of which they are individuals. If we assume for now that the quantum description is complete, then we are left with a dilemma: either PII is false, the quantum particles are individuals and there must be some principle of individuation of type (1) above; or quantum particles are not individuals and PII is obviated in this context.

French (1989) has argued that this means there are two main different metaphysical packages such that the choice between them is underdetermined by quantum mechanics: in the first quantum particles retain classical individuality but they are unable to enter into certain states (the 'symmetrization postulate' states that bosons can only occupy symmetric states and fermions can only occupy antisymmetric states), and furthermore they can enter into entangled states like the one above; the alternative metaphysical picture abandons the idea that quantum particles are individuals at all, perhaps in favour of a field theoretic construal of them. Problems remain with both these approaches; in the case of the individuals package it is worth noting that the naming or labelling of the particles is problematic. This is because a descriptivist account of reference is unworkable if PII fails, and because a rigid designation account seems to imply the wrong statistics, because we ought to count a two-particle state as distinct from the same one with the two particles interchanged.

However, three metaphysical and methodological reasons have been offered by various authors for preferring the nonindividuals interpretation of quantum particles: (i) PII is incompatible with the individuals package under fairly reasonable assumptions, but abandoning this framework allows that it is true;[7] (ii) Positing individuals plus states that are forever inaccessible to them is ontologically profligate amounting to the acceptance of "surplus structure"; (iii) a principle of individuality of type (1) above must be metaphysical in the sense that it posits what van Fraassen has called "empirically surplus factors". (Hence, van Fraassen argues that all this is all the more reason to say "goodbye to metaphysics" (1991, p. 480).)

None of these considerations are conclusive though: (i) There is no empirical way to confirm PII and so concluding that quantum particles are not individuals to safeguard this principle might be merely the expression of a metaphysical or metalogical preference based on experience of macroscopic objects. (ii) There are many cases in the history of science where so-called surplus structure in the formulation of a theory has later been found to be of empirical importance (see French 1995, 1996). The surplus structure in Hilbert space allows for states that are neither symmetric nor antisymmetric and hence for particles which are neither fermions nor bosons but instead obey "para-statistics". (iii) Van Fraassen's point about empirically surplus factors will obviously not persuade the realist. Hence, the underdetermination is not easily broken.

Of course our best quantum theories are field theories and the realist might be tempted to dismiss the problems of individuality arising for many-particle quantum mechanics on this basis. There are several problems with this. Firstly, as with classical mechanics, the fact that non-relativistic particle quantum mechanics has had enormous empirical success and is a paradigm of a good scientific theory means that the realist ought to be able to say what it would be to be a realist about it. Otherwise realism will only apply to the one true theory of the world, if there is one, and, since we are clearly not there yet, would be of no relevance to actual theories. Secondly, we ought to be able to recover the concept of fundamental particles used widely by physicists and chemists from the ontology of field theory, and so questions about their nature will remain meaningful.

Thirdly, quantum field theories are no easier to interpret realistically

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[7] These reasonable assumptions are the Principle of Statistical Mechanics (which states that equipossible states of affairs are equiprobable), and the Completeness assumption (which states that there are no hidden variables not described by the quantum formalism).

than ordinary quantum theory and raise new and equally compelling interpretative problems. Quantum fields are not analogous to classical fields, for the field consists of operators parametised with space-time points:

> these operator values associated with the space-time points are not specific values of some physical quantity. The specific or concrete values are, as one initially expects, the states, or equivalently, the catalogue of probability amplitudes for all possible measurements. (Teller 1990, p. 613)

Thus, the operators represent not the values of physical quantities but those quantities themselves. Teller is clear on how the interpretative problems of non-relativistic quantum mechanics (particularly the measurement problem) are inherited by quantum field theories. This leads Redhead to argue against a "classical-style realism of possessed values, *not* against a broader realism of physical structure" (1996, p.7):

> realism 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. (Ibid., p.2)
> Success requires "explanation with reference to validating the structural framework of the theory" (Ibid., p.7)

Fourthly, the problem of individuality is not solved by shifting to field theories; if anything it is more intractable. As Teller points out:

> Conventional quantum mechanics seems incompatible with a classical notion of property on which all quantities always have definite values. Quantum field theory presents an exactly analogous problem with saying that the number of "particles" is always definite. (Op. cit., p. 594).

In quantum field theories, the particle number for a given state of the field (how many particles there are) is dependent on the frame of reference adopted. So particles seem to lose their reality in the field theoretic approach. Teller himself advocates an interpretation in terms of "quanta" which are excitations of the field that may be aggregated like particles (we can say there is a state with so many quanta), but cannot be enumerated (we cannot say this is the first, this the second, and so on); quanta are not individuals.[8] The problem of individuality becomes that of whether fields themselves are individuals or whether they are properties of spacetime points; this pushes the problem back to whether spacetime points are individuals. This latter issue is bound up with the debate about substantivalism in the foundations of relativity to which I shall now briefly turn.

The analogue of the dispute about realism in quantum mechanics in the case of general relativity is the debate between substantivalists and relationalists. To a first approximation, the former hold that the points of the spacetime manifold exist independently of the material contents of the universe, while the latter hold that spatiotemporal facts are solely about the relations between various elements of the material contents of spacetime. (This debate is usually traced back to Newton and Leibniz, though this is perhaps anachronistic (see, for example, DiSalle 1994)). The problem for the relationist is that the field equations of general relativity have a solution where spacetime is entirely empty, the so-called de Sitter solution. Hence, the theory seems to imply that spacetime can exist and has properties and structure, independently of its material contents. Furthermore, the theory seems to quantify over spacetime points and predicate properties of them.

On the other hand, the problem for substantivalism is that the general covariance of the field equations of general relativity means that any spacetime model and its image under a diffeomorphism (a differentiable, one-one and onto mapping of the model to itself which preserves topological structure) are in all respects equivalent to one another; all physical properties are expressed in terms of generally covariant geometrical objects. In other words, since the points of spacetime are entirely indiscernible one from another, it makes no difference if we swap them around so long as the overall structure remains the same. This is made more apparent by the so-called 'hole argument' (Earman and Norton, 1987) which shows that if diffeomorphic models are regarded as

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[8] Decio Krause (1992) has recently developed a formal framework for non-individual entities based on an extension of set theory to include sets which have a cardinality but no ordinality; sets of quanta would have this feature. A similar project has been undertaken by Dalla Chiara and her co-workers.

physically distinct then there is a breakdown of determinism. Substantivalists cannot just bite the bullet and accept this since, as Earman and Norton argue, the question of determinism ought to be settled on empirical / physical grounds and not philosophical ones.

So should we believe in substantival spacetime or just in its material contents and the relations between them? In an attempt to solve this problem, Robert DiSalle (1994) has suggested that the *structure* of spacetime be accepted as existent although it is not supervenient on the reality of spacetime points. A similar view has been proposed by Carl Hoeffer; he argues that the problems for spacetime substantivalism turn on the "ascription of primitive identity to space-time points" (1996, p. 11). By "primitive identity" he means roughly the primitive thisness of (1) above. Hence, it seems that the insistence on interpreting spacetime in terms of an ontology of underlying entities and their properties is what causes the problems for realism about spacetime.[9]

3. Realism about Structure

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. Hence, two questions must be addressed:

(i) What is *structure*?
(ii) In what sense is structural realism a species of realism?

In order to answer the first question one must have a conception of what scientific theories are, and one must explain what it means for two theories to share the same structure. The standard conception of structure is either set theoretic or logical. Either way it is assumed that a structure is composed fundamentally of basic entities – individuals – that have properties. The view that this conceptual structure reflects the structure of the world is called "particularism" by Teller (1989) and "exclusive

[9] For a recent defence of structural realism about spacetime see the paper by Steven French in this volume.

monadism" by Dipert (1997)[10]; it is adhered to by philosophers from Aristotle and Leibniz to modern scientific realists. However, it is a largely unconscious consensus that has enjoyed little discussion, perhaps because few have contemplated an alternative. In particular, consider the doctrine that David Lewis calls Humean supervenience:

> [A]ll there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another... We have geometry: a system of external relations of spatio temporal distance between points [of spacetime, point matter, aether or fields or both]. And at these points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. [...] All else supervenes on that. (1986, p. x)

Recall that intrinsic properties are those which may be possessed independently of all other entities, such as charge, mass, and so on; extrinsic properties are non-intrinsic properties, such as, being North-East of Bristol. By 'all else' Lewis means all truths of causation, laws and identity over time. Lewis argues that all that exists, according to physics, is an interconnected web of intrinsic properties and spatio-temporal relations. There are no abstract entities nor any necessary connections. "[A]ll the facts there are about the world are particular facts, or combinations thereof" (ibid., p. 111)

Lewis argues that Humean supervenience is only contingently true, and that:

> If physics itself were to teach me that it is false, I wouldn't grieve. (Ibid, p. xi)

Indeed, it is surely natural science, and in particular mechanistic materialism, that has inspired this doctrine. Although Lewis considers that quantum mechanics may indeed teach that Humean supervenience is false, this is a lesson he refuses to learn, on the grounds that quantum mechanics is "imbued with instrumentalist frivolity", "double thinking deviant logic" and "supernatural tales" (ibid.). Yet if we are to be

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[10] Dipert argues for a structuralist metaphysics in terms of the theory of graphs.

scientific realists (as Lewis would claim) we should surely have our metaphysics informed by our best physics, and we can hardly object that we will only do this if the result coincides with our prejudices. The interpretation of quantum theory may well be fraught with difficulty but the theory has produced many novel predictions and has been well-confirmed to an unprecedented degree of precision. I have already explained how quantum theory challenges the assumption that the entities which physics describes are individuals. I want to turn now to what it may have to tell us about the ontology of relations, and in particular, whether relations other than spatiotemporal ones are supervenient on the properties of their relata as Humean supervenience requires.

If two electrons are in a joint state that is 'entangled' (like the singlet state) then according to quantum mechanics they do not have any intrinsic properties other than their essential ones. Paul Teller proposes the existence of 'non-supervenient relations' (see, for example, 1989), that is relations that do not supervene on the monadic properties of their relata, in the interpretation of entangled states in quantum mechanics. On this view, facts about relations must be understood as irreducible to facts about the non-relational properties of individuals; hence this is opposed to particularism as defined above. As I mentioned above these relations are part of a classical ontology of individuals in Teller's picture, however, it is worth investigating the nature of these non-supervenient relations in order to appreciate how quantum mechanics challenges classical intuitions about ontology, like those which motivate Lewis' notion of Humean supervenience.

Jeremy Butterfield (1992) has argued they are equivalent to what Lewis (1986) calls "external relations". According to Lewis, an internal relation is one which supervenes on the intrinsic properties of its relata, in the sense that there can be no difference in the relations between them, without a difference in their intrinsic properties. For example, if two objects are related by 'bigger than', this relation supervenes on the sizes of the two objects. On the other hand, an external relation is one which fails to supervene on the intrinsic properties of its relata, but does supervene on the intrinsic properties of their "composite". The example Lewis gives is of the spatial separation of a proton and an electron orbiting it (a hydrogen atom), where this system is understood classically as if it were like the Moon orbiting the Earth. This relation will not supervene on the intrinsic properties of the relata (their duplicates could be further apart). Lewis then seems simply to define the composite of the electron and nucleus as the set of the two of them with their spatiotemporal properties, so that their spatial separation does supervene on them taken together. The composite cannot be just the set of the two of them (ibid., p. 62).

All the external relations that I can think of are such spatial or spatiotemporal relations. Consider the relation of 'being each other's mirror image'; does this supervene on the properties of the composite of two objects? If we suppose that this picks up all the spatiotemporal relations of the objects then it would seem so. The same presumably goes for the relation of 'being inside of'. However notice that such relations also supervene on the intrinsic and relational properties that each element of the composite has independently of the whole or the other part. So if a book is inside a bag we can imagine that this relation consists in nothing more than the positions of the two objects relative to everything else there is in the world. Similarly, the spatial separation of the electron and its proton (or the Moon and the Earth) supervenes on the relational, in particular, spatial properties each has quite independently of the other or the composite as a whole (the position of each relative to the Sun say). The existence of such relations does not trouble Lewis because it does not threaten Humean supervenience which is fundamentally the thought that there are no necessary connections between distinct existences. Spatiotemporal relations may not supervene on intrinsic properties but they do supervene on relational properties of the relata that are mutually independent.

The entangled states of quantum mechanics do not supervene on the intrinsic properties of their relata, because in an entangled state each particle has no state of its own but rather enters into a product state. The only intrinsic properties that an entity in an entangled state has that are independent of the other entities in that state are its essential properties such as charge, mass and so on, and the only relational properties it has involve the other entities with which it is entangled. Hence, unlike external relations, the non-supervenient relations into which several quantum particles may enter are not even supervenient on the relational properties which their relata possess independently of each other. They are much more independent of the properties of the individual particles than spatio-temporal relations between classical objects. This would seem to refute Humean supervenience in so far as the doctrine is supposed to be inspired by science as Lewis claims.

I suggest that we abandon the attempt to interpret physical theory in terms of underlying objects and properties of which the world is made, about *structure* and *relations* directly. Now to answer question (ii) above, structural realism needs to be differentiated from empiricist views of science. According to Bas van Fraassen, the opposition between his constructive empiricism, (the view that the acceptance of scientific theories involves as belief only that they are empirically adequate) and scientific realism, is really that between empiricism and metaphysics. I have argued elsewhere (2000) that even the constructive empiricist cannot do without some metaphysics, in particular, without a commitment to objective modal relations. It is just such a commitment that I think structural realism needs in order to be a realist position that can satisfy the intuition behind the no-miracles argument. If science tells us about objective modal relations among the phenomena (both possible and actual), then occasional novel predictive success is not miraculous but to be expected. Furthermore, the fact that scientific theories support counterfactual conditionals is also explained. What differentiates the resulting form of structural realism from standard scientific realism is that the latter regards the mind-independent modal relations between phenomena as supervenient on the properties of unobservable objects and the external relations between them, rather than this structure being ontologically basic. Hence, the answer to question (i) above is that the structure described by scientific theories is the modal structure of the phenomena.

In a paper delivered in Leiden in 1999 (forthcoming), van Fraassen argues that the heart of the problem with my radical structuralism is this:

> it must imply: what has looked like the structure of something with unknown qualitative features is actually all there is to nature. But with this, the contrast between structure and what is not structure has disappeared. Thus, once the position is adopted, any difference between it and 'ordinary' scientific realism also disappears. It should, once adopted, not be called structuralism at all! If there is no non-structure, there is no structure either. But for those who do not adopt the view, it remains startling: from an external or prior point of view, it seems to tell us that nature needs to be entirely re-conceived, with the appearances classified as pure illusion" (p. 17)

My view is this: scientific realists take it that the appearances are caused by unseen objects and that the behaviour of these objects can be invoked to explain the appearances. But the resources of the manifest image cannot be (directly) used for satisfactory representation in physics, hence, mathematics has an ineliminable role to play in theories. When theories are empirically adequate they tell us about the structure of the phenomena and this structure is (at least in part) modal structure. However there is still a distinction between structure and non-structure: the phenomena have structure but they are not structure.

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