What is This Thing Called Structure? (Rummaging in the Toolbox of Metaphysics for an Answer)*

Steven French
School of Philosophy, Religion and History of Science
University of Leeds

1. Introduction

Apparently, Stanislaw Ulam, the mathematican and physicist, who invented the Monte Carlo method, once said that every action should have at least two motivations. Ontic structural realism (OSR) certainly meets that criterion. The first motivation is one it has in common with the so-called 'epistemic' form (Worrall 1989), namely that of offering a response to the ontological changes apparently manifested throughout the history of science, as represented by the infamous 'Pessimistic Meta-Induction'. This response was been traced back by Worrall (*ibid*.) to Poincaré and is embodied in the emphasis on the relevant equations as representing the structure that underlines such changes. Crucially, however, despite suggestive remarks, Worrall did not extend his considerations into the quantum domain.

The second motivation begins there, or in modern physics more generally and seeks a form of realism 'fit for purpose' in this domain. The progenitors of this strand of the structuralist project are Cassirer and Eddington who recognised the implications of quantum physics for the traditional object-oriented metaphysics and highlighted the significant role of certain 'higher principles' and symmetries in modern physics. There are, of course, crucial differences with the current structuralist iteration: first of all, and most obviously, Cassirer and Eddington were definitely not realists! Secondly, following Born and Heisenberg, they took the implications of the newly articulated quantum statistics to be that particles could no longer be regarded as individuals and hence argued on those grounds that an object-oriented stance must be dropped in favour of a structuralist one. As is now well known, the relevant physics does not in fact preclude regarding quantum particles as individuals (French and Krause 2006), and so a form of metaphysical underdetermination is generated with regard to the 'individuality profile' of the particles (see Brading and Skiles 2012; for an overview see French forthcominga). van Fraassen (1991) presents this as a challenge to the realist: how can she maintain her ontological commitments to such particles when she cannot even say whether they are individuals or not (at least, on the basis of the physics)? The response of the ontic structural realist is to urge a shift in those commitments, away from a view of the particles *as objects* and towards the underlying structure.

Both of the above motivations feature in Ladyman's classic paper (Ladyman 1998) setting out both the basis of OSR and its extension to quantum theory.[1] Of course, one can always ask the question: what if they were to cleave apart (see French 2006)? One might, for example, worry that the structural

continuity emphasised by Worrall and exemplified by the history of our understanding of light in classical terms, to use his example, cannot be maintained through the classical-quantum transition. One option, in that case, would be to argue that this transition is perhaps not as sharp or dramatic as is often portrayed and that a form of continuity can still be maintained, albeit in somewhat different form than that set out by Worrall. In particular, given the second motivation above, and the significance of symmetries, as captured in group-theoretic terms, in quantum physics, any proposed continuity should accommodate the latter. Thus Thébault has argued that '…we can isolate the structures that both connect and generalize the relationships between the various classical and quantum formal structures' (2016, p. 90) and offers a structural framework cashed out in terms of the combination of a state space with Poisson bracket structure and a set of observables with Lie algebra structure. Crucially, this framework is explicitly dynamical and in a paper that significantly foreshadows certain features of OSR, Saunders (1993) took the likes of Laudan and Kuhn to task for failing to pay sufficient attention to the continuities inherent in the relevant *dynamics*. If we properly address the latter, he maintained, we cannot help but notice the importance of the Hamiltonian formulation and Fourier decomposition for Heisenberg, or that of Poisson brackets (again) for Dirac, to give just a couple of examples. Of course there are differences between the classical and quantum forms of these devices – else how would there be any theoretical advance ?! – and so Saunders coined the resonant phrase 'heuristic plasticity' to capture the way they are applied, albeit in modified form. In a sense, then, the extent to which one will accept there is appropriate continuity between the theories depends on just how 'plastic' one takes these devices to be.

The alternative would be to simply bite the bullet and abandon the attempt to offer a response to the purported problem of ontological change in favour of the second motivation. One might support such a move by appealing to recent dismissals of the Pessimistic Meta-Induction and associated attempts to construct 'local' forms of realism, grounded in the specific features of particular theories (Saatsi 2017; Vickers 2019). Following this approach, OSR would be presented as a form of realism specifically tailored to the demands of quantum physics, say, again highlighting the significance of the relevant symmetries for this theory.

I'll come back to the issue of how these two motivations mesh, or not, at the end of this essay but in either case, we already have the beginnings of an answer to the core question of this paper – what is structure? It is given, in part, by the combination of the relevant laws and symmetries. I say 'in part' because this combination yields more possibilities than are actually observed. My 'go to example' here is that of Permutation Invariance (PI), which, of course, underpins the above metaphysical underdetermination regarding the individuality of quantum particles. PI is captured in mathematical terms by the permutation group, two representations of which are the symmetric and anti-symmetric, corresponding to Bose-Einstein and Fermi-Dirac statistics respectively. In this formal sense, then, the two most fundamental kinds in the world 'drop out' of the symmetry under permutations of quantum particles. Going beyond that formal sense and metaphysically fleshing out that sense of 'dropping out' remains a topic for further discussion: one option is to rummage in the toolbox of

metaphysics (French and McKenzie 2012 and 2015) and deploy one of the standard notions of dependence to explicate the claim that the kind is dependent on the symmetry, in a sense. However, McKenzie (2014) and Wolff (2012) have argued that standard forms of this particular 'tool' aren't up to the job. As an alternative, the notion of a determinable and its associated determinates have been suggested as offering a means for metaphysically capturing the relevant relationship. Again, I shall come back to this.

Now of course, as is also well known, other forms of particle statistics beyond those corresponding to the bosonic and fermionic kinds are also possible: once we move beyond permutations in situations involving only two particles and consider three or more, a whole slew of other representations become available, corresponding to so-called parastatistics. It would be too quick to dismiss these other representations as mere 'surplus' mathematical structure, not least because of their potential to be applied to concrete physical situations: indeed, one such paraparticle representation was presented as a possible resolution of the quark statistics problem in the mid-60s, only to be abandoned in favour of what was to become quantum chromodynamics (French 1995). Nevertheless, as things stand, the combination of laws and symmetries gives us more than we currently need. Hence, if we are going to set out what is the structure of the world, in the sense of *this* world, we need to acknowledge that only certain of the possibilities inherent in the framework are actualised. Thus, following Cassirer, this world-structure should be portrayed as a combination of laws, symmetries and specific observed outcomes, such as the bosonic and fermionic kinds, which can be characterised as 'existential witnesses' (Wilson 2012), in the sense that they pick out this world as the actual one among the various possible worlds. Yet again, I shall return to this later in the essay.

In specifying what is structure, something also needs to be said about how these features are inter-related. Consider the laws and symmetries: should the latter be taken as 'meta-laws' that constrain the former? Cassirer, again, offered an alternative to such a straightforwardly hierarchical view, arguing that laws and symmetries should be understood as mutually conditioning one another, yielding a kind of 'Parmenidean whole' (for further discussion, again see French 2014). That still leaves the relationship between laws/symmetries and specific measurement outcomes. Granted that the relationship between Permutation Invariance and bosonic and fermionic kinds might be captured in terms of determinables and determinates, as mentioned above, some have argued that in order to account for specific measurement results, structural realists need to take a stance on the measurement problem in the foundations of quantum mechanics (Esfeld 2015). The demand seems to be for a specifically structuralist solution but it is not at all clear what form that might take. Here we bump up against another form of underdetermination, namely that of the interpretation of quantum theory itself (French and Saatsi 2020): if one is an adherent of the 'consciousness-causes-collapse' or GRW views, then, putting things simply, the wave function encodes certain potential outcomes that are actualised through the action of either consciousness or a kind of probability field, respectively; or if one is an Everettian, of course, it represents different branches of the multiverse, in each of which definite outcomes are actualised. The latter, with its further elaboration in terms of the world 'emerging' as a kind of 'pattern' might seem particularly suited to a structuralist stance. However,

given what I shall say below about the modal nature of structure (at least on certain accounts), we might also look to a recent revival of the modal interpretation of quantum mechanics that takes observables rather than states to have ontological priority, with the Hamiltonian, incorporating its own symmetries, defining that subset of observables which acquires definite actual values (Lombardi 2019). From this perspective, the process of measurement comes to be seen as one of symmetry breaking (*ibid*., p. 38) and articulated as it is in terms of a symmetry based conception of particle kinds on the one hand and a metaphysics of property 'bundles' on the other (again, I'll come back to this), this seems to offer some hope of naturally meshing with OSR in general.[2]

Thus the ontic structural realist should perhaps hold off on acceding to the above demand for a 'solution' and instead note that a variety of stances towards the measurement problem are possible, depending on whether one can give structuralist renderings of the different interpretations of quantum theory. Indeed, the extent to which one can give such a rendering and thereby tie a given interpretation into the broader structuralist picture might be adduced as a way of breaking the underdetermination. These are issues for another time. I noted above that with this picture we have the beginnings of an answer to the question 'what is structure?' and one might wonder what more is being asked for. It is to that issue that I'll now turn.

2. What is Structure?

When I first started presenting seminars and talks on OSR, way back in the day, this was the most commonly asked question[3] and the temptation was simply to scribble the following on a whiteboard

$$[P, H] = 0$$

and declaim 'It's that! *That's* the structure I'm talking about!!' And what that is, of course, is a representation of the afore-mentioned conditioning role of PI, represented by the requirement that the Hamiltonian must commute with the permutation operator. Understood one way, as indicated above, invariance under permutations has been taken to yield a metaphysics of non-individual particles; understood another way, it divides up Hilbert space in such a way that these particles can still be interpreted as individuals but subject to accessibility constraints (see French 1989). Both understandings presume an object-oriented stance – drop that and take the above as representing a feature of the structure of the world and you have the core of OSR (or so I claim!).

Not surprisingly perhaps, simply pointing to the above commutation relation did not seem to satisfy the audiences at the time. Some took this as painting OSR as a form of Platonism in taking the structure of the world to be mathematical (see, for example, Cao 2003; and for a response, French and Ladyman 2003). Granted the difficulty in clearly delineating mathematical structure from physical structure, particularly given concerns about how to accommodate causality in the quantum domain (see French 2014 Ch. 8), the commitment is to the latter, rather than the former. What more is then being asked for by our central question?

Here a note of frustration creeps in from the ontic structural realist's side. Consider the notion of 'object', implicitly appealed to by most non-structural

realists: there's a certain asymmetry in the debate whereby structural realists are (constantly) asked 'what is structure?' but their non-structural friends and colleagues are almost never required to give an answer to the corresponding question 'what is an object?'. And of course it is not as if the answer to the latter is utterly straightforward. A quick glance at the relevant entry in that crucial resource, *The Stanford Encyclopaedia of Philosophy*, reveals a rich and multi-faceted metaphysical debate (Rettler and Bailey 2017), surveying as it does three broad questions about the category *object*:

What, if any, is its *contrast* or *complement*?
What is its *extension?*
What is its *nature*?

If we just take the first and the obvious contrast with properties, we are presented with the following break-down:

–Objects are Subjects; Properties are Predicates
–Objects are in Space and Time; Properties are Not
–Objects are Singly-Located; Properties May Multiply Locate
–Objects are Concrete; Properties are Abstract
–Objects don't obey the Identity of Indiscernibles; Properties do
–Objects are Sense-Perceptible; Properties are Not
–Objects are Uninstantiated; Properties are Instantiated

And if we delve deeper, into the notion of instantiation for example, further questions blossom:

• is instantiation a transitive or a non-transitive relation?
• is instantiation a symmetrical or a non-symmetrical relation?
• is instantiation a cross-categorial relation?
• is instantiation an internal or an external relation?
• is instantiation an essential or an accidental relation?
• is instantiation a necessary or a contingent relation?
• does the instantiation relation have instances?
• is instantiation a universal or a particular relation?
(see also Cumpa 2018)

And so it goes. Perhaps, when it comes to objects, it is felt that the corresponding question – what is an object? – doesn't need to be asked of the *non*-structural realist because she has a well-known and widely acknowledged range of metaphysical options that she can appeal to if pressed, as evidenced by the above. Perhaps, then, the structural realist should avail herself of a similar set of metaphysical tools or devices that she can deploy in response to our question.

3. Rummaging in the Toolbox

Let us take a leaf out of the *Stanford Encyclopaedia* entry and focus on the contrast with properties. Just as we can use the latter as a foil to help illuminate the metaphysics of objects, so we can do the same when it comes to structure. In particular, I shall focus on two broad sets of tools from our metaphysical toolbox:

the first proceeds from the bottom up, as it were, and has to do with fusion, whereas the second operates from the top down and concerns the determinable-determinate relationship already touched upon. Within that latter context I shall also explore the usefulness of a third tool, involving the notion of potentiality, in when it comes to articulating the metaphysics of laws and symmetries as structural features .

3.1 Tool$_1$: fusion

There is a widely held view that there exists some fundamental level at which our description of the world terminates and that this level is populated with certain 'basic building blocks', which are taken to have some form of ultimate ontological priority over other features of reality, that are then arranged in some kind of hierarchy on this basis. This view has been challenged on a number of fronts. Some have argued, inductively, that we should expect future physics to be like that of the past, in presenting a series of ever deeper levels (Schaffer 2003). In response it has been suggested that such arguments rely on an implicit and speculative assumption that goes beyond the kind of naturalistic approach to metaphysics that focuses on our current best theories (McKenzie 2011, p. 246). Alternatively, certain features of current physical theories have been appealed to, such as the dualities found in string theory and QFT and the 'effective' field theoretic understanding with regard to the latter, in order to undermine the above framework (McKenzie 2017).

Concerns have also been raised about the extent to which the 'basic building blocks', as standardly conceived, can explain the features of the further levels in the hierarchy. One response is to reconceive these 'blocks' along structuralist lines and afford symmetry principles and laws, for example, such ontological priority (French 2014; forthcomingb). Of course, as noted above, the fundamental level cannot *only* be populated by such features, given the way they encode the kinds of possibilities represented by parastatistics, for example, and so specificity must also be allowed for – in this case through the bosonic and fermionic representations of the permutation group, as again we've already noted.

There is, however, a further challenge to the above widely held view that should be considered. Within this view, these 'basic building blocks' are typically conceived of in terms of substances that possess or instantiate or whatever … properties, yielding a 'vertical' form of categorical priority insofar as this substance + properties combination is taken to be prior to objects or events or states of affairs or whatever. However, Paul has pointed out that there is also a 'horizontal' form of priority in that substances are taken to be prior to properties (Paul 2013). The former, as just stated, *possess* or *instantiate* the latter, or as Sider has put it, '… particulars, not properties, wear the pants' (Sider 2006, pp. 389–90; quoted in Paul ibid., p. 94). Substance, as Paul notes, is taken to be '… specially suited to play a role where it determines the most ontologically basic nodes of the structure of Reality.' (Paul 2013, p. 93). And it plays such a role by 'making concrete' or instantiating or possessing, in some sense, properties. Of course, you might well wonder how exactly substance does this. The originator of the trope theoretic view of properties, Williams, as quoted by Paul, suggests that substance '… engenders concreteness at the same time as it provides particularity, not because particularity is concreteness, but because by being the

occasion for predicates, prime matter permits that concurrence of predicates which is concreteness' (Williams 1958, p. 508), which is not all that helpful really.

At this point, one could adopt a kind of Lockean 'primitivist' stance and acknowledge that not only can we not say what substance is, since by 'being the occasion for predicates' it lies beyond them, but we can't say how it does what it does. Alternatively, we could analyse further this notion of 'being the occasion of predicates', running the risk perhaps of regress. Or we could throw our hands in the air and declare substance to be metaphysically otiose. This is more or less Paul's reaction:

'I reject the notion that we need more than one ontological category to provide the ontological structure that substantial categorical priority was traditionally invoked to support. In effect, the idea is that the categorical difference between substance and property should be collapsed at the fundamental level, since we can use purely qualitative entities—perhaps relations and fusions of *n*-adic properties—to build the fundamental external and internal structure of Reality.' (Paul 2013, p. 109)

In this rejection we can see a resonance with the work of Cassirer and Eddington, both of whom advocated a shift from things-as-substances to relations as the ground of objectivity in science (French 2003; French 2014 pp. 79-83 and pp. 91-99). For them, as noted already, if such things-as-substances, or objects, could not be regarded as individuals, according to quantum mechanics, then they should be dispensed with. Given that we can so regard them, subject to certain caveats, the argument has shifted, as also indicated above: now it's the ambiguity regarding whether they can be said to have an 'individuality profile' that motivates their elimination. But of course, even if one were to adopt the objects-as-individuals horn of the underdetermination, one might still prefer not to accept substance into one's metaphysical pantheon, adopting instead, say, Muller's and Saunders' relations based approach to individuality in the quantum context (Muller and Saunders 2008; but for concerns, see Norton 2015).

Paul's response is motivated not only by the idea that we don't need substance to build a world, as it were, but also that it actually creates metaphysical problems where none need exist. Thus she invites us to consider recent debates over the nature of laws (I'll come back to this), where, she argues, the implicit categorical bias towards substance '… creates the need for an explanation of what the underlying causal or counterfactual connections are between the parts that are strung together to give the overall pattern of the mosaic' (2013 p. 102). For advocates of the Armstrong-Dretske-Tooley view this need for an explanation is satisfied, ultimately, by the necessary connections existing between the relevant universals and one can then account for the supposed governing function of laws in these terms; for dispositionalists, it is the powers manifested by the relevant parts of the mosaic that do all the explanatory work.

However, if we reject substantial categorical priority, as Paul argues, there is simply no need for any such explanation and likewise no need to make sense of the supposed governance of laws. Instead, '[w]hat makes it the case that we have a particular linking of properties and relations … is simply the existence

of the fundamental distributional property that, in effect, *is* the pattern.' (Paul 2013, pp. 102-103). As she says, this can be viewed as a 'new sort of Humeanism', in that '[t]he distributional property guides the pattern … across locations by being more fundamental than that pattern, and supports counterfactual and causal inferences across times by being the more fundamental thing that simply exists at the different locations.' (ibid., p. 103).

As I said, I'll come back to this issue of how we should understand laws from a structuralist perspective shortly but for the moment I want to focus on the nature of these fundamental distributional properties. Thus, according to Paul, instead of thinking of properties as that which need to be 'occasioned' by substance, we can take them, understood *n*-adically to include relations, as our fundamental 'building blocks' and construct the 'structure of Reality' on that basis via an operation of 'fusion'. She takes the latter from what she calls the 'traditional spatiotemporal view' of world building:

'On this view, the material world is a kind of glued-together jigsaw puzzle constructed using spatiotemporal composition as the glue. The effect of this method of building is that properties of larger spatiotemporal regions are built by spatiotemporally fusing together smaller, qualitatively rich spatiotemporal regions. In other words, on the spatiotemporal view, properties of larger regions are constructed via the spatiotemporal fusion of their qualitatively rich spatiotemporal parts, so the qualitative character of a larger spatiotemporal region supervenes on the spatio- temporal fusion of its smaller spatiotemporal parts.' (Paul 2012, p. 227).

Thus, 'the compositional structure of the material world derives from the fusion of spatiotemporal parts' (*ibid*., p. 229). Here Paul rejects the emphasis on spatio-temporality on the grounds that it is incompatible with the foregrounding of configuration space in certain interpretations of quantum mechanics. Leaving to one side the concern that this may not seem such a powerful motivation to some, Paul advocates an alternative 'mereological bundle theory', according to which,

'The overall structure of the world is created by the fusion of fundamental properties, not by fusions of fundamental localized particles or their equivalents, qualitatively rich spatiotemporal regions, leaving room for the likely possibility that some of the fundamental properties fused to make the world are holistic properties effectively distributed across a region.' (ibid., p. 244)

Particles can then be reconceptualised as 'fusions' of *n*-adic properties in a move that, again, resonates with the core of OSR. Indeed, Paul herself notes that the kinds of qualitative entities, such as relations, that she is concerned with '… can serve as structural 'nodes' and can be arranged into the appropriate patterns' (2013, p. 110) and that her view '… may also complement an even more radical sort of structuralism, the ontic structuralism of Ladyman (1998) and French and Ladyman (2003) ' (*ibid*.). From this perspective, the claim that 'there are no objects' amounts to saying that 'we collapse the difference between object, property and substance' so that 'collections or fusions of purely qualitative entities can perfectly well serve as non-relational nodes for a relational structure that fits the empirical constraints of the ontic structuralist.' (ibid., pp. 110-111).[4]

Such a metaphysical underpinning for OSR then offers the possibility of a response to the question, raised by some commentators recently: what instantiates the structure (Dorato 2016)? Or as Psillos puts it, differently but relatedly: without objects to instantiate the properties, how could laws, as universals, yield any regularities and hence have any 'concrete and worldly content' (Psillos 2016)? Such questions presuppose the existence of a metaphysical gap between properties and laws and the regularities of the world, or more generally between structure and 'the' world, whereby this gap is supposedly only closed by this mysterious relation of instantiation. The response bluntly consists in denying the existence of the gap to begin with (see French 2016) and Paul's account offers an appropriate justificatory framework for such a denial.

Given that, the ontic structural realist might appeal to Paul's notion of 'fusion' as an appropriate device taken from the toolbox of metaphysics and deployed to help answer our original question, what is structure: structure is ultimately a fusion of *n*-adic properties, constructed from the bottom up, as it were.

Nevertheless, further concerns may arise, centred now around the nature of this device and whether it is sufficiently naturalistic. How are we to understand 'fusion'? We could dismiss the question and insist that fusion is primitive but then we'd be in no better a position than if we had taken the 'occasioning' of properties to be likewise. Instead we might approach our new question from two directions: how are we to understand fusion metaphysically? And how are we to understand it physically? The former encourages us to consider how the notion can be related to other, similar metaphysical concepts, the most obvious being composition, whereas in answering the latter we might consider what physical analogues it can be effectively 'hung on'. As we'll now see, these two possible ways of understanding the notion are intertwined.

Fortunately, Paul herself sets out an answer to the first question above. In the appendix to her (2012) she emphasises that she adopts a mereological perspective with composition as the 'basic building relation' (*ibid*., p. 250) with the basic notion of 'proper part' understood as primitive and proper parthood taken, as is standard, as irreflexive, asymmetric and transitive. Of course, the 'parts' here are qualitative so what we have is qualitative composition, or fusion, facilitated by a principle of supplementation (plus, as she says, uncontroversial presuppositions about identity and existence), that states that if something has a proper qualitative part, then it has at least one other proper qualitative part (*ibid.,* p. 251). As Paul notes, there is no explicit tying of this qualitative composition or fusion to spatio-temporal occupation and she rejects a general qualitative fusion axiom, thereby taking the composition to be restricted.

This compositional framework can then accommodate two more specific models that represent the world as constructed from the fusion of properties. The first incorporates two composition relations, one for the qualitative parts, that is, the properties, and the other for spatiotemporal parts. This starts with the properties qualitatively fused together with spatio-temporal locations '…to create a mosaic-like lowest compositional level of located, unextended qualitative fusions distributed through a network of spatiotemporal relations.' (2012 p. 252) These unextended fusions are then composed via a different principle to yield extended entities, along standard mereological lines.

However, the worry with this proposal is that quantum physics seems to present us with examples that cannot be accommodated by this 'mosaic' model – photons in a laser beam, for example, where one has to face the difficulty of defining localised states for the particles (see Ceravolo and French forthcoming). Paul herself gestures toward an alternative 'global' model, according to which '…the extended world is wholly and immediately constructed from a fusion of *n*-adic properties, including spatiotemporal relations and perhaps a structuring lawlike relation, resulting in a distribution of properties across a spatiotemporal manifold' and spatio-temporal parts are no more than a convenient fiction (Paul 2012, pp. 254). This, she claims, can accommodate certain interpretations of quantum mechanics, such as wave function realism and the Everett interpretation but its not clear how it can accommodate the photon example, or the issues to do with identity associated by both Bose-Einstein and Fermi-Dirac statistics more generally. One might speculate, following Ladyman and Ross (2007, p. 21) that different *sui generis* compositional models are needed for different quantum systems (again see Ceravolo and French forthcoming) but without specific details it is difficult to say more within the context of Paul's framework. What is needed is the identification of some physical analogue to 'fusion' that would render the relevant metaphysics more naturalistic; or in other words, the metaphysics still needs to be *applied* to the physics.

This point is further highlighted when we consider the issue of the 'concurrence' of predicates that, for Williams, as we saw in the quote above, is *concreteness*; in other words, it is via this concurrence that the structure can be said to have concrete and worldly content. The further question is, how do we account for that concurrence, or, putting it slightly differently, for the fact that only certain properties are found together giving us the kinds of entities that we observe, from bosons and fermions, to photons and protons etc? There is nothing in Paul's fusion based account that seems to offer any such metaphysical explanation. Chakravartty, for example, does at least explicitly address this issue by appealing to a further notion of 'sociability', taken as a 'brute fact' (2007, p. 171). Again, however, the very bruteness of this notion raises concerns – basically this also seems to be a piece of free floating metaphysics that is introduced solely as a metaphysical explanans and that doesn't appear to be tied to any physical principle (French 2013; for a response see Chakravartty 2013). At the very least, one can argue that if an account can be found that doesn't involve such brutality, insofar as the relevant metaphysical notion can be attached to some appropriate analogue, such an account is to be preferred.

3.2 Tool$_2$: determinability

As noted above, Paul's approach may be seen as 'bottom-up' in the sense that properties as basic building blocs are fused to yield structure. The alternative account may be characterised as top-down insofar as the properties can be said to 'drop out' of the structure, characterised, as noted previously, by laws and symmetries (French 2014). Here again, it is claimed, we have a one-category ontology and the structure is made concrete via the 'concurrence' of properties, where the physical analogue of the latter is given by the connection between the relevant properties, such as charge, mass and spin, that characterize particle kinds and the irreducible Hilbert space representation of the (restricted) Poincaré group (the 10-dimensional non-compact Lie group of isometries of

Minkowski spacetime). Likewise, as we've seen, we can understand the distinction in statistical behaviour that we label 'bosonic' and 'fermionic' in terms of the symmetric and anti-symmetric representations of the permutation group, respectively. From this perspective, 'sociability' is just the metaphysical counterpart of the above physical connection. Nevertheless, there is further metaphysical work to be done. Just as one might wonder what is involved in 'fusing' properties, so one might ask for further details on the nature of this 'dropping out' – the difference being that in the former case we lacked a physical analogue, whereas in the latter we don't have an appropriate metaphysics.

As mentioned above, in (French 2014) it was suggested that, as far as those features to do with symmetries are concerned, the structure-property relationship can be captured by that between determinables and determinates (for an overview, see Wilson 2017).[5] Our question now is: can we say more about the determinable-determinate relationship itself (or at least, more than is given in French 2014)?

It turns out that we can. Denby (2001) offers an interesting formal schema that the structural realist can appropriate as a further metaphysical tool to help explicate the relationship between structure and properties. It may not seem that this appropriation is appropriate, given the object-oriented nature of Denby's device, but the structural realist has the means to 're-tool' it to her purposes, as we'll see.

The core idea is to think of a determinable as a 'classification' of particulars (and here we might immediately think of the Wignerian programme that underpins the above relationship between symmetry and kinds), whereby

D is a determinable iff D is a pair (S, f) where:
(i) S is a metric space; and
(ii) f is a function from concrete particulars into the points of this metric space

S defines the possible classificatory locations and how they are related and the points of this space represent the determinates. The function *f* defines which particulars go where on the classification, or in other words, it determines their extension. *d* is then a determinate$_a$ iff *d* is a pair (D, E_i) where :

(i) D is a determinable; and
(ii) E_i is the extension of point *i* in the metric space encoded by D.

This captures the idea that the identity of any determinate is bound up with its determinable so that each determinate can be said to belong to its determinable. Furthermore, no particular manifests (to use a more neutral term than 'instantiates') more than one determinate belonging to a given determinable; if a particular manifests some determinate, it also falls under its determinable; and if a particular falls under a determinable, it manifests some determinate or other of that determinable. However, this schema entails no constraints on the manifestation of determinates belonging to distinct determinables, or on which determinate of a given determinable a particular falling under it must manifest.

Significantly, it encodes a general metaphysical picture of properties that elevates the distinction between determinables and their determinates from what might be viewed as a local curiosity to a central feature of the nature of

properties generally (*ibid*.) which obviously meshes nicely with the structuralist view of the relationship between symmetries and properties. Furthermore, and crucially, it reverses the traditional order of ontological priority between determinables and determinates. Determinables have typically been thought of as Boolean compounds of determinates. However, according to Danby's account, a determinate has an entire determinable as a constituent and a determinable typically has more structure than can be recovered by Boolean operations on determinates, where this structure is represented by its metric space's distance relation. This offers a way of formally encoding the modal nature of a determinable, such as PI for example, which, as we've noted, incorporates further possible kinds beyond those of bosons and fermions. In addition, Danby's account treats the characteristic features of a determinate, including its relations to other properties and the degree of similarity it confers on its instances - as deriving wholly from features of the associated determinable (which, as just noted, is understood as constituent). Finally, if one feels inclined to view things in Lewisian terms, it reverses tradition by taking the primary bearer of 'naturalness' – granted, a problematic notion at the best of times - to be the determinable rather than the determinate.

Here again, then, we have a metaphysical tool that we can deploy to help sharpen up and clarify the claim that fundamental properties like being a boson/fermion, mass, charge and spin etc. 'drop out' of the relevant symmetry: the relationship, characterised by this 'dropping out', can be captured in terms of that which holds between a determinable and its determinate and Danby's account offers a useful formal framework in terms of which that relationship can be understood.

There is an immediate worry however: as we've seen, at the core of Danby's account is the idea of regarding a determinable as a 'classification' of particulars within a broadly set-theoretic framework but that seems to go completely against the grain of a structuralist stance. My response is to appeal to what I have called elsewhere 'the Poincaré manoeuvre' (French 2014 pp. 66-68): this effectively denies the ontological significance of any such invocation of particulars, or objects more generally, by taking them to be merely heuristic devices that enable us to present in mathematical terms the structure that we take to have ontological priority. Its a move that has been appealed to time and again throughout the history of structuralism, beginning with Poincaré (hence the name) who noted how we may begin our reflections in geometry by thinking about certain figures, which then leads us to consider the possible transformations those figures may undergo, which transformations may then be codified via group theory … at which point we may focus on these alone and throw away the figures we started with as mere 'heuristic crutches', useful only to get us to this group theoretic destination.[6]

So, generalising this manoeuvre, those of us who write sinistrodextrally may set down set-theoretic structure from left to right in the form <*A*, *R*>, where *A* is a set of elements and *R* a family of relations, but following the Poincaré manoeuvre we can read and ontologically interpret it dextrosinistrally. Likewise, in the case of determinability, the structuralist can still avail herself of the tool supplied by Danby's account by performing the manoeuvre and reconceiving the 'concrete particulars' in terms of determinable-determinate structure. Thus she can begin by classifying the pututative 'particulars' – that is, elementary

'systems' in Wignerian terms – in terms of symmetry groups, then metaphysically reconceptualise the former via group theory, taking the symmetries, understood as determinables, as that which has ontological priority (for more on the Poincaré manoeuvre, see Wolff 2019 and, in response, French 2019).

Relatedly, Danby presents his account in a nominalistic context, invoking no primitive modal notions and effectively outsourcing the modality associated with determinables to the relevant counterparts in certain possible worlds. The structuralist could follow this Lewisian track and take, for example, the non-standard statistical possibilities encoded in PI as manifested in other possible worlds (for Humean forms of structural realism, see Lyre 2010). Alternatively, she can run the Poincaré manoeuvre once again and allow modality to re-enter the actual world, thereby making good on the claim that '… ontic structural realism is in part a commitment to objective modal structure in the concrete world …' (Ladyman 2019). Doing so, however, raises a further set of metaphysical issues having to do with how we regard modality.

4. Modality

The debate over modality is often portrayed as one that holds between two opposing positions: that of the dispositionalist, who takes the modality inherent in natural laws, say, as ultimately deriving from the dispositions, capacities, or, more generally, powers of the relevant particulars; and the Humean who, as touched on above, rejects any such ascription of modality to laws and accounts for our modal 'talk' in terms of possible worlds or somesuch device. Within this context there are, again, various tools available to the structuralist.

Obviously she should not follow the standard dispositionalist line, with its emphasis on particulars, but she could, for example, understand modality in terms of a *disposition* of the world-as-a-whole (see Chakravartty 2019). The idea, then, would be that the world is disposed to yield, in some sense, various features characterised in terms of Permutation Invariance, Poincaré symmetry and so forth. However, such a shift in focus is not straightforward, metaphysically speaking. Standardly, dispositionalism is cashed out in terms of the Stimulus and Manifestation Condition and the Dispositional Identity Thesis. The former allows us to grasp the nature of a disposition in terms of the manifestation of a particular effect in response to a given stimulus; so, for example, when a test charge is brought up to a fixed charge – stimulus – a force (and consequent acceleration) results – the manifestation. The latter metaphysically ties the disposition to the relevant property insofar as the property is (metaphysically) identified in terms of the dispositions, or powers; thus charge, for example, is identified in terms of its disposition to manifest a force when a test charge, say, is brought up to it.

However, there is an obvious concern with nailing down the relevant stimuli when it's the world-as-a-whole that is disposed to yield a certain manifestation. Perhaps that can be accommodated by recent moves towards stimuli-less accounts (Mumford 2011) but other problems remain. In the context of the Dispositional Identity Thesis it is not clear what the relevant property would be that would be identified with the appropriate dispositions (see French 2019, 2020). One option would be to take that property as 'being the world'. In that case, we would have one property associated with myriad different

dispositions, corresponding to the different symmetries. Perhaps, instead, one could associate the relevant properties of 'the world' with the appropriate laws. But then the world-as-a-whole, understood as a particular, seems metaphysically otiose as it is the laws that would be the actual seats of the relevant dispositions.

Thus, it would seem that, regarded as metaphysical tools, both the standard dispositional account and the above shifted version are not fit for structuralist purposes. Nevertheless, there are other devices in the toolbox that could be appropriated.

There is, for example, a long history of understanding modality 'in the world', as it were, in terms of *potentiality*. Vetter has recently taken this further and elaborated the notion through a formal framework that analyses it in terms of predicate logic with identity together with the predicate operator POT (Vetter 2015). Within such a framework, the claim that 'It is possible that P' is defined as: 'Something has an iterated potentiality for it to be the case that P' (*ibid*., p. 197). Since potentiality comes in degrees, Vetter characterises it in terms of the determinable-determinate relationship, again, whereby the specific degrees to which a particular determinable can be possessed are its determinates; so a concrete block is less breakable than that standard philosophical example, a porcelain vase, the two objects possessing different determinates of the determinable 'breakability'.

We can see how this plays out in the case of laws. Previously Vetter identified a metaphysical gap between the dispositions possessed by particular objects and the laws that are typically claimed to supervene on the latter. Standardly, the Stimulus and Manifestation Condition is invoked in order to obtain the relevant law from the particular dispositions; so, the idea is that Coulomb's Law can be obtained from a metaphysical consideration of repeated iterations of a test charge being used to stimulate the appropriate manifestation from a given charge (Bird 2007). However, as Vetter noted, all that we obtain in such cases is the conjunction 'charge x experiences a force f_1 when brought to a distance r_1 from charge y' & 'charge x experiences a force f_2 when brought to a distance r_2 from charge y' & … so on. There is, in effect, a gap between such a conjunction and the law statement itself (Vetter 2009).

According to her potentiality account, we should view such situations quite differently: objects that have charge have a certain potentiality to exert a force in accordance with Coulomb's Law and they have this potentiality to a maximum degree; thus electric charge is identified as the maximal potentiality to exert a force. In effect, then, Vetter's account identifies the nomological disposition with the determinate of potentiality (understood as a determinable). And on this basis she claims to derive Coulomb's Law (Vetter 2015 p. 286).

However, there is still a gap: Coulomb's Law can be understood as metaphysically necessary only if the identification of charge with maximal potentiality is necessary. But why should we accept this? Here we have a gap in explaining the status of the metaphysical necessity of Coulomb's Law.

One option is to adopt a 'shallow' view of laws à la Hume or Lewis (again we might refer back to our discussion of Paul's view here). Thus Vetter suggests that we add potentialities to the 'natural properties' that underpin the regularities in the Humean 'mosaic' (*ibid*., p. 289). Leaving aside the point that such a suggestion would send both Hume and Lewis spinning in their respective graves, it effectively introduces further metaphysics in order to bridge a gap that

was created by adopting a certain metaphysical stance in the first place: namely one that is oriented towards an ontology of particulars.

If we drop this stance and instead of pursuing what is in effect a 'bottom up' approach, take things from the top down, then an alternative option emerges: we deny the existence of any metaphysical gap in the first place by ascribing the relevant potentialities directly to the laws and symmetries that (partly) constitute the structure of the world (French 2018). Appropriating Vetter's account as a tool would then offer one way of metaphysically characterising the sense in which the world-as-structure is inherently modal. Take our old friend PI one more time and the way it encompasses more possibilities than the Bose-Einstein and Fermi-Dirac statistics that we observe in this the actual world: there is the *potential* – fleetingly realised in the 1960s in the case of quarks – for non-standard statistics to be manifested.

Now, there may appear to be a problem here, which can be seen if we compare this structuralist view with that of Sider (2011). On Sider's account the fundamental structure is given by first-order quantification theory, set theory plus fundamental physics and Vetter comments that '[i]f the fundamental physics is part of the structure of the world, then the world has no potentialities to have a different physical outlook.' (2015, p. 260). However, this is, again, to take a bottom-up and particular-oriented stance. If, for example, we take our 'fundamental physics' to embrace symmetry principles (as determinables) then we arrive at an entirely different destination, where the potentiality to 'have a different physical outlook' is encoded (mathematically) in the relevant structure (not forgetting the role of the relevant 'existential witnesses').[7]

Referring back to the debate over the metaphysics of laws, the structuralist offers a perspective that can perhaps be described as a 'third way' between both the Humean and the dispositionalist. Insofar as the former identifies laws, understood as represented by the relevant axioms in some 'best system', with regularities in the mosaic, laws are 'in' the world, albeit stripped of any modality on this account. Insofar as the latter reduces that modality to that of the underlying dispositions or powers, the laws themselves may be eliminated (Mumford 2004) and hence cannot be taken to be 'in' the world. According to the structuralist, however, the laws are both modally informed and 'in' the world – indeed, they *are*, in part, the world![8]

Furthermore, such a perspective offers a different view of the contentious issue of the supposed governing role of laws. As already touched on above, such a role presupposes a metaphysical 'gap' between the laws and the phenomena they are supposed to govern. Humeans, of course, do not see any such gap and thus deny such a role but then they must face the problem of the 'explanatory circle': how can laws explain the phenomena if, on the Humean account, they are, ultimately, identified with the phenomena (see, for example, Dorst 2019)? Dispositionalists, on the other hand typically accept such a governing role but as Mumford has argued, if the laws 'flow from' or supervene on the underlying powers or dispositions of the relevant particulars (something that Vetter disputes as we have seen), then it is difficult to see how they can be said to govern the behaviour of the latter. On the structuralist view, just as in Paul's approach, there is no metaphysical gap in the above sense, nor is there any governing role for laws, or symmetries to play, again in the above sense. Nevertheless, we can still understand their explanatory function by, for example,

appealing to the Woodwardian framework. Once again, consider PI: we can explain its role in explaining phenomena such as that of the halting of the collapse of white dwarf stars (French and Saatsi 2018) by appealing to the potential alternative representations encoded within the principle. Note, however, in denying the above metaphysical gap, this does not negate the need for some account of the relationship between such symmetries and laws and specific measurement outcomes, but that would involve, as we have seen, some choice of an interpretation of quantum theory.

Returning, finally, to our twin motivations, a further worry arises, to the effect that this appeal to 'existential witnesses' in pinning down the possible structures to one that is fit for purpose in the context of modern physics, generates a form of context-dependence that undermines the other motivation regarding structure retention through theory change. The core of this concern consists in the claim that modal relations that are relative to an epistemic context cannot be regarded as fundamental 'in a world' where that context holds (see Ruyant, forthcoming). Since the modal relations sketched above in terms of PI are indeed relative to the particular epistemic context in which we find ourselves they cannot be regarded as fundamental, or so the argument goes.

The example given is that of early theories of light that only hold in the absence of magnetic fields. If we take it as necessary that, in the context where there are no magnetic fields, the angle of reflection of alight beam is equal to the angle of incidence, it does not follow that in that context, it is necessary that the angle of reflection of alight beam is equal to the angle of incidence. That would only be the case if the context were necessary but '[t]he fact that there is no magnetic field at some place in the universe is not necessary but contingent. ' (*ibid*., p. 9). That is seen to be problematic for the structural realist insofar as the relevant law of angles cannot be taken to correspond to the fundamental modal structure of the world but only to the structure *given that particular context*; that is, it is relative to that context.

An obvious move would be to say that the given modal statement approximates the relevant necessary law but then it is unclear how to measure the extent of such approximation (*ibid*.). Consider another example, that of Galileo's law of free fall which can be taken as retained in contemporary theories in the sense given by Post's Correspondence Principle (1971). Yet the range of contexts in which it does so is, of course, tiny and the law is highly contingent, to the extent that it seems implausible to claim that it in any way approximates the supposedly necessary laws of General Relativity (Ruyant forthcoming). Alternatively one might emphasise the fundamental nature of the laws that the structural realist is focussing on but, it is argued, the analysis can be applied 'quite straightforwardly': a modal relation that states that it is necessary that R, say, cannot count as fundamental in a world where it is the case that 'it is necessary that in context C, R holds' (*ibid*., p. 13).

Of course, such judgments of context dependence and hence modal relativity are all made in retrospect. At the time at which he supposedly proposed his law, Galileo was not aware of its highly limited range of applicability. Thus the above concern might be folded into the attitude of fallibility which all realists should adopt: from our current epistemic vantage point we may not be aware of the extent of the context in which our currently held laws and theories hold. And of course, we currently take to be fundamental

those laws and principles that we (currently) believe to hold across all possible contexts; that is, we identify the relevant context with the fundamental level, with the caveat, of course, that we may discover that this level is not, in fact, the most fundamental.

Indeed, take the Standard Model, undergirded as it is by PI and other symmetry principles: we know, or at least strongly suspect, that this cannot be the fundamental 'theory of everything', not least because quantum field theory, on which it is built, is widely regarded as 'merely' an effective field theory, applicable only over a certain energy range, and, of course, it does not incorporate gravity. So we can accept that the modal force of PI is limited to this particular context but then the motivation for structural realism was always to come up with a form of realism appropriate for current physics – the context dependence was always there, right from the start. And of course, that context is delineated, at least in part, by the relevant 'existential witnesses'; again, our world is a bosonic and fermionic world, not a parastatistical one. But for modal relations to be 'in' a world in the first place they must be tied to that world via certain existential witnesses that delineate the relevant epistemic context. Far from undermining structural realism, this incorporation of determinates as a feature of the structure à la Cassirer yields an account fit to represent this, the actual, world.

5. Conclusion

Finally, let us return to our original question, what is structure? I have suggested that to answer this question we need to deploy certain tools appropriated from the toolbox of metaphysics and as in the case of objects, alternative options are available. So, for example, following Paul, we could take structure to be a 'fusion' of properties in the sense outlined above. However, although I am sympathetic to her attempt to construct a one-category ontology, fusion as a tool is problematic inasmuch as it has no mathematico-physical correlate. That's not an issue with the other 'tool' that I've looked at, namely the determinable-determinate relationship. In that case, rather than starting with the metaphysics, we begin with this idea of properties 'dropping out' of the symmetries, where this is represented mathematically by the relationship between the relevant group and its representations and can, I suggest here, be captured via devices such as Danby's, viewed through the lens of the Poincaré manoeuvre of course.

This generates the further worry about what, exactly, the metaphysics is contributing in this latter case. One answer is that it contributes to our understanding by playing a kind of umbrella role in covering both 'everyday' examples and the more arcane situations that we find in modern physics (Chakravartty 2013; French 2018). Thus consider again the further tool of potentiality taken from Vetter's work. Her account is heavily focussed on the language of possibility that we use in everyday life: for her, adjectives such as 'fragile' express the relevant sense of potentiality at this level. When it comes to physics, the language is different, of course, and it is the mathematics of group theory that acts as the language in terms of which the relevant symmetries are expressed. As in the case of our everyday talk, we can take this as revealing or encoding the relevant possibilities and what the deployment of the tool of potentiality allows us to do is to conceive of this encoding in terms that can be

related to other forms of potentiality, including those exhibited by fragile vases in 'everyday' life. It is through such connections that we may then achieve a measure of understanding (French 2018; for a response see Vetter 2018).

In conclusion then, there is a range of devices in the toolbox we can use to make further sense of these options. The trick is to ensure the tool is 'fit for purpose' when it comes to the physics but even if it isn't, it can sometimes be beaten into shape!

References

Berenstain, N. (2017), 'The Applicability of Mathematics to Physical Modality', *Synthese*, 194: 3361–3377.

Bird, A. (2007), *Nature's Metaphysics: Laws and Properties* Oxford: Oxford University Press

Brading, K. and Skiles, A. (2012), 'Underdetermination as a Path to Ontic Structural Realism', in E. Landry and D. Rickles (eds), *Structural Realism: Structure, Objects, and Causality*, The Western Ontario Series in Philosophy of Science 77. Dordrecht: Springer, pp. 99–116.

Cao, T. (2003), 'Structural realism and the interpretation of quantum field theory', *Synthese* 136: 3–24.

Ceravolo, F. and French, S. (forthcoming), 'What is a Naturalized Principle of Composition?', *American Philosophical Quarterly*.

Chakravartty , A. (2007), *The Metaphysics of Science*. Cambridge: Cambridge University Press.

Chakravartty, A. (2013) 'Realism in the Desert and in the Jungle: Reply to French, Ghins and Psillos', *Erkenntnis* 178: 39–58.

Chakravartty, A. (2019), 'Physics, metaphysics, dispositions, and symmetries – À la French', *Studies in History and Philosophy of Science* 74: 10-15

Cumpa, J. (2018), 'A Naturalistic Ontology of Instantiation', *Ratio* 31: 155-164.

Dorst, C. (2019), 'Humean Laws, Explanatory Circularity, and the Aim of Scientific Explanation.', *Philosophical Studies* 176: 2657-2679.

Duguid, C. (2017), *Humean Metaphysics and the Philosophy of Science*, PhD Thesis, University of Leeds.

Denby, David A., 2001, 'Determinable Nominalism', *Philosophical Studies*, 102: 297–327

Dorato, M. (2016), 'The physical world as a blob: Is OSR really realism?', *Metascience* 25:173–181.

Esfeld, M. (2009), 'The Modal Nature of Structures in Ontic Structural Realism'. *International Studies in the Philosophy of Science*, 23: 179–194.

Esfeld, M. (2015), 'Review of Steven French, *The structure of the world. Metaphysics and representation*. Oxford: Oxford University Press 2014', *Mind* 124: 334-338.

French, S. (1989), 'Identity and Individuality in Classical and Quantum Physics', *Australasian Journal of Philosophy* 67**:** 432-446.

French, S. (1995) 'The Esperable Uberty of Quantum Chromodynamics', *Studies in History and Philosophy of Modern Physics* 26: 87–105.

French, S. (2006) 'Structure as a Weapon of the Realist', *Proceedings of the Aristotelian Society* 106 (2): 167–85.

French, S. (2013) 'Semi-realism, Sociability and Structure', Erkenntnis 178: 1–18.

French, S. (2014), *The Structure of the World: Metaphysics and Representation*. Oxford: Oxford University Press.

French, S. (2016), 'Response to my critics' *Metascience* 25:189–196.

French, S. (2018), 'Toying with the Toolbox: How Metaphysics Can Still Make a Contribution' *Journal for General Philosophy of Science* 49, pp. 211-230.

French, S. (2019), 'Defending Eliminative Structuralism and a Whole Lot More (or Less)' *Studies in History and Philosophy of Science* 74: 22-29

French, S. (2020), 'Doing Away with Dispositions: Powers in the Context of Modern Physics', in A. Meinke (ed.), *Dispositionalism. Perspectives from Metaphysics and the Philosophy of Science*, Springer Synthese Library, Springer.

French, S. (forthcominga), "Metaphysical Underdetermination as a Motivational Device"

French, S. (forthcomingb), 'Fundamentality' in *The Routledge Companion to the Philosophy of Physics*, eds. A. Wilson and E. Knox; Routledge.

French, S. and Krause, D. (2006), *Identity in Physics: A Historical, Philosophical and Formal Analysis.* Oxford: Oxford University Press.

French, S. and Ladyman, J. (2003), 'Remodelling Structural Realism: Quantum Physics and the Metaphysics of Structure', and 'The Dissolution of Objects: A Reply to Cao', *Synthese* 136: 31-56 and pp. 73-77.

French, S. and Ladyman, J. (2011), 'In Defence of Ontic Structural Realism', in A. Bokulich and P. Bokulich (eds), *Scientific Structuralism*. Dordrecht: Springer, pp. 25–42.

French, S. and McKenzie, K. (2012), 'Thinking Outside the (Tool)Box: Towards a More Productive Engagement between Metaphysics and Philosophy of Physics'. *The European Journal of Analytic Philosophy* 8: 42–59.

French, S. and McKenzie, K. (2015), 'Rethinking Outside the Toolbox: Reflecting Again on the Relationship between Philosophy of Science and Metaphysics', in T. Bigaj and C. Wuthrich (eds), *Metaphysics in Contemporary Physics*. Poznan Studies in the Philosophy of the Sciences and the Humanities. Amsterdam: Rodopi, pp. 145–74.

French, S. and Saatsi, J. (2018), 'Symmetries and Explanatory Dependencies', in J. Saatsi and A. Reutlinger (eds.), *Explanation Beyond Causation*, Oxford: Oxford University Press, pp. 185-205.

French, S. and Saatsi, J. (2020), *Scientific Realism and the Quantum*. Oxford: Oxford University Press.

Ladyman, J. (1998) 'What is Structural Realism?', *Studies in History and Philosophy of Science* 29: 409–24.

Ladyman, J. (2019), 'Introduction: Structuralists of the world unite', *Studies in History and Philosophy of Science* 74: 1-3

Ladyman, J. and Ross, D. (2007), *Everything Must Go*. London: Routledge.

Lombardi, O. (2019), 'The Modal-Hamiltonian Interpretation: Measurement, Invariance, and Ontology' in O. Lombardi (ed.), *Quantum Worlds: Perspectives on the Ontology of Quantum Mechanics*. Cambridge: Cambridge University Press, pp. 32-50.

Lyre, H. (2010), "Humean Perspectives on Structural Realism", in F. Stadler (ed.), *The Present Situation in the Philosophy of Science*. Dordrecht: Springer: 381–97.

McCabe, G. (2004), 'Does an elementary particle have a unique intrinsic state?', *philsciarchive.pitt.edu/archive/00001999/01/intrinsic.pdf*

McKenzie, K. (2011) 'Arguing Against Fundamentality', *Studies in History and Philosophy of Modern Physics* 42: 244–55.

McKenzie, K. (2014), 'Priority and Particle Physics: Ontic Structural Realism as a Fundamentality Thesis', *British Journal for the Philosophy of Science* 65: 353-380.

McKenzie, K. (2014), 'On the Fundamentality of Symmetries' , *Philosophy of Science 81*, pp. 1090-1102.

McKenzie, K. (2017), 'Relativities of fundamentality', *Studies in History and Philosophy of Modern Physics* 59: 89-99.

McKenzie, K. (forthcoming), 'Structuralism in the Idiom of Determination ' *British Journal for the Philosophy of Science*.

Mumford, S. (2004), *Laws in Nature*, Oxford: Oxford University Press.

Mumford, S. (2011), 'Causal Powers and Capacities', in *The Oxford Handbook of Causation*. ed. H. Beebee, P. Menzies, and C. Hitchcock, pp. 265-278, Oxford: Oxford University Press.

Norton, J. (2015), "Weak Discernibility and Relations between Quanta", *Philosophy of Science*, 82: 1188–1199.

Paul, L. A. (2013), 'Categorical Priority and Categorical Collapse', *Proceedings of the Aristotelian Society* 87: 89-112.

Post, H.R. (1971), 'Correspondence, Invariance and Heuristics', *Studies in History and Philosophy of Science* 2: 213–55.

Psillos, S. (2016), 'Broken Structuralism', *Metascience* 25: 163-171.

Rettler, B. and Bailey, A. M. (2017), 'Object', *The Stanford Encyclopedia of Philosophy* (Winter 2017 Edition), Edward N. Zalta (ed.) https://plato.stanford.edu/archives/win2017/entries/object/

Ruyant, Q. (forthcoming), 'Structural Realism or Modal Empiricism?', *British Journal for the Philosophy of Science*.

Saatsi, J. (2017), 'Replacing Recipe Realism', *Synthese,* 194: 3233-3244.

Saunders, S. (1993) 'To What Physics Corresponds', in S. French and H. Kaminga (eds), *Correspondence, Invariance, and Heuristics; Essays in Honour of Heinz Post*. Dordrecht: Kluwer, 2010: 295–326.

Schaffer, J. (2003), 'Is There a Fundamental Level?,' *Nous*, 37: 498-517.

Sider, T. (2006), ''Bare Particulars'', *Philosophical Perspectives* 20: 387–97

Sider, T. (2011), *Writing the Book of the World*, Oxford University Press.

Thébault, K. (2016), 'Quantization as a Guide to Ontic Structure', *British Journal for the Philosophy of Science* 67: 89-114.

van Fraassen, B.(1991), *Quantum Mechanics: An Empiricist View*, Oxford University Press.

Vetter, B. (2009), 'Review of Alexander Bird: *Nature's Metaphysics: Laws and Properties.* Oxford: Oxford University Press, 2007', *Logical Analysis and History of Philosophy* 8: 320-328.

Vetter, B. (2015), *Potentiality: From dispositions to modality*. Oxford: Oxford University Press.

Vetter, B. (2018), 'Digging Deeper: Why Metaphysics is More Than a Toolbox' *Journal for General Philosophy of Science* 49: 231-241.

Vickers, P. (2019), 'Towards a realistic success-to-truth inference for scientific realism' *Synthese* 196: 571-585.

Williams, D. C. (1958), 'Form and Matter ii', *Philosophical Review,* 67: 499–521.

Wilson, J. (2012) 'Fundamental Determinables', *Philosophers Imprint* 12.

Wilson, J. (2017), 'Determinables and Determinates', *The Stanford Encyclopedia of Philosophy* (Spring 2017 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/spr2017/entries/determinate-determinables/

Wolff, J. (2012), 'Do Objects Depend on Structures?', *British Journal for the Philosophy of Science* 63: 607-625.

Wolff, J. (2019), 'Why Eliminativism?' *Studies in History and Philosophy of Science* 74: 16-21.

Worrall, J. (1989), 'Structural realism: The Best of Both Worlds?' *Dialectica* 43: 99–124.

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[1] However, he subsequently shifted his response to the underdetermination, from an 'eliminativist' stance towards objects to one that allows for a 'thin' metaphysical conception of them (see French and Ladyman 2011).

[2] There remains the concern as to how the relevant symmetry is broken without introducing an extraneous element, that effectively plays the same role as the classical environment, or consciousness, or a probability 'field'; that is, some account has to be given of how a given sub-structure can break the symmetry associated with another. As Lombardi acknowledges (Lombardi 2019, p. 47), there is more work to be done here, perhaps invoking a 'closed-system' account of decoherence. (I'm grateful to Claudio Calosi and Juha Saatsi for discussions on this.)

[3] And it still is, at least within the general philosophy of science community, suggesting there is further proselytization to be done!

[4] Comparisons can also be drawn with Chakravartty's incorporation of a version of bundle theory into his structurally inclined 'semi-realism' (Chakravartty 2007; cf. also Lombardi 2019 for a

quantum mechanical rendering) and also with Schaffer's monism, insofar as we might conceive of the 'world-bundle' as a fusion of qualitative properties with spatio-temporal locations.

[5] Echoing Wilson, Paul acknowledges that determinables might be among the fundamental properties and relations.

[6] Eddington famously deployed a similar move with regard to the rotation group in quantum mechanics (see French 2014, p. 87).

[7] There is more to say about the comparison between Sider's structuralism and ontic structural realism but that should wait for another opportunity (but see lectures 4 and 5 in Sider's John Locke Lectures: https://www.philosophy.ox.ac.uk/john-locke-lectures).

[8] Crucially what the Humean and the dispositionalist also omit or cannot accommodate are the symmetries, although for moves in the right direction when it comes to the former, see Daguid forthcoming.