The Epiphenomena Argument for Symmetry-to-Reality Inference

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Abstract

A new argument is given for the thesis that only symmetry-invariant physical quantities are real. Non-invariant quantities are dynamically epiphenomenal in that they have no effect on the evolution of invariant quantities, and it is a significant theoretical vice to posit epiphenomenal quantities.

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An oft-asserted norm in the interpretation of physics is the principle of symmetry-to-reality inference. The principle has been presented in two distinct but related forms. Sometimes it is suggested that states related by a symmetry have the same representational capacities (Belot, 2013). Other authors (Baker, 2010; Dasgupta, 2016) assert a somewhat different principle: quantities that fail to be invariant under symmetries cannot be real. That is, non-invariant quantities are not physically significant, or they are not candidates for interpretation as fundamental quantities.[1]

In this paper I will present a new-ish argument for this second form of symmetry-to-reality inference. The argument has its roots in extant work on symmetry and surplus or redundant structure, but it departs from these prior arguments in a way that gives it the resources to avoid some powerful objections raised by Dasgupta (2016).

Dasgupta has argued that no *formal* definition of symmetry can justify symmetry-to-reality inference, and in particular that the dynamical definition of symmetry cannot jus-

[1] For present purposes, I will not define the notion of a quantity being "real" in more precise terms than this, but the details can be filled in in a number of ways; for one good attempt, see North (2021).

tify it. But the argument I will present in this essay–the argument from epiphenomena–accomplishes exactly that.

A dynamical symmetry is a symmetry that preserves the dynamical laws (the laws of time evolution) in a particular sense. The dynamical definition requires that symmetries must *commute* with the dynamics.

Think of a symmetry not (first and foremost) as a transformation on total histories, but on instantaneous states at a time. Then the dynamical definition requires that it doesn't matter to the final state *when* you apply the symmetry. That is: Suppose we have a state that evolves in time, changing from s_0 at t_0 to s_f at t_f. Then if T is a transformation on states, T is only a symmetry if $T(s_0)$ evolves into $T(t_f)$. That is, it doesn't matter whether we apply the symmetry earlier (at t_0) and let the state evolve, or if we let the state evolve (into s_f at t_f) and then apply the symmetry. The final state is the same whether you apply the symmetry before or after the evolution."

1 Smoothness requirements

If this definition is going to do the job of supporting symmetry-to-reality inference without running afoul of obvious counterexamples, it must be complicated a bit. Consider a theory with multiple stable equilibrium states. For concreteness, we may imagine a classical theory whose laws permit a state in which one particle is stationary at the center of a potential well, and also a state in which two particles are stationary at the centers of two such wells. Neither of these states will change with time; the particles will simply stay put forever.

As a result, a transformation permuting these two states and leaving all other states unchanged will count as a symmetry by the dynamical definition above. This is obviously not desirable. Clearly a two-particle state is not physically equivalent to a one-particle state, so symmetry-to-reality inference is unjustified in the case of this "symmetry." Moreover, it clashes irreconcilably with a physically intuitive grasp of what we mean by a transformation that "preserves the laws."

To fix this bug, it suffices to require that symmetry transformations must act smoothly on the (independent and dependent) variables used to formulate the kinematically possible states. For example, if the position variable x is one of our theory's canonical variables, a transformation $T(x) = (x \text{ if } x \neq 1,\ 0 \text{ if } x = 1)$ would not be a symmetry; neither would the transformation we just examined that takes a two-particle state to a one-particle state. Such a transformation couldn't possibly be written as a continuous, differentiable function of the theory's variables.

Dasgupta (2016) has objected to this sort of smoothness requirement in an instructive way. The requirement amounts to a stipulation that the differential and topological structure of a theory's variables represent real structure rather than surplus structure. Why else would we require that symmetries must preserve this structure? But then, Dasgupta argues,

> the resulting definition is objectionably arbitrary. For whatever physical feature we pick as our privileged feature F, it will follow just by virtue of the resulting definition of symmetry that it is impossible to run a symmetry-to-reality inference on F and conclude that it is unreal. [...] So what is different about the differentiable structure [...], or indeed any other supposedly privileged feature F? What is so special about them, such that they are by definition immune to being rejected as unreal on the basis of the symmetry-to-reality inference? (Dasgupta, 2016, 865)

It is entirely fair to demand an answer to this question. I think an answer can be given, based on our understanding of how we can plausibly expect dynamical laws of nature to behave. Such laws govern the relationships between a theory's quantities at different times; they should not act on these quantities discontinuously, because if they did, there would be some series of states that the theory treats as arbitrarily similar to each other, but which the laws treat as highly dissimilar.[2] This would be a sign that our choice of variables used to describe the physics in question was all wrong, and the theory would have to go back to the drawing board. In other words, our pre-existing partial interpretation of the theory would be too wildly wrong for symmetry-to-reality inference to be a good guide to the construction of a more complete interpretation.[3]

[2] One might say that a match of this sort between a theory's variables and its dynamics is an important theoretical virtue, and a mismatch is such a bad theoretical vice that the theory can be assumed, pretty much automatically, to be unsatisfactory.

[3] Of course it is impossible to begin the project of interpreting a physical theory without first fixing *some* aspects of a theory's interpretation (Ruetsche, 2011, 7). If I don't first specify whether a wavefunction represents a particle's quantum state or (by some odd convention) the food left in my fridge, no definition of symmetry can be usefully applied to it. Typically a theory (like quantum mechanics) is first empirically confirmed in a partially-interpreted form, and once it is sufficiently well confirmed a more complete

Dasgupta himself suggests that the only acceptable answer as to why we should privilege a theory's differential structure is because this requirement is needed in order to preserve the data–in order to ensure that symmetry-related states make the same empirical predictions. But if this is the reason, it leads to an epistemic circularity that Dasgupta claims is problematic.

To illustrate the problematic circularity with an example: in the time before relativity, one might reasonably have stipulated that a transformation cannot possibly preserve the data unless it leaves unchanged which events are simultaneous. But we would never require this today, because we have examples of excellent theories in which absolute simultaneity is unreal, and some transformations that alter simultaneity relations (Lorentz boosts) leave the data unchanged. But we only came to understand this via symmetry inference.

"In this way," Dasgupta continues,

> our belief about whether a given feature (like spatial distance) fixes the data is based on prior beliefs as to whether the feature is real, which in turn is based on prior beliefs about what the symmetries of the physical laws are. So we cannot (on pain of inferential circularity) define symmetries to be transformations that preserve features that fix the data (in either the *de re* or the *de dicto* sense). (Dasgupta, 2016, 864-865)

But this accusation of circularity seems uncharitable. Even if the smoothness requirement were (contrary to my reading of the facts) justified only by its preserving empirical data, Dasgupta has established only that symmetry-to-reality inference is *sometimes* the right method for determining that a certain feature does or doesn't need to be held fixed in order to fix the data. We may have other means of accessing some (incomplete) information about which features need to be preserved. If some of the criteria for a symmetry are settled on these separate grounds, there is no inferential circle–at least not if there are *other* criteria that are settled on other grounds (such as the dynamical criterion of preserving the laws' action on states).

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interpretation is constructed, holding fixed the stipulations made in the partial interpretation.

For present purposes, this final transformation of the partial interpretation into a full interpretation is the crucial stage of a theory's life cycle, since is at this stage that symmetry-to-reality inferences are useful. Once a theory's interpretation is complete, after all, symmetry-to-reality inferences are no longer useful, since at that point we have fully determined which of the theory's quantities are real.

Dasgupta seems to have lost sight here of the inherent limitations on the role symmetry inference must play in interpreting physics. Symmetry inference cannot proceed if we begin with a completely uninterpreted theory. (After all, such a "theory" could not even possess empirical content.) Rather, it is a process for taking a partially interpreted theory and reaching conclusions about its most satisfactory complete interpretation.

Even Dasgupta's preferred epistemic account of symmetry (Dasgupta, 2016, Sec. 6) shares this feature, since the theory's representations of empirical phenomena must be given a prior interpretation for symmetry inference along Dasgupta's lines to proceed. Granted, this presumes a less complete and committal partial interpretation than the one presumed by dynamical symmetries with a smoothness requirement. But it is not circular to begin from some weak commitments about what is real (i.e., the differential structure of our partially interpreted theory's variables) and argue to conclusions about which *other* things are not real (such as absolute velocity). Since Dasgupta's objection fails to identify a real circularity, it gives us no grounds for rejecting the dynamical account. There may be other reasons for preferring Dasgupta's less-complete partial interpretation as a starting point, but this particular argument does not succeed.

2 Extant redundancy arguments

The dynamical picture of symmetry is the basis for a couple of the most popular and compelling arguments for symmetry-to-reality inference. These are the redundancy or surplus structure arguments. In their most common form, though, they are subject to some damning objections.

Baker (2010, Sec. 2) defends a form of redundancy argument. The idea of the argument is that only invariant quantities are "dynamical difference-makers." The idea is that there is good reason to believe a quantity is unreal if it makes no difference to the time-evolution of physical states in accord with the laws. (We might say in that case that it is dispensable from all dynamical explanations.) Intuitively, this seems to follow from the dynamical definition of a symmetry. If I change the value of an invariant quantity (say a particle's mass) this change will make a difference to the future evolution of the state, and so a transformation changing that quantity will not commute with the dynamics. The opposite, one might argue, goes for non-invariant quantities. Since changing their value commutes with the dynamics, it must not make a difference to the future evolution of the state.

This depends on the generalization that symmetries never affect the state's future evolution. For some symmetries this is uncontroversially true. Gauge transformations in gauge theories like electrodynamics are an example; a gauge transformation on the present state of the potential doesn't even affect the potential's own future evolution.[4] But for many other symmetries, the generalization is only correct if we assume non-invariant quantities are unreal from the outset.

The essential point here was made (against Leibniz) by Sklar (1974, 180). For many non-invariant quantities, such as absolute position and velocity in Newton's absolute-space version of his mechanics, their present value is a dynamical difference-maker to the future values of non-invariant quantities! In particular, if I change the present value of absolute velocity, that affects the future evolution of absolute position. So to assume that this sort of non-invariant quantity is not a difference-maker is to assume it is unreal (perhaps together with other related non-invariant quantities). This argument for symmetry inference is therefore a vicious circle (Dasgupta, 2016, 846-847).

To be sure, it remains the case that only invariant quantities can be dynamical difference-makers for other invariant quantities! In Sec. 3 we will see whether this fact can be leveraged into a better argument that isn't circular.

A second sort of redundancy argument has seen a lot of play in the philosophy of space and time. It begins from the observation that non-invariant quantities do not (in a certain sense) factor into a theory's laws. The dynamical laws can be fully stated with reference only to invariant quantities.

This is fairly obvious when it comes to the dynamics of the invariant quantities. Symmetry transformations commute with the dynamical laws, and they leave the values of invariant quantities unchanged while changing the values of non-invariant quantities. Thus one doesn't need to keep track of the values of the non-invariant quantities in order to predict how the invariant quantities will change. The action of the laws on the invariant quantities doesn't require the non-invariant quantities as "input." In this sense, the dynamics of the invariant quantities can be written without mentioning non-invariant quantities.

[4]Except insofar as the potential must still be a smooth function of time, of course. For "small" gauge transformations connected to the identity, this means the potential's future evolution may remain unchanged outside an infinitesimal region of the present.

But what about the dynamics for the non-invariant quantities? Don't *those* require non-invariant quantities as input? Yes, but there is an asymmetry (no pun intended). In general, a dynamics for non-invariant quantities cannot be formulated without entailing the existence of some invariant quantities. For instance, if you write down a dynamics for absolute position, *relative* position is constructible from this as a quantity: one can't define a state describing absolute positions and their evolution without also describing relative positions. So it's possible to state a dynamics for invariant quantities without presuming the existence of non-invariant quantities–but not vice versa.

Moreover, whatever dynamics governs non-invariant quantities (assuming they exist) is entailed by the dynamics for the invariant quantities. Dasgupta (2016, 849) puts this point somewhat differently: "a feature is redundant to some laws if and only if its values are irrelevant to whether the laws obtain. Absolute velocity is redundant to NG in this sense..." That is, it is redundant to the *dynamical* laws of Newtonian gravity. Assuming there is such a thing as absolute velocity, and it obeys the kinematical laws, it automatically follows that it obeys the dynamical laws as long as the relative velocities obey *their* dynamical laws. This generalizes to other non-invariant quantities. As long as the invariant quantities obey the dynamical laws, there is no room for the non-invariant quantities to violate them. In this sense, you don't need to check the non-invariant quantities to see whether a state over time (a history) is dynamically possible.

This sort of redundancy creates a situation analogous to the one considered by Earman (1989) in his discussion of his two spacetime Symmetry Principles. Recall Earman's principle SP1:

SP1 Any dynamical [external] symmetry of T is a spacetime symmetry of T. (Earman, 1989, 46)

This principle posits that there should be no redundant spacetime structure, in the sense we've been discussing. If a putative spatiotemporal property or relation isn't needed in order to state the dynamical laws–to "support" them, in Earman's terminology–then we should infer spacetime doesn't really have that property, at least not as part of its objective structure.

The present redundancy argument for symmetry inference asks us to generalize SP1 to all symmetries, not just external ones. If some putative quantity is not needed to support the laws, it must not be a real quantity. Although Earman does not address whether such a further step is justified outside the context of spacetime, North (2009, 2021) has advocated it as a general principle for interpreting physics.

Earman justifies SP1 based on what he calls an Occamist argument: “The theory that fails (SP1) is [...] using more space-time structure than is needed to support the laws, and slicing away this superfluous structure serves to restore (SP1).” (Earman, 1989, 46-47) Occam tells us not to multiply entities beyond necessity; Earman is suggesting that the right definition of “necessity” for spacetime structure is necessity in supporting the laws. Perhaps the same goes for all physical quantities. If so, we have a sound redundancy argument for symmetry inference.

Dasgupta is not impressed with this argument. His objection is that it puts the laws on an unjustifiably high pedestal. “Earman’s idea,” he writes, “is that if you can write the laws without mentioning some feature in the metaphysics, then that is reason to think that the feature is unreal. But why should this be so? Why think that every real feature must be mentioned when writing down one half of your theory?” (Dasgupta, 2016, 849)

The response might go that ontological inference in physics proceeds via positing laws and seeing which things are needed to make sense of those laws. What other reason could one have for believing in some physical thing?

Dasgupta would likely respond that this is an overly parochial conception of inference to the best explanation. Surely one can be justified in positing the existence of a thing without much understanding of its role in laws, if other evidence of its existence emerges. But this response does not get us all the way to the conclusion that it can be justifiable to posit quantities that play no role in the laws.

Dasgupta initially states his case in the form of a rhetorical question, to which Earman’s defenders may well respond: why *shouldn’t* we think that the only real features are the ones needed to support the laws? To some this seems highly intuitive or even obvious. Consider North’s perspective:

> The reason for the inference to a Galilean structure for Newton’s laws is not just that no experiment could detect the additional structure of Newtonian spacetime (even though that is true). The reason is that positing no more structure than what is needed for the laws is *evidence* that we have inferred the *correct* structure to a world governed by those laws. (North, 2021, 75)

Here North comes very close to saying that symmetry-to-reality inference itself is a basic norm on theory choice. On her view, a theory with the structure needed to support the laws, and no more, is a theory with exactly the *right* amount of structure. She refers to such a theory as "well-tuned." A preference for well-tuned theories is North's *matching principle,* which she treats as a theoretical virtue on a par with (or even above) Occamist simplicity.

As a fan of robust theoretical virtues, I am tempted to agree with North's matching principle. But it is not obvious to me that it's a *basic* principle, and treating it as basic is not much good in the fight against skeptics like Dasgupta. Moreover, Dasgupta backs up his rhetorical question–why treat the laws as our only guide to the metaphysics?–with a powerful point:

> Keep in mind that even though one can formulate NG without mentioning absolute velocity, absolute velocity is nonetheless a difference-maker and is indispensable to explanations of physical phenomena in an NG system, in the senses discussed above. Why then is the mere fact that one can formulate the laws without mentioning it a reason to think that it is unreal? (Dasgupta, 2016, 849)

Here Dasgupta directly attacks Earman's reasoning in support of SP1. Earman claims that structure unnecessary to support the laws is "superfluous." But supporting the laws is only one of several theoretical roles that a quantity might play. It might, alternatively, play the role of dynamical difference-maker (the way absolute velocity helps determine and explain the future evolution of absolute position, if the latter is real). If we can show that a quantity is superfluous to the laws, but we cannot show that it is superfluous as a difference maker, is it really superfluous? To the contrary, it could be superfluous in the "supporting the laws" role while being indispensable in the "difference maker" role.

Dasgupta's point here is equally effective against North, who grants that her matching principle is defeasible: "[A]ll things being equal, we should infer a match in structure between laws and world. Those who believe in a mismatch are saying that other things are not equal, and must argue as much." (North, forthcoming, 9) Dasgupta's argument about difference-making means that other things are not equal–not unless we assume from the outset that non-invariant quantities are unreal. An argument for the unreality of absolute velocity that proceeds from the premise that absolute position isn't real is an argument that shouldn't convince anyone.

3 The argument from epiphenomena

Is there hope for a compelling, non-circular justification of symmetry inference based on dynamical definitions of symmetry? Potentially one could accept North's matching principle as a basic norm of theorizing, and argue further that it is an extremely strong norm, strong enough to override other norms (aside from the imperative of empirical confirmation). This may even be a sound argument, but it is unlikely to persuade the unconvinced.

More decisive would be a direct argument against the reality of non-invariant quantities, on the grounds that they exhibit some sort of theoretical pathology. I think a strong argument of this sort is available, beginning from some of the same facts that have been employed to argue that non-invariant quantities (under dynamical symmetries) are undetectable. The argument aims to establish that non-invariant quantities are *epiphenomenal* in a problematic sense, and that positing such epiphenomenal quantities is a theoretical vice.

The basis for the argument is that non-invariant quantities exhibit a very radical sort of isolation from the rest of the world, in the sense that nothing else depends on their values. In particular, nothing else can reliably be brought into correlation with with the values of non-invariant quantities.

This causal or dynamical inefficacy of the non-invariant quantities is explained by Roberts (2008, 158-162). Suppose, for example, that we were trying to correlate the absolute speed of an object (say, my prized Powermaster Optimus Prime figure) with some invariant quantity, such as the amount of money in my wallet. We might try to set up some reliable mechanism to put more money in my wallet the greater the absolute speed of Optimus Prime. This mechanism would have to operate in accord with the dynamical laws, and for it to be reliable, the laws would have to ensure that the money counted out will be proportional to the speed.

But velocity boosts are a dynamical symmetry of the laws, and for any given object in a given state, there is some boost that reduces its absolute speed to zero. So take a state in which our supposedly reliable mechanism puts five dollars in my wallet. We may transform that state, via a boost, to one in which Optimus Prime's absolute speed is zero. But if we apply this transformation to the state, the dynamical laws will still act the same way on the invariant quantities, including the money in my wallet. So the same amount of money will end up in my wallet whether Prime's absolute speed is zero or non-zero. Invariant quantities like the money in my wallet cannot be reliably correlated with non-invariant quantities. (A parallel argument can be made for any non-invariant quantity.)

In this sense, the non-invariant quantities are *epiphenomenal.* I use this term pointedly, because the situation here has clear parallels to the thesis of epiphenomenalism in the philosophy of consciousness. If conscious experience is epiphenomenal, as some have argued, then phenomenal conscious experience is caused by physical events but cannot exert causal influence over the physical. Your experience of pain cannot even be the cause of your verbal exclamations of pain. (Note that this does not mean that consciousness is undetectable; it is meant to be detectable, by definition.)

I don't mean to assume that epiphenomenalism about consciousness is obviously unviable. But if it is an acceptable view, that is only because the problem of consciousness is so difficult to solve in any other satisfactory way. The positing of epiphenomenal properties is clearly a high price for a theory to pay. That is to say, epiphenomenal properties are a significant theoretical vice–and their absence is a virtue.

Elsewhere a similar point has been made against so-called "primitive ontology" hypotheses in the foundations of quantum mechanics. These hypotheses solve the measurement problem by taking the quantum state and adding further objects whose dynamics are guided by the state. Bohmian mechanics is one example. Albert (2015, Ch. 7) observes that in these theories, the quantum state affects the evolution of the primitive ontology, but the primitive ontology has no effect on the state. (In Bohm's theory, for example, the configuration of the particles has no dynamical consequences for the wavefunction.) In my terms, the primitive ontology is an epiphenomenal part of the theory.

This is not to say that primitive ontology theories are automatically unacceptable. Perhaps they offer the only viable solution to the measurement problem, in which case surely they ought to be accepted. But as Albert rightly points out, their epiphenomenal posits are a theoretical vice. Advocates of Bohm's theory have responded to this concern by interpreting the quantum state as a law of nature rather than a concrete physical thing (Durr *et al.*, 1997).

So there is some consensus in recent work on the interpretation of quantum mechanics, at least, that theories without epiphenomenal physical quantities are preferable. In the Bohmian case, though, the Bohmians' response has been to deny the existence of the state–the structure that *wasn't* epiphenomenal–so that the primitive ontology no longer counts as epiphenomenal. They have chosen this option because they believe that the primitive ontology is required to explain measurements while the quantum state is not.

There is no justification, however, for employing a similar move to make room for the reality of non-invariant quantities in a theory with dynamical symmetries. This would require an interpretation of the theory on which no invariant quantities exist. But as Roberts (2008, Sec. 6) points out, not only are we clearly capable of measuring at least some invariant quantities, but in addition, measurement results must be publicly recorded and communicated using invariant quantities. Clearly our means of recording and communicating results are interchangeable, and some of them are invariant (Roberts gives the example of the relative positions of ink on a page). But this interchangeability would not be possible if any of our recording or communication devices were not invariant, since non-invariant quantities are epiphenomenal and so cannot be reliably correlated with invariant quantities.

As a final point, which may already be obvious to the reader, invariant quantities can generally be constructed from a sufficiently complete class of non-invariant quantities. (Relative positions can be written as a function of absolute positions, the electromagnetic field as a function of the potential, etc.) The reverse, on the other hand, is not true–non-invariant quantities can't be constructed from invariant ones–not without adding further information. This makes it more difficult to see how one could coherently deny the reality of invariant quantities while affirming that the non-invariant ones are real.

So clearly, if the norm of avoiding epiphenomenal ontology can only be satisfied by dispensing with one class of quantities–invariant or non-invariant–the non-invariant quantities must be the ones to go.

To sum up, in theories with dynamical symmetries, we find that the properties described by a state break down into two classes. The "A-properties" (the invariant ones) include properties essential to measurement and the recording and communication of measurement results. The (non-invariant) "B-properties," on the other hand, are epiphenomenal (dynamically isolated from the A-properties), and a satisfactory (partial) interpretation can make sense of experimental predictions perfectly well without mentioning any B-properties. So the question we face is whether a complete interpretation of the theory would be better with or without the B-properties. Since epiphenomenal properties are a major theoretical vice, my argument goes, it is better to find a way to do without the B-properties in the complete interpretation of the theory.

This argument is distinct from the sort of Occamist argument from undetectability defended by Ismael and van Fraassen (2003) and Dasgupta (2016), and from North's matching principle argument. But it is compatible with the premises of these arguments. So insofar as the reader is moved by these other arguments, they can be combined with the epiphenomenalism argument into a formidable case for the unreality of non-invariant quantities.

References

Albert, David Z. (2015), *After Physics*, Harvard University Press.

Baker, David John (2010), "Symmetry and the Metaphysics of Physics," *Philosophy Compass* 5:1157–1166.

Belot, Gordon (2013), "Symmetry and Equivalence," in Batterman, Robert (ed.), *Oxford Handbook of Philosophy of Physics*, Oxford University Press.
URL `http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780195392043.001.0001/oxford` `(retrieved 11 Jan. 2019)`

Dasgupta, Shamik (2016), "Symmetry as an Epistemic Notion (Twice Over)," *British Journal for the Philosophy of Science* 67:837–878.

Durr, Detlef, Sheldon Goldstein and Nino Zanghi (1997), "Bohmian mechanics and the meaning of the wave function," in Shimony, A., R.S. Cohen, M. Horne and J.J. Stachel (eds.), *Experimental Metaphysics: Quantum Mechanical Studies for Abner Shimony, Volume One*, Springer Netherlands, Boston Studies in the Philosophy and History of Science.

Earman, John (1989), *World Enough and Spacetime*, MIT press.

Ismael, Jenann and Bas C. van Fraassen (2003), "Symmetry as a Guide to Superfluous Theoretical Structure," in Brading, Katherine and Elena Castellani (eds.), *Symmetries in Physics: Philosophical Reflections*, Cambridge: Cambridge UP, 371–392.

North, Jill (2009), "The "Structure"of Physics: A Case Study," *Journal of Philosophy* 106:57–88.

North, Jill (2021), *Physics, Structure, and Reality*, Oxford: Oxford UP.

North, Jill (forthcoming), "A New Approach to the Relational-Substantival Debate," *Oxford Studies in Metaphysics* .

Roberts, John T. (2008), "A Puzzle about Laws, Symmetries and Measurability," *British Journal for the Philosophy of Science* 59:143–168.

Ruetsche, Laura (2011), *Interpreting Quantum Theories*, Oxford: Oxford UP.

Sklar, Lawrence (1974), *Space, Time, and Spacetime*, University of California Press.