15

Realist Representations of Particles

The Standard Model, Top Down and Bottom Up

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> It is the sense in which Tycho and Kepler do not observe the same thing which must be grasped if one is to understand disagreements within microphysics. Fundamental physics is primarily a search for intelligibility—it is a philosophy of matter. Only secondarily is it a search for objects and facts (though the two endeavors are as hand and glove). Microphysicists seek new modes of conceptual organization. If that can be done the finding of new entities will follow.
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> Norwood Russell Hanson (1965/1958, pp. 18–19)

15.1 Fixing the Content of Realism: Reference and Description

Scientific realism is commonly understood as the idea that our best scientific theories, read literally as descriptions of a mind-independent world, afford knowledge of their subject matters independently of the question of whether they are detectable with the unaided senses or, in some cases, detectable at all. It is a staple of the field of history and philosophy of science to wonder whether any such prescription for interpreting theories (and models and other scientific representations; I will take this as read henceforth) is plausible given the history of theory change in specific domains of the sciences. A lot of ink has been spilled on the question of whether, or under what circumstances, a realist interpretation of theories is reasonable. Antirealists of various kinds have argued that given the lessons of changing descriptions of targets of scientific interest over time, adhering to realism is something of a fool's errand. Conversely, realists of various kinds—often referred to as *selective* realists—have sought to identify some

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principled part of theories regarding which there has been continuity across theory change in the past, thus fostering the reasonableness of expectations of continuity in the future.

My focus in this essay is not the historical framing of these particular debates about realism per se, but rather a key feature of them that amounts to a more general problematic for realism. The shared strategy among selective realists for dealing with descriptive discontinuity across historical theory change has been, unsurprisingly, *selectivity* in what they take to be correct about a theory, proposed in discussions of how certain claims have had or do have greater epistemic warrant than others, such that continuity regarding these claims may then serve as a bulwark for realism even while discontinuity rules more generally. Hence the now familiar maneuver of associating realism with only certain parts of theories, such as those involved in making successful novel predictions, or concerning experimental entities or mathematical structures. In each case we find concomitant arguments about the typical preservation of the relevant parts of theories across theory change, both as a reading of history and as a promise for the future.

Here emerges the key feature of debates surrounding the shared strategy of selective realism on which I will focus. The hope of selective realism is that less is more. By associating realist commitments with less, the hope is that it will become easier to defend—indeed, that it will amount to a plausible epistemology of science. It is by no means easy, however, to know how much is enough. Consider, in connection with any given theory, an imagined spectrum of epistemic commitments one might make regarding its content. At one end of the spectrum one believes almost nothing; at the other end, one believes everything the theory states or suggests. Arguably, if realism is purchased at the cost of believing almost nothing, it is largely empty; if instead realism is made more substantial by licensing ever greater quantities of substantive belief, it runs an ever greater risk of (for example) falling prey to concerns arising from theory change. The realist, then, in any given case, must perform a kind of balancing act appropriate to that case. Let me label this challenge *the realist tightrope*. On one side, there is the temptation to affirm less and less, and on the other, the temptation to affirm more and more. Giving in to either of these temptations may spell disaster, but it is no easy feat to get the balance *just right*.

The potential benefit to realism of walking the tightrope is wide-ranging, in that it is relevant to both historical and ahistorical defenses of the position. As noted, if the realist were able to get the balance just right in some particular domain of science, she might then be in a position to furnish a narrative of continuity of warranted belief across theory change in that domain, past, present, and future. But the tightrope is something that must be walked not only in connection with historical lineages of theories, but also in connection with any given theory, for it is often a challenge to work out how any one theory should be

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interpreted in a realist way. As Jones (1991) notes, it can be rather unclear how best to articulate the subject matters of theories in physics (as per his examples), where different interpretations can amount to different explanatory frameworks, each suggesting a different ontology. This he presents as a challenge to realism, which "envisions mature science as populating the world with a clearly defined and described set of objects, properties, and processes, and progressing by steady refinement of the descriptions and consequent clarification of the referential taxonomy to a full blown correspondence with the natural order" (p. 186). In this characterization of realism we catch a glimpse of how the tightrope must be walked both synchronically and diachronically.

How shall we understand the spectrum of commitment, from thinner to more substantial? I take it that an understanding of this is implicit in most discussions of realism; indeed, it is implicit in Jones's characterization. The thinnest possible realist commitment is to the mere existence of something, which we capture by speaking of successful reference. We say that the term "ribonucleic acid" or "black hole" refers, which is (typically) shorthand for saying that it refers determinately to something in the world. From here, commitment becomes increasingly substantial as realists assert descriptions of the properties and relations of these things. A very substantial commitment may involve asserting all of the descriptions comprising or entailed by a theory, but it is often expressed otherwise, not by believing everything—often not in the cards in any case, since theories often contain known idealizations and approximations—but by asserting increasingly detailed descriptions of whatever the realist does, in fact, endorse. For example, an entity realist might describe the natures of the entities she endorses in terms of certain causally efficacious properties. A structural realist might describe the natures of these same entities in terms of certain structural relations. One can imagine yet further, finer-grained descriptions of the natures of these properties and structures. On the thin end of the spectrum we have bare reference, and on the other end, ever more comprehensive or detailed descriptions of the natures of the referents.

With this understanding in hand, a clearer picture of the realist tightrope emerges. Believing as little as possible and thereby asserting successful reference alone, which might seem a more defensible position than believing significantly more, might also seem to run the risk of rendering realism empty of much content.[1] The more one believes, however, the wider one opens the door to both the epistemic peril of believing things that may be weeded out as theories develop and improve, and the metaphysical peril of defending finer- and finer-grained descriptions of the subject matters of realist commitment, in virtue of

[1] Stanford 2015 argues that it would make realism into something that is, if not empty, so weak that antirealists need not dispute it. I will return to this contention in section 15.5.

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the inevitably and increasingly abstruse concepts and objections to which metaphysical theorizing is prone. In some cases the epistemic and metaphysical perils come together: in these cases, succumbing to the temptation to articulate the natures of the referents of a theory in some fine-grained detail yields descriptions that may become outmoded by subsequent developments in the relevant science. An examination of precisely this sort of case, to which I will turn now, forms the backbone of what follows.

The Standard Model of particle physics, one of the landmark achievements of twentieth-century science, itemizes a taxonomy of subatomic particles along with their properties and interactions. Beyond mere reference to these entities, however, their nature has been subject to realist wonderment and debate throughout the history of theorizing in this domain. In ways that are well known and which I will consider momentarily, the particles of the Standard Model are radically unlike what could be imagined in classical physics—thus providing an example of how descriptions of the physical and metaphysical natures of something conceived in connection with earlier theorizing would have to be relinquished in light of subsequent theorizing. Just what the natures of these things enumerated by the Standard Model are, however, is still far from clear. Indeed, if realist attempts to characterize them are any guide, there is no consensus at all. Advocates of different forms of selective realism, for example, have characterized them in very different ways. And all the while, realists and antirealists alike have suggested that in the absence of some unique characterization, realism is untenable. After considering various possibilities for thinking about the identity and individuality of particles, for instance, van Fraassen (1991, p. 480) concludes that we should say "good-bye to metaphysics." Ladyman (1998, p. 420) holds that tolerating metaphysical ambiguity regarding these issues would amount to a merely "ersatz form of realism."

In earlier work I have offered judgments that might be construed as echoing these kinds of sentiments. "One cannot fully appreciate what it might mean to be a realist until one has a clear picture of what one is being invited to be a realist about" (Chakravartty 2007, p. 26). But having a clear picture is compatible, I submit, with a number of different and defensible understandings of how best to walk the realist tightrope in any given case. In the remainder of this essay I endeavor to explain why this is so, taking particles as a case study. In the next section I briefly substantiate the contention that many questions regarding the natures of particles are still very much up for grabs in contemporary physics and philosophy of physics with a synopsis of a handful of the conceptual conundrums surrounding them. In sections 15.3 and 15.4, I examine, respectively, what I describe as the two main approaches to thinking about the natures of particles and their properties, which have in turn shaped varieties of selective realism—"top-down" approaches, emphasizing formal, mathematical descriptions furnished

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by theory, and "bottom-up" approaches, emphasizing causal interactions and manipulations at the heart of experiment. In the final section, I argue that realism is a commitment that can be shared, defensibly, by those who subscribe to different and even conflicting conceptions of the natures of particles.

15.2 Searching for a Realist Interpretation of "Particles"

The electron is the veritable poster child of scientific realist commitment. Most proponents of both realism and antirealism (rightly or wrongly) take various facts about observable phenomena as uncontroversial, but seriously contest the status of the unobservable. Though theories at every "level" of description—from social and psychological phenomena to biological and chemical phenomena through to the subject matters of physics—all theorize about putatively unobservable objects, events, processes, and properties, realists often cite subatomic particles as a shining example of entities conducive to realism. On the one hand, given the mind-boggling success of the uses to which we have put twentieth-century theories concerning them, not least in a host of startlingly effective technologies from computing to telecommunications to medical imaging, this may not seem surprising. On the other hand, perhaps it should be a cause for concern after all, because even a cursory foray into our best attempts to grasp the natures of particles and particle behavior are fraught with conceptual difficulties, and our best scientific theories are far from transparent on this particular score.

Trouble rears its head at the start with the term "particle." What is a particle in this domain? There is, of course, a classical conception of what a particle is, which is easily graspable and conceptually undemanding, relatively speaking, but this conception is simply inapplicable at atomic and subatomic scales in light of twentieth-century developments in theory and experiment. Classical particles are solid entities that can be envisioned colliding with and recoiling from one another in the ways that billiard balls appear to behave, phenomenologically. The natures of particles described by the Standard Model are not in this way intelligible. They appear to behave in the manner of discrete entities in some contexts but like continuous, wave-like entities in others. It is unclear whether all of their properties are well defined at all times, though we can ostensibly detect them and measure their values under certain conditions. As intimated earlier, there is controversy as to whether they can be regarded in any compelling way as individuals; if they can, it is certainly not in the way we commonly think about identity conditions and individuation in classical contexts, in terms of differential property ascription and allowing for their re-identification over time.[2] The natures

[2] Arguably, one may overstate this last point. Cf. Saunders 2006, p. 61: "there are many classical objects (shadows, droplets of water, patches of colour) that likewise may not be identifiable over time."

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of particles conceived today may become enmeshed over arbitrarily large spatial distances—as per quantum entanglement—in ways not previously conceived.

All of this suggests the strangeness of particles from a classical point of view, but this should not be inimical to realism all by itself—if one adopts a thinner conception of realism about particles framed in terms of reference. It is in the nature of theoretical development that sometimes the features of target systems of scientific interest that come to be viewed in a new light will appear strange from the point of view of what came before. This by itself suggests only a common and understandable propensity to regard the unfamiliar as strange. The challenge to realism here is no mere strangeness *en passant*, but the fact that in this case in particular, our attempts to interpret our theories in more substantial ways, so as to make their content intelligible to ourselves, have resulted in a great deal of unsettled debate and lasting conceptual puzzlement. Taking this as a basis for realism regarding a more substantial conception of particles, an antirealist might be forgiven for wondering whether an *argument* here against realism is in fact required, since it would appear that collectively, realists cannot themselves decide what they should believe.

Consider, for example, the question of the basic ontological category to which particles belong. There is a long history here of being flummoxed, even upon careful consideration of the relevant physics, regarding what this might be. The term particle is commonly associated with the notion of objecthood, but we have already noted that particles cannot be objects if "objecthood" is allowed to carry classical connotations. In quantum field theory, particles are often described as modes of excitation of a quantum field. This does not sound very object-like in any traditional sense, which leads many to claim that particles are not objects after all. Yet even physicists who observe that with the advent of quantum field theory the ontology of the quantum realm might be thought of in terms of fields rather than particles are happy to talk about particles at will. This suggests that they either regard particle-talk as merely elliptical for states of fields, or that they do in fact regard particles as non-classical objects of some sort, perhaps standing in some sort of dependence relation to fields. Generally, there is nothing like a precise specification of a basic ontology to be found, thus leaving the answer to the question of an appropriate assignment of category ambiguous. Here one might think that philosophers would lend a hand, but a sampling of the views of philosophers merely reveals the trading of ambiguity for transparent disagreements.[3]

[3] The sample to follow is by no means comprehensive, given the long history of differing interpretations, but representative of some of the most recent literature. Not everyone cited is a realist, necessarily, but all are attempting to clarify the relevant ontology.

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For example, Jantzen (2011) considers the permutation invariance of particles: representations of a physical state of particles of the same type that interchange the particles are taken to represent the same state. This is fatal, he thinks, to a particle ontology, where particles of a type are discrete objects that share state-independent properties and have state-dependent monadic properties, conceived as "approximately independent" (p. 42) of the properties of other things. Is it obvious, however, that objects need have precisely these features? Necessary conditions for objecthood are themselves up for grabs. Thus, while Bain (2011) acknowledges the prevalent view that relativistic quantum field theories are not amenable to particle interpretations if this requires that particles be localizable and countable (as expressed in terms of local and unique total number operators, which these theories do not support; see Fraser 2008), he argues that since the theorems on which this conclusion is based do not hold for *non*-relativistic quantum field theories, the characterization of localizability and countability at issue here must depend on classical features of these latter theories (specifically, regarding the structure of absolute spacetimes) that do not apply to the former theories. This suggests that the characterization of objects assumed here is inapplicable to non-relativistic quantum field theories, which then leaves open the possibility of a different conception of particles (or localizability and countability) in this different theoretical context.

No doubt the possibility of retooling our concept of objecthood in such a way as to admit particles will not appeal to everyone—perhaps it is too much of a promissory note on which to rest a substantial realism. In that case, perhaps a field interpretation of "particle" ontology is the way to go. Like many others, however, Baker (2009) and Bigaj (2018) hold that while particle interpretations of quantum field theory are problematic, the same is true of field interpretations. Perhaps we could simply stop worrying about what ontological category particles inhabit and instead satisfy ourselves with a clear understanding of the nature of their properties. Alas, further difficulties await, for the precise natures of these properties are themselves elusive. Consider the property of spin, which is one of a handful whose values are viewed as necessary and jointly sufficient for classifying particles into their respective kinds. What is spin? It is very difficult to say. Spin is usually described as a "sort of" internal or intrinsic angular momentum; the scare quotes are essential to the description, because there is no analogue of this property in everyday experience or otherwise familiar terms that allows for a more "visualizable," physical, dynamical (despite the term "spin" connoting some sort of rotation) understanding of it. Spin is causally exploited in many technologies including microscopy (more on which in section 15.3), and the Standard Model gives us a mathematical framework for discussing it (more on which in section 15.4), but it is difficult to say *what it is*.

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At the very least, in the absence of an intuitive grasp of the natures of properties of the sort just suggested, perhaps we could say something about them in terms that philosophers find perspicuous. Are these properties monadic, dyadic, or polyadic? Are they intrinsic or extrinsic or essentially relational? Mass is commonly cited as an exemplar of an intrinsic property, but Bauer (2011) thinks that it is extrinsic, since it is "grounded" in and thus ontologically dependent on the Higgs field. French and McKenzie (2012) contend that there are no fundamental intrinsic properties by means of an argument appealing to gauge theory,[4] which is integral to the Standard Model, but Livanios (2012) does not find this argument compelling. Lyre (2012, p. 170) maintains that properties such as mass, charge, and spin are "structurally derived intrinsic properties," which suggests something of a hybrid, intrinsic-extrinsic nature. And in some cases an examination of the natures of these properties brings us full circle, back to a consideration of the ontological category of things that best corresponds to particle-talk, as when Berghofer (2018) holds that the relevant properties are, in fact, intrinsic and non-relational, but features of fields, not particles, and when Muller (2015, p. 201) contends that we would be better off with a new conception of objects: particles, he argues, are "relationals"; "objects that can be discerned by means of relations only and not by properties."

The purpose of the preceding whirlwind tour has not been to suggest that progress cannot be made on questions surrounding the ontological natures of particles. No doubt some and perhaps many of the issues disputed in the preceding discussion may ultimately be resolved in ways that produce a measure of consensus. The point here is a different one. If, in order that realism be a tenable epistemic attitude to adopt in connection with the Standard Model, we were to require a degree of communally sanctioned, fine-grained clarity regarding description that could only follow from having resolved all such debates, this would suggest a prima facie challenge to the very possibility of realism here and now. As the brief glimpse into a number of contemporary debates just presented makes plain, any attempt to clarify the ontology of the Standard Model quickly and inevitably draws one into contentious metaphysical discussions. In the following two sections I will examine the two overarching approaches to prosecuting these debates that have formed the basis of selective realist pronouncements regarding the natures of particles and their properties, with the eventual goal of arguing for a rapprochement between them *qua* realism—one that clarifies how realism can be a tenable, shared epistemic commitment even in cases where realists disagree about details of description.

[4] Offering a different argument, McKenzie 2016 takes this position with respect to various properties including mass, but excluding spin and parity.

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15.3 The Nature of Particles I: Top Down

As it happens, the two approaches to thinking about how best to interpret the Standard Model I have in mind reflect a longstanding division of labor within the community of physicists. On the one hand there is theoretical physics, which views particles through the lens of formal, mathematical descriptions furnished by theory, and on the other hand there is experimental physics, which views particles through the lens of the sorts of detections and manipulations of them that are part and parcel of laboratory practice. These communities of scientists are not, of course, strictly isolated from one another; they must often work together. Nevertheless, their approaches to the subject matter are of necessity shaped by the kinds of work they do. Corresponding to this rough division, in the philosophy of science, there are what I will refer to as "top-down" approaches to interpretation, which place primary emphasis on mathematical descriptions of the properties and interactions of particles found in high theory as a source of insight into the natures of particles in the world; on the flipside there are what I will call "bottom-up" approaches to interpreting the natures of particles, which place primary emphasis on their behaviors in the trenches of concrete interventions characteristic of experimental investigation. As we will see, both approaches offer insight into the natures of particles, and both leave important questions open.

Let us begin with the top-down approach to thinking about particles. The Standard Model provides a remarkably elegant description of fundamental particles, their properties, and their (electromagnetic, weak, and strong) interactions, neatly systematizing them by means of symmetry principles. A symmetry is a transformation (or a group of transformations) of an entity or a theory in which certain features of these things are unchanged. That is, the relevant features are preserved or remain invariant under the transformation. The kinds of transformations relevant to physical descriptions include translations in space or time or spacetime, reflections, rotations, boosts of certain quantities such as velocity, and gauge transformations. When the states of systems are related by symmetries, they have the same values of certain quantities or properties—including those used to classify particles, such as mass, charge, and spin. To take an everyday example, if one rotates a square by 90 degrees, one gets back a square. "Squareness" is invariant under this transformation, which maps the square onto itself. With the notion of a symmetry in hand we may define a symmetry *group* as a mathematical structure comprising the set of all transformations that leave an entity unchanged together with the operation of composition of transformations on this set (satisfying the conditions: associativity; having an identity element; every element having an inverse).

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There are a variety of accounts of realism about particles that one might characterize as top down. What they have in common is the (explicit or implicit) operating principle that insight regarding the natures of particles should be intimately and exclusively connected to interpreting the mathematical formalism I have just described. This is all we need to understand the natures of particles, nothing more. There is nothing in my description of the top-down approach that suggests that it should provide *exclusive* insight into the natures of particles, but in practice, this is how realists who take this approach proceed. To take this extra step from adopting a top-down approach to thinking, furthermore, that this is our best or only legitimate source of insight into the natures of particles requires some further motivation or argument. Let me now briefly consider a couple of arguments of this sort, and for each suggest one of two things: either the top-down description of particles provided does not preclude supplementation with bottom-up description; or if it does, it is unclear why the top-down characterization should be judged superior *qua* realism. Obviously, this will not amount to a comprehensive survey of all possible arguments for an exclusive commitment to the top-down approach. Nonetheless, I take it to be suggestive of a plausible general moral, that the necessity or irresistible appeal of this commitment is unproven.

Motivating at least some realists who are exclusively committed to top-down characterizations of particles are desiderata such as descriptive or ontological intelligibility or simplicity. In section 15.4 we will see in some detail how the bottom-up approach is typified by an ontologically robust understanding of the causal or modal natures of the properties of particles, but for the time being it will suffice to note that some realists who focus their attention on symmetries hold that this focus alone is sufficient for understanding the natures of these properties, thus precluding any "inflation" of our ontological commitments in ways recommended by bottom-up realists about particles. If the Standard Model is simply interpreted as describing properties such as mass, charge, and spin as invariants of certain symmetry groups, we might rest content with this purely mathematical, theoretical apparatus for describing the natures of properties. On this view it is unnecessary to appeal to the causal roles of things in order to identify or understand them. Armed with symmetries, we might then understand the natures of the relevant properties without appealing to the notion of causal features or roles at all, thus articulating realism in terms of a simpler ontological picture.

Let us then consider whether the content of a realism about particles can be provided solely through an examination of symmetries and invariants. It is difficult to see how it could, given that questions about what realists justifiably believe cannot be separated from matters of how evidence furnishes justification. Detection and measurement are intimately connected to determining what

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things there are, in fact, in the world. Are properties thus conceived, as things one might identify as existing or being exemplified in the physical world—things about which one might be a scientific realist—identified independently of their causal roles? Perhaps there are cases in which this happens, but the present case does not seem like one. While there is no doubt that symmetry groups comprise a beautiful framework for codifying particles and their properties, all that examining them can achieve in isolation is to generate descriptions of *candidate* entities that may then be put to the test of experimental detection. It is one thing to describe the natures of some target of realist commitment in terms of the formal or mathematical aspects of a theory, but generally, in order for descriptions to have the sort of content required to support realism, they must be taken to *refer* to some thing or things in the world, and establishing successful reference requires more than the examination of a formalism. Some supplementation seems necessary.

A nice illustration of this is furnished by permutation symmetry, which arose earlier in section 15.2. Recall that in quantum theory, state representations of particles of the same type in which the particles are interchanged do not count as representing different states of affairs. An examination of the permutation group yields certain "irreducible representations" corresponding to all of the particles, the fermions and bosons, populating the Standard Model. However, in addition to these fermionic and bosonic representations, there are also so-called "paraparticle representations," and unlike fermions and bosons, paraparticles do not appear to exist—at least, not in the actual world subject to scientific realism.[5] Thus, merely examining the mathematical formalism of the theory is insufficient for the identification of entities to which realists should commit. To avoid being misled about the ontology of the world, there would seem to be no substitute for getting one's hands dirty with the causal roles of properties in the context of experimental work using detectors, and this suggests that there may be something to the thought that properties of particles have some sort of causal efficacy after all, in virtue of which they are amenable to detection, measurement, manipulation, and so on. But now we have entered the territory of the bottom-up approach to understanding the natures of particles, to which we will return in the following section.

Let us consider a second possible motivation for an exclusive reliance on the top-down approach for the purpose of illuminating particles. Perhaps the boldest motivation yet proposed stems from a version of selective realism that was designed specifically (in the first instance) to serve as an account befitting

[5] The closest we have come to generating empirical evidence in this sphere is the detection of paraparticle-like states, though not paraparticles themselves, under very special conditions. For a brief discussion, see Chakravartty 2019, p. 14.

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fundamental physics: ontic structural realism. There are many variants of the view, but generically, the common thread is what one might call a reversal of the ontological priority traditionally associated with objects and properties relative to their relations. In much traditional metaphysics, objects and/or properties are conceived as having forms of existence whereby their relations are in some way derivative (and not vice versa). Some variants of ontic structural realism simply boost the ontological "weight" of the relevant relations relative to their relata such that they are all on a par, ontologically speaking. Others take the relations to have greater ontological priority, and the most revisionary formulations do away with objects and properties altogether, eliminating them in favor of structural relations which are then viewed as ontologically subsistent in their own right, thus constituting the concrete furniture of the world.[6] If particles are conceived as being entirely dependent on relations described by symmetries—or stronger yet, as epiphenomena of these relations—it may well seem that a top-down approach to describing their natures should be sufficient.

As is true regarding any proposal for realism there are several aspects of this view that one might seek to clarify, but perhaps the most fundamental concern that has been raised is whether ontic structural realism can render intelligible the idea that things described in purely mathematical terms—such as symmetries and invariants, which are standardly regarded as (at best) abstract entities—can be understood to constitute the world of the concrete. Merely stipulating that some mathematical structures are subsistent appears to achieve no more than to substitute the term "concrete" with "subsistent." Something more is needed, and no doubt with this in mind, advocates of the position sometimes explicate the sense of concreteness or subsistence at issue by saying that the relevant structures are *causal* or *modal*.[7] Esfeld (2009, p. 180), for example, is explicit that on his variant of ontic structural realism, "fundamental physical structures are causal structures." French (2014, p. 231) is clear that on his, "we should take laws and symmetries—and hence the structure of which these are features—as inherently, or primitively, modal," and take this *de re* modality as serving the explanatory functions commonly associated with attributions of causality, such as helping us to explain what it means for something to be concrete.

If one goes this route, however, the first of our potential rationales for favoring a top-down approach to interpreting the natures of particles based on the promise of a comparatively simple or streamlined ontology is ruined, because it is difficult to see how a reification of symmetries and other mathematical structures endowed with causal or modal efficacy should count as less

[6] For a detailed and comprehensive exploration of the many variants, see Ladyman 2014/2007.

[7] Cf. Ben-Menahem 2018, p. 14: "causal relations and constraints go beyond purely mathematical constraints; they are (at least part of) what we add to mathematics to get physics."

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ontologically inflationary than an understanding of particles based on an ontologically robust conception of causal or modal properties, as suggested on the bottom-up approach, to which we will turn next. There is no obvious reason to think that Occam's razor should point us toward the former and away from the latter. As a guide to a description of the natures of particles that might satisfy the aspiration to walk the realist tightrope by adding something substantial to an otherwise spartan commitment to successful reference, the top-down approach furnishes a great deal, but not in so compelling a manner as to make it an irresistible choice of interpretation, or an exclusive choice, for realists. One reason for this, as I will now suggest, is that the natures of particles look significantly different from the bottom up.

15.4 The Nature of Particles II: Bottom Up

From the point of view of detection, which is intimately linked to many of the strongest cases that can be made for realism in specific instances, more abstract descriptions of the properties of things are somewhat removed from the work of physics. Where the focus of experimental work is the physical discernment of interactions between particles and between particles and detectors, often requiring extraordinarily precise adjustments and manipulations of both the experimental apparatus and the target entities under investigation, more precise descriptions of concrete natures are necessary. It is here that the determinate properties of particles, whose values are detected and manipulated in such work, take center stage. This is not to say that group theoretic structures are irrelevant to describing these properties, but simply that the descriptions afforded by symmetries and invariants are at a remove from the specificities of experimental work. As Morganti (2013, p. 101) puts it, "[w]hen one focuses on invariants . . . one moves at a high level of abstractness." In contexts of experimentation and detection, it is necessary to move in the direction of more determinate description; the specific values of mass, charge, etc. (pertaining to different particles) at issue in these contexts are not given by descriptions of symmetries (cf. Wolff 2012, p. 617).

In the realm of experiment it is what we can *do* that is our best guide to what there is and what these things are like—that is, to the ontology of our targets of investigation. What we can do in the arena of particle physics is entirely dependent on the precise values of the properties of particles. Since all of this doing involves designing and engineering instruments to interact with those parts of the world we aim to explore, and generating certain kinds of effects, it is natural to describe it in terms of causal interactions, relations, and processes. Thus it is no surprise that selective realists who take a bottom-up approach to

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understanding the natures of particles typically emphasize the roles of determinate property values in causal interactions, relations, and processes. Perhaps the most obvious (but not the only) example of a position taking this approach is entity realism, wherein certain descriptions of the causal roles of entities are interpreted as the basis of experimental work that ostensibly generates an argument for this form of realism. Some who take these descriptions seriously as filling in our understandings of the natures of particles go further, giving more detailed characterizations of the natures of their properties as being inherently causal or modal, invoking conceptions of properties such as dispositions, propensities, and capacities—types of properties whose natures comprise abilities to do certain things.

Having seen just a moment ago how the top-down approach lends itself to increasingly detailed descriptions of the natures of particles, it may now be clear (on the basis of the preceding paragraph) that the same is true here. It is all too easy to drift from an initial question regarding the nature of some target of one's realism to further, deeper questions, and in attempting to answer these deeper questions, giving ever more detailed descriptions—all the while with little concern for the realist tightrope. Just as one might, from the top down, begin by thinking that the descriptive content of one's realism should be informed by a specification of the relevant symmetry groups, but then end up some way down the road, after twists and turns of elaboration, advocating for reified mathematical structures imbued with primitive causality or modality, one may perform analogous feats from the bottom up. One might begin by thinking that the causal roles of certain properties associated with particles are central to the descriptive content of one's realism, and then through earnest inquiry find oneself somewhere down the road defending one or another specific conception of causation, in just the way that some come to understand the natures of these properties as inherently modal or dispositional. Mirroring the moral of section 15.3, let me now suggest that bottom-up characterizations do not preclude supplementation with top-down description. And in some cases, it is unclear why either should be judged superior *qua* realism.

With a long history of empiricist concerns about the intelligibility of dispositional properties in the background, fueled by concerns about the metaphysical excesses of scholastic and neo-Aristotelian philosophy more generally, the notion that properties of particles should be understood dispositionally is unsurprisingly controversial. A dispositional *essentialist*, for example, takes the natures of the relevant properties to be exhausted by dispositions for certain kinds of behavior: the identities of these properties—their essences—are dispositional. Could we not simply deflate this scholastic-sounding reference to essences? Consider Livanios's (2010, p. 301) query: "if the identity of the fundamental physical properties . . . can be provided via symmetry considerations, why can't we claim that

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being invariant under the action of fundamental symmetries is an *essential* feature of the fundamental physical properties?" From the bottom up there is an immediate reply: what is the "action" of the symmetries? Presumably the intention here is not to claim that a mathematical *description*—a linguistic entity—is part of the essence of something in the world. This would be to conflate descriptions with that which they describe. Thus, the point must be that the symmetries are themselves things in the world. They are part of the ontology of the world and thus conceived, they are part of the essences of fundamental properties. But now the view is sounding a lot like dispositional essentialism, and certainly no less weighty as metaphysics!

Two points can be extrapolated from this brief illustration of how opposing metaphysical sensibilities sometimes play out in realist interpretations of scientific theories and models. In replying to the attempt to deflate the substantial metaphysical claim inherent in their proposal for how to understand the properties of particles, dispositional essentialists need not reject the top-down approach *simpliciter*, or broadly conceived, for as we have already acknowledged, there is nothing in group theoretic descriptions of symmetries and invariants that is incompatible with their view—on the contrary. Rather, it is simply the case that their entirely reasonable, bottom-up preoccupations regarding realism have not been well appreciated by their critics, which we noted earlier in terms of the relatively general or abstract knowledge afforded by symmetry groups and, in contrast, the utter centrality of the determinate values of properties in setting up, generating, detecting, and recording the effects of causal interactions and processes. A second point worth noting, though I will not detail it here in connection with this particular example, is how elaborate metaphysical proposals may become on *any* approach to explicating realism. Under the guise of empiricist or neo-Humean rejections of metaphysical excess, some pots call kettles black. Both pots and kettles, however, threaten to topple the realist off of her tightrope.

What, then, of the determinate property values of particles and their associated causal profiles? Perhaps the most serious concern about emphasizing these aspects of particles for the purpose of describing their natures is the worry that no such account can adequately explain certain constraints we find exhibited in their behaviors. For example, in any closed system, the values of properties such as mass-energy, momentum, charge, and spin are conserved—their totals remain constant. Emmy Noether proved in 1915 that for every continuous global symmetry of the Lagrangian there is a conserved quantity (and vice versa). But how might the causal efficacy of a particle, understood by means of an account of the causal profiles associated with its properties, explain the conservation of properties in an *ensemble* of particles (cf. Bird 2007, p. 213)? It is difficult to see how the properties of a particle can be parlayed into a constraint on a *collection* of particles, given that the relevant constraint must pertain to the collection, not to

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any given particle. Similarly, consider principles of so-called least action: for any given system and a specification of some initial and final conditions, the evolution of the state of the system will minimize a quantity referred to as "action." It is difficult to see how the causal profiles associated with a particle and its properties could somehow generate the minimization of action in systems more generally.

In order to explain constraints on behavior such as those expressed in principles of conservation and least action in terms of the causal natures or profiles of properties, it would seem we must think of these properties as belonging to the systems to which these principles apply, and this is inevitably controversial. Taking the dispositional variant of the bottom-up approach as an illustration once again, Harré (1986, p. 295) maintains that some dispositions may be grounded in "properties of the universe itself"—a phenomenon he labels "ultragrounding"—attributing the idea to Mach's discussion of inertia in the context of Newtonian thought experiments. Imagine two globes connected by a spring balance and rotating, alone in the universe. Newtonians held that there would be a force tending to separate the globes, registered in the spring balance, but on a Machian reading there is no reason to believe that the globes would have inertia in an otherwise empty universe; it is better to think of the disposition to resist acceleration as grounded in the universe itself. Bigelow, Ellis, and Lierse (1992, pp. 384–385; cf. Ellis 2005) go so far as to contend that the actual world is a member of a natural kind whose essence includes various symmetry principles, conservation laws, and so on. It is a short step from this to thinking that the system-level behaviors associated with these principles are properties of the world—a very large system indeed.

The standard objection to this family of speculations is that it is ad hoc.[8] Granted, explaining constraints on the behaviors of systems of particles in terms of properties of the entire world may seem, prima facie, rather convenient, especially in the absence of any independent motivation for the *explanans*. If one takes a bottom-up approach to understanding the natures of target systems of scientific interest, however, it is simply a mistake to suggest that there is no independent motivation. Just as particles are investigated empirically in carefully designed and executed experiments, systems of particles are likewise investigated. It is an empirical fact, not a convenient fact, that certain kinds of systems exhibit behaviors that conform to various principles of conservation and least action. Having adopted a methodology of associating causal profiles with certain types of particles and their characteristic properties, it is hardly an unmotivated extension of this methodology to do likewise in connection with certain types of systems, such as closed systems.

[8] For recent discussion on both sides of this fence, see Smart & Thébault 2015 and Livanios 2018.

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Now, as it happens, the world itself is a system of this type. From the perspective of the bottom up, the attribution of a causal profile to it on the basis of a consideration of empirical investigations into members of the type cannot be said to be based on merely wishful speculation. And neither should it seem peculiar in the era of quantum theory, in which systems are routinely viewed as having properties, such as entanglement, that cannot be reduced to the properties of their parts. What may appear superficially as ad hoc speculation inevitably sounds more credible when the metaphysical terminology in terms of which it is sometimes expressed ("natural kinds," "essential properties") is given a plausible interpretation in the language of scientific description. Consider, for example, the possibility entertained earlier that particles are in fact best understood as field quanta. In that case the properties of systems suggested above would be properties of fields, and fields are global in the sense that they permeate the whole of the world. Anyone moved by *this* description would then be in a position to ask yet further questions about the natures of particles and their properties, depending on whether one is a substantivalist about fields, or interprets the values of field quantities as properties of spacetime points, or . . . . But let us stop here.

Having refined and extended a bottom-up description of particles in such a way as to answer a preeminent concern, let us once again inquire into how this approach fares in comparison to its counterpart, top down. Here, once again, it is very difficult to make a case one way or the other on the basis of some imagined criteria of descriptive or ontological intelligibility or simplicity. On a permissive enough conception of causation one may see it as an appropriate descriptor of many different things. Ben-Menahem (2018), for instance, applies the label "causal" to any general constraint on change, where constraints determine what may happen, or is likely to happen, or what cannot happen. On such a conception, symmetries, conservations laws, and variational principles (such as the principle of least action) all qualify as causal. But are they causal in the sense advocated by someone looking top down, as a primitive feature of certain mathematical structures, or are they causal in the sense of, say, a dispositionalist looking bottom up, where the (potential for) behaviors associated with the properties of various kinds of entities and systems determine their identities? And does anything hang on this choice, from the point of view of defending realism? In closing, let me attempt to shed some light on the latter question.

15.5 The Content of Realism Redux: Anchoring Interpretation

I began this essay by citing a celebrated challenge to scientific realism. Given that no one thinks that most scientific theories and models (including many

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of our very best ones) are entirely correct, not merely in connection with the idealizations and approximations we know of, but also in other ways we have yet to discover, everyone appreciates that they will evolve over time as scientific inquiry proceeds. Hence the various strategies found among realists, especially selective realists, for identifying those aspects of theories and models that have sufficient warrant to command realist commitment, both as a guide to interpretation in the present and to reasonable expectations about what will survive into the future. From this I distilled a more specific challenge to anyone hoping to be successfully selective, which I called the realist tightrope: believing too little or too much of a theory that is not entirely correct may well appear to spell trouble. Believing too little—in the limit, the bare reference of central terms, or claims regarding the existence of their referents—may seem tenuous, but the more comprehensive or detailed the descriptions of such things one endorses, the more one runs the risk of falling foul of future developments in the relevant science, and/or metaphysical objections to the increasingly fine-grained natures proposed. Where does the proper balance lie?

In the case of the Standard Model, walking the tightrope seems especially fraught. Understanding the natures of the particles described by the theory has always been difficult, and serious proposals for illuminating these natures have inevitably required increasingly speculative and technical theorizing. Given this state of affairs, it is hardly surprising that there is so much disagreement among realists about how best to describe what particles are, exactly. On the surface this may appear a victory for antirealism, for if there is nothing determinate here to be found under the heading of "realism" to which all realists subscribe, but instead a thousand splintered commitments to conflicting and (what will appear to some as) increasingly esoteric interpretations, the camp of realism may look more like a ball of confusion than anything endorsing a shared epistemic commitment. This dismal portrait of the cognitive landscape of realism in connection with the Standard Model is, however, though perhaps understandable on the basis of what we have seen, entirely misleading. I submit that there is in fact something substantial to which all or most realists subscribe in the context of the Standard Model, even as they debate how this commitment is best elaborated. Here in conclusion I will attempt to explain how this can be so.

In order to understand how different and conflicting descriptive commitments among realists regarding particles are compatible with a shared commitment *qua* realism, we could do worse than to begin by looking at how scientists approach this area of physics. Here, just as Jones (1991, p. 191) notes in connection with the analogous case of multiple candidate interpretations of quantum mechanics, one may reasonably worry about "the failure of any interpretation to provide an 'explanatorily satisfactory' link between the mathematical formalism and the world of laboratory experience." He continues:

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> The general approach of one interpretation may suit a physicist more than the general approach of others, and he or she may spend some time adapting it to issues that he or she thinks particularly important and developing arguments as to why its lacunae are not devastating for its coherence. But every physicist will admit that such allegiance is to some degree a matter of taste. No physicist is unaware of competing interpretations, and none expects decisive evidence or arguments for one against the others.

Analogously, in the case of the Standard Model, the challenges of connecting the domain of abstract theorizing, conceived in terms of interpreting a mathematical formalism, and that of concrete experimentation, conceived in terms of interpreting laboratory experience, have a basis in the work of physics, all of which is mirrored in philosophers' attempts to elaborate the natures of the phenomena revealed by these practices. And as I will now contend, just as physicists across these domains can be realists despite differences in how they characterize their shared subject matter, philosophers of science can too.

To begin, note that terms like "physics" and even "fundamental physics" are rather broad designators. This is true not only in the sense that there are a variety of subareas of physics to which these terms are applied, but also in the sense that even within subareas, different approaches to one and the same subject matter can and often do take the form of highly disparate forms of scientific practice. Galison's (1997) detailed study of what he describes as the partly autonomous subcultures of physics in the twentieth century—experimenting; theorizing; and instrument making—furnishes a helpful and meticulous illustration. These subcultures, he contends, are "intercalated" in that they constrain, guide, and inspire one another, but they also develop and function significantly independently of one another and are thus identifiable as separate subareas of research and practice, with separate conferences, journals, and so on.

Most importantly for present purposes, the significant autonomy associated with these different subareas generates significantly different understandings of the subject matter. This is the source of Galison's provocative adaptation of the anthropological notion of a "trading zone": "an intermediate domain in which procedures could be coordinated locally even where broader meanings clashed" (p. 46). Subcultures of physics do not associate precisely the same meanings with the technical terms used in communication with one another: "Theorists and experimenters, for example, can hammer out an agreement that a particular track configuration found on a nuclear emulsion should be identified with an electron and yet hold irreconcilable views about the properties of the electron, or about philosophical interpretations of quantum field theory" (p. 46); when working together, they set aside "the 'deep' and global ontological problems of what an electron 'really' is" (p. 48). The upshot of a careful consideration of different approaches to the physics of particles is thus clearly and immediately consequential for philosophers interested in questions of scientific knowledge: "the significance of these partially separate lives is that—once one abandons 'observation' or 'theory' as the basis for a univocal account—no single narrative line can capture the physics of the twentieth century, even within a single specialty" (p. 9).[9]

What's good for the goose of particle physics, however, is good for the gander of philosophy of particle physics. Indeed, the various projects of interpretation of the natures of particles and their properties displayed in previous sections have demonstrated just this. Reflecting the different conceptions of particles adopted by physicists who approach them from the different vantages of mathematical theorizing and experimental detection, philosophers often view the natures and properties of particles in different ways, typically depending on the scientific practices on which they are most focused or with which they are most concerned. None of this all by itself is an argument for or against realism, but it does shed crucial light on the question of what it means to be a realist in this domain, if one is that way inclined. Just as scientists in different subareas of physics may believe in electrons—sharing an ontological commitment, but *under different descriptions* (more precisely: partially different and overlapping descriptions)—so too may philosophers of science. Realism, in the limit, is a commitment to the existence of something, to the idea that through theoretical descriptions and/or experimental detections, ideally both, we have picked out what Einstein, Podolsky, and Rosen (1935) described so evocatively as an "element of reality." Triangulating, using our best tools of mathematical and causal investigation, we have managed to pick something out in the world.

Thus we see how the challenge posed by the realist tightrope, with which we began, is misleading. Realism about *x* does not face mortal danger on either side by believing too much (believing increasingly refined descriptions of *x*) and believing too little (simply believing in the existence of *x*). A supplemental metaphor is needed. From a realist perspective, successful reference is, in fact, all that is required to *anchor* realism, and it is a shared judgment that such anchoring has been achieved that unifies different sorts of realists about any given *x*. This is compatible, of course, with further description rendering realist commitment more substantial, with all the risk and reward this entails. To the extent that further descriptions of the precise natures of things like particles are believed, the anchor of reference is compatible with there being different species of realist commitment (e.g., selective realisms), unified *qua* realism more broadly (as a

[9] Galison 1997, pp. 833–835, tells the story of how Sidney Drell and James Bjorken aspired to write a book on quantum field theory in the early 1960s, but ended up producing two separate volumes, one geared to experimentalists (concerned more with measurable quantities) and the other to theorists (concerned more with formal properties of theories, such as symmetries and invariances). Some of the differences between the volumes amounted to a "radical difference in the ontology" (p. 835).

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genus) by a commitment to shared reference. It is also compatible with combining a high degree of confidence in our having picked something out in the world with lesser degrees of confidence in some or all of the descriptions of the nature of this thing elaborated in finer-grained ways by different versions of realism and in the metaphysics of science. As intimated earlier, talk of "particles" is loose—objects of some kind?; events?; some sort of hybrid?—and likewise, groups of cohering causal properties?; emergent or derivative features of an ontologically subsistent structure? Reference is the anchor.

Admittedly, the notion of anchoring is not by itself so comprehensive as to yield determinate answers to further questions that realists are often pressed to confront. Is a causal theory of reference best for anchoring? If so, the commitments shared by different sorts of realists may sometimes prove maximally thin, though depending on the strength of the evidence they may prove epistemically significant nonetheless. In many cases, as in the present case, a causal-descriptive or minimal descriptive theory (appealing to a shared subset of descriptions) may be appropriate, since physicists and philosophers alike generally agree on a number of features of particles, their properties, and interactions, with differences of interpretation emerging only in their finer-grained proposals for how best to understand the natures of these things. Should different species of realists, imbued in different ways by top-down and bottom-up approaches to particles, hold lower degrees of belief in their finer-grained interpretations than in the coarser descriptions they jointly affirm with others? If degrees of belief in finer-grained proposals are sufficiently low, this may suggest the wisdom of a pragmatic pluralism of accounts; if they are sufficiently high, this may suggest an agreement to disagree between different camps. Clearly, there is plenty of work here left to do in grappling with these issues.

All of this said, it is nevertheless the case that while the intuitive pull of the realist tightrope can be strong, it is properly resisted. Feeling the pull, Stanford (2015) contends that claims about what exists or about which terms successfully refer are not at issue in debates about realism; instead, antirealist arguments should be construed as targeting only scientific descriptions of the "fundamental constitution and operation of various parts of the natural world." One may naturally wonder here about the relevant sense of "fundamental." Is the intention to target some special part of the spectrum of increasingly refined descriptions of some focus of scientific investigation offered by some realists? This would be puzzling: there is no obvious point at which these descriptions become "fundamental" and, in any case, different species of realism disagree about much description while still belonging to the genus. Perhaps instead, "fundamental" is being used in the way familiar to us from accounts of ontological or explanatory reduction, in which some entities or phenomena are arguably "reducible" to other, more fundamental ones. But this is likewise unpromising, even granting

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the premise of reductionism, in the absence of some convincing argument to the effect that less fundamental things should not be considered real. If it turns out that superstring theory is true, then it will turn out that particles are modes of vibration of strings, but it is at best unclear how this would make them any less real.

While many realists disagree about the natures of particles and go to great lengths to explain, in conflicting ways, how such talk should be interpreted, they are no less realist *about particles*. This suggests that realism *simpliciter* is something to which one may subscribe along a spectrum of descriptions, from the minimal, as in the case of assertions of reference, to the most refined views of metaphysical natures.[10] Indeed, Stanford (2015, pp. 410–411) acknowledges that in some cases the sheer weight of theoretical and experimental evidence for the existence of something (e.g., atoms) is so great that it is implausible to imagine that future scientists will change their minds. Given that they may change their minds about certain fundamental descriptions, however, and that it is dubious that we are capable of predicting what subset of our current descriptions will be retained in future, realism thus conceived would be "so weak that . . . no historicist opponent will think it worthwhile to contend against it" (p. 416). It is all too easy, though, to place this shoe on the other foot. If the evidence is sufficiently strong as to indicate that we have successfully picked something out in the world, this is music to realist ears—and a justified expectation that this will be preserved across theory change suggests that some significant portion of the theoretical and experimental knowledge justifying this expectation will be preserved as well, furnishing a basis for even more substantial conceptions of realism.

Let us take some final inspiration from those engaged in theorizing and experimenting. Late in his life the great theoretician Werner Heisenberg (1998/1976) betrayed a striking ambivalence between top-down and bottom-up approaches to characterizing the nature of matter: "The question, What is an elementary particle? must find its answer primarily in experiment"; "theory . . . cannot add much to this answer" (p. 211)—but later he could not resist adding, "The particles of modern physics are representations of symmetry groups and to that extent they resemble the symmetrical bodies of Plato's philosophy" (p. 219). To return to earth once more from Plato's heaven, nothing smooths the way better than speaking to an experimentalist. Randal Ruchti is part of the High Energy Physics Group at the University of Notre Dame which participates in experiments at the Large Hadron Collider at CERN, for which they developed a hand-held detector that can be placed in high energy particle beams to yield visual representations of particle interactions. The discourse of

[10] Cf. Magnus 2012, p. 122: "Retail arguments [i.e., arguments stemming from evidence specific to the case at hand] for believing in particular things can give us good reasons to believe that those things exist on the basis of their connections to other things, while leaving questions of things' fundamental nature either unmentioned or unresolved."

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experimental particle physics is so rife with collisions, scattering, and detections of "packets" of energy and momentum that realism about particles is a natural default, but Ruchti is quick to add: "don't ask me what they are!"

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