A Trope-Bundle Ontology for Field Theory

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Field theories have been central to physics over the last 150 years, and there are several theories in contemporary physics in which physical fields play key causal and explanatory roles. This paper proposes a novel field trope-bundle (FTB) ontology on which fields are composed of bundles of particularized property instances, called tropes (Section 2), and goes on to describe some virtues of this ontology (Section 3). It begins with a critical examination of the dominant view about the ontology of fields, that fields are properties of a substantial substratum (Section 1).

1 Fields as properties of a substantial substratum

The dominant view about the ontology of field theory over the last two centuries has been that fields are properties of substantial substratum. In the 19th century this substance was taken to be a material ether. In the 20th century, the immaterial spacetime manifold took on the role of substantial substratum.

For most of the 19th century, the causal and explanatory functions of field theories were assumed by a material, mechanical ether. Field theories of optics, electricity, magnetism and later electromagnetism were developed in which the field corresponded to a collection of properties of a material ether. Scientists articulated the hope that a unified theory could be extended to gravitational and other phenomena, where a single material ether would be the seat of all physical action. George Green and Lord Kelvin, for example, developed optical theories in which light was the vibration of a mechanical, elastic, solid ether (Green 1838, Kelvin 1904). This ether was made up of tiny ether particles. Lagrangian mechanics, augmented with a few auxiliary hypotheses, were used to obtain many sophisticated optical results: derivation of Fresnel's laws of reflection and refraction of light, phase shifts on reflection and elliptical polarization. From the start, however, these theories were extremely complex and ultimately only able to account for a narrow range of optical phenomena. As they were extended to new domains, ad hoc hypotheses were needed to make them work. For example, the value of the ether's resistance to distortion (shearing) needed to be set at one value to account for double refraction and another to account for Fresnel's laws.

Yet none of these difficulties was seen to impugn the mechanical ether hypothesis itself. The approach was extended to Maxwell's unified dynamical theory of light, electric and magnetic phenomena. Thus in the 1890s Joseph Larmor developed a sophisticated theory in which the ether is a kind of primitive continuous matter or proto-matter to which Maxwell's equations apply (Larmor 1900). The electromagnetic field consists of undulations of this ether and electrons are singularities in the ether. The dynamics of ordinary matter are caused by the proto-material ether. Larmor and others around the turn of the century understood the materiality of the ether to amount to the fact that it has mechanical properties and can engage in mechanical interactions. Larmor's account ran into difficulties, and some of these difficulties were taken to be endemic to any material ether theory. No one was able to develop an empirically adequate theory of electrodynamic phenomena based on the principle of least action and the interaction between matter and a proto-material ether.

The most important response to this problem was H.A. Lorentz's theory in which the electromagnetic field consists of a collection of properties of an immaterial ether. Lorentz's ether functioned as a unique, immutable reference frame for electrodynamics. Lorentz explicitly rejected mechanical ether theories and adopted as his fundamental assumption "that ponderable matter is *absolutely* permeable [to the ether], i.e., that the atom and the ether exist in the same place" (Lorentz 1895, Sect. 1). Matter has no effect on the ether, but the ether can causally affect matter, and the ether remains the seat of the electromagnetic field. In addition, the null result of the Michelson-Morley experiment was accounted for by the Lorentz-Fitzgerald contraction, itself taken to be directly caused by motion of matter with respect to the ether. Of course, no experiment was able to distinguish the rest frame of the ether. Worse, Einstein's highly successful 1905 special theory of relativity was taken to be inconsistent with the postulation of any privileged frame of reference. Fully aware of this, Lorentz still could not give up the ether. In his 1909 book *The Theory of Electrons* Lorentz offers a detailed account of the virtues of Einstein's approach, in the middle of which he remarks:

> Yet, I think, something may also be claimed in favour of the form in which I have presented the theory. I cannot but regard the ether, which can be the seat of the electromagnetic field with its energy and its vibrations, as endowed with a certain degree of substantiality, however different it may be from ordinary matter (Lorentz 1909, quoted in Schaffner 1972, p. 115).

Lorentz's intuition here seems to be that the only way the electromagnetic field can play the causal and explanatory roles it does is if the field is a substantial entity. This substantiality appeared to Lorentz to be secured by an immaterial ether.

19th-century field theories were formulated within the context of 19th-century metaphysics, and of course the dominant metaphysical posits of that century were the connected notions of substance and attribute. The notion of substance traditionally involves three elements. First and most intuitive is the idea that a substance is something that can have independent existence, whereas an attribute cannot but is rather a dependent entity. Second, substance plays the role of bearer of attributes: a substance has attributes inhering in it but need not itself inhere in anything. Third, substance functions to individuate one property from other, possibly exactly alike properties.

Field theories with a material ether ontology are the quintessential scientific articulation of a substance-attribute metaphysics. Here, a material ether is a substance and classical fields consist of properties (attributes) inhering in that substance; the ether is a sort of peg upon which field properties are hung. The notion of a material substratum is relatively straightforward, and within particular ether theories this substance is posited to have essential properties of compressibility, resistance to shearing, and so on, independent of any additional, contingent attributes (such as field properties) it may have. The three traditional elements of the substance concept are well exemplified here. Clearly, a material ether can exist without any field, but the field cannot exist without the ether, giving the ether independent physical existence. As well, the ether bears properties, specifically the field properties. Finally, the ether functions to individuate field properties. Two exactly-alike field values are individuated and indexed by the ether, the substantial substratum in which they inhere. If there ever were a case for a traditional substance-attribute metaphysics, classical field theory would seem to be it.

It is more difficult to see how an immaterial ether, such as Lorentz's, can play the role of substantial substratum. For one thing, it is something of a mystery how an immaterial ether, absolutely permeable to material objects, can function as the bearer of a field, such as the electromagnetic field, that has a certain degree of materiality (it has energy and it causally interacts with ordinary matter). For another, the independent existence of the ether is mysterious, since it is simply posited to play the role of supporting the field, a seemingly ad hoc postulation. Third, there is the vexed question of whether the immaterial ether has essential properties in addition to the field or other accidental attributes it may bear. Lorentz's proposal seems to be that the immaterial ether has no essential properties, but rather is simply the "seat" of the field. An ether denuded of properties shares all the metaphysical troubles that face any bare particular. For example, points in the ether have an individuality, a haecceity, which enables them to be indexed and makes it possible for there to be more than one of them. But among the properties that bare particulars lack are any that would allow one to be distinguished from another. The implication is that there can at most be one point in the ether, or if there is more than one they can't be indexed. It appears that such an ether could play no useful role in the ontology of physical field theory. For these reasons we may be inclined to augment Lorentz's immaterial ether with certain geometrical properties, such as topological, differential and metrical properties, so that it can fulfill the role of indexer and individuator of field properties. This appears to be a promising strategy and it is, moreover, precisely the direction taken by the ontology of 20th century field theories.

That fields are properties of a substantial substratum remains the received view to the present day. Now it is no longer an ether that is providing the substance, but rather the spacetime manifold. In contemporary physics, the spacetime manifold has replaced the ether as the substratum in which field properties inhere.

The ontology can be stated quite briefly: a field is an assignment of a collection of properties or field values (described by numbers, vectors or tensors) to points in spacetime. Field properties are causal properties and spacetime points function as independent causal agents in field theories, on a par with the causal agency of other physical objects. Space-time points are necessary for field theory, since without them there is nothing to which field properties can be assigned and hence there can be no physical fields. As well, spacetime points are sufficient since no additional substance, matter or mechanism is needed. As Hartry Field puts it, "acceptance of a field theory is not acceptance of any extra ontology beyond spacetime and ordinary matter" (Field 1989, 183; cf. Field 1980, 35). John Earman describes the role of spacetime substance similarly:

> When relativity theory banished the ether, the spacetime manifold *M* began to function as a kind of dematerialized ether needed to support the fields…. [I]n

> postrelativity theory it seems that the electromagnetic field, and indeed all physical fields, must be construed as states of *M*. In a modern, pure field-theoretic physics, *M* functions as the basic substance, that is, the basic object of predication (Earman 1989, 155).

On this approach, examples of classical fields that are properties of the spacetime substance include the metric field and stress-energy field of the general theory of relativity, and the electromagnetic field. Earman distinguishes first-order and second-order properties of spacetime points. First-order properties are the points' topological and differential properties, and field values constitute second-order properties.

We ought to question, however, whether the spacetime manifold, an immaterial ether with geometrical properties, can fulfil its role as the substantial substratum for classical field theories. For one thing, a worry raised earlier about the Lorentzian ether remains unresolved. Fields in contemporary physics are material objects; they contain mass-energy and interact causally with other material objects. At the very least, more needs to be said about how an immaterial spacetime, absolutely permeable to material objects, can function as the bearer of a material field. For another, the assumption that the spacetime manifold is a substance is controversial and faces a significant challenge from the hole argument of Earman and John Norton (Earman 1987, Norton 2004). *Cateris paribus*, it would seem preferable that a field ontology not be committed to spacetime substantivalism.

Perhaps an adequate ontology for classical fields could do without spacetime substance. David Malament has pointed out that the above characterization of fields as assignments of properties to points of spacetime can equally well (that is, poorly) be used to describe middle-sized material objects, such as his sofa.

> The important thing is that electromagnetic fields are "physical objects" in the straightforward sense that they are repositories of mass-energy. Instead of saying that spacetime points enter into causal interactions and explaining this in terms of the "electromagnetic properties" of those points, I would simply say that it is the electromagnetic field itself that enters into causal interactions (Malament 1982, 532).

On this approach, field theories introduce a new kind of entity, fields, into our ontology. Fields have mass-energy, just like the kinds of physical entities with which we are more familiar, and they have additional properties unique to each field. Along similar lines, Paul Teller has proposed an inversion of the role of substance and attribute, this time in the context of a thorough-going relationalism about spacetime. Rather than attributing a field property to a spacetime point, he suggests attributing a relative spatio-temporal location to a bit of the substance making up the field (Teller 1991, 382). Spatio-temporal relations are then carried by the field stuff directly.

It has been argued that, as it stands, the Teller position falls short of characterizing a genuine alternative. Hartry Field claims that if fields have all the geometric structure and causal powers that he attributes to spacetime, then there is no point in positing a separate, causally inert spacetime. Further, if we dispense with spacetime, as Teller does explicitly, the above response is trivialized: what Field calls "spacetime" Teller is simply calling "field," and the two approaches are equivalent (Field 1989, 183). The same point has been made by Robert Rynasiewicz. Fields can be seen as properties of spacetime points, where the latter are construed as independently-existing individuals with specific additional (geometric) properties. Or fields can be viewed as collections of independently-existing individuals that have both causal (field) properties and the same geometric properties as did the spacetime points. These two pictures are ontologically equivalent; the difference between them is purely terminological, amounting to a disagreement over what should be called what (Rynasiewicz 1996, 302-3; according to Rynasiewicz, Malament has acknowledged that his comments are intended to be read in this way). If this line of reasoning is correct, a consensus about the ontology of field theories in physics emerges, roughly that fields are properties of some substantial substratum, variously called the spacetime ether, spacetime manifold, or field stuff.

I suggest that this line of reasoning is not correct, and that Teller has articulated a genuine alternative—or at least that his approach is compatible with a very different ontological picture. The idea that the two approaches are equivalent may be plausible only if both approaches are formulated within the context of a substance-attribute ontology (although perhaps not even then: Belot [2000, 584] argues that this equivalence is implausible under certain relationalist assumptions). Taking a closer look at the roles that the substantial substratum plays in these approaches reveals an important difference between them. A substance-attribute ontology is indeed natural for the former view, on which fields are properties of a dematerialized ether. Here, the spacetime ether is clearly a substance, functioning to individuate and index the field attributes. This role for space is a traditional one. For instance, given two objects that are exactly alike, one knows they are two objects, and not one, because they are located at different points in space. I suggest that on the latter view, where fields are independently-existing entities, the most natural ontology is one in which fields are composed of bundles of properties and relations. The "substance" making up the fields is nothing other than properties and relations. The Teller proposal is best understood within a pure property-bundle ontology, and it provides a genuine alternative to an ontology based on the spacetime manifold playing the role of immaterial substratum.

However, an ontology in which objects are composed of bundles of properties faces at least one well-known difficulty. This difficulty stems from the fact that properties are universals, where exactly alike properties of multiple objects are actually multiple instantiations of a single universal. The whiteness of this piece of paper and the exactly alike whiteness of that pen are strictly identical, since both objects instantiate the same universal, namely that shade of whiteness. So a property-bundle theory is committed to the necessary truth of the principle of the identity of indiscernibles. If an object is nothing more than a bundle of universals, then it is logically impossible for there to be two bundles with exactly the same properties. For two bundles composed of the same (universal) properties have all the same components, hence they would simply be the same bundle. However, it seems a contingent truth, if it is true at all, that distinct particulars must differ in their properties or relations (so the principle of the identity of indiscernibles is, if true, only contingently true). These difficulties are particularly acute in the case of field theory, where numerically distinct yet exactly alike point field values seem entirely plausible, as Earman has emphasized (1989, 197; cf. Parsons and McGivern 2001).

2 Fields as trope bundles

Tropes are property instances, and they can be used to construct an ontology that is both nominalist, thus dispensing with universals, and bundle-theoretic, thus dispensing with the substantial substratum. It would seem that tropes are promising building-blocks for an ontology for field theories that can underwrite their causal and explanatory roles in contemporary physical theory. The remainder of this paper attempts to make good on this promise.

Recall that exactly alike properties of multiple objects are multiple instantiations of a single universal. By contrast, exactly alike tropes of multiple objects are independent particulars. On this approach, the whiteness of this piece of paper and the exactly alike whiteness of that pen are numerically distinct tropes. An ontology in which objects are composed of bundles of tropes is not committed to the identity of indiscernibles. There is no special difficulty with having two bundles of exactly alike properties and relations, since each bundle contains its own particular tropes.

Trope-bundle ontologies face other worries, however. One challenge concerns the nature of the bundling relation that ties a collection of tropes together into an object. Tropes typically occur in *compresent* collections or bundles; for example, a patch of green paint can be analyzed as a collection of compresent tropes that include, *inter alia*, a green trope, a *being at 18^o C* trope and a place trope (this relation is called "concurrence" by Chris Daly [1997] and D.C. Williams [1997]). A key problem for trope ontologies is to give an account of this compresence relation. On the one hand, this compresence relation itself may be external to, and not founded upon, members of the collection of tropes that form its relata. Call this external relation compresence$_{EX}$. In this case the compresence relation does not supervene on the tropes it relates; it is an additional relational trope binding the two or more tropes in the bundle. On the other hand, compresence may be an internal relation, a consequence of the tropes themselves and not anything ontologically extra beyond the tropes in the bundle. Tropes bound by compresence$_{IN}$ are necessarily and essentially bundled. Compresence$_{IN}$ means that the independent particular—the bundle of tropes—cannot exist without each and every trope that composes it. A successful trope-bundle ontology needs to include a satisfactory account of compresence relations between bundled tropes.

A second worry about trope ontologies concerns how bundles of tropes, which are nothing more than instances of properties or relations, can play the substantial roles of bearing attributes and having independent existence. The notion of substance involves three related ideas. One is the idea that a substance is something that can have independent existence, whereas an attribute cannot but is rather a dependent entity. Second, substance functions to individuate one property from other, possibly exactly alike properties (recall that the property-bundle approach ran into difficulty here). Third, substance is the bearer of attributes. A substance has attributes inhering in it but need not itself inhere in anything. Clearly, a successful trope-bundle ontology needs to show how these substantial roles are fulfilled by trope bundles.

It will be instructive to look at one well-known attempt to develop a trope ontology for field theory, that of Keith Campbell (1990). Campbell posits an ontology based exclusively on classical fields and spacetime. On his approach, a field, such as the electromagnetic field, pervades all spacetime. He is motivated to resist the unfounded compresence$_{EX}$ relations because of what he sees as their derivative ontic status: “some tropes, the monadic ones, can stand on their own as Humean independent subsistents, while others, the polyadic [relational] ones are in an unavoidably dependent position” (1990, 99). The state of a field in four-dimensional spacetime is represented in the ontology by a *single* trope, and the field has no real, detachable parts. If more than one field exists, each one consists of a single trope. In the same way, all of spacetime itself corresponds to a single infinite, partless, edgeless trope (1990, 145-151). In this way, Campbell attempts to finesse the bundling problem by eschewing compresence$_{EX}$ relations entirely. Fields are essentially infinitely extended entities, he asserts, and if a field exists then it must *necessarily* be compresent with spacetime. Thus the compresence relation, in this case, is compresence$_{IN}$: it supervenes on, and is nothing ontologically over and above, the field trope itself (1990, 132-3).

As an account of the ontology of classical field theory, Campbell’s proposal is unsatisfactory in several ways (cf. Moreland 1997, Molnar and Mumford 2003). A useful rule of thumb in analytic ontology is to avoid making substantive assumptions about how the world must be wherever these can be avoided. As Campbell puts it, an adequate ontology "should leave open, as far as possible, … plainly *a posteriori* issues" (1990, 159). Yet Campbell's proposal is based on a number of very large such assumptions, some of which are not consistent with classical field theory. For example, it assumes that if a field exists it is necessarily co-extensive with all spacetime; such an assumption is not consistent with classical field theory, as the latter is usually taken to allow for the physical possibility of null field values and so regions of spacetime in which the field is not present. Moreover, it seems to get the modalities wrong. On Campbell's approach, each and every occurrence of a trope in a bundle becomes a matter of necessity. However, we usually conceive of the world in terms of varying degrees of necessity. We want to distinguish, for instance, between those compresences of tropes that are necessary and those that are contingent.

In addition, Campbell's proposal is poorly motivated. The second-class ontic status Campbell imputes to relational (dyadic and polyadic) tropes comes from the fact they need to be borne by at least two other tropes, while "[m]onadic tropes require no bearer" (1990, 99). But most monadic tropes *do* require a bearer, or at least are dependent on one or more other tropes for their existence. A particular quality of greenness, a specific instance of *being at* 18^{o} *C*, and so on, all require a complex of other tropes to sustain them and are thus equally in an "unavoidably dependent position." Even a classical field trope, as Campbell conceives it, depends upon a spacetime trope for its existence. There may be some lone tropes that can exist independently of the compresence of any other trope (Campbell's spacetime trope, for instance), but these are the exception rather than the rule. That dyadic and polyadic tropes require other tropes for existence does not distinguish them ontologically from monadic tropes, and is certainly no motivation for attempting to eliminate them from the ontology.

Campbell's proposal seems barely distinguishable from the very substance-attribute approach that trope theory is trying to do without. The field trope depends for its existence on a spacetime "peg," while the spacetime trope does not depend for its existence on any other trope. The spacetime trope performs the trick of augmenting the dependent particular (the field) in such a way that the pair becomes an independent particular. In short, the spacetime trope functions as a substantial substratum and, apart from its thoroughgoing eschewal of universals, Campbell's proposal amounts to a variant of a substance-attribute field ontology. We can do better.

The best place to begin an ontological assay of classical fields is with a characterization of what a field is. As it is usually described, a field consists of values of physical quantities associated with spacetime locations or spatiotemporal relations. We shall have more to say about what constitutes the "value of a physical quantity" below; for the moment think of intuitive values such as 0.3 Gauss of magnetic field strength. This central element of the field concept is, as a rule, given the following ontological gloss: in a field, values of a physical quantity inhere in and are properties of the ether or spacetime manifold. A field (a set of field values inhering in spacetime points) is thus a complex dependent particular that relies on a manifold or ether for its existence. We have explored this ontology and the challenges it faces (Section 1). We shall now pursue an alternative ontology, the field trope-bundle (FTB).

The general structure of the field trope-bundle ontology is based on Peter Simons' "nuclear theory" (1994, 567-9). This ontology is characterized by kernels of compresent_{IN} tropes that are themselves related by compresent_{EX} relations. Simons is concerned exclusively with a trope-bundle ontology for particles and everyday objects. Our present task is to extend his approach to the case of physical fields.

The first step in the field trope-bundle construction identifies a kernel or core of tropes which must all be compresent. This kernel is necessary for a field to be a complex independent particular. The kernel at each point consist of three kinds of tropes, one or more G tropes, one or more F tropes, and an *x* trope. A G trope is a particular topological or metrical property instance of the spacetime at a point. F tropes are particular instances of field values (such as 0.3 Gauss magnetic field strength). Each G and F trope carries with it its own particularity, since *being a particular* is a basic fact about every trope. But particularity alone is not enough for G and F tropes to have independent existence. To see why, note that while particular entities can be aggregated, it is no part of the concept of particularity that particular entities must have numerical identity (i.e. can be indexed or labelled). Quantum-mechanical particles, for example, provide an example of particular entities that can be aggregated but do not have numerical identity (Redhead and Teller 1991; Teller 1995). The ontology of field theory, by contrast, requires that field values have a stronger individuality, one which supports indexing.

The complex of G and F tropes requires the *x* trope to index it. The *x* trope can be understood as a particular "way" that an G-F trope complex can be, namely one with a particular indexed identity. The *x* trope is thus not, by itself, substantial or substance-like and cannot exist without something else, the G-F trope complex, for it to be a way of. The collection of various *x* tropes has merely set-theoretic structure (ordinality and membership) and is not to be associated with a spacetime manifold. In Minkowski spacetime, for example, the G tropes are all exactly alike, while the *x* tropes each differ in their numerical identity. The kernel just described, consisting of a G-F trope complex and an *x* trope bound together, are the building blocks of fields.

We have been speaking of a G-F-*x* trope kernel at a point, but such talk may be inaccurate. F and G tropes may be best understood as irreducibly relational. Electromagnetic field values, for instance, can be understood as constituted by their counterfactual relations to other field values specified in the electromagnetic field equations, a hidden relationality. Geometrical property instances may also be understood as relational. This is accommodated naturally within the trope-bundle approach by accounting for relational property instances in terms of polyadic tropes that are compresent with more than one point field value (itself consisting of an *x* trope and any monadic tropes). Here field regions, rather than the point field values, are the basic independently-existing kernels.

The bundling relation *within* the kernel is $\text{compresence}_{\text{IN}}$: the compresence of the G-F-*x* tropes within a bundle supervenes on the tropes themselves. This is a consequence of the fact that within a kernel all tropes are necessarily compresent. We also need to account for relations between, and compresence of, independent fields. Distinct fields consist of independently-existing field kernels. Two independent field kernels may be compresent$_{EX}$, where this sort of compresence is an external relation constituted by one or more relational tropes, called E tropes. If a field consists of more than one kernel, or if there is more than one independent field, then field kernels require some E tropes to be bundled with them, although which E trope or tropes is a contingent matter. In this way, E tropes are more loosely bound to the field kernels than are the tropes within the kernels themselves. Field kernels do not require specific E tropes in order to exist, and it is possible that the same (independently-existing) field kernel be part of different compresence$_{EX}$ relations, that is, be bound to different E tropes.

One virtue of the FTB ontology is that it responds, at least in part, to the two main challenges facing trope-bundle ontologies in general: the role of substance and the nature of the compresence relation. On the FTB proposal, each field point or, in the case of relational tropes, field region can be an independent particular. It isn't that the field inheres in a substantial substratum, but rather that each field kernel is substantial. Recall that the notion of substance involves three related ideas. One is the idea that a substance is something that can have independent existence. This is true for field kernels as we have defined them (an alternative will be presented shortly). Another role of substance is that it functions to individuate one property from other, possibly exactly alike properties. Trope bundles in the FTB ontology fulfill that role, because tropes, as particulars, are automatically individuals, and the ontology contains a specific mechanism for rendering bundles numerically distinct. A third role for substance is as the bearer of attributes, and field kernels in the FTB construction play this role as well. Field kernels may function as the bearer of attributes by means of a compresence$_{EX}$ relation, where these attributes are also tropes. However, these particular attributes are not essential for the existence of the field kernel. This is in keeping with the ontological asymmetry between substance and attribute, where the substance exists independently but the attribute depends on the substance. It should be noted, however, that there remain significant difficulties in elucidating an external compresence relation for tropes (Simons 1994, Daly 1994).

A second virtue is that the FTB ontology is flexible and can accommodate the diversity of field theories in contemporary physics. This point is worth emphasizing, especially in light of the suggestion below that a trope-bundle approach might prove useful for analyzing ontological aspects of quantum field theory. One way a trope-bundle approach is flexible is with respect to what are the particular tropes that count as field values. So far we have referred to definite-valued field values, that is, field values that are determinate quantities of a physical variable (such as 0.3 Gauss magnetic field strength). It is worth noting that dispositions and propensities are equally tropes (Molnar and Mumford 2003) and equally good candidates for field values. Another way a trope-bundle approach is flexible is with respect to the size of the field kernel. We began with the assumption that the field values plus geometrical property instances at a point constituted a kernel, and we then expanded the kernel to finite regions in order to include compresent$_{IN}$ relational property instances as well.

It may be that compresence$_{IN}$ is not limited to any finite region of the field, in which case the field as a whole is made up of a single kernel.

Another flexibility in the approach worth noting concerns whether the field kernel has independent existence. A kernel is a core of tropes which must all be compresent, and as we have seen, a field kernel can be an independent particular. This seems natural in the case of classical field theory. A system can contain an electromagnetic field and nothing else, for instance, so it is clear that the field can exist independently of anything else; kernels in the electromagnetic field are independently-existing entities. However, nothing in the FTB ontology requires that this be so. It may be the case that a field kernel cannot exist independently of a periphery of other tropes to which it is bound by compresence$_{EX}$ relations. This dependence between the kernel and the periphery would be token-type, so that tropes within the kernel depend on there being some trope compresent$_{EX}$ in the periphery of a certain type. In the same way, middle-sized physical objects must be compresent with some temperature trope, although they do not generally depend on any one specific temperature trope for their existence. The FTB ontology for quantum field theory sketched below provides an example of field kernels that are dependent particulars in an analogous way.

3 Examples of the FTB ontology

Consider a simple idealized example in electrostatics, that of two isolated point charges q and q' at rest in a vacuum, separated by a distance r. The total electric field is

(1) $$\boldsymbol{E}(\boldsymbol{x}) = \boldsymbol{E}_q(\boldsymbol{x}) + \boldsymbol{E}_{q'}(\boldsymbol{x}) .$$

The electric field at point x due to charge q is

(2) $$\boldsymbol{E}_q(\boldsymbol{x}) = \frac{q}{r_x^2}\boldsymbol{e}_x$$

Where $\mathbf{e}_x$ is the unit vector from q to x and r_x is the distance from q to x. Here is a law of nature concerning the force $\mathbf{F}_{q'}$ on test charge q' at point x_q:

(3) $$\boldsymbol{F}_{q'} = q'\boldsymbol{E}_q(\boldsymbol{x}_{q'})$$

$\mathbf{E}_q$ is composed of a set of $\mathbf{E}_q$ kernels. These are compresent$_{EX}$ with $\mathbf{E}_{q'}$ kernels and with *G-x* kernels. For simplicity, we consider each kernel non-relationally, that is, as an independently-existing individual.

The electric field $\mathbf{E}_q$ produces and explains the force on q', and the FTB ontology provides an account of how it does so. Each kernel contains, among other things, a trope that causes a charge to feel the force described in (3) when the charge is compresent$_{EX}$ with the kernel. The independent existence of the $\mathbf{E}_q$ and $\mathbf{E}_{q'}$ is accounted for in terms of the contingent compresence$_{EX}$ of their field kernels. The distinctness of exactly-alike $\mathbf{E}_q$ field values is accounted for by the fact that each field kernel contains an indexing trope. In this way, the FTB ontology for electrostatics accounts for a number of physical features of this example. By contrast, a substance-attribute ontology requires an immaterial substratum to account for these features. In contemporary physics the spacetime manifold is supposed to play the role of immaterial substratum, but, as we saw in Section 1, that ontology faces significant challenges.

When we move to the quantum context, it is plausible that the FTB ontology will enjoy even more significant advantages over substance-attribute ontologies, since this context is quite hostile to traditional notions of substance. Elsewhere I have argued that canonical quantum field theory (QFT) should be understood as a theory about physical fields. I introduced the vacuum expectation value (VEV) interpretation of QFT, on which VEVs for field operators and products of field operators correspond to field values in physical systems (Wayne 2002; Wayne [in preparation]). The FTB ontology provides a promising ontology for QFT on the VEV interpretation.

The VEV interpretation of QFT begins by noting that the standard formulation of QFT contains a set of spacetime-indexed field operators for each quantum field. Consider a simple model for quantum field theory consisting of a single non-interacting, neutral scalar quantum field described by a set of spacetime-indexed Hermitian operators $\Phi(\boldsymbol{x}, t)$ that satisfy the Klein-Gordon operator-valued equation. In this model, certain expectation values play a crucial role. These are simply the expectation values for the product of field operators at two distinct points in the vacuum state, $<0|\Phi(\boldsymbol{x}, t)\, \Phi(\boldsymbol{x}', t')|0>$. These vacuum expectation values (VEVs) describe facts about the unobservable quantum field that have measurable consequences. In particular, one can calculate the probability amplitude of the emission of a quantum of the meson field in a small region around $(\boldsymbol{x}, t)$ and its subsequent absorption in a small region around $(\boldsymbol{x}', t')$ as an integral over appropriate two-point VEVs. This probability amplitude contributes directly to processes which involve the meson field as a mediating force field. It should be noted that it is in fact a Lorentz-invariant combination of two-point vacuum expectation values which plays a role in models of quantum field theories of interest to physicists. A time-ordered product $T\{\Phi(x)\ \Phi(x')\}$ of field operators can be defined, and the time-ordered two-point VEV $<0|T\{\Phi(x)\ \Phi(x')\}|0>$ is the covariant Feynman propagator for the meson field, integrals over which are represented graphically by a line in a Feynman diagram. This propagator plays an important role in the derivation of experimentally testable predictions from the model using covariant perturbation theory.

Two-point VEVs provide a perspicuous way to interpret one part of the physical content of our model. On the interpretation being proposed here, these two-point VEVs describe field values in models of physical systems containing quantum fields (although, as we shall see below, two-point VEVs correspond only to a subset of the field values in these models). As mentioned in the previous paragraph, two-point VEVs contribute to probabilities for joint emission and absorption of a quantum of the meson field. They also contribute to probabilities for values of other observables formed as products of field operators, such as total energy and momentum. In this way, field values in the meson model correspond to physical field values which play the desired ontological role: the field values produce and explain observed subatomic phenomena.

The central claim of the VEV interpretation of quantum field theory holds that VEVs in standard quantum field theory correspond to field values in physical systems containing quantum fields. It is a useful fact about quantum field theory that certain VEVs offer an equivalent description of *all* information contained in the quantum field operators, their equations of motion and commutation relations. In general, a set of VEVs uniquely specifies a particular $\Phi(\boldsymbol{x}, t)$ (satisfying specific equations of motion and commutation relations) and vice versa. As Arthur Wightman first showed, for expectation values fully to describe a quantum field operator, one must specify not only VEVs at each point,

(4) $$<0 \mid \Phi(\boldsymbol{x}, t) \mid 0> \quad \text{for all } \boldsymbol{x}, t,$$

but also vacuum expectation values for the products of field operators at two different points,

(5) $$<0 \mid \Phi(\boldsymbol{x}_1, t_1)\, \Phi(\boldsymbol{x}_2, t_2) \mid 0> \quad \text{for all } \boldsymbol{x}_1, t_1, \mathbf{x}_2, t_2,$$

at three points, and so on (Wightman 1956; cf. Schweber 1961, 721-742). In these expressions for vacuum expectation values I let $\Phi(\boldsymbol{x}, t)$ stand for the adjoint field as well, $\Phi^{\dagger}(\boldsymbol{x}, t)$; in general, vacuum expectation values contain both field operators and their adjoints. Wightman determined that a complete specification of an interacting quantum field operator requires vacuum expectation values of all finite orders. In Wightman's reformulation of quantum field theory, operator-valued field equations are replaced by an infinitely large collection of number-valued functions constraining relations between expectation values at different spacetime points (Wayne [in preparation]).

The VEV interpretation highlights three ways in which quantum fields differ from classical fields, and all three of these differences are well accommodated within the FTB ontology. First, VEVs determine probabilities for field values, and these probabilities may be understood as propensities, unlike the classical case in which field values are all definite-valued. This widening of the notion of field value, from a definite value in the classical case to a set of propensities in the quantum case, is naturally accommodated within the FTB ontology. As we have seen, tropes, which are simply particular property or relation instances, include dispositional and propensity instances as well. More precisely, a quantum field is composed of a set of kernels, where each kernel is made up of one or more geometrical G tropes, an indexing *x* trope, and an F trope, all compresent$_{IN}$. Each F trope in a quantum field is a propensity for an *n*-point field value, and each F trope corresponds, in the VEV interpretation, to one *n*-point vacuum expectation value. Each kernel is itself compresent$_{EX}$ with other kernels making up the quantum field, corresponding to other *n*-point values, and with kernels of independent fields. As we have seen, compresence$_{EX}$ is an external relation constituted by one or more relational E tropes.

Secondly, quantum fields contain single-point and *n*-point field values, understood as *n*-point kernels on the FTB approach. This is in contrast with classical fields, which consist exclusively of single-point values. Thus F tropes in quantum fields are irreducibly relational in a way that F tropes in classical fields are not (recall that F tropes in classical fields may be relational in another way, namely in their dependence on the neighbourhood of a point). As noted above, the FTB approach naturally accommodates this expansion of the kernel to regions in order to include these compresent$_{IN}$ relational tropes. Indeed, because quantum fields contain *n*-point VEVs of all orders there may be no finite region of a quantum field that is separable from the rest of the field. This is accommodated by such a quantum field having a single kernel.

Thirdly, a quantum field does not determine the state of the system. The actual state of a physical system containing a quantum field corresponds to a specific state vector/operator combination, yet on the VEV interpretation the state vector plays no role in specifying the field values of a quantum field. The implication for the FTB ontology is that the kernel of a quantum field cannot exist independently of some additional tropes, those comprising the state of the system. A quantum field kernel must be compresent$_{EX}$ with state tropes, and the kernel depends for its existence on compresence with some trope of the state-trope type.

4 Conclusion

Ontological parsimony, flexibility, and moderate nominalism are attractive features of field trope-bundle ontologies for field theories in physics. FTB approaches have significant advantages over traditional substance-attribute approaches, and this paper has sketched, in a very preliminary way, how such trope-bundle ontologies can be constructed for classical and quantum field theories. Clearly, much work remains to be done to flesh out these constructions. However, I hope to have shown that these ontologies are promising choices to underwrite the causal and explanatory roles physical fields play in contemporary physics.[1]

References

Belot, G. (2000). "Geometry and Motion." *The British Journal for the Philosophy of Science* **51**(Supp): 561-595.

Campbell, K. (1990). *Abstract Particulars*. Oxford, Blackwell.

Daly, C. (1994). "Tropes." *Proceedings of the Aristotelian Society* **94**: 253-261.

Earman, J. (1989). *World Enough and Space-Time: Absolute Versus Relational Theories of Space and Time*. Cambridge, Mass., MIT Press.

Field, H. (1980). *Science without Numbers*. Princeton, Princeton University Press.

Field, H. (1989). *Realism, Mathematics, and Modality*. Oxford, UK, Blackwell.

Green, G. (1838). "On the Laws of the Reflexion and Refraction of Light at the Common Surface of Two Non-Crystallized Media." *Transactions of the Cambridge Philosophical Society* **7**(1): 113.

Kelvin, W. T. (1904). *Baltimore Lectures on Molecular Dynamics and the Wave Theory of Light*. London & Baltimore, C.J. Clay and Sons.

Larmor, J. (1900). *Aether and Matter*. Cambridge, Cambridge University Press.

Lorentz, H. A. (1895). *Versuch Einer Theorie Der Electrischen Und Optischen Erscheinungen in Bewegten Körpern*. Leiden, E.J. Brill.

Lorentz, H. A. (1909). *The Theory of Electrons*. Leipzig, B.G. Teubner.

Malament, D. (1982). "Review Essay: Science without Numbers by Hartry Field." *Journal of Philosophy* **79**: 523-534.

Molnar, G. and S. E. Mumford (ed.) (2003). *Powers: A Study in Metaphysics*. Oxford, Oxford University Press.

Moreland, J. P. (1997). "A Critique of Campbell's Refurbished Nominalism." *Southern Journal of Philosophy* **35**: 225-245.

Parsons, G. and P. McGivern (2001). "Can the Bundle Theory Save Substantivalism from the Hole Argument?" *Philosophy of Science* **68**(3): S358-S370.

Redhead, M. and P. Teller (1991). "Particles, Particle Labels, and Quanta: The Toll of Unacknowledged Metaphysics." *Foundations of Physics* **21**: 43-62.

Rynasiewicz, R. (1996). "Absolute Versus Relational Space-Time: An Outmoded Debate?" *Journal of Philosophy* **93**: 279-306.

Schaffner, K. F. (1972). *Nineteenth-Century Aether Theories*. Oxford and New York, Pergamon Press.

Schweber, S. S. (1961). *An Introduction to Relativistic Quantum Field Theory*. Evanston, IL, Row Peterson.

Simons, P. (1994). "Particulars in Particular Clothing: Three Trope Theories of Substance." *Philosophy and Phenomenological Research* **54**: 553-575.

Teller, P. (1991). "Substance, Relations, and Arguments About the Nature of Space-Time." *The Philosophical Review* **100**(3): 363-396.

Teller, P. (1995). *An Interpretive Introduction to Quantum Field Theory*. Princeton, Princeton University Press.

Wayne, A. (2002). "A Naive View of the Quantum Field." *Ontological Aspects of Quantum Field Theory*. M. Kuhlmann, H. Lyre and A. Wayne. Singapore, World Scientific**:** 127-133.

Wayne, A. ([in preparation]). "The VEV Interpretation of Quantum Field Theory."

Wightman, A. S. (1956). "Quantum Field Theory in Terms of Vacuum Expectation Values." *Physical Review* **101**: 860-866.

Williams, D. C. (1997). "On the Elements of Being: I." *Properties*. D. H. Mellor and A. Oliver. Oxford; New York, Oxford University Press**:** 112-124.

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