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Introduction: The Philosophy of Vectors

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Vectors are deployed in successful scientific representations of physical reality. Is there an element of reality that corresponds to there? If yes, what kind of entity is it? If no, what accounts for the utility of vectors in our theories? These are among the questions discussed in this special issue.

The nine articles fall into three groups. The first one is concerned with the history of vector concepts in mathematics, and with the applicability of such concepts to physical reality. Peter Simons tells the story of the vectorists' victory in the 'great quaternionic war', and asks whether the language of vector algebra will be, or should be, replaced by the language of geometric algebra. The second paper, by Marc Lange, reviews the debate between 'staticists' and 'dynamicists' about how to justify the parallelogram law of vector addition. Lange argues that we need an account of laws of nature that admits different degrees of nomic necessity in order to make sense of that debate. Ingvar Johansson's paper discusses how the International System of Units might best be extended to vector quantities in classical mechanics, and argues that duration in directed time ought to be the basic vector.

The papers in the second group discuss how vectorial properties fit into various metaphysical theories of properties. Ralf Busse argues that fundamental vector fields do not refute Humean Supervenience, contrary to what is often claimed. For this purpose, he offers a detailed development and evaluation of three conceptions of such fields. Peter Forrest proposes a theory of vector fields that is compatible both with the relativistic assumption that space-time is curved and with realism about universals. Claus Beisbart then argues that physics does not construe vectorial quantities as intrinsic to their bearers.

The papers in the third group tackle the important special case of physical forces. Jessica Wilson proposes a causal argument against realism about component forces, while Olivier Massin argues that Newtonian forces are real, symmetrical and non-causal relations. Finally, Alastair Wilson defends realism about both

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resultant and component forces on the grounds that the distinction between them is frame-relative.

Together, these papers illustrate the importance and fruitfulness of detailed metaphysical investigation of vectorial quantities. They continue, and reinforce, we hope, the current trend to move from toy examples to more realistic ones in metaphysical theorizing.

Vectors and vectorial properties

In physical theories, vectors are associated with points of space or space-time. It is therefore plausible to construe what they stand for either as properties of such points or of their occupants, or else as relations between them and something else. The topic of the worldly counterparts of mathematical vectors is thus naturally treated as a chapter in the theory of properties and relations. Historically, that branch of metaphysics has suffered from a scarcity in its diet of examples. For a long time, attention was restricted to monadic properties, while relations were neglected. Likewise, graded monadic properties, sometimes with the exception of mass, were typically ignored in favour of all-or-nothing properties. Discussions of vectorial properties have been few and far between (among the early exceptions are Tooley 1988; Bigelow and Pargetter 1989; Robinson 1989; and Johansson 1989.). The aim of this special issue is to bring them, or ways to do without them, under more intense metaphysical scrutiny.[1]

By a 'vectorial property' or 'vectorial quantity', we mean a property or quantity that is represented by a vector in modern physical theories. Examples in classical physics include determinates of velocity, momentum, acceleration, force, electric current, electric field strength, and magnetic field strength; in quantum theories also determinates of spin and quark colour.[2] In some of these examples, the vector quantities are *field values*: they are the value of a function, a field, defined on all space-time points.

[1] The lamented poverty in the diet of examples is in evidence even with David M. Armstrong, who has given us some of the most detailed metaphysical theories of properties. In Armstrong (1988), he develops an account of resemblance among properties, using mass as an example. But as argued convincingly by Maya Eddon (2007), the account runs into severe problems dealing with electric charge and electric field vector quantities.

[2] Some quantities, such as stress-energy or distance, are represented by *tensors*. It is sometimes said that the concept of a tensor is more general than that of a vector – a vector can be construed as a special case of a tensor. However, one could argue that vectors are conceptually prior, since tensors may be defined as functions that take vectors (as well as co-vectors, which in turn are defined in terms of vectors) as arguments.
There is not much discussion of tensors in the present volume, except in Forrest's contribution. It remains an interesting question what, if any, further philosophical issues arise from considering tensorial quantities as well as vectorial ones.

We do not suggest that a vectorial quantity could not be represented non-vectorially.[3] Nor do we suggest that non-vectorial properties in our sense could not be represented by vectors.[4] As we will see, the fact that there appear to be properties revealingly represented by vectors is something that many metaphysical theories find hard enough to account for.

A vectorial quantity is one that is represented by a vector. But what is a vector? One might expect this introduction to start with a definition of this mathematical notion. But different definitions are offered in different branches of mathematics and physics, and it would unduly constrain the discussion if we took one of them as canonical here. Naïvely, we think of a vector as an 'arrow' in space, characterised by its length and its direction. It may be either *bound* – possessing a definite initial point – or *free*. Free vectors may be construed as equivalence class of bound vectors. In Euclidean geometry, a vector is taken to be a directed segment of a straight line. The representation of vectors by an n-tuple of numbers is also familiar. However, such representations are relative to coordinate systems. There are two ways to avoid such relativity. One can take a (bound) vector to be a function from a point and a coordinate system to an n-tuple that satisfies a certain condition – the 'vector transformation law'. Alternatively, one can define vectors without reference to coordinate systems as directional derivatives, as is done in some textbooks on the general theory of relativity (e.g. Wald 1984).[5]

In this as in many other cases, a rich and fruitful concept transcends particular definitions that may be offered. We trust that the reader has an intuitive understanding of the notion. More discussion of the concept of a vector in mathematics is provided by the opening piece.

How do our philosophical theories change once vectorial properties figure in our diet of examples? Answers are to be found in the contributions to this volume. We will let them speak for themselves. In this introduction, we merely want to draw attention to general claims about properties that become questionable in the light of vectorial examples. For this, we can draw on the extant literature on vectorial quantities, limited though it is. Without pretense of either originality or exhaustiveness, we will discuss three theses that consideration of vectorial properties may show to be up for revision – the theses we call 'One over many',

[3] Different assignments of vectors to points need not correspond to different vectorial quantities. Suppose that in every possible world, for every point, if field f_1 assigns vector v, then field f_2 assigns vector $2v$. Then if these fields represented different properties, the difference between them would be hyperintensional. Given that we are not committed to the hyperintensionality of vectorial properties, we can allow that they are not just represented by vectors, but also by intensions, or (if no point exists in more than one world) by classes of possible points.

[4] For example, we could represent colours by vectors in the colour solid.

[5] Sometimes vectors are defined in a 'functional' or 'top-down' manner, as elements of mathematical structures that satisfy the vector space axioms. However, this account would classify many things as vectors that intuitively are not, such as real numbers.

'Factorization', and 'Determinate exclusion'. Along the way, we will flag points of contact with the discussion in the articles of this volume.

Vectoriality and One over many

One over many Properties are shared by many things.

Theories of properties tend to take it as a datum that a property is a 'One over many', that there typically are many things that share it (cf. e.g. Armstrong 1978, 41). This feature is supposed to do explanatory work: it explains why some predicates apply to more than one thing, why some things affect us in the same way, and why things resemble each other. A philosophical theory needs to account for that datum. The most straightforward solution to the 'One over many' problem is provided by a theory of universals, according to which one and the same property is wholly present in different instances. But even rivals to theories of universals typically take the 'One over many' as something to be accounted for.[6]

Considerations of vectorial properties lead us to challenge the datum. The question whether a vectorial property F had by x is shared by y often does not have a determinate answer. This observation, and the recognition that it leads to problems for theories of universals, is due to Peter Forrest (1990).

Consider a sphere, such as the surface of a perfectly round cousin of the earth, and two vectors v_x and v_y of equal length attached at different points x and y. Suppose that v_x represents property F_x, and v_y represents F_y. Are F_x and F_y the same property? Presumably, they are if v_x and v_y have the same magnitude and the same direction, i.e. if they are parallel. But how do we determine, on a curved space like a sphere, whether two vectors in x and y are parallel? Put informally, we pick up v_x, move it to y without ever wiggling, and then check whether it aligns with v_y. As it turns out, the notion of not wiggling the vector while on the move can be made precise: it is called *parallel transport* along a path. However, the result of parallel transport depends on the path along which you move the vector. For illustration, let x and y be on the parallel 45° north, half-way between the equator and the north pole, and on opposite sides of the globe (we may take x to be on the null meridian and y at 180°). Both v_x and v_y are pointing north. If γ is a path starting from x, the point where vector v is attached, we denote the result of parallel transporting v along γ by $T_\gamma(v)$. Let *par* be the path from x to y along the 45° parallel, and let *mer* by the path from x to y on a great circle. Then $T_{par}(v_x) = v_y$ and $T_{mer}(v_x) = -v_y$. This shows that parallel transport is path-dependent on a curved space. One might hope that for any two points, there is a privileged path that combines then, and that

[6] Campbell (1990, 27) calls it the "B-question" for trope theorists and Rodríguez-Pereyra (2002, 14), too, accepts that resemblance nominalism has to address this as "one of the oldest philosophical problems".

sameness of direction is determined by parallel transport along that path. The obvious choice for such paths is geodesics, the shortest connections between two points. On a sphere, the geodesics are great circles.

But this suggestion runs into problems, too. Let x and y now be on the equator, 90° apart, with vectors v_x and v_y both pointing north and of equal length. Let z be the north pole, and let γ, γ' and γ'' be geodesics from x to y, y to z, and x to z, respectively. Then $T_\gamma(v_x) = v_y$, but $T_{\gamma'}(v_y) \neq T_{\gamma''}(v_x)$, thus showing that the relation that holds between two vectors if there is a geodesic γ such $T_\gamma(v) = v'$ is not transitive, and hence not an equivalence relation.[7]

There are general impossibility theorems regarding equivalence classes on spheres satisfying certain conditions. They are reported in Forrest (1990, 548). While the details will differ for non-spherical curved spaces, the general situation will surely be the same.

Of course, the considerations above do not conclusively establish that a vectorial quantity is not a One over many. Here are a few ways to defend this claim; for convenience of exposition, we will speak in the voice of a friend of universals, rather than the voice of someone who tries to solve the problem of the One over many in some other way.

First, universals may be *fragile*, as it were, not surviving transport from one point to the other. They may still be universals in virtue of being wholly present in distinct points in worlds with flat space-times. However, if our universe has a curved space-time, this response would take away from the motivation for postulating vectorial universals. Forrest (1990, 552) tentatively endorses such a solution, comparing these repeatable but non-repeated universals to Hegelian ‘concrete’ universals.

Secondly, universals may be *relatively abundant*, such that the vector v_x represents both a universal F that is shared by x and y, and a distinct universal F' is shared by x and z. (Vectorial universals would still not need to be fully abundant, even among points. There may be no corresponding universal shared by all three of x, y, and z.) This response is at odds with the insistence of prominent theorists of universals, such as Armstrong, that universals are sparse.

Thirdly, universals may be *invidious*: even though it appears that there is nothing to choose between different partitions of the vectorial quantities into equivalence classes, some produce cells that correspond to a universal, while others do not. Of course, we would need to be given a story about what breaks the seeming metaphysical symmetry. The perspectival theory of Mormann (1995) (discussed in Forrest 1996) may count as an implementation of that strategy.

[7] Another problem with the geodesic proposal is that for antipodean points, there are multiple geodesics, leading to different results.

Even if vectorial quantities were shareable, it would still not be clear in what way directionality makes for similarity. ~~Compare three vectorial properties represented in a two-dimensional Cartesian space: is $\overrightarrow{(0,0)(1,1)}$ less similar to $\overrightarrow{(0,0)(1,2)}$ than the latter is to $\overrightarrow{(0,0)(1,4)}$?~~ Magnitudes may motivate one answer, directions another one, and it is not clear which one should be privileged. Directions may seem in general unsuited as similiarity-makers: two vectors having the same orientation, but different senses seem similar in one, but very different in another way.

Vectoriality and intrinsicality

A second claim about properties that consideration of vectorial properties calls into question is the following:

Factorization All fundamental properties and relations are intrinsic.

Factorization bans the irreducibly extrinsic. This claim has been prominent in the discussion of David Lewis's thesis of Humean Supervenience. It is in connection with that thesis that the question whether vectorial properties are intrinsic has received attention (Tooley 1988; Robinson 1989; Bigelow and Pargetter (1989; Armstrong 1997, 76; Lewis 1999b). In this volume, the question is taken up by Busse and Beisbart.

It should be noted that Factorization is much weaker than Humean Supervenience, and may be accepted even by some anti-Humeans. It does not entail that composite things do not have fundamental properties, and is thus compatible with certain forms of emergentism. It does not even entail that there are fundamental properties of points or point-sized things. (Factorization is compatible with an atomless mereology. It is also compatible with monism, the view that all fundamental properties are exemplified by one thing, the whole world.) Further, Factorization does not entail that all fundamental relations are spatiotemporal.

Before considering the question whether vectorial properties may count as intrinsic, it is worth asking whether any of them are fundamental. If not, they do not provide a threat to Factorization.

In philosophers' discussions of fundamental properties, electric charge is usually one of the putative examples, along with mass. Many vectorial properties, such as magnetic field strength, velocity, or force, are not fundamental. Magnetic field strength supervenes on the distribution of electric charge in space-time, velocity supervenes on positions at various times, and forces are determined by masses and charges. However, quark colour is also vectorial; it features prominently in the critique of traditional accounts of properties presented in Maudlin

(2007).[8] Quark colour has a strong claim to be a fundamental property. According to modern physics, there are four fundamental forces: weak, strong, electromagnetic, and gravitational. While mass is associated with gravity and electric charge with the electromagnetic force, quark color is associated with the strong force. Roughly, quark colour stands to the strong force like electric charge stands to the electromagnetic force. (Indeed, it sometimes called 'colour charge'.)[9]

Are fundamental vectorial properties like quark colour intrinsic? The answer may depend on which conception of intrinsicality is right, of course. We briefly consider three approaches: *invariance under duplication, modal independence*, and *essential independence*.[10]

Suppose we understand the intrinsicality of a property in terms of duplication: it is intrinsic if it is invariant among duplicates. Many would agree with Lewis that "offhand, [. . .] two things can be duplicates even if they point in different directions" (1994, 226). However, the intuition seems negotiable, and indeed Lewis himself does reject it. The intuition is perhaps strongest if we consider two points *x* and *y*, in the same world, with differently directed vectorial quantities, and a lonely point *z* in another world. It seems that *z* may be a duplicate of both *x* and *y* (whether or not we agree with Robinson (1989, 408) that a vectorial quantity could not be instantiated in lonely point). By the symmetry and transitity of duplication, *x* and *y* are then duplicates, and hence the vectorial quantity is not intrinsic.[11]

On another conception, an intrinsic property is one whose instantiation by something does not have any implications for the rest of the world. Being ten feet from an elephant is not intrinsic because my having it implies the existence of an elephant in a part of the world that does not overlap me. If implication is cashed out modally, this can be parlayed into a modal independence criterion for intrinsicality. We need not go into the technical difficulties of doing this (see Weatherson

[8] The details work out slightly differently, since the vectors that represent quark colours do not belong to the tangent space, but rather to a more complex example of what is called a 'fibre'. See Maudlin (2007, pp. 94–96).

[9] The parallel transport argument does by no means exploit all metaphysically interesting aspects of quark colours, and of the theory (quantum chromodynamics) in which they figure. It only turns on their being vectorial properties instantiated in points on curved spaces. Nothing in the arguments depends on the local gauge freedom that they display. For a philosophical discussion of gauge theories, see Healey (2007).

[10] Provided intrinsicality is understood in terms of essential rather than modal independence, Factorization is compatible with necessary connection between distinct existences, and may thus be attractive even to anti-Humeans. See Molnar (2003) for an anti-Humean view of dispositions according to which they are intrinsic. Molnar characterizes intrinsicality by essential independence.

[11] This argument relies on the assumption that lonely objects may exemplify vectorial properties. Some definitions of intrinsicality, e.g. the one by Lewis and Langton (1998), combine the requirement that intrinsic properties are invariant under duplication with the requirement that they can had by both lonely and accompanied objects. On this more demanding conception, a stronger case can be made for the non-intrinsicality of vectorial properties.

2001; Lewis 2001; and Denby 2006).[12] The pertinent question, for present purposes, is whether there is any reason to think that vectorial properties fail to satisfy modal independence conditions. Vector fields are sometimes required to vary continuously from point to point. But we could take this to be a merely nomological and not a metaphysical necessity. However, a suitably general modal independence condition will require that a given vectorial property can be had by a lonely object.

One might thus argue that whether vectorial properties are intrinsic depends on the thorny question whether they can be exemplified by lonely objects. If they can, then they are plausibly modally independent but not duplication-invariant. If they cannot, then perhaps they are duplication-invariant but not modally independent.

On a third conception, a property is intrinsic if it is essentially independent, i.e. if its essence does not in any way involve other things.[13]

We might expect that modal independence implies essential independence, since an essential dependence would be necessary.[14] But with vectorial properties, even this is questionable. Suppose that *F* is a vectorial property that happens to be exemplified in an accompanied point *x*. An account of *F*'s essence, of what it is, arguably needs to tell us in virtue of what it differs from *F′*, another vectorial property that is not, but might be exemplified in *x*. It is extremely hard to see how this could be achieved without mentioning points distinct from *x*. This seems to be threaten the essential independence of *F*.

After considering different accounts of intrinsicality, we do not have a clear verdict about whether vectors represent intrinsic properties.[15] Suppose that they do not. Could the factorization thesis be saved by construing them as intrinsic relations?[16] The trouble with this suggestion is that in general, they do not seem to be relations at all. Any choice of further relata beyond the point at which the vector is attached seems to be artificial.[17]

[12] If properties are abundant, satisfying modal independence conditions will at best be a necessary condition for intrinsicality, and certainly not a sufficient one.

[13] Again, there are different ways to spell this out: a property *F* is "identity-independent", according to E.J. Lowe (1998, 149) e.g., if there is no function *f* such that it is part of the essence of *F* to be identical with the *f* of another thing.

[14] Though Keller's "Contingent essence" challenges this assumption. 3

[15] There are further questions regarding vectoriality and intrinsicality that we cannot discuss here. Weatherson (2006) contains an interesting discussion about whether vectorial properties threaten plausible principles linking the duplication of parts to the duplication of a whole.

[16] The letter of the Factorization thesis could also be saved by taking vectorial properties to be exemplified by something larger than a point, perhaps a neighbourhood. As vectorial properties are certainly *ascribed* to points rather than neighbourhoods, this would require treating questions of ascription and of exemplification differently.

[17] However, as Massin argues, there is a natural choice in the special case of Newtonian forces.

A naïve proposal would be to take a vectorial attribute to relate the two end points of the arrow. But there are two objections to this. First, the length of the arrow, and according to this proposal, the second relatum, is due to a conventional choice of scale. Secondly, on a curved space, the arrow does not point to anything in space-time at all, but rather to a point in the tangent space – presumably an abstract entity not suitable for being a relatum of a fundamental relation.

Alternatively, the vectorial attribute might be taken to relate the point where the vector is attached with the ray in space starting out from that point. But this suggestion seems to wrongly make the exemplification of a vectorial attribute dependent on the existence of that ray. There could be two duplicates sharing a vectorial property even though one of them is surrounded by infinite space and the other by finite space. These considerations do not refute the suggestion that vectorial properties are relations. Busse's article considers more sophisticated versions of that view.

If vectorial properties falsify Factorization, there is an interesting question about whether a suitably weaker claim is both compatible with their existence and able to preserve some of the intuitions behind it. Jeremy Butterfield (2006) has argued that the claim that velocity is *barely extrinsic* (roughly, intrinsic to an arbitrary small neighbourhood) does justice to some of the motivations of intrinsicality theses.

Vectoriality and exclusion of determinates

A third widely accepted principle about properties that vectorial properties invite us to reconsider concerns W.E. Johnson's relation between determinables and determinates (cf. Johnson 1921, 171):

Determinate exclusion Nothing has two determinates of the same determinable.

The paradigm of a determinable is colour. The idea behind the principle that determinates exclude each other is simple: nothing can be red and green (though it may, of course, have green parts and red parts).[18] It is natural to construe force vectors as representing determinates of a determinable, namely force. After all, force vectors can be added, and it is tempting to generalize Johansson's thesis (this

[18] 'Determinate' is here understood as 'ultimate determinate'. On another usage of 'determinate', both red and scarlet are determinates of colour; but of course they do not exclude each other. The principle could be revised as follows:

Determinate exclusion Nothing has two determinates of the same determinable unless one of them is a determinate of the other.
For discussion, see e.g. Funkhouser (2006).

issue) that scalar quantities "can in a physically meaningful way only be added to (or subtracted from) other determinates of the same determinable" to vectorial quantities. But clearly, one thing can be subject to different forces. A boat may be pulled by two horses, on either side of the canal; a proton may experience both ~~gravitational~~ and electromagnetic forces. Thus we have a *prima facie* case against the exclusion of determinates.

A vector has a magnitude and a direction. Quantitative properties also have magnitudes, and relations have directions; different theories have been developed to understand these two features. It is a third, and even more difficult task, to understand their interplay, brought to the fore in the discussion about whether directions can be 'added' (in some sense of this word). Is there, on a fundamental level, something like vector addition? If so, is it ontologically productive? Does it result in something new, a resultant vector? Does it do away with what it is applied to, the component vectors? This is the question addressed by the three final papers in this volume. It is in some ways akin to a question about superposition states: do we have to understand them as intrinsically complex, as superpositions of two states, or do they have some claim to be themselves fundamental? A similar question also surfaces in the discussion of causality: do partial causes do themselves causal work, or are they causally relevant only in so far they are parts of some total cause?

Note that once we abandon the exclusion principle (as urged e.g. by Armstrong 1978, 113), there is some pressure towards denying that a vectorial determinate even excludes itself. We would have to distinguish between a given quantity being exemplified once, twice, or *n* times, for any *n*. The pressure arises from continuity reasoning. Suppose that two different vectorial properties F_1 and F_2 with different direction and the same magnitude can be exemplified in the same point. Then surely F_1 can be exemplified in the same point as F_3, which is half the sum of F_1 and F_2 (it has the same length as those, and its direction bisects the angle between them). By repeating this process, we obtain the possibility of two co-exemplified vectorial quantities that are arbitrarily close in direction. By invoking a continuity principle, we obtain the result that F_1 can be exemplified twice in the same point.

The defender of an exclusion principle has various options.

First, she might deny the reality of component forces, and only accept resultant ones. There are independent arguments for this.[19] In her contribution to this special

[19] Another argument against component problems would be that their acceptance multiplies possibilities beyond what is needed to account for physical reality by forcing us. e.g., to distinguish a situation where a force of magnitude 2 acts on a particle from a situation where two forces, of magnitude 1 each, act on the same particle in the same direction. In response, defendants of component forces could claim that only some component forces are real (Creary 1981; Bigelow and Pargetter 1989).

issue, Jessica Wilson presents another exclusion argument, relying on causal considerations, against the reality of component forces. But as Massin argues, this is a high price to pay.

Second, she might deny that different component forces fall under one determinable. Perhaps the determinables are 'force exerted by Bucephalus' and 'force exerted by Pharlap', or, more fundamentally, 'gravitational force' and 'electromagnetic force'.[20] If forces are relations, as Massin argues, then the relational properties derived from those relations would not be determinates of the same determinable. How could a defender of that kind of response respond to the extension of Johannsson's point about the physical meaningfulness of addition? She might consider it to be merely nomologically necessary that forces can be added, rather than something that true in virtue of the nature of these quantities; or she might deny the reality of resultant forces, as Massin does.

Third, she might deny that component forces acting at the same point are really had by the same thing. Rather, they are had by spatio-temporally coincident things. The resultant force would then be had by the mereological sum of these coincident entities. They would make for a nice parallelism between addition of vectorial quantities and addition of scalar quantities like mass and electric charge. They are additive in the following sense: if none of the *xs* overlap, the quantity had by the (mereological) sum of the *xs* is the sum of the quantities had by the *xs*. On the coincidentalist proposal, vectorial quantities would be additive in the same way. Nonetheless, the proposal seems implausible.[21,22]

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[20] See Johansson (1989). The exclusion problem considered here is implicit in his discussion. He solves it for forces by making the distinction just mentioned. He solves it for accelerations by denying that they are properties; rather, they are tendencies. Presumably, the determinable-determinate distinction does not apply to tendencies.

[21] Note, though, that Armstrong's theory of quantities also posits coincident entities for independent reasons.

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