Ontological categories for fields and waves

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Abstract: Fields and waves are prominent features of modern physics. They are also important for engineering applications as well as biology and medicine. Therefore these entities should be represented in applied formal ontologies for these domains. While there have been some contributions with respect to a field approach in Geo-Ontologies, very little has been done for fundamental fields like electromagnetism. In this paper I will discuss and evaluate two ontological options for fields: Fields as qualities of points or regions in space and fields as substantial entities. Furthermore, I argue that waves are processes involving fields, therefore dependent on fields, although these may in turn be dependent on some material substrate.

1 Introduction

Fields and waves are central concepts both in classical and quantum physics. As they are of importance not only in pure science, but also in applications in engineering and biology they should figure in ontologies for these domains. More obviously than waves, fields do not belong to commonsense or everday ontology, but rather to what has been called "secondary theory" [SM03], that is they figure almost exclusively in advanced and mathematically formulated scientific theories. Other than entities like force, speed or weight they do not belong to pre-scientific "folk physics". Even in scientific theories fields are a latecomer as they only came into their own with the electrodynamics of the late 19th century. Although some waves are a feature of everyday experience and could in principle be treated independently from fields, in mature classical physics waves presuppose a field description even if they occur in a material substrate like water waves or sound waves. Therefore the task of systematically fitting fields and waves into a top-level ontology should start from the characteristics of these entities as they are dealt with in physical theories rather than from common sense conception of, e.g., water waves. This is the aim of this paper. I will start with introducing the concept of a field and argue that it is more fundamental than that of a wave. Then I collect the main characteristics of fields that have to be respected by the ontological suggestions. As for these, I discuss two options for fields: fields as qualities of points or regions of space or spacetime and fields as substantial entities in their own right. Finally I get to waves as entities dependent on fields or special spatiotemporal patterns of fields. First of all the interdependence of fields and waves has to be made clear. From the standpoint of physicss field is the more fundamental entity. A wave is a propagation of a “disturbance” in or a particular state of a field in space and time. So we will first deal with static fields and then with waves as a special kind of disturbance in a field.

2. Fields

2.1 Fields in physics

What is a field? Let us start with the standard description in physics and try to extract characteristics that should be reflected by the ontological category for fields. To speak of a field in mathematical physics means that we assign values of certain physical quantities to points in space continuously. These values are mathematical functions of the space coordinates and time: u = u(x,y,z,t). These field quantities can be quite diverse in nature. I will focus on the most important ones: scalars like temperature, pressure, gravitational potential can be represented by a (usually real) number, and vectors like velocity, electric or gravitational field strength are represented by vectors, that is quantities with a magnitude and a direction. (For simplicity we will ignore more complex entities like tensors that can be used to represent tensions in threedimensional elastic solids.) Some of these are physically fundamental quantities like electric field strength, others appear in a mesoscopic theory like fluid dynamics, but could in principle be reduced to other quantities on a lower level which would sometimes allow a non-field-theoretic description. I will ignore this possibility of reduction as the mesoscopic level is often the one we want to capture in an ontology for engineering or biological applications and for the important case of electromagnetic waves the more fundamental theory is also a field theory. (In fact, at the current state of physics *all* fundamental theories are (quantum) field theories.) For the purposes at hand, electric and magnetic fields will suffice as leading examples as they are among the most important ones in engineering and technology.

Apart from the general representation of qualities that are continuously located in space fields are essential for the interaction of other non-field-entities. To quote from an advanced textbook on electrodynamics: “Although [electric field strength] E and [magnetic field strength] B thus first appear just as convenient replacements for forces produced by distributions of charges and current, they have other important aspects. First, their introduction decouples conceptually the sources from the test bodies experiencing electromagnetic forces. If the fields E and B from two source distributions are the same at a given point in space, the force will be the same, regardless of how different the source distributions are. This gives E and B … meaning in their own right, independent of the sources. Second, electromagnetic fields can exist in regions of space where there are no sources. They can carry energy, momentum and angular momentum and so have an existence totally independent of charges and currents.” [Jac75: p.3]. According to this position fields can be treated independently from the charges (more generally the sources) that bring them about, because there are different source configurations that bring about the same field configuration in a certain spatial region and we can describe the latter without explicit reference to the former. Furthermore, the fact that fields have qualities like energy and momentum is taken as an argument for unterstanding fields realistically as independent existents on a par with material bodies.

If fields are to be taken realistically as physical qualities distributed in space we are led to the question: qualities of what substance (understood as the bearer the qualities are ontologically dependent on)? When the mathematical apparatus of field theory was developed in the 19^{th} century for optics, elastic bodies and electromagnetism the field quantities were all thought to reside in a material medium, in some stuff they were states or properties of, namely the elastic body or the fluid in mechanics of elastic solids and hydrodynamics and in optics and electromagnetism a postulated all pervading universal medium (with some strange properties, but resembling an elastic solid in many salient respects), the so-called ether (cf. [He61], [Da00], [Bu85]). So for fields like the pressure field of a gas we can take the gaseous matter as the substance the pressure is a quality of, but for fields without material substrate it is not obvious how to proceed. For the field as interaction medium we can distinguish several options (following Lange [La02]): instrumentalism, realism and dispositionalism. Instrumentalism implies (temporally retarded) action at a distance between the interacting bodies. According to Lange dispositionalism means that the field quality is ascribed to a spatial region because of a hypothetical conditional: *If a test charge with value q was present at space-point x with the electric field value E(x), it would experience a force qE(x)*. Conversely, the value and direction of the field at x are given by the value and direction of the force on the test charge $E = F/q$. But to reduce the field to distal interactions of charges with each other would be an elimination of the field, ontologically speaking. If we take the ascription of dispositions as a shorthand for conditionals as Lange does above, this will also amount to some kind of elimination. But if we take dispositions as real properties, that is a kind of dependent entities similar to qualities as is argued by, for instance [EL94] and [Jan07] and as BFO does [Spe06], dispositionalism will not help us avoiding the question for the substance exhibiting the field quality. It will collapse into a kind of realism. Without going into further detail we will take arguments mentioned above that fields carry energy as strongly supporting a realistic option for fields.

Batchelor and Hastings have recently offered some suggestions how fields and waves could be included in the framework of top-level ontologies for biology and medicine [BH12].They start with considerations from classical (or even “folk”) physics, but suddenly slip into “quantum mode” by discussing photons which have no place in a wave ontology based on classical physics. They seem to think that photons could be something like the material/substantial aspect of a light wave and so serve as participant for the wave process and probably bearer of the field qualities (for the electromagnetic field). This seems confused, because quanta like photons are not the “stuff”, “matter” or “substrate” of the electromagnetic wave. Photons are not just a different granularity level of description. Light waves are not „waves of stuff made of photons“ in the sense water waves are waves of stuff made of water molecules. Because of the peculiarities of quantum theory it is clear that quantum entities like photons need to be considered separately and the ontology of the entities of quantum mechanics and quantum field theory is not a consolidated field (cf. [Ku10] for an overview and discussion). I will not enter into this discussion, just stress that one should be careful not to mix classical and quantum entities or think of photons as something like everyday “billiard ball” particles. Photons are “field quanta” and as such very different from classical particles and as the name indicates the notion of field quanta is conceptually dependent on the notion of a quantum field. For example, photons (and other quantum entities) share with fields the feature of superponibility which is not shared by classical corpuscles. The way photons “combine” to form a (macroscopic) field is mathematically analoguous to the way overtones (harmonics) “combine” (or are contained) in a complex wave on a violin string. So there is no reduction of classical fields to non-field-entities, but to quantum fields. Before I come back to the still open question of the bearer of the field qualities, I will collect important properties and types of fields.

2.2 Features of fields

In the following section I will present and briefly comment on the ontologically important features of fields as they can be extracted from the treatment in standard phyisics textbooks.

Superposition: Fields can be “superposed”. This means that values of the component fields can be added at a point in space very similar to the vector addition of mechanical forces to obtain a resultant. This is due to the linear field equations used to describe fields and waves so this important feature will also hold for waves. It implies that fields "occupy" space without "filling" space in the sense ordinary matter does. Matter and field can coexist/overlap in a spatial region [La02]. (Actually the "matter fields" of fundamental physics do fill space in a sense although the superposition principle holds there as well, but there are different features responsible for the de facto repulsive force, not a repulsive field.)

Not countable: Fields are not easily understood as countable entities like ordinary material objects or corpuscles They have similarites to „stuffs“, that is continuous masses described by mass nouns. This feature stems probably from the models in which fields were qualities of something treated as continuous stuff (like a continuous elastic body). But they are not easily treated in analogy to everyday mass nouns like water either. One cannot say “two litres of field” as one says “two litres of water”. This seems to show that fields are described well neither by count nor by mass nouns. The closest analogue seem to be states or qualities of a substance or a stuff.

Determinable/Determinate: For field quantities, a structure of determinate values (“1 statcoulomb”) of a determinable magnitude (“static electrical field strength”) is needed (top-level ontologies like DOLCE [MBGGOS03] and BioTop [BSSH08] provide this).

Interaction: A charge q reacts to the strength of the field E at its locus x, it experiences a a force with strength qE. E could have been caused by another charge q' and in this way fields are a medium of interaction, that is two electric charges q, q' interact by means of the field. Fields interacting with non-field-entities could be desribed by means of dispositions (of fields and material objects) and their realization processes, similar to the model described by [RJ11], cf. also [EL94].

Sources of fields: Charges are “sources” of the field, they are responsible for fields coming into being in their neighborhood, so we need an ontological relation connecting a charge with the field it brings about. This relation of sources to fields could be called "production" and would relate a material object with a salient “source” quality with the appropriate field.

For types of fields the following rough distinctions can be made:

Fields with a material substrate: e.g. in hydrodynamics, meteorology etc.

Fields without material substrate: electromagnetic field, gravitational field (In quantum field theory there would also be matter fields, the fundamental fields representing the constituents of matter like electrons etc.)

Time-independent fields: Fields that do not vary in time, like the electrostatic field inside a charged capacitator.

Time-varying fields: Fields changing in time, also processes involving fields as participants. Not all processes involving fields imply that the fields change in time. In the standard description of the movement of a test charge caused by an external electrostatic field this extrernal field is treated as static, because the minimal change in the external field by the field of the test charge is neglected.

Looking at this list the main requirements to be fulfilled by an ontology of fields are that they can occur independently of a material substrate, that they can be superimposed, time-dependent and that they can be connected both to their sources as well as to non-field-entities they interact with.

3. Ontological options for fields

As mentioned above a central reason for adopting realism is that the field can store and transmit energy. Following physics, something does not have to have rest mass to be real. If we take fields without material substrate seriously it seems that there are two options how to include them in an ontology. (The historical option of an ether as substrate for electrical fields is obsolete.) Either the field qualities are qualities of space(time) points or regions. These entities then act as quasi-substances the field qualities are dependent on. Or fields are entities in their own right, they are actually themselves a kind of substance.

3.1 Fields as properties of space(time) points

Why not take fields as qualities dependent on spatial points and regions? Some may be reluctant because such a position seems to imply a so-called substantivalist position with respect to space, i.e. regarding space as a substance the field quantities would be attributes of. Although the recent discussion on the ontic status of spacetime focusses on the curved spacetime of General Relativity rather than a flat background space as we consider here, there is still a lively debate on the old question about the ontic status of space (or spacetime) without a clear majority position, so a substantivalist position is still a live option. In a second step one could try to reconstruct space in terms of relations of field values at all the points, but it is much easier to accept a background space with a certain geometric and topological structure as "given" and substantial. An advantage of this approach is that spatial and temporal points and regions are already established categories in major top level ontologies like BFO [Spe06] and DOLCE [MBGGOS03]. Although the definitions of these categories might have to be amended so that entities like spatial points or regions could figure in relations (object properties) like `hasFieldValue` to express their new role as bearers of field qualities. A disadvantage is that this may commit us to more realism with respect to space time than we may want to. And historically, the acceptance of fields as entities in their own right was not developed according to this model, but in the framework of a relational conception of space(time) [Schi49].

3.2 Substantial fields

The other option would be to take fields as entities in their own right, characterized by nothing but their field qualities. The quality of having a certain value (and direction) of field strength (measurable by a small test charge) characterises the field in some spatial point or region. So fields are substantial, although different from most ordinary substances as can be seen by the features listed above. They will have an unusual relation to space. They will not fill space in the sense that they occupy a region exclusively, because they may be superimposed with each other and they can also coexist with ordinary objects at the same point/region. At the portion of space occupied by my body there exist also the earth's magnetic and gravitational fields without excluding each other. They often do not have sharp boundaries either. They cannot be moved the way ordinary substances can be moved. Despite their dependence on sources it does not seem plausible to say that a moved charge "drags" along the field it creates, but rather that the field surrounding the moving charge is different from or deformed with respect to the field of a charge at rest. Because fields are in some respects like "stuff", we cannot individuate "field portions" in the way we do it with ordinary objects. Therefore it is difficult to follow a field portion moving through space and probably better to abandon the idea in favor of changing the field values along the path of a particle. The question also arises if we should speak of one all-pervading field that can take on different types of quality (like gravitational or electric) and respective values at different points or if we assume many fields and distinguish them with respect to their different types and sources, like the gravitational field of the moon or the magnetic field of the earth. The latter option seems closer to scientific usage to me and the former looks somewhat like re-introducing absolute space, but the ramifications of these options would have to be examined further.

4. Waves

4.1 Characteristics of waves

Waves depend on a “medium”. Everyday examples like waves on a string or a membrane are spatio-temporal periodic patterns or processes involving these material entities. A wave on a string is a specific spatiotemporal pattern of the vertical displacement of the string against its equilibrium position. Although the term “field” may seem slightly odd in such one- and twodimensional cases the mathematical description will in essence be field-theoretic, that is employing the same concepts and tools as in the cases when every point in a threedimensional region of space gets assigned a field quantity. For the vibrating string the field quantity is the displacement along the length of the string. Therefore from the field perspective it is not essential for waves whether they occur in a medium that can be identified with a commonsense object (like wave on a violin string) or regionally bounded amount of stuff (like a water wave in a pond) or whether they occur in a field without a material substrate. Nevertheless we can make these differences and, as in the case of fields distinguish waves with a substantial material bearer from waves in a field without material substrate. But it is important to keep in mind that the material bearer will admit of a field-theoretic description with continuous variables mapped onto the spatio-temporal region occupied by the bearer.

More specifically wave fields or field waves are (1) time-varying with a special periodic pattern, can (2) be characterised by amplitude, frequency and wave length (or wave number) and wave velocity (I will ignore complications like the “group velocity” of a wave packet for now, although this would be important in electrical engineering, signal theory etc.) The amplitude is the “height” of a wave, the frequency describes the temporal periodicity (how many wave fronts pass in a given time) and the wave length is the spatial interval from one wave crest to the next. (the so-called wave number describes how “dense” the wave is packed spatially (how many crests in a certain spatial interval). As in the case of fields we have waves with a material substrate like water waves or sound waves in air and electromagnetic waves like radiowaves, visible light, x-rays that are patterns in a field without a material subtrate.

4.2 Ontological options for waves

One rather obvious ontological option for waves would be to understand waves as special processes involving fields (or in the case of material bearers the bearers). If a wave is a process, ontologically speaking, what are the characteristics of the process that make it a wave and not some other process? In this case there might be a problem with BFO as top level ontology, because processes cannot have qualities in this ontology. But maybe we do not have to ascribe the wavelength etc. to the process. If we clearly distinguish between waves and fields, the characteristics (amplitude, direction, frequency, wave-length) of the wave can be seen as the very properties of the field that make this particular state or configuration of the field a wave. So these properties would be ascribed to the field as participant, not to the wave as a process. This would also show that for waves with material bearers we would always need the field in addition to the bearer. This is the case, because, e.g., a wave length cannot be ascribed to a string simpliciter as that string can exhibit different wave lengths (according to its harmonics) depending on the way it is excited. In field physics, a wave can be seen as a special field configuration, a solution of a special case of a field equation, so it seems somewhat artificial to describe the field as a participant in the wave process as if this field configuration was something easily distinguishable from the wave. Therefore it would have to be explored further whether waves can be more appropriately be understood as special fields. Useful subclasses of waves would include:

Longitudinal wave: e.g. sound wave in air (wave of the pressure field): The direction of oscillation is the same as the direction of propagation.

Transversal wave: e.g. light: The direction of oscillation is perpendicular to the direction of propagation.

5 Conclusion and outlook

The physical field is an important category of physical reality that figures in biological and technical applications and therefore they should be represented in ontologies for these domains. As fields have several features that make them quite different from everyday material objects this is not an easy task. In this paper I have tried to get the preliminaries for adaequate ontological representations of fields clear. As a first step I collected the most important features of fields and discussed two option for representing them ontologically. One option is to understand fields as qualities of spatial regions. This has the advantage that no new categories have to be introduced, because top level ontologies already include spatial points and regions and qualities and their definitions could be amended to allow the ascription of field qualities to spatial regions. The disadvantage is that one may have to support a problematic substantivalist conception of space. The option that seems closer to physics is to take fields as substantial entities. In this case we have to implement the features of fields, especially the fact that the can be superimposed and coexist with matter at the very same spatial point. Waves can occur both in entities that admit of non-field descriptions and in fundamental fields, although a field description is also possible for the former case. Therefore it seems plausible to treat waves as dependent on fields. They can be represented as processes involving fields, although there seems to be some tension with the usage in physics, so more work has to be done to see whether this option is preferable or whether waves should be treated as a special subclass of fields. We also saw that the threedimensionalist approach by BFO has some problems with characteristics of processes. This has to be investigated further and alternative options, e.g. fourdimensionalist top-level ontologies have to be taken into account. Also more the concrete representation of the characteristics of waves and fields in the framework of such top-level ontologies has to be worked out.

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