Waves and fields in bio-ontologies

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ABSTRACT

Modern bio-ontologies aim for interoperability through alignment to a common upper level ontology and the use of common relationships. A precondition for such alignment is that all of the entities that are needed for annotation of the data for the domain in question are able to be represented beneath the same upper level ontology. Waves, such as electrocardiography, brain waves and sound waves, are relevant in many different domains within the life sciences. Working within the framework of the Basic Formal Ontology, we will discuss the classification of waves. We begin by evaluating existing bio-ontology terms for waves and fields and – where applicable – their classification beneath BFO, finding quite divergent representations. Thereafter, we will present our strategy for unification, first considering those waves, such as sound waves, that are borne by some physical medium, such as air, and subsequently considering electromagnetic waves and fields, which are of particular relevance for ontologies in neuroscience.

1 INTRODUCTION

Waves have relevance in many different domains within the life sciences. Brain waves are electrical changes in the brain caused by patterns of communication between neurons, which can be characterized in the frequency domain (cycles/sec, e.g. delta, theta, alpha, beta waves), in the time domain (changes in voltage with characteristic spatial and temporal distributions), or both. Human audition depends on the translation of sound waves into neural signals by our hearing system. The functioning of the heart is studied through electrocardiography (ECG) which measures the electrical activity of the heart over a period of time, assessing the rate and regularity of heartbeats. Waves and patterns of gene expression control cellular development and can be perturbed to study toxicity (Zimmer *et al.*, 2011).

However, the correct categorisation of wave phenomena within ontologies has been contested. What is a wave – an object, an event, a property? Maybe waves are *sui generis*? In this paper we will address this question.

The remainder of the paper is organised as follows. We present relevant background material in the remainder of this introduction, before turning in section 2 to survey waves and fields in existing biomedical ontologies. Section 3 considers waves borne by media, while section 4 investigates electromagnetic waves, looking at fields and the wavefunctions of atoms and molecules along the way. Finally, section 5 contains our conclusions and future work.

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1.1 Basic Formal Ontology

As research in the life sciences becomes increasingly data-driven, ontologies are being developed to address the needs of data organisation, standardisation and integration. The number of different ontologies is increasing, and ensuring interoperability has correspondingly become more urgent (Smith *et al.*, 2007). One of the considerations affecting interoperability is alignment to common upper level ontologies, which allows different ontologies to be reasoned over in conjunction and to be interlinked with common, well-understood bridging relationships (Smith and Ceusters, 2010). The most widely used upper level ontology within the bio-ontology community is the Basic Formal Ontology (BFO, Grenon and Smith (2004)), and we will work within that context. Other upper-level ontologies include DOLCE (Gangemi *et al.*, 2002) and GFO (Herre *et al.*, 2006).

BFO distinguishes at the upper-most level between *continuants* that exist in full at all times they exist and continue to exist over time, including objects such as organisms, atoms, planets and galaxies, and *occurrents* that happen or unfold in time, including processes such as the life of an organism, a football match, a supernova. Continuants are further distinguished between those that are *independent* and *dependent* – where the latter cannot exist without an independent continuant as bearer. John is an example of an independent continuant, as is his hair, but his hair colour is an example of a dependent continuant, since it cannot exist without the hair existing. Dependent continuants are further distinguished between those that are fully present in their bearers at all times they exist, i.e. qualities, such as hair colour, and those that are *realizable*, that inhere in their bearers by virtue of what would happen to the bearer should a particular set of circumstances obtain (Röhl and Jansen, 2011), for example, the fragility of a glass. Realizable dependent continuants are realized as processes, and are referred to in common language by various names such as 'disposition', 'tendency', 'role' and 'function'.

Waves and fields have variously been categorised within existing bio-ontologies as processes, dispositions, material entities and qualities. The topic has recurred in discussions in community mailing lists such as BFO-Discuss (BFO Discuss Members, 2012), without reaching consensus on the correct representation for these entities. To our knowledge, however, the topic has not previously been given comprehensive treatment – to which task we here turn.

2 WAVES AND FIELDS IN BIO-ONTOLOGIES

A range of 'wave' and 'field' appearances in biomedical ontologies can be observed by sampling the BioPortal collection (Noy *et al.*, 2009) (all versions as of April 2012).

The Electrocardiography Ontology (Winslow and Granite, 2012) contains several 'wave' terms, including 'ECG wave', which has textual definition *'A uniformly advancing disturbance in which the parts moved undergo a double oscillation; any wavelike pattern'.* In the Logical Observation Identifier Names and Codes (LOINC) vocabulary (Huff *et al.*, 1998), many terms mention waves related to electrocardiography, including 'A wave', that has textual definition *'Early wave; Atrial wave; Velocity ratio; Point in time; [. . .] Echography; Cardiology.'* While LOINC as a vocabulary does not focus on classification, the electrocardiography ontology does contain an alignment to BFO. Here, ECG wave is classified as a specifically dependent continuant – a property, leaving aside the question of whether the property is a quality or a disposition.

In the study of the brain in both medical research and neuroscience, various different methods such as EEG record electrical activity revealing brain waves and this is reflected in standard terminologies such as the NCI Metathesaurus, which includes terminology such as 'brain wave', and sleep ontologies defining categories of sleep such as 'slow wave sleep'. The Neuro Electro Magnetic Ontologies (Frishkoff *et al.*, 2009) include many terms for different sorts of brain wave activity. For example, 'alpha wave activity', with working definition *'Alpha wave activity is an oscillation in brain electrical (EEG) activity in the frequency range of 8-12 Hz.'*. 'Alpha wave activity' is classified as a subtype of 'biological process' in NEMO, as illustrated in Figure 1. The definition of the immediate parent, 'oscillatory brain electrical activity', is *'A process that occurs when there is rhythmic or repetitive neural activity in a brain region or distributed network of regions.'*

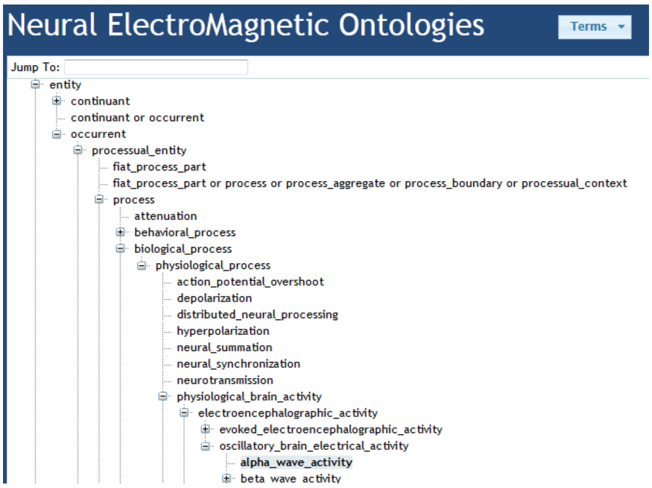

Fig. 1. 'Alpha wave activity' in the Neural Electromagnetic Ontologies

Studies of the perceptual mechanism of sound necessitate in some cases the categorisation of sound within bio-ontologies, and indeed 'sound wave' appears as a term in some ontologies. For example, 'sound' in NEMO is defined as *'A sound is a longitudinal mechanical wave that is composed of frequencies within the range of human hearing (approximately 20 Hz–20 kHz).'*. 'Sound', however, is not classified beneath 'process' in NEMO, but beneath 'object', implying that sounds are considered to be independent and material entities. Contrastingly, the NanoParticle Ontology (Thomas *et al.*, 2011) includes 'sound wave' as a subtype of 'wave' as a subtype of 'process'. Here, 'wave' is defined as *A disturbance which carries energy radiated from a source and which propagates through space (vacuum or space occupied by a medium) and time.* and 'sound wave' as *'A longitudinal wave which transports energy (sound energy) produced by a vibrating object through a medium in which the back and forth motions of the particles result in regions of high (compression) and low pressure (rarefactions) in the medium'.*

Furthermore, fields of various sorts are well represented in bio-ontologies. NEMO in particular contains several 'field' terms, including 'electromagnetic field' with various subtypes such as 'electrodynamic field', all of which are classified beneath the upper level term 'quality'. 'Electromagnetic field' is defined as *'An electromagnetic field is a spatial quality that inheres in an electrically charged particle (or multiple charged particles).'* Also, 'scalp topography electrical field' is included, defined as *'scalp distribution of one or more electrical fields that are generated in the brain or body and are volume conducted to the scalp surface.'* However, since fields can occur in a vacuum, if fields are qualities, it is not straightforward to see what they are qualities of.

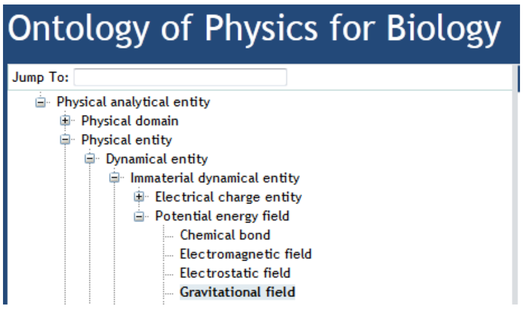

Fig. 2. 'Gravitational field' in the Ontology of Physics for Biology.

Fields are also of importance outside neuroscience, for example as experimental methodology in organic chemistry. The Ontology of Physics for Biology (Cook *et al.*, 2011) includes 'gravitational field', which is defined as *'. . . by which material entities exert an attractive force on each other that is proportional to the product of their masses'* and classified as illustrated in Figure 2. In contrast to NEMO, the Ontology of Physics for Biology is not aligned with BFO, and presents its own upper level. In this case, the upper most entity is 'physical analytical entity' which is defined as *'A physics analytical entity is a formal abstraction of the real world created within the science of classical physics for describing and analyzing physical entities, attributes, and processes.'*

Armed with this evidence for the appearance of waves and fields beneath a wide range of ontological categories, we turn to our analysis of these entities.

3 WAVES BORNE BY MEDIA

I sit on the beach. A wave comes towards me. It rearranges the pebbles on the beach, and dissipates. While the front edge of the wave on the beach moves back and forth, the sea remains overall where the sea is.

I sit on a hill. I throw a pebble into a pool. Then another. The ripples spread out and interfere with one another. They vanish. The pool remains where the pool is.

We will argue that ordinary waves, such as ocean waves and sound waves, are processes. Alternatives to this view that we will discuss are that waves are substantial (objects), that they are categorical properties (qualities) like shapes, and that they are realizable properties (dispositions).

In defence of the view that waves are processes, we observe that processes are occurrents, and they are countable, temporally limited and superposable.

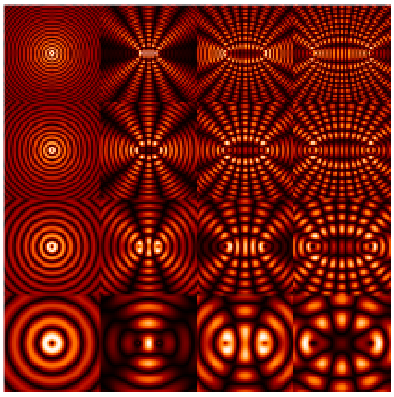

Fig. 3. Circular waves with different wavelengths and distances of the wave point sources.

Examples of travelling waves are illustrated in Figure 3[1]. It is tempting to identify a travelling wave with the water or air that apparently moves across the surface of the sea or across a room. This is the view that waves are *composed* of moving material objects, and therefore *are* themselves material objects. However, two arguments for why this isn't a good general strategy are (1) the argument from standing waves and (2) the argument from additivity.

A standing wave is one where the peaks and troughs on the surface of the water, or the volumes of denser or sparser air inside a wind instrument, hold still. Standing waves also have particular relevance in chemistry, where they provide a model for the nature of chemical bonds. The peculiar aspect of standing waves is that they appear to be stationary. That means that we cannot identify standing waves with a moving parcel of water or air because, at least at a bulk level, there are no such moving parcels.

Even in the case of travelling waves, which do move, if you look carefully at the water, you will see that the water itself does not move in the exact way that we would say the wave moves. Rather, as the wave passes a local portion of water, it makes a circular motion around the horizontal direction perpendicular to the direction of the wave and doesn't in fact travel very far. Something is being transmitted across the entire distance that the wave travels, but it isn't portions of the medium. Again, the wave that starts as the stone hits the water and travels out to the edges of the water is not composed of a portion of water that moves from the centre out to the edges.

Now, we consider the argument from additivity. The additivity of waves is the fact that many waves can occupy the same portion of medium at the same time. This is illustrated in Figure 3 where waves from two point sources cross over each other in their travelling paths, causing interference. Each of the two waves corresponding to two point sources is however preserved despite their interference with each other at the points at which they overlap.

This can also be seen in the case of timbre. Very few musical instruments produce a pure sine wave; the sound they make is almost invariably a superposition of the fundamental and harmonics. Analysing the sound of a bassoon does not involve anatomising the column of air in the bassoon, but rather decomposing the sound wave into its component waves.

Thus, we cannot identify a wave with its medium.

It might be claimed that what is being transmitted is the shape. As the wave travels through the water, it is the raised shape of the crest that is being transmitted between portions of water. This is a better description of the transmission journey of the wave through the medium, but it cannot be the whole story either, though, because something is needed to maintain the shape of the medium, and that something in the common story is usually referred to as the wave. So either this story is circular, or there is still an explanatory gap. Furthermore, if I stand on the beach, I can be knocked over by a wave. One can't be knocked over by a mere shape. Thus we conclude that we cannot identify a wave with the shape of the medium.

A fully dispositional account would say the following: what moves is the disposition. In the case of an ocean wave, it's the disposition to go up and down. Dispositions can be blocked; they can mutually manifest or they can mutually prevent each other from manifesting. What happens when two waves coincide and they cancel each other out is that the disposition $w1$ (to go down) prevents the disposition $w2$ (to go up) from manifesting.

This is an important part of the story. However we cannot identify the wave with the disposition *per se*, because the disposition is not so much transferred from portion of medium to portion to medium as created afresh. In terms of Mumford and Anjum's view of events (2010), where the manifestation of a disposition is simply the creation of new dispositions, existing portions of the medium acquire dispositions which are then manifested in propagating like dispositions on throughout the medium.

The dispositional account is particularly important because there are certain vibrations that are particularly favoured by a musical instrument. An unfretted string, or an unkeyed wind instrument, will vibrate at certain frequencies if blown or struck. These are the normal modes. All objects have them. They are dispositions. So the medium in which the wave travels has certain dispositions, and these dispositions are realized in the wave itself – a process.

A counterargument to all this might be that a processual wave has no causal powers. This would make it difficult to explain the fact that I can be knocked over by a wave, or that humans can react in predictable ways to sounds that they hear, and so on. This objection is misplaced, though, since processes are themselves causes. Causal powers – dispositions – are borne by the medium that carries the wave.

But what can be said about waves that appear to have no medium?

4 ENERGY AND ELECTROMAGNETIC WAVES

While waves travelling in material media are perplexing, they are much more straightforward than electromagnetic waves such as light waves, where there does not appear to be any material medium

[1] Image created by `User:FlorianMarquardt`, accessed from `http://en.wikipedia.org/wiki/Image:W`.

involved. In these cases, we will argue that they are themselves material entities, which participate in their own wave processes.

Three arguments against the materiality of photons are (1) that photons 'are' in some sense energy (2) their masslessness and (3) their insubstantiality. We shall counter all three of them.

4.1 That photons are not energy

The first observation to make is that energy comes in many varieties: kinetic energy, gravitational potential energy, electrical energy and mass–energy. We can therefore straight away exclude the possibility that all energy is to be identified with photons. But what is energy? Energy, in whatever form, is the capacity to do work, and hence is a disposition. Even kinetic energy is a disposition: it can be dissipated by friction, or passed on to another object in a collision. Recall that an object in motion does no work unless it accelerates or decelerates something.

The second observation is that photons are not just energy. They have intrinsic angular momentum. Unlike a macroscopic object, say, a cricket ball, they cannot gain or lose their angular momentum. Spectroscopy, the science of the interaction of electromagnetic radiation with matter, gives us a detailed understanding of the structure of atoms and molecules by virtue of, among other things, the angular momentum gained and lost by electrons in their interactions with photons.

Perhaps the origin of the folk belief that photons are energy is in descriptions of particle–antiparticle annihilation where the energy latent in matter is 'released'. What in fact happens in the case of an electron meeting a positron is that the negative charge of one cancels the positive charge of the other, but their angular momenta do not cancel. Rather, the photons produced in the collision carry away the mass–energy as energy, the linear momenta of the colliding particles and the angular momenta of the colliding particles.

4.2 Against the argument from masslessness

Photons have no mass, but nonetheless have momentum. If material entities are restricted to those that have mass, then photons cannot be material entities, rendering their ontological placement a puzzle.

We can counter the masslessness argument as follows. Imagine a massless cricket ball, the surface of which bears a small but evenly-distributed electrical charge. Because it is charged, it will develop a coating of dust and bits of grass and become visible. It will also interact in the usual sort of way with the players. Imagine that it also has spin. If it meets another cricket ball, it imparts angular momentum to it. It will behave more or less entirely like an ordinary, if very light, cricket ball except that unless it is intercepted by a fielder, it will disappear into space when the batsman plays it.

This hypothetical ball is spatially extended and has a history that can be pointed to. Despite its masslessness, it is substantial. The situation with the photon is just the same, except that they are uncharged. Photons, as we have seen, have intrinsic angular momentum, extend across space as waves, and interact with their environments.

We see, therefore, that while mass may be a sufficient condition for materiality, it is not necessary in the case of photons. We therefore propose that possessing spin is also a sufficient condition for materiality. Equally, there are spinless particles, but those have mass. Hence spin is a sufficient condition for materiality but, just like mass, not a necessary one.

Unlike our massless cricket ball, however, we have good reason to suppose that photons are insubstantial. If insubstantial entities cannot be material entities, then photons cannot be material.

4.3 Against the argument from insubstantiality

In order to tackle the argument from insubstantiality, we will need to consider fields.

What do we know about fields? They are spatially extended; they can be stronger or weaker at different points in space, evolve over time, and those that we are most familiar with, gravitational and electromagnetic fields, fall away with the inverse square of distance without ever quite reaching zero. (The distance dependences of the fields associated with the strong and weak nuclear forces are different, but we shall not consider them here.)

If I am in a field, am I 'in' something? If I am in the Earth's gravitational field, then I experience a force proportional to my mass and the Earth's mass. If I am in the magnetic field of an NMR machine, then I as a whole feel nothing, but charged particles inside me, and inside my wallet, are set in motion.

If object X, then, is in a field whose source is object Y, that means that both X and Y manifest a particular disposition. For X it depends one-sidedly on X and many-sidedly on Y and *vice versa* for Y. The intensity of the field at the given point is then proportional to the force exerted by X, which is manifested as an acceleration.

Photons, being wavelike as well as particlelike, are well described by a field.

As an example, one insubstantiality argument goes as follows: photons of the same frequency, and hence the same momentum, are indistinguishable, therefore have no history peculiar to them, therefore are insubstantial.

We argue that insubstantiality is in fact irrelevant to whether we consider photons to be material. The reasons should be clear if we look at atoms and molecules.

If you look closely enough, matter is fieldlike. The wavefunctions of particles are spatially extended and have different values at different points in space. They also evolve over time. Exactly what sort of thing a wavefunction is, on the other hand, is not agreed upon. The interpretation of what the different complex values of the wavefunction at different points in space is not clear.

Electrons and nuclei on close inspection seem to be just as insubstantial as photons. Their wavefunctions diminish over space without ever going to zero and they are indistinguishable. Even quite large systems, such as fullerene molecules, still behave as waves in the two-slit experiment (Nairz *et al.*, 2003), and indeed we observe that the exact determination of the molecular scale surfaces of ordinary biological scale objects is beset by the same difficulties (Hastings *et al.*, 2011a).

The consequence of insubstantiality, then, is not that electrons, nuclei, atoms and small molecules are immaterial, but rather that they are not entirely substantial in the ordinary macroscopic sense, as has been observed before by Lucas (2006), among others. There may be no exact size scale where macroscopic substantiality takes over, but this should not unduly concern us. These molecules are material, and so – we conclude – are photons.

So, photons are material entities that participate in (or are the agents of) their own travelling wave processes. This necessitates distinguishing between *photon* (qua material entity) and *light wave* (qua process).

5 DISCUSSION AND FUTURE WORK

Accurate description of physical reality is at the heart of scientific ontology construction (Smith and Ceusters, 2010), but strange phenomena within quantum mechanics pose many challenges for this effort. BFO was designed with ordinary biological-scale reality as its main area of application, and as such left aside the sorts of questions that arise from categorisations that need to be accurate at the very small or very large scales. However, as the project matures and more and more ontologies seek alignment with BFO in order to interoperate in a common framework, addressing these questions becomes of increasing relevance.

We have argued that waves are best classified as processes, and that light and other electromagnetic waves are material entities that participate (or are the agents of) their own travelling wave processes. As we observed earlier, this matches the categorisation used in some bio-ontologies. For example, NEMO classified brain-related waves as processes, and the NanoParticle Ontology classified sound waves as processes. For harmonisation of wave terminology more broadly, we propose clearly distinguishing between the related entities a) the wave process; b) the shape of a particular or characteristic wave (a quality); c) representations or measurements of wave phenomena (such as images on paper or a screen), which are information artefacts; and d) the dispositions that inhere in the material by virtue of which it can carry that type of wave. Indeed, NEMO distinguishes between 'wave activity' and 'waveform', with the latter being an information entity linked to the corresponding 'wave activity' entity with the 'is about' relationship. We leave aside for future work explicating the relationship between wave processes and their representations along the lines done for chemicals in (Hastings *et al.*, 2011b).

The categorisation of fields is still debated. A puzzle about fields is that if they are properties, they appear to extend beyond the spatial boundary of their bearers. But, we observe that changes in the bearer propagate outward into the field precisely as light travels – i.e. as a wave. While some would claim that bare space can at least bear dispositions – e.g. the disposition to be filled (Hastings *et al.*, 2011a) – others would oppose. The NEMO definition of electromagnetic field as spatial quality that inheres in a charged particle is particularly problematic in this regard, since it refers to 'spatial' quality and not to any of the dispositional properties for interaction, as well as not addressing the extension of the field beyond the boundaries of the particle. Considering our treatment of electromagnetic waves, and that fields are closely related to the waves that propagate them, one way to resolve the issue would be to claim that the field is a property of the material wave, similar to the approach we have discussed for photons. However, this does not account for the overall pattern of field strength across a spatial extent. Another alternative would be to refer to the appearance of a pattern in a measuring device – a quality of the representation. This suffers from the usual problem of involving measurement in the definition of physical entities.

6 CONCLUSION

We have proposed that waves within bio-ontologies be categorised as processes, and that electromagnetic waves are material entities that participate in their their own propagation processes. Applying this proposal to the various bio-ontologies that include wave terminology would harmonize and benefit interoperability, facilitating tools that harness multiple bio-ontologies at the same time. Future work will involve extending the treatment of fields contained herein and providing an account of wave identity over time.

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