The Ontology of Electromagnetism

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Electromagnetism is usually understood as a theory describing how charged particles and eletromagnetic fields interact. In this paper I argue that a double ontology comprising both particles and fields is problematic. Either we should think of electromagnetism as a theory about charged particles directly interacting with each other, or as theory of fields whose local interactions are manifested as field quanta, called "particles." From a purely theoretical point of view the choice between a particle and a field interpretation does not matter much when it concerns classical electromagnetism; both interpretations are possible and, as shown by Quine, there is a general method for translating a theory about one kind of objects into a theory assuming another kind of objects, provided these theories are empirically equivalent. From an empiricist point of view, however, the particle interpretation is the choice, since some particles are directly observable. Testable predictions of electromagnetism are predictions of the motion of charged bodies, in theory represented as particles, so this must be the empiricists' choice of ontology. In quantum electrodynamics one is however forced to chose a field ontology, since a particle ontology for this theory is impossible. So called "quantum particles" are field quanta, which cannot be treated as individuals making up a domain of quantification. There is thus a tension regarding ontology between classical and quantum electrodynamics. But this tension is nothing else than the much debated measurement problem of quantum mechanics.

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1. Introduction. What is real: Particles, fields or both?

Some physicists hold that electromagnetic fields are not real, but merely calculational devices; the electromagnetic field at a certain point is nothing else than an expression for the effect distant charged particles would have on a charged particle placed at that point. For example Wheeler and Feynman

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(1949, 426) proposed quite some time ago such an interpretation of electromagnetism:

> This description of nature differs from that given by the usual field theory in three respects: (1) There is no such concept as "the" field, an independent entity with degrees of freedom of its own. (2) There is no action of an elementary charge upon itself and consequently no problem of an infinity in the energy of the electromagnetic field. (3) The symmetry between past and future in the prescription for the fields is not a mere logical possibility, as in the usual theory, but a postulational requirement.

Others, in particular quantum field theorists, such as Weinberg (1977, 23), take the opposite view, holding that only fields exist:

> The inhabitants of the universe were conceived to be a set of fields—an electron field, a proton field, an electromagnetic field—and particles were reduced to mere epiphenomena. In its essentials, this point of view has survived to present day, and forms the central dogma of quantum field theory; the essential reality is a set of fields subject to the rules of special relativity and quantum mechanics; all else is derived as a consequence of the quantum dynamics of these fields.

A philosopher who has elaborated this field view in a Kantian vein is Auyang (1995). There is also a third option concerning the ontology of electromagnetism, viz., to hold that both charged bodies and electromagnetic fields exist. This appears to be a common view among both physicists and philosophers, and, moreover, it is usually the view of many textbooks in electromagnetism. Several philosophers have joined the debate, see for example Lange (2002), Frisch (2005, 2008), Belot (2007), Muller (2007), Vickers (2008) and Pietsch (2010).

In this paper I will argue:

i) A double ontology comprising both particles and fields is problematic. Either we should think of electromagnetism as a theory about charged particles directly interacting with each other, or as a theory of fields whose local interactions are manifested as field quanta, which are called "particles."

ii) From a purely theoretical point of view the choice between a particle and a field interpretation does not matter much when it concerns *classical* electromagnetism; both interpretations are possible and, as shown by Quine (1981, 17–19), there is a general method for translating a theory about one kind of objects into a theory assuming another kind of objects, provided these theories are empirically equivalent.

iii) From an empiricist point of view, however, the particle interpretation is the choice, since some particles are *directly* observable. Testable predictions of electromagnetism are predictions about the motion of charged bodies and since bodies in theory are represented as particles, this must be the empiricists' choice of ontology.

Some say that we observe electromagnetic fields; but if saying so the word "observation" must be taken in a broader sense. The simple fact that the terms "electric field" and "magnetic field" were introduced by the founding fathers of electromagnetism, Faraday and Maxwell, tells us that these things at the beginning of the history of electromagnetic theory were highly theoretical objects. That we now talk about field values as observables indicates that our inferences from direct observations to field values are uncontroversial. However, the fact that field values can be *derived* from direct observations does not mean that fields are objects.

iv) In *quantum electrodynamics* one is however forced to chose a field ontology, since a particle ontology for this theory is impossible, as proved by Malament and others. So called "quantum particles" are field quanta, not particles; such quanta lack identity criteria, which means that they cannot be treated as individuals making up a domain of quantification.[1]

v) There is thus a tension regarding ontology between classical and quantum electrodynamics. But this tension is nothing else than the much debated measurement problem of quantum mechanics.

In section 2 I will first discuss how we may identify the ontological commitments of a theory and present Quine's method for changing ontology between two empirically equivalent theory formulations. In section 3 I will spell out how this may be done in classical electromagnetism and in section 4 I will rehearse a recent debate about the consistency of classical electromagnetism. The outcome of that debate was that the purported inconsistency came from inconsistent ways of calculating the force on a charged particle; in one expression the self-field was included, in another not. Since self-fields are necessary in a consistent theory, but conceptually awkward, if thought of as entities distinct from their sources, I will in section 5 discuss the relation between particles and fields and give my arguments against a double ontology. In section 6 I argue that we in fact assume bodies in our ontology, since it is these things we directly observe when testing our theories. In section 7 I will discuss the problem with a particle ontology in quantum electrodynamics, concluding that fields are those entities we may accept as real and that a particle ontology of relativistic quantum theory is impossible.

[1] This does not contradict Wheeler and Feynman's stance since their paper explicitly concerns only classical electromagnetism.

2. Ontological commitment

The theoretical skeleton of a physical theory consists of a number of equations relating physical quantities to each other and rules for measuring these quantities. These equations and rules do not contain much of ontological commitment, if anything at all. One may consistently accept electromagnetism as a true theory, while denying that quantities are things, i.e., denying that quantitative predicates refer to quantitative properties; from the truth of a sentence of the form Fa, where "F" is a quantitative predicate such as "…has charge q," it follows that *a* exists, but not that *F* exists, hence predicates need only have extension.

When we describe the content of these equations in complete sentences we commit ourselves to some ontology. (Example: "The electromagnetic field at point x determines the motion of a charged particle at that point." The speaker of this sentence is committed both to the existence of an electromagnetic field and of a particle.) We cannot avoid making some ontological assumptions when we express an abstract theory in complete sentences. But there is a slack here; when asserting the truth of an equation we can do that in different ways, leading to different ontological commitments. The ontological question related to electromagnetism may, therefore, be stated as: Which things are we committed to accept as existing when we accept electromagnetism as (approximately) true? Are there really any fields? Are particles real? Do both fields and particles exist?

It is desirable to have a general methodology for answering these questions, and, luckily, one such is available. The first step was proposed by Quine quite some time ago in his (Quine 1976), which was a paper he read 1939 at the fifth International Conference for the Unity of Science in Cambridge, Mass. The idea is now well known, by Quine famously expressed as "To be is to be the value of a variable." In other words, we accept those things as existing that are needed as values of variables in a theory we believe to be true, when this theory is expressed in first order predicate logic.

I fully endorse this principle and also Quine's ensuing criterion for acceptance of a purported kind of entity, viz., that acceptable objects in our ontology must satisfy an identity criterion, by Quine famously phrased as 'No entity without identity.'[2]

An identity criterion tells us when two distinct singular terms refer to the *same* thing. If this condition is not fulfilled, we can be certain to talk

[2] Why not extend to second order logic and include quantification over properties and relations? The short answer is that in so far as properties and relations can be reduced to sets of objects and sets of n-tuples of objects it is superfluous and when not we would by this move accept intensional entities as values of variables and such entities have no clear identity criteria. So I agree with Quine that we should restrict ourselves to first order logic.

about the particular *thing a*, only if we use the singular term "a." But, is that acceptable? I think not; if we only can refer to *a* by using "a," a critic might reasonably say that we have no reason to distinguish between the linguistic item "a" and its purported reference, the object *a*, in cases where the purported referent is a theoretical, postulated entity.[3,4]

One cannot directly read off the ontology of electromagnetism from an ordinary textbook, because there is no unique way of expressing the theory in first order predicate logic. It is possible to quantify over fields, over particles, or over both particles and fields. Which paraphrase should we choose? This choice reflects our ontological commitments.

Before we continue a comment about the word "particle" is in order. In physical theories the word "particle" is often used, but we should not interpret it to mean an object without spatial extension. When occurring in an expression such as "A particle with mass *m* and charge *q*…" it cannot literally mean a point object, for if that were the case we would postulate an object with infinite mass (and charge) density and that conflicts with physical theory. The reference of "particle" is simply an object about which we, in a particular context, disregard its spatial extension and inner structure. We merely assume it being confined to a certain volume and treat it as a unit in interactions with other things, thus disregarding its spatial extension and inner dynamics, if any such there is.

Hence, in *classical* mechanics and *classical* electromagnetism, the word "particle" may be interpreted as referring to a body, a spatially extended object which can be identified and later re-identified as the *same* body. (These things, moreover, are the ultimate things we observe when we submit our theories to empirical testing.) By contrast, in quantum mechanics and quantum field theory, the meaning of the word "particle" is a field quantum; photons are quanta of the electromagnetic field, electrons are quanta of the electron field, etc, as Weinberg put it in the quotation above, and these quanta do not in general satisfy any identity criterion.

Weinberg wrote that particles (in quantum field theory) were mere "epiphenomena" and I take him to mean precisely that they are not individuals, only discrete portions of conserved quantities.

Some might wonder how discrete portions of a quantity could fail to be individual things. Well, think of water: we usually do not ask whether a certain glass of water is the same glass of water as another one. A glass of water is an amount of water, not an individual object. In most contexts we treat

3 The medieval notion of identity as haecceity, "thisness," hence conflicts with Quine's demand on identity.

4 Quine's argument was different, he argued that we need an identity criterion for talking about an entity because otherwise quantifying over a domain of objects makes no sense.

it merely as a portion of the substance water. This does not contradict that under certain conditions we can apply an identity criterion and ascertain that two descriptions of a glass of water refers to the same water portion, i.e., treating it as an individual. The same goes for portions of charge and energy; generally speaking they are portions of quantities, whereas under very specific conditions two descriptions of such a portion satisfy an identity criterion. The only difference is that a glass of water can be divided into smaller portions, whereas a photon or an electron cannot. Hence, the number of quanta in a system gives information about the amount of the relevant quantity, not about the number of individual objects.

2.1 Alternating the ontology of a theory

We may adopt either an ontology of fields or an ontology of electrically charged bodies as the entities talked about in classical electromagnetism; as we will se below, both are possible and accepting electromagnetism as an approximately true theory does not force us to make a choice. (But a particle interpretation of relativistic quantum theory is impossible, as will be discussed in section 7.)

The general argument for such a possibility was given by Quine (1981). He showed that a theory about a class of objects can be translated into another empirically equivalent theory about another kind of objects using what he calls *proxy functions*. The idea is this: assume that in theory T1 a set of objects $\{a_i\}$ are assumed to exist and being the values of the variables in T1. Now assume someone has invented another empirically equivalent theory T2 assuming another kind of objects $\{b_j\}$ being the values of the variabels in T2. We can always construct a mapping, a proxy function f, from the set $\{a_i\}$ to the set $\{b_j\}$.

Suppose the sentence $P(x)$, being part of T1, is true of each member of a subset $\{a_k\}$ of $\{a_i\}$. The proxy function associates with each element in $\{a_k\}$ an element in $\{b_j\}$ such that true sentences $P(x)$ in T1 are mapped onto true sentences in T2. Thus the map of $\{a_k\}$ is a subset of $\{b_j\}$.

The map of $\{a_k\}$, i.e., a subset of $\{b_j\}$, may not be the extension of a single predicate defined in T2, but it is always possible to construct a complex predicate with this extension using those defined in T2. The generalisation to two-place, three-place, etc., predicates is trivial. So true sentences in T1 are mapped onto true sentences in T2 and no observations can distinguish these theories. As Quine (1981, 19) put it:

> The apparent change is twofold and sweeping. The original objects have been supplanted and the general terms reinterpreted. There has been a revision of ontology on the one hand, and of the ideology, so to say, on the other. They go together.

This procedure is always possible so long as T1 and T2 are empirically equivalent and we may accept Quine's conclusion that "Structure is what matters to theory and not its choice of objects." (Quine 1981, 20). We may in fact with good reason further say that the two theories are merely *two formulations of the same theory*. Theories are abstract things and why not use empirical equivalence as identity criterion for theories?

The structure that matters to electromagnetism are the fundamental laws, i.e., Maxwell's equations + Lorentz law. Maxwell's equations state relations between electromagnetic quantities and Lorentz' law together with Newton's second law connect these electromagnetic quantities to the directly measurable quantities MASS and ACCELERATION attributable to observable bodies. This connection provides electromagnetic theory with an empirical foundation of observations.

3. Semantics of classical electromagnetism

Accepting a law as true does not entail that we must accept that the general terms used in that law refer to universals; it suffice that these general terms have extension. So if we assume that charged particles, i.e. bodies, exist and are the referents of singular terms, we may consistently hold electromagnetism to be true while denying both that electromagnetic fields and charges exist; they are merely attributes of bodies. Another option is to quantify over fields instead of particles.

Let us, as an example, see how this may be applied to Maxwell's first equation and express it in first order predicate logic. I begin with its integral form:

$$\iint_S \mathbf{E} d\mathbf{S} = \iiint_V \rho d\mathbf{V} \tag{1}$$

This equation says that the total flux of the electric field **E** through a sphere S enclosing a space volume V equals the volume integral of the charge density ρ.[5] This volume integral equals the total charge q in that volume. Assuming that charges are attributes of bodies and that we always can separate bodies from each other so that a body can be thought of being alone inside a sphere, we may now express Maxwell's first law as a statement about charged bodies:

> Maxwell's first equation: For all charged bodies x, the charge q of x satisfy the equation $q = \iint_S \mathbf{E} d\mathbf{S}$, where S is a closed surface surrounding x and no other charged body is inside S.

[5] The expression "flux of electric field" is common but misleading, since it invites the thought that the electric field is something that can "flow" from point to point, i.e., that it is a kind of substance. But that is wrong.

Here I have tried to express the tacit assumptions made when using Maxwell's equation for calculating fields and/or charges. The crucial thing is that "q" is a parameter, determined by the volume integral of charge, not a variable bound by a quantifier. Hence we do not assume that it *refers* to a quantity. The label "q" is in a concrete case replaced by a number expressing the quantity of charge attributed to a body and quantities, i.e., quantitative attributes, are not assumed to be entities. Similarly for electric field; it may be viewed as a quantitative attribute of bodies, not a thing that we need to accept as existing.

Maxwell's first equation is a fundamental law of electromagnetism. Holding this version of it true entails that we accept that the following two conditions are satisfied:

1. There exists charged bodies which are the referents of x.
2. These bodies satisfy the predicate 'x has a charge q that satisfy the equation $q = \iint_S \mathbf{E} d\mathbf{S}$, where S is a closed surface surrounding x.'

It is thus not assumed that the expressions "q," "E" or "$\iint_S \mathbf{E} d\mathbf{S}$" $refer$ to any properties; what is needed is $only$ that these predicates have extension, i.e., are true of existing things.

Let us now turn to the differential form of Maxwell's first equation:

$$\triangledown \mathbf{E} = \frac{\rho}{\epsilon_0} \tag{2}$$

This equation literary tells us that the divergence of the electric field and the charge density are proportional. The natural way of expressing it using first order predicate logic is:

> Alternative formulation of Maxwell's first equation: The value of the electric field **E** at every point x is such that its divergence is proportional to the charge density at that point.

Here we have switched ontology; we assume the existence of the electric field. Observe the definite article; electric field is here treated as one single object, in analogy with how we often talk about substances, such as water. Often when we talk about water we mean all the water there is, treating this totality as one single object.

One may observe that field values at different points are not treated as individuals, it is the entire field that is the object talked about. A field is identified by its value at each point in spacetime. It has no position in space, it is literally everywhere.

One is prone to conclude that in this formulation we have added points in space to our ontology. Whether this really is necessary or if points in space can be translated to relational attributes to bodies is a topic for debate, but this is not the place to discuss this further.

Since we know that the differential and the integral form of Maxwell's equation are two formulations of the same law, we have a clear case of swapping ontology without changing neither the structure, nor the empirical content, of the theory.

Without going through the same procedure with the other laws of electromagnetism I presume that this kind of reinterpretation between electromagnetism as a theory of charged particles and as a theory of fields is possible. Moreover, the very fact that one may disagree about the ontology without disagreeing about electromagnetism's empirical correctness illustrates Quine's point.

So we may either interpret electromagnetism as a theory about particles, or about the electric and magnetic fields. But why not say that both particles and fields exist? This seems to be the common view among physicists. However, I see a conceptual problem in doing so. This problem is most clearly seen by considering the status of so called self-fields. This brings us to a recent debate concerning a purported inconsistency of classical electromagnetism.

4. Inconsistency of classical electromagnetism?

Mattias Frisch (2005, 32–34) argues that classical electromagnetism is inconsistent. He states four premises, all held to be true in electromagnetism, that entail a contradiction:

1. There are discrete finitely charged particles.
2. Charged particles function as sources of electromagnetic fields in accord with Maxwell's equations.
3. Charged particles obey Newton's second law (and thus in the absence of non-electromagnetic forces, their motion is governed by the Lorentz force law).
4. Energy is conserved in particle-field interactions, where the energy of the electromagnetic field and the energy flow are defined in the standard way.

Belot (2007) and Muller (2007) have both discussed this argument and arrived at roughly similar verdicts: the formal derivation of the contradiction is correct, but the inconsistency comes from an inconsistent application of **E**, i.e., the electromagnetic field, in the equations. Their argument is in short that Frisch in one expression for the energy assumes that the force on a charged particle depends on the *total* electric field:

$$\mathbf{F} = q(\mathbf{E}_{tot} + \mathbf{v} \times \mathbf{B}) \tag{3}$$

where $\mathbf{E}_{tot} = \mathbf{E}_{ext} + \mathbf{E}_{self}$, i.e., the total field acting on the charge is the sum of the field from other charges and the self-field emanating from the very charge itself, whereas in another expression for the energy he in fact uses only the *external* field in calculating the force and hence the energy. No wonder that an inconsistency arises.

One may think that there is something fishy about the idea of a charged particle acting on itself via its self-field, hence that Lorentz law explicitly and consistently should be expressed as that the force on a particle is produced only by external fields. Feynman et al. (1964, sec. 28.5) discusses this solution, but immediately rejects it:

> However, we have then thrown away the baby with the bath! Because the second term in Eq. (28.9), the term in $\dddot{x}$, is needed. That force does something very definite. If you throw it away, your'e in trouble again. When we accelerate a charge, we must require more force than is required to accelerate a neutral object of the same mass; otherwise energy wouldn't be conserved. The rate at which we do work on an accelerating charge must be equal to the rate of loss of energy per second by radiation. ... We still have to answer the question: Where does the extra force, against which we must do this work, come from? ... For a single accelerating electron radiating into otherwise empty space, there would seem to only one place the force could come from—the action of one part of electron on another part.

So consistency demands of us that we hold that the self-field contributes to the force on a charged particle. The somewhat astonishing fact is that even in the absence of external fields it requires more work to accelerate a charged particle than an uncharged particle with similar mass! (See also Bauer and Dürr (2001, Theorem 1 and Lemma 5) or Komech and Spohn (2000, proposition 2.3) for a proof of the need to take self-fields into account.)

One may observe Feynman's last phrase "the action of one part of the electron on another part." Thus he does not conceive of the self-field as something distinct from the charged particle, it is "another part" of it. One may assume that Feynman adheres to a ontology purely of particles, thinking of fields only as calculational devices, as he did in his joint paper with Wheeler, quoted above. Adopting this view, one might, instead of talking about self-fields, distinguish between the *bare mass* and the *invariant mass* of a particle. The difference between these numbers is equivalent to the effect of the self-field in the calculations of force and energy.

This view is plausible when we think of *classical* electromagnetism, where we may assume that the word "particle" refers to a body, an extended object. However, Feynman's application to electrons (in the quote above) is troublesome, as we shall see when discussing relativistic quantum field theory; electrons cannot be conceived as individual objects, they are merely field quanta.

5. Why not a double ontology?

Belot (2007, 268), in contrast to both Feynman and Weinberg, adopts a double ontology:

> The Maxwell-Lorentz equations (under the present understanding) describe a genuine interaction between the electromagnetic field and a charged particle that already treats the self-field of the particle.

Belot's position seems to be the common one; the real world is populated both by charged particles and electromagnetic fields (including self-fields) and electromagnetism is a theory describing how these entities interact. But I beg to disagree! If talk of interaction, exchange of energy, is to have any meaning one must be able to identify the interacting objects independently of each other. This is impossible when it comes to the self-field of a charged particle; the only way to identify the self-field is by determining it by its source, the charged particle. This is the reason, one might think, why Feynman (in the quotation above) holds that the self-field is a part of the particle.

It is deeply confusing to say that a particle interacts with itself via its self-field. Instead we should either say that fields exist and charge densities are attributes of the fields, or that charged bodies exist and fields are attributes of these bodies. As was shown at the beginning of section 3, in neither case are we forced to say that attributes exist.

This conclusion should be rather straightforward already when looking at Maxwell's first equation; knowledge about the flux of **E** through the surface of a closed area determines the charge inside that surface, and vice versa. Neither the field, nor the charge, has any further relevant properties enabling us to treat them as entities distinct from each other. This makes it hard, I would say impossible, to think of the relation between charge and field as a causal relation between different things, nor as some sort of interaction between them, for the same reason.

It is often said that charges are the sources of electric fields. This should not be interpreted in causal terms, neither should it be viewed as stating the ontological priority of charges over fields. If it is to have any significance whatsoever, I take it as indicating an epistemological point: knowledge about charges enables us to infer values of the electric field at different points and the word "charge" is usually used as an abbreviation for "charged body," a term that sometimes refers to a thing we are able to observe directly. But, perhaps, source-talk is merely a manner of speaking.

Taking a single-ontology view, either conceiving fields as attributes of charged particles, or charges, i.e., charged particles, as attributes of fields, it is immediately clear that we must include the so-called "self-field" term in the expressions for **E**, in order to have a consistent theory. This is ok so long as we do not view the relation between self-field and charge as an interaction between different things.

My conclusion, so far, is that of the three possible ontologies for classical electromagnetism we should reject the particle-and-field ontology as deeply troublesome; either we should conceive electromagnetism as a theory about particles or about fields. We may switch between a particle ontology and a field ontology, but we should not think of these two kinds of entities as interacting with each other.

There is profound analogy in this respect between Maxwell's equations and Einstein's field equations, the fundamental law of general relativity theory:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{4}$$

These 16 equations (both μ and ν take the values 0, 1, 2, 3) may be interpreted as stating that two quantitative descriptions of the world, the stress-energy-tensor $T_{\mu\nu}$ and the spacetime description $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda$, i.e., a function of the metric tensor $g_{\mu\nu}$, are proportional. By itself eq. (4) does not say that the universe consists of two interacting entities, matter-energy and spacetime. Nor is there anything in this equation suggesting a causal mechanism going from matter-energy distribution to the spacetime geometry, or vice versa.

When expressing the content of these equations in complete sentences with subject-predicate structure we either say something like "the matter/energy of the universe has a certain spacetime-structure" or "the spacetime structure of the universe has a certain matter-energy distribution." The point is that by itself, eq. (4) does not determine what to treat as object of predication and what to treat as attribute. Similarly, we may swap between charged particles and fields as objects of predication.

We may say that in modern theoretical physics the distinction between object and attribute is merely a matter of linguistic convention, necessary for formulating declarative sentences, but not reflecting any physical fact. (I am repeating the point made in section 3.) The core feature of physical equations is that they state relations between physical quantities. However, when we submit our theories to empirical testing we need to identify objects which can be attributed values of quantities. So the question is: what kind of objects do we need when expressing observations supporting our theory?

6. What do we observe?

Physics, like any empirical theory, must make contact with the external reality as observed by us humans. And what we observe, independently of any theory, are first and foremost medium sized bodies. (In experiments we observe detectors, and these are medium sized bodies.) No matter what we think of the causes of bodies' motions, of charges, electromagnetic fields or whatsoever, we easily agree on statements about positions and state changes of visible bodies. In classical mechanics and classical electromagnetism such bodies are represented as particles, so particles are unavoidable in our ontology. By contrast, fields are never *directly* observed; the values of electric and magnetic fields are inferred from observations of states of bodies. So we need bodies in our ontology anyway; this is a fact about ourselves as observers of the external world.

This conclusion may seem to conflict with Quine's ontological relativity, the stance that ontology is relative to choice of predicates used in our preferred theory formulation. But in fact it does not. The fact that we can use proxy functions for translating true sentences in one theory, or in our vernacular language, into true sentences in an empirically equivalent theory is certainly correct. This, however, does not conflict with the empirical fact that we humans express our observations in our natural languages by discerning bodies and saying things about them.

How do I know that we all do that? Well, research on prelinguistic children's perceptual activities strongly indicates that babies long before they master language are able to focus on moving bodies, they see continuously existing physical objects that move. Here is one conclusion of such research:

> A basic process for perceiving spatiotemporally connected and continuous objects arises early in development, without significant tutoring. …This process is likely to be universal across human cultures, leading all people to perceive, act on, and talk about the same spatiotemporal bodies. (Spelke and Newport 1998, 297)

So we may, using empirical evidence, conclude that the ontology of our immediate observation reports is an ontology of bodies and it is such reports we can agree upon, irrespective of theoretical convictions. Such reports make up the intersubjective basis for science.

We can use proxy functions for translating this ontology to e.g. local fields or, as in Quine's *Word and Object*, from rabbits to time-slices of rabbithood. But anyone holding that fields, or some other arcane objects, are the ultimate building blocks of nature, must base his claim on empirical evidence; and empirical evidence, when expressed as observation reports, is expressed in terms of bodies.[6]

This empiricist stance does not entail that one rejects unobservable things as non-existing; it only means that one holds that all evidence for a theory ultimately consists of observations and we may have strong evidence for many not directly observable things.

There is, however, a metaphysical argument for adopting a field ontology instead of a particle ontology in classical electromagnetic theory. For if we conceive of the physical world as populated by particles, i.e., bodies confined within well defined portions of space and interacting with each other, we face the ancient-old conundrum: how could two things at different places interact without anything in between transmitting the interaction? How is action-at-a-distance possible? The desire to get rid of this conundrum has been, I guess, a strong reason to adopt a field ontology instead of a particle ontology.

Our skepticism about action at-a-distance comes from a illicit tacit assumption about space, viz., that it is a sort of "container" for physical events. If we reject that picture and take relativity theory into account, we realise that spatial distance is relative to observer. The objective distance measure is the spacetime interval, and the spacetime interval between two events connected by being the emission and absorption of one and the same photon is zero. (And such exchanges of photons is the way bodies interact in electromagnetism.) There is, from an observer independent point of view no distance at all between these two events; in fact they might better be described as two descriptions of the same event. (Cf. coin flipping: "heads up" and "tails down" is the same outcome.) So I do not think we should take action-at-a-distance in electromagnetism as a problem; it merely appears problematic because we do not experience the fact that spatial distance is observer-dependent.

This is in my view the preferable ontology for classical electromagnetism. But, alas, it does not hold water when we move to quantum field theory, the Lorentz invariant quantised version of electromagnetism.

7. Relativistic quantum electrodynamics

The particle interpretation of quantum theory has come under heavy criticism from among others Gerhard Hegerfeldt (1998b,a) and David Malament

6 This conclusion contradicts Quine's thesis of inscrutability of reference. Quine might be right in holding that just by talking to other people and agreeing on the truth of occasion sentences we have not sufficient reason to conclude that others have bodies in their ontology; but cognitive research has given us additional evidence.

(1996). The latter argued that there can be no relativistic quantum theory of (localisable) particles, which entails that quantum electrodynamics cannot be interpreted in terms of particles. The paper started a debate and Halvorson and Clifton (2002) has defended Malament against several objections.

Malament's argument is based on four conditions, which seem entirely reasonable demands on any relativistic quantum theory describing anything that can be called "a particle." The conditions are (M is Minkowski spacetime, U is a unitary operator, Δ is a subset of M assigned to a projection operator P_Δ):

1. Translation Covariance Condition: For all vectors a in M, and all spatial sets Δ, $P_{\Delta+a} = U(a)P_\Delta U(-a)$ (where $\Delta + a$ is the set that results from translating Δ by the vector a).

2. Energy Condition: For all future directed, unit timelike vectors a in M, if H(a) is the unique self-adjoint ("Hamiltonian") operator satisfying $U(ta) = e^{-itH(a)}$, the spectrum of H(a) is bounded below, i.e., there exists a real number k(a) such that $\langle \phi, H(a)\phi\rangle \geqslant k(a)$ for all unit vectors ϕ in the domain of H(a).

3. Localisability Condition: If Δ_1 and Δ_2 are disjoint spatial sets in a single (common) hyperplane, $P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1} = 0$

4. Locality Condition: If Δ_1 and Δ_2 are spatial sets (not necessarily in the same hyperplane) that are spacelike related, then $P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1}$

The translation covariance and the energy condition are rather obvious constraints on any relativistic theory. The localisability condition states what we mean by a particle, viz., an object that can be found in a well defined portion of space. The locality condition is weaker than the traditional condition that no object can travel with infinite speed. It merely says that the projection operators P_{Δ_1} and P_{Δ_2} commute, i.e., that the probability of detecting a particle in Δ_1 is statistically independent of whether a detection experiment is performed in Δ_2 and vice versa.

From these assumptions Malament proves:

> Theorem: If the structure $(H, a \mapsto U(a), \Delta \mapsto P_\Delta)$ satisfies conditions (1)–(4), then $P_\Delta = 0$ for all spatial sets Δ.

Malament (1996, 6) comments:

> We can think about it this way. Any candidate relativistic particle theory satisfying the four conditions must predict that, no

> matter what the state of the particle, the probability of finding it in any spatial set is 0. The conclusion is unacceptable. So the proposition has the force of a "no-go-theorem" to the extent that one considers (1) through (4) reasonable constraints.

Halvorsen and Clifton points out that this does not show that it is impossible to construct particles as supervenient on localised fields, but they formulate a theorem, which with very reasonable assumptions excludes this possibility.

So an interpretation of electromagnetism that takes as its ontological basis electrons and other charged quantum particles, conceived as being confined to definite volumes in space, is out of the question, if we represent states of those particles by vectors in Hilbert spaces. The field interpretation is the only remaining option; a field is by its very nature not confined to limited portions of space, it does not satisfy the localisability condition.

This fact is related to another well-known feature of so called "quantum particles," viz., that in general they lack identity criteria.[7] Since quantum particles lack identity criteria, we cannot quantify over them and treat them as objects interacting with other objects in quantum field theory. (And this is the fundamental reason, I think, why we got into the trouble with self-fields.)

It has been argued, for example by Segal (1964) and Barrett (2001) that empirical evidence supporting relativistic quantum field theory consists of observations of particles, i.e., objects being at a particular place at the time of observation:

> It is an elementary fact, without which experimentation of the usual sort would not be possible, that particles are indeed localised in space at a given time. (Segal 1964, 145).

Halvorsen and Clifton comments:

> It seems to us, however, that the moral we should draw from the no-go theorems is that Segal's account of observation is false. In particular, it is not (strictly speaking) true that we observe particles. Rather, there are 'observation events', and these observation events are consistent (to a good degree of accuracy) with the supposition that they are brought about by (localisable) particles. (Halvorson and Clifton 2002, 23)

I fully agree with Halvorsen and Clifton: what we directly observe are state changes in detectors, not particles. Such observations may be interpreted as

[7] French and Krause (2006) discusses identity criteria in physics and entertain the possibility of attributing quantum particles a primitive identity, a form of "thisness." I do not see any gain in accepting this proposal. It appears to me being a case of *obscurum per obscurus*.

the presence of a particle in the detector, but it is not a logical consequence of the observation sentence "the detector was triggered." The field interpretation of triggering events, viz., that the detector absorbs quanta of external fields, which are not localisable particles, is also possible. And I would say, mandatory. If we assume that the detection was triggered by a particle which was present in the detector at the moment of triggering, it must have been present in a portion of space close to the detector not only at the moment of detection but also just before; it follows that an object with a well defined position at every moment in time moves from point to point in a continuous trajectory. Hence, at the moment just before triggering the detector it must have been present in another nearby portion of space, etc. In other words, a particle must have followed a trajectory up to the moment of detection. But we know from interference experiments that that's wrong; so called "quantum particles" cannot be attributed definite trajectories. A particle interpretation of the time evolution of a quantum system conflicts with both theory and experiment. The fact that quantum systems interact with macroscopic devices at reasonably well defined portions of space only shows that quantum systems *interact* as particles, not that they *propagate* as particles.

But also quantum field theory is based on observations of bodies; so this theory alone cannot fully account for its observational basis![8] This is the (in)famous measurement problem of quantum mechanics. I have elsewhere (Johansson 2007, ch. 6) argued for a collapse interpretation of the measurement problem, but this is not the place to dig into that topic further.

Thus, we should be careful to distinguish classical and quantum contexts when using the word "particle." In the classical domain it means a body where we disregard its extension and inner structure but attribute a definite trajectory to it, whereas in the quantum realm the word "particle" and its cognates (electron, photon, etc.) signifies a portion of a conserved quantity, a field quantum, lacking identity and well defined trajectory.

8. Summary

The natural and common interpretation of *classical* electromagnetism as describing how charged particles interact with electromagnetic fields is in my view untenable. Particles and fields cannot be thought of as interacting things; either we should think of fields as calculational devices; the electric

[8] In the Bohm interpretation of quantum mechanics it is taken for granted that there are particles that follow definite trajectories and that these particles are guided by "pilot waves." In other words, they postulate some new kind of interaction between particles and pilot waves without telling us how this might work, nor do they predict any new observable phenomena. It is not a fifth kind of interaction beside the four hitherto known. In my view, Bohm's followers get more problems than those they attempt to solve.

field at a certain point is a description of the effects of distant particles may have on a test particle at that point, or we may take the opposite view by holding that talk about charged particles are nothing else than descriptions of electric fields. From a purely theoretical point of view both positions are possible. But since bodies are fundamental from an epistemological point of view, and bodies are represented in classical electromagnetism as particles, the choice for an empiricist must be to adopt particle ontology of *classical* electromagnetism.

When moving to the quantised version of electromagnetism, quantum field theory, we must choose an ontology of fields because a particle interpretation of a relativistic quantum theory is impossible. The relativistic quantum theory cannot be viewed as consisting of particle-like objects with well-defined spatial boundaries. But our evidence for this theory are observations of precisely such things, viz., observations of measurement devices. So quantum field theory, and in fact quantum theory in general, has a problem of giving an account of its empirical basis using only its own concepts. This is the measurement problem.

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