On conceptual issues in classical electrodynamics: Prospects and problems of an action-at-a-distance interpretation

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Abstract
Some conceptual issues in the foundations of classical electrodynamics concerning the interaction between particles and fields have recently received increased attention among philosophers of physics. After a brief review of the debate, I argue that there are essentially two incompatible solutions to these issues corresponding to Fred Muller's distinction between the extension and the renormalization program. Neither of these solutions comes free of cost: The extension program is plagued with all problems related to extended elementary charges, the renormalization program works with point charges but trades in the notorious divergences of the field energies. The aim of this paper is to bring back into the discussion a third alternative, the action-at-a-distance program, which avoids both the riddles of extended elementary charges as well as the divergences although it admittedly has other problems. It will be discussed, why action-at-a-distance theories are actually not a far cry from particle-field theories, and I will argue that the main reasons for rejecting action-at-a-distance theories originate in certain metaphysical prejudices about locality and energy conservation. I will broadly suggest how these concepts could be adapted in order to allow for action at a distance.

Keywords: electrodynamics, action at a distance, locality, energy conservation

1. Introduction

Modern classical electrodynamics is formulated as a particle-field theory, i.e. its fundamental ontology comprises both fields and charges. By contrast, 19th century electrodynamics was dominated by pure field theories on the one hand, developed primarily by Michael Faraday and James Clerk Maxwell, and by pure particle or action-at-a-distance[2] theories on the other hand pursued among others by André-Marie Ampère and Wilhelm Weber. The essential characteristic of pure field theories is that charges and currents are derived entities, secondary to the field concept. In aaad theories the situation is just the opposite: While fields may be used for ease of description, they are secondary to the concept of charges and currents, i.e. on the fundamental level fields can be dispensed with. Here and later on, we take as a necessary and sufficient condition for considering an entity as secondary, that it possesses no degrees of freedom on its own.

Broadly, modern particle-field theories emerged in the early 1900s from Maxwell's pure field theory after the discovery of charge quantization and of the first elementary particles. These discoveries essentially prompted the need to amend the by then dominant field theories with

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[2] henceforth abbreviated as aaad

particle concepts accounting for the atomistic nature of matter. Thus, in important respects modern particle-field theories can be interpreted as a merging between action-at-a-distance theories and pure field theories: "[t]he electron theory has quite a few similarities with the [aaad] theory of the two electric fluida as advocated especially by Wilhelm Weber." (Lorentz, 1905, p. 7; my translation)[3]

In 20th century physics neither pure field theories nor pure aaad theories played a prominent role. The most important proponent of pure field theories was arguably Albert Einstein with his search for unified field equations, that could account both for the evolution of the field and for the particle motion by just using the gravitational field $g_{\mu\nu}$ and the Maxwell field φ_μ: "it is common to all these attempts [of developing a unified field theory] to conceive physical reality as a field" (Einstein, 2001, p. 112).

Pure aaad as well played at best a minor role with only rare publications on the subject—e.g. by Jakow Frenkel, Karl Schwarzschild, Hugo Tetrode, and Adriaan Fokker[4]. In the 1940s, John Wheeler and Richard Feynman (1945, 1949) reconsidered electrodynamic aaad. Since Feynman eventually came to play an important part in laying the foundations for quantum electrodynamics, quite plausibly his earlier work on aaad provided insights for his later ideas. In his Nobel lecture (1965), he sketches some connections between these two strains in his work.

All these researchers turned to aaad for conceptual reasons connected mainly with difficulties in the description of the interaction between particles and fields. Some of these problems have recently been the subject of a debate between philosophers of physics triggered mainly by a provocative article and a penetrating book by Mathias Frisch (Frisch, 2004, 2005). Among the discussants only Frisch (2005) mentions aaad, but he is in general rather unsympathetic to it. Moreover, he discusses aaad mainly in the specific version of Wheeler and Feynman and as a—in his view failed—solution to the problem of founding the arrow of radiation (2005, Ch. 6). My article aims at bringing action at a distance back into the game as a viable alternative to particle-field programs, when it comes to tackling some of the notorious conceptual issues plaguing classical electrodynamics.

Section two will review the recent debate by philosophers of physics on conceptual problems of particle-field theories. My analysis will rely on the excellent overview which Muller (2007) gives on the status of the corresponding debate in the physics community. Two programs, which Muller terms the renormalization and the extension program, have been proposed as solutions to the conceptual problems. These programs are incompatible in several respects. I will compare the advantages and disadvantages of both approaches and then argue that there is a third option that is worth considering—namely aaad formulations of electrodynamics. Aaad is surely not the universal solution to all problems, but I will establish it as a viable alternative.

Section three will address the question why we should worry about different interpretations of classical electrodynamics and their respective conceptual problems, mainly by pointing to the notoriously difficult relation between classical theories and the quantum domain, e.g. in connection with locality and determinism. I will argue for approaching this relation from both the classical and the quantum side. Important insights may result from comparing interpretations of classical theories that take different stances concerning locality and / or determinism, e.g. from comparing local particle-field electrodynamics with non-local aaad electrodynamics. I will also point out, why the current situation in classical electrodynamics

[3] Cp. also Darrigol (2000, pp. 325-327) and Pietsch (2008).
[4] For references see Wheeler and Feynman (1949, p. 425).

involving two incompatible research programs cannot be the final word regarding the conceptual problems, even if both approaches provided fully satisfactory solutions.

Section four will weigh virtues and vices of aaad approaches in electrodynamics. Aaad is the only option, which relies on point-particles and at the same time evades the notorious divergences of the field energies. Another advantage, which it shares with pure field theories, is ontological sparseness. Finally, an interesting case can be made for aaad from its mathematical equivalence with pure field theories. The equivalence was pointed out by William Thomson and by Maxwell for 19th century electrodynamics, but there are no fundamental reasons why with the necessary ingenuity it could not be established for the modern theory. By contrast, particle-field views are neither equivalent to pure field theories nor to aaad. The proximity to pure field views can be turned into an argument for aaad views.

On the negative side, the main problems of aaad fall into three categories: (i) those connected with advanced action, which also plague the renormalization program, (ii) those connected with the postulation of ideal absorbers and emitters, and finally (iii) those having to do with general metaphysical intuitions about locality and energy conservation. I will argue that the rejection of aaad electrodynamics has mainly relied on the last class. Therefore, the rest of the article will explore how these intuitions could be altered in order to allow for aaad.

Sections five and six will deal with the two main metaphysical arguments against aaad (e.g. Frisch 2005, pp. 79-80): based on locality and conservation of energy[5]. While both concepts in their usual formulation indeed rule out aaad, I will broadly propose analogous concepts, which are compatible with aaad, while at the same time satisfying the original intuitions supporting locality and conservation of energy. A certain weak notion of locality implies only that the strength of the interaction diminishes reasonably fast with the distance between interacting bodies. This type that I will call (somewhat paradoxically) 'action-at-a-distance locality' does not require contact between interacting bodies, while nevertheless preserving the pragmatic significance of locality. Conservation of energy can be reconciled with aaad, if energy is interpreted relationally. Then, conservation of energy is a functional dependence between the mutual distances and the relative velocities of all bodies belonging to a closed system.

2. Comments on the recent debate

The debate began with an argument by Frisch (2004, 2005) claiming to prove the inconsistency of classical electrodynamics. In the ensuing discussion the focus somewhat shifted away from this inconsistency claim and its implications for physical theorizing to what Frisch recently called "arguably the philosophically more interesting issue": That is "the fact that a host of conceptual problems arises when one tries to develop a classical theory of charged particles interacting with electromagnetic fields in a way that includes self-interaction effects" (2008, p. 96).

The debate on Frisch's book produced an astonishingly dissonant reply by other philosophers of physics (Muller, 2007; Belot, 2007; Vickers, 2008). While there is general consensus that the inconsistency, that Frisch claimed to exist in classical electrodynamics, arose from his explicit exclusion of self-forces from the Lorentz force law there seems to be little agreement as to if and to what extent this exclusion was warranted or not. While Muller (2007) outright rejects Frisch's construal of classical electrodynamics, Belot (2007) and Vickers (2008) are in different degrees more sympathetic. Also, while there seems to be some agreement on

[5] Frisch mentions a third issue, the difficulties connected with formulating an initial value problem in retarded aaad. Since this seems to be rather a pragmatic issue than a metaphysical one, we will not further address it here.

where the conceptual problems in classical electrodynamics lie—(i) diverging self-energy of point charges, (ii) pre-accelerations and (iii) self-acceleration (Frisch, 2004, pp. 537-540; Muller, 2007, pp. 264-265)—opinions differ on if these problems are to be resolved as well as how they can be resolved: Frisch (2003) opts for an inconsistent version of classical electrodynamics suggesting that the mentioned problems are not generally in need of resolution. Instead, he urges for a revision of the criteria for theory acceptance in science. Muller (2007)—on the other end of the spectrum—believes that the problems already have convincing solutions and that the ubiquitous practice of physicists opting for a Lorentz force neglecting self-energies is merely an instance of idealization or approximation: "a majority of the exact equality signs (=) in most physics papers, articles and books means approximate equality (≈)" (p. 261).

Muller (2007) sets himself two aims: to counter Frisch's inconsistency claim and what he terms Frisch's inadequacy claim. The latter states, that all consistent revisions of classical electrodynamics are beset with conceptual problems which are not resolvable or whose resolutions imply a price that is too high in the eyes of most physicists (Muller 2007, p. 253). Muller successfully counters both claims by presenting an overview over the extensive literature discussing these problems and by laying out two programs, which make substantial attempts at solving all three conceptual problems mentioned above.

2.1 The renormalization and the extension program

Muller broadly distinguishes two approaches for addressing the conceptual issues in classical electrodynamics—one he calls the *renormalization program*, the other the *extension program*. The renormalization program bites the bullet on problem (i): in spite of the energy divergences this program assumes elementary charges to be point-like. Consequently, there is a need to 'renormalize' the energy, i.e. to make the divergent energy finite in order to extract physical meaning from the energy content of a particle. As Dirac, arguably the first proponent of the renormalization approach, writes: "We shall retain Maxwell's theory to describe the field right up to the point-singularity which represents our electron and shall try to get over the difficulties associated with the infinite energy by a process of direct omission or subtraction of unwanted terms." (1938, p. 149) Another approach favored among others by Max Born also opts for point-charges, but changes the Maxwell equations in the immediate vicinity of the point-charges in order to get rid of the divergences (Born 1933, Kiessling 2004). However, unlike the renormalization and extension programs, this suggestion seems not to have caught on.

The extension program, which dates back to Max Abraham and Hendrik A. Lorentz, solves problem (i) of the divergent self-energy of point-charges by assuming that elementary charges are not point-like but continuously extended. Thereby the divergences disappear. The apparent self-forces of elementary charges can then be explained through the mutual interaction of the different parts of the particles.

In what follows it will be discussed that both research programs are fundamentally incompatible in at least two important respects: in the extension program extended particles and the Lorentz force $\boldsymbol{F} = Q[\boldsymbol{E}+(\boldsymbol{v} \times \boldsymbol{B})]$ are fundamental. In the renormalization program point charges and the Lorentz-Dirac force (or related extensions of the Lorentz force) are fundamental.

2.2 Conceptual problems of classical electrodynamics

Let me summarize from my own point of view some of the conceptual problems in classical electrodynamics[6]. First, there is the mentioned divergence of the self-energy of point charges, which has been known ever since the expressions for field energies were formulated in the late 1800s.

A second crucial problem concerns the origin of the radiation that accelerated particles emit. When an external force (no matter if electrodynamic in nature or not) acts upon an electrical charge (elementary or not) it turns out that the reaction in terms of acceleration of the particle does not correspond exactly to the action imposed on the particle in terms of external force. The missing portion of the force is in general interpreted as a self-force—due to the interaction of the electron with its own field.[7] That there is a discrepancy in the force balance was first discovered in the fact that according to Maxwell's Equations charges radiate energy, whenever they are accelerated (Larmor 1897). In fact the radiated energy is the negative of the work performed by the self-forces.

It must be stressed however, that prima facie the radiation of energy cannot *explain* the discrepancy between action and reaction, it *results* from it. An explanation of the radiation-reaction should not point to the emitted radiation but rather to the self-forces, which alone can restore the force balance (at least if advanced action is excluded). An explanation should describe the internal mechanism that is responsible for the imbalance between imposed force and the acceleration of the charge. Intriguingly, point particles by definition cannot possess internal forces, since by stipulation point particles have no internal structure whatsoever. Thus, an *explanation* of the radiation reaction seems feasible only for extended particles.

On the other hand, point particles are mostly held to be preferable for diverse conceptual reasons. If the *elementary* charges are posited to be extended, one trades in a host of other issues. The main problem facing extended elementary charges concerns the unknown nature of the forces holding these charges together by counterbalancing the electrostatic forces. Also, there is until today no empirical evidence whatsoever that electrons do have a structure in the order of magnitude of the classical electron radius or of the kind of structure on any other scale: rigid or elastic, oval or spherical etc. Let us finally emphasize, that what we are concerned with is not if the particles we consider point-like today, i.e. electrons and so forth, have a substructure or not. It is rather a question if there is an infinite 'matryoshka' of further and further substructures, if there is always another doll or not. Either charges are continuous all the way down or we will encounter at a deeper level the problematic divergences all over again.[8]

Thus, while the extension program trades in an explanation of the origin of the self-forces for the conceptual issues having to do with extended elementary particles, the renormalization program seems to lack in principle an explanation for the self-forces just because it assumes

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[6] A large class of solutions to the Lorentz-Dirac equation of motion exhibits pre-accelerations and self-accelerations, which violate energy conservation. A discussion of these problems is omitted here, since some recent literature suggests that they can be avoided (cp. Rohrlich, 2007, pp. 257-264 and references therein).

[7] Feynman was in general not very sympathetic to the idea of self-forces, which constituted one of the main reasons, why he turned to action at a distance: “Well, it seemed to me quite evident that the idea that a particle acts on itself, that the electrical force acts on the same particle that generates it, is not a necessary one—it is a sort of a silly one, as a matter of fact.” (Feynman 1965, p. 156)

[8] This is not meant to reiterate the worry about foundational looping that Frisch has expressed about the extension program (2008, p. 102). Foundational looping, a term Frisch borrows from Mark Wilson, happens when a supposedly more fundamental theory needs to draw on the resources of the higher-level theory. By contrast, my point here is that if you opt for the extension program you have to commit yourself to matter being of essentially continuous character—which may of course be difficult to reconcile with atomism.

point-particles. A way out of this dilemma is to somehow make the *emitted* radiation explanatorily relevant in the renormalization program. If the emitted radiation can somehow causally account for the imbalance between action and reaction, this would save the point-particle approach—although by most accounts it implies backward causation. Such an approach was first pursued by Dirac (1938). According to Dirac the self force resulting in the radiation reaction equals half the difference between the retarded force and the advanced force due to the particle itself and evaluated at its location (p. 154). Although Dirac (1938) takes a rather instrumentalist perspective, it is clear that if he really wants to save the point-particle view he has to take the advanced forces involved to be explanatorily relevant. Then unlike in the extension program, in the renormalization program the observed Lorentz-Dirac force is not just a short description for the real Lorentz forces acting inside the charges, Dirac has to take the new extended Lorentz force as a fundamental law—as the fundamental force governing the motion of charged particles.

Here, we encounter another fundamental difference between the extension program and the renormalization program. While the former in principle accepts the Lorentz force to be fundamental and explains observed deviations through Lorentz forces within the elementary charge, the renormalization view must subscribe to a change of the fundamental force law, namely to the Lorentz-Dirac force. While in the extension program the observed difference between the external force and the observed reaction is explained in terms of the inner structure of the particle acted upon, in the renormalization program the fundamental force law itself is changed.

As we will further elaborate in Section three it would be odd to consider the problems surrounding the diverging self-energy and the origin of the radiation reaction to be solved, as long as there are two incompatible options around: one program holding extended particles and the Lorentz force to be fundamental and another program holding point particles to be fundamental and arguing for a change in the fundamental force law to take account of the radiation reaction.

2.3 The action-at-a-distance program

Let us move on to the main subject matter of this essay, which is to put back on the table another option dealing with the conceptual issues portrayed above: that is an aaad interpretation of electrodynamics broadly construed in the way Wheeler and Feynman formulated their aaad-electrodynamics in the 1940s. Aaad provides an easy solution to the divergences troubling the renormalization program while at the same time maintaining point charges and thus avoiding the difficulties connected with postulating extended elementary charges. This is not meant to suggest that I am necessarily convinced that aaad is *the* way to tackle the problems depicted above. I just want to enrich the current discussion by arguing that this option, although neglected in recent physics, is at least not worse than the other ones.

One can best think of the relationship between the aaad and the particle-field programs as different interpretations of the same mathematical formalism of classical electrodynamics. However, in part owing to some established terminology (as in 'Wheeler-Feynman theory' or 'particle-field theories') I will also refer to the different interpretations as different theories. This is also in accordance with both standard accounts of scientific theories, i.e. the semantic and the syntactic view, where theories always comprise both mathematical formalism and its interpretation. Furthermore, in real theories (as opposed to toy models of theories) the distinction between formalism and interpretation is always somewhat blurry as is the question, which parts of a theory are empirically relevant and which not.[9]

Although the aaad program may at first sight seem much more radical than the other options, aaad is actually not such a far cry away from modern classical electrodynamics. It is only more restrictive in that it adds to the framework of classical electrodynamics (to what Muller calls its Lakatosian core) an ideal emitter and an ideal absorber—i.e. it adds the postulate, that all observed radiation has a material source, is emitted by charged particles, and that all observed radiation has a material absorber, is absorbed by charged particles. Then all fields can be calculated from the matter distribution (in principle), i.e. fields have no proper degrees of freedom and thus become secondary quantities.

Proper degrees of freedom are taken here as a necessary and sufficient condition for entities to be fundamental *in a specific theory*: necessary, because entities without proper degrees of freedom can be expressed by other terms and thus eliminated on the fundamental level; sufficient, because entities with proper degrees of freedom cannot be fully expressed by other terms. Similar intuitions lie behind Feynman's notion of fields as bookkeeping devices as well as behind Maxwell's notion of charges and currents as secondary quantities. Note, that I am not taking any stance here on the metaphysical question, if one can conclude from the fundamentality of an entity to the existence or reality of this entity.[10]

The difference between aaad theories and particle-field theories thus is not huge—it only involves the additional postulate of an ideal emitter and absorber, one that is quite difficult to verify or falsify empirically, as we will see in Section four. In principle, it would even be enough to postulate *either* an ideal emitter *or* an ideal absorber, since one such entity already allows expressing the state of the field through the motions of the emitting or absorbing particles, respectively. However, it seems more faithful to the idea of aaad and the interpretation of fields as bookkeeping devices to assume, that there are always particles interacting at 'both ends' of the field, that there are no field-lines dangling in the void neither in the future nor in the past. In addition, various symmetry reasons speak in favor of postulating both absorber and emitter.

Finally, I want to resist the attempts to identify the aaad program with any specific approach like the Wheeler-Feynman theory or Weber's theory. Such a step would be detrimental, as it would link aaad with specific conceptual problems that are not necessarily part and parcel of aaad. For example, the problems connected with advanced action are not genuine to aaad but inherited by the Wheeler-Feynman theory from Dirac's rendering of radiation reaction within a particle-field view. *Any* electrodynamic particle-field interpretation can be quickly turned into an aaad interpretation by postulating the existence of ideal absorbers and emitters.

3. Why worry about classical theories

Before we continue to discuss action at a distance as an alternative to the extension and renormalization programs, let us first address a fundamental worry: Why should we care about interpreting classical theories given that they have been superseded by quantum theories? Why

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[9] A detailed discussion concerning the role of theories and models in classical electrodynamics is given in Frisch (2005, Ch. 1).

[10] Possibly, the fundamentality of an entity in our best theories is not a sufficient condition for the reality of this entity. One problem for such an inference could be underdetermination, i.e. that there might be equally well supported theories relying on totally different fundamental entities. A good example for this is the comparison between pure field and pure particle electrodynamics in the 19th century (Pietsch, 2008).

should we address conceptual problems in classical electrodynamics (CED) in view that there is a more fundamental theory in quantum electrodynamics (QED)?

My argument for considering different interpretations of CED and their respective conceptual problems will draw largely on Rohrlich and Hardin's (1983) notion of 'established theories', which is endorsed by a number of philosophers of physics including Frisch (2009, pp. 257-258) and Torretti (1990, p. 80)[11]. Established theories are mature theories which in spite of having been superseded by more fundamental theories remain a permanent part of science within certain limits of validity. Established theories play a crucial role in Rohrlich and Hardin's specific brand of scientific realism, enabling them to reconcile the progressiveness of science with the argument from pessimistic metainduction, according to which evidence from the history of science makes it likely that all theories will once be superseded.

From this point of view, the difference between established and fundamental theories is of purely epistemic nature, a matter of *knowing* the limits of validity. Consequently, both types of theories should be treated in much the same way, including matters of interpretation and conceptual assessment: „Any mature theory [established or not] can continue to grow, to develop, and to encompass previously unknown phenomena. Whole journals are devoted to nonrelativistic mechanics. Two established theories, quantum mechanics (which receives its validity limits from quantum field theory) and electrodynamics (established by quantum electrodynamics) led to the development of the laser, long after they became established. Not surprisingly, established theories are the building blocks not only of the curriculum, but of almost all research in physical science. They take as their proper domains most of the phenomena with which we are acquainted." (Rohrlich & Hardin, 1983, p. 608)

Based on the notion of established theories, four reasons can be given for interpreting classical theories: (i) Since established theories continue to be applied, dealing with different interpretations and their respective conceptual problems is essential for guaranteeing the sensible use of the theories. (ii) Established theories generally enjoy an autonomous and ineliminable character, not least in terms of interpretations. This holds in particular for classical theories, which provide the language for the description of all quantum observations and quantum measurements. (iii) Interpreting classical theories can help us to understand better the notoriously difficult relation between the classical and the quantum domain. (iv) Finally, there is an argument from scientific practice in theoretical physics, namely that conceptual issues in classical physics are being discussed by theoretical physicists largely without reference to the quantum domain.

Let us look at each of these reasons in further detail. (i) A strong argument for worrying about conceptual problems and different interpretations of classical theories derives from the observation, that classical theories play a crucial role in applications—an observation which lies at the very heart of the concept of established theories. Since interpretations provide the link between formalism and facts, any applied theory is in need of an interpretation (Rohrlich, 1988, p. 306). Also, dealing with different interpretations and their respective conceptual problems is crucial for determining the range in which a theory can be safely applied. As an example, one should be careful in applying CED in the microscopic domain, given the energy-divergences of point-particles and the uncertainties concerning the exact nature of extended fundamental particles.

Furthermore, there are always pragmatic reasons for keeping different interpretations of applied theories. Different interpretations can provide natural viewpoints for different

[11] I am grateful to one of the referees for urging me to engage with this concept.

phenomena. A field view is better suited for dealing with electromagnetic interaction via media or for dealing with optical phenomena, while an aaad view is the intuitive perspective for dealing with the interaction between distant particles or currents. Even a superficial look at current scientific practice and at the history of discovery of electromagnetic phenomena can substantiate this claim.

(ii) Even though quantum theories constitute today's most fundamental level of physics, the language of our observations and measurements is purely classical, indicating a strong autonomy of classical physics. This circumstance has been particularly stressed in the Copenhagen interpretation of quantum mechanics, but it is largely independent of the individual commitments to one or the other interpretation of quantum theory. As is stressed by Rohrlich, we are faced with a *mutual* dependence between the quantum and the classical level, which relativizes the alleged exclusive dominance of quantum theories over classical physics: „The situation makes quantum mechanics incomplete without its classical approximation: the lower-level theory must be contained in the higher-level one as a suitable approximation in order that we can carry out the necessary measurements of the higher-level theory.“ (Rohrlich, 2007, p. 5; cp. also Rohrlich, 1988, p. 309) In particular when complicated limiting processes are involved, as is the case for the relation between classical and quantum physics, Rohrlich stresses the autonomy of established theories as regards interpretations (1988, p. 307).

Another author who presents a strong case for the ineliminability of classical theories is Robert Batterman (1995, 2002). Batterman argues that classical theories can be retrieved from quantum theories only via a *singular* limiting relation, in which the finer theory does not smoothly approach the coarser one. According to Batterman, “any pair of theories related by such singular limits will give rise to new physics requiring a new explanatory theory of the asymptotic domain“ (2002, p. 78).

(iii) As Batterman and Rohrlich's construal highlights, the relation between the classical and the quantum domain is notoriously complicated and controversial. This holds in general but also for specific theories like the relation between QED and CED.[12] Given such a state of affair, it seems necessary to approach the intertheoretic relation both from the quantum and from the classical side, regarding formal and interpretational aspects. That reduction is never a one-way road has been stressed by philosophers of science and by philosophically inclined physicists alike, such as Rohrlich (1988, p. 304), Abner Shimony (1987, p. 419-424), or the Nobel laureate and condensed-matter theorist Philip W. Anderson (1972, p. 396). Starting with quantum mechanics, one might consider different limiting processes recovering the classical domain. Starting with classical theories serves to clarify, which limits one should be looking for in the first place. It might be of particular interest to look at different interpretations of classical theories which take different stances concerning crucial concepts like locality or determinism. This provides an important motivation for comparing *local* particle-field electrodynamics with *non-local* aaad interpretations and the way these programs fare regarding conceptual problems arising in CED.

(iv) Finally, there is an argument from the way conceptual and interpretational issues of CED are treated in theoretical physics. Remarkably, they are rarely framed in the context of a reduction of QED to CED. Much of the literature on conceptual problems in CED, referred to for

[12] Still in the recent third edition of his monograph, Rohrlich (2007) stressed that a full reduction of QED to CED has not been accomplished: „can relativistic quantum electrodynamics be reduced to relativistic classical dynamics of charged particles? The answer must be positive, but so far, nobody has yet provided such a mathematical reduction.“ (p. 254; see also Spohn 2004, p. 146).

example in Muller's résumé (2005), is restricted to the classical domain—beginning with the classic monographs by Rohrlich (2007) and Yaghjian (2006). Also, both Frisch's inconsistency claim and Muller's rebuttal remain within the classical domain—although in both cases it would have been plausible to strengthen the respective arguments either by showing that the same alleged inconsistencies exist in QED or that the alleged inconsistencies do not arise in the fundamental theory or are an artifact of reduction. Whatever the reasons for treating CED as a self-contained theory, this shows that both physicists and philosophers of physics share the intuition that there is a need for coming to terms with conceptual issues in CED taken for itself.

Thus far, we have given four reasons why classical theories like CED should be interpreted and examined for conceptual coherence in spite of having been superseded. However, an argument is still missing for why precisely the conceptual differences between the extension, the renormalization and the aaad program should matter. One might well think that the differences between the extension and the renormalization programs are irrelevant since they lie outside the range of application of CED (Spohn, 2004, p. 16). After all, these differences concern mainly the microscopic structure of the fundamental particles, which is anyways necessarily simplified and idealized in the reduction of QED to CED (Rohrlich, 1988, pp. 298-299). Thus, should interpretations of CED just be pluralistic concerning the structure of fundamental particles?

While such an agnostic viewpoint admittedly works well for most contexts in which CED is applied, two or three competing programs cannot be the final word in the whole story. A strong argument against agnosticism relies on the requirement of 'vertical coherence' for established theories, i.e. mathematical and conceptual consistency with coarser and finer levels of mature theories (Rohrlich and Hardin, 1983, pp. 604-605). While classical theories surely fail *quantitatively* in the microscopic domain, there should be some *qualitative* resemblance between the macroscopic and the microscopic rendering of phenomena. Plausibly, only one of the three programs will turn out fully consistent with QED. After all, several questions that can decide between the programs in the classical domain have analogues in QED, e.g. if elementary charges have an inner structure or not. Similarly, the question whether fields have independent degrees of freedom from charged particles can be posed in terms of photons and charged particles in QED.

Besides ontological issues, the three programs differ also in the explanations of several macroscopic phenomena. As described in Section two, in the extension program the radiation reaction is explained by forces acting inside the electron, while such an explanation is not available in the renormalization program due to lack of inner structure in the electron. There is just no a priori argument for why these different explanations of the radiation reaction should all be and remain equally good and suitable. Recall for example, that in the extension program different structures of the fundamental particles will result in different macroscopic force laws—which may once become empirically distinguishable.

In summary, given the enormous differences between the three accounts of CED in terms of ontology and fundamental equations it seems unlikely that all of them will fare equally well with respect to conceptual coherence, consistency with the quantum level, and future developments in electrodynamics.

4. Virtues and vices of action at a distance

4.1 Virtues

Most of the conceptual problems connected with the interaction between particles and fields do not arise in pure particle theories, which are often referred to as aaad theories. The reason is quite simple: there is no interaction between point-charges and fields, since one of these entities, namely the fields, is taken not be fundamental. The fields are just “bookkeeping variables” (Feynman 1965, p. 163), shortcuts for calculating the interaction between particles. Then, the divergence of the field energy in the vicinity of a particle is just a mathematical artifact without physical relevance. These are not *physical* infinities as in theories where fields are part of the fundamental ontology, consequently the awkward infinities (of the retarded as well as of the advanced fields) vanish from the theory.

A related advantage of the aaad view, which it shares with the pure field view, is its ontological sparseness. Since there seems to be a clear correspondence between the ontologies of quantum and classical electrodynamics—photons and charged particles vs. fields and charged particles—we should worry about this issue, even if classical electrodynamics is not a fundamental theory.

An interesting case can be made for aaad theories from an unexpected point of view. In an important sense, pure field theories are more closely related to aaad theories than to particle-field theories. In the late 1800s, the particle approach and the pure field approach were proclaimed to be mathematically equivalent by many of the leading figures in electrodynamics of the time—including Maxwell and William Thomson[13]. Particle-field theories however can never be mathematically equivalent with field theories or with aaad theories, just because they involve additional fundamental entities with additional degrees of freedom. In a sense then pure field theories and pure particle theories belong to the same class of theories and particle-field theories form a different class.

Still in the *Treatise* (1873), Maxwell acknowledges the equivalence of pure field theories and pure particle theories: “Since, as we have seen, the theory of direct action at a distance is mathematically identical with that of action by means of a medium, the actual phenomena may be explained by the one theory as well as by the other, provided suitable hypotheses be introduced when any difficulty occurs.” (§62) Apparently, Maxwell considers the intertheoretic relation between the two approaches, the pure field view and the pure particle view, as a case of underdetermination at least with respect to the evidence at that time. A choice between both theories can be reached only by weighing epistemic virtues like the simplicity of the theories or the adequacy of the description. Accordingly, Maxwell sees himself as an “advocate” of the field view rather than a “judge” between both views (1873, p. xii).

When Michael Faraday developed the field view on electrodynamics[14] he considered it the only true interpretation of the phenomena. He spent considerable effort on trying to establish the incompatibility of his approach with the then popular view of aaad electrodynamics as favored by continental physicists like André-Marie Ampère or Wilhelm Weber. It was left to William Thomson to establish most of the connections between Faraday's view and aaad. A key concept for this endeavor proved to be the electrostatic potential φ, which fits equally well in both approaches. In a quite similar way, the vector potential $\boldsymbol{A}$ later turned out to be conceptually neutral with respect to the two approaches. A considerable number of Thomson's achievements in electrodynamics rely on this fruitful elaboration of the connection between field-theory and aaad (Darrigol, 2000, pp. 113-126).

[13] As is not generally known today, Maxwell in his *Treatise* expounded a pure field theory and not a particle-field theory. Charges and currents in Maxwell's theory were derived concepts. (Darrigol, 2000, pp. 164-165)
[14] Faraday's theory was also a pure field view, where charges and currents were derived concepts. (Darrigol, 2000, p. 78)

It is of course speculation that a similar equivalence between a pure field and an aaad view could be established with respect to modern classical electrodynamics, but there are no obvious reasons why it should be impossible. If feasible, the equivalence could be turned into an argument both for aaad and for pure field views since such a double perspective has already proved fruitful in the history of electrodynamics.

4.2 Vices

So much for the virtues of aaad. What about the vices? If mentioned at all in the relevant contemporary literature, aaad is discussed only in passing and generally just in the framework of the Wheeler-Feynman theory. The latter represents a serious obstacle to a balanced assessment of aaad, since the Wheeler-Feynman approach brings along a series of problems which are in general not genuine to aaad. Furthermore, modern discussions of aaad tend to be cripplingly short. Jackson's otherwise extensive monograph discusses the Wheeler-Feynman theory in a single neutrally phrased paragraph lacking any arguments for or against the framework (1999, p. 611-612). Spohn gives a two-page outline of the Wheeler-Feynman theory and appears equally reluctant to bring forth any arguments for or against it. He concludes with the remark that aaad accomplishes „agreement with the conventional theory" (2002, pp. 41-42).

Rohrlich is the only one to actually formulate reasons, why the Wheeler-Feynman theory has much less appeal today compared with the 1940s (2007, pp. 20-21, pp. 194-196). According to Rohrlich, the Wheeler-Feynman theory is no longer the only framework that is free of self-energy difficulties and satisfies time-symmetry. More importantly, „the autonomous nature of the radiation field (as also evidenced by the existence of photons) makes the elimination of all electromagnetic fields somewhat arbitrary and not justified. Finally, the absorber conditions [...] do not seem to lend themselves easily to inclusion in a set of basic assumptions of a theory." (p. 196)

Thus, Rohrlich's dismissal comes basically in two sentences. In their shortness, these remarks are regrettably murky. It is not clear, how the 'existence' of photons could provide supporting evidence for the autonomous nature of the radiation field. After all, pretty much the same reasoning applies to photons as to the radiation field, i.e. it might well be that photons possess no degrees of freedom of their own, making them secondary quantities and thereby allowing for aaad. Finally, the absorber condition is not at all an awkward assumption from an aaad perspective. Rather, it follows directly if fields are taken to be derived quantities and have no degrees of freedom of their own. Why there should be any particular difficulties with including statements about degrees of freedom into the set of basic assumptions of a theory remains unclear.

The neglect of aaad in contemporary literature, which was exemplified here, makes it necessary to refer largely to historical literature for an assessment of aaad, much in the spirit of Maxwell's remark that "[i]t is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always completely assimilated when it is in the nascent stage." (1873, pp. xiii-xiv) Furthermore, CED has undergone few changes since the first decades of the twentieth century.

One may group the problems of aaad electrodynamics in three different classes: (i) those connected with the inclusion of advanced action, (ii) those having to do with the existence of an ideal absorber and emitter, and finally (iii) metaphysical issues connected with locality and energy conservation.

(i) The first class of problems although certainly pressing and often brought forward against the Wheeler-Feynman version of aaad concerns problems that trouble Dirac's renormalization program just as much (Frisch 2004, p. 539). In exchange for this difficulty the Wheeler-Feynman theory avoids self-interaction and works with point-particles. Generally, the commitment to advanced action is not made explicit in Dirac's program but it is part and parcel of this view, since it is required for fixing the force balance as was explained in the last section. So, even if advanced action is beset with a variety of problems, this cannot be a reason for rejecting aaad, since it has not led to the outright rejection of the Dirac theory either.

Furthermore, not all aaad versions of CED are troubled by advanced action. As emphasized at the end of Section two, electrodynamic aaad should not be identified with a specific version like the Wheeler-Feynman theory. In a sense, the Wheeler-Feynman theory is the aaad version of Dirac's theory by relying on point-particles and the Lorentz-Dirac force law. Naturally, there exists also an aaad version of the extension program, which is distinguished from its particle-field version by postulating an ideal emitter and an ideal absorber. Of course, the aaad version of the extension program does not involve advanced action.

As with the renormalization program, the aaad version of the extension program can also provide a new perspective on some conceptual riddles of the extension approach. Let me sketch a few very speculative thoughts, how this might work concerning the lack of empirical evidence for any extension or structure of the electron. Aaad with its different conceptions of energy conservation and locality may allow to reinterpret what is now thought to be a local charge distribution of an extended particle as distant spurious causes, acting in a retarded manner on a point-particle. These spurious causes could be thought of as unnoticeable microscopic changes, e.g. in the device responsible for the electromagnetic action on the particle. They would be of the same magnitude as the radiation emitted by the particle and thus serve as an explanation for the radiation reaction of the particle and for the emitted radiation. In such a picture, retarded action provides a full description and advanced action can be dispensed with. Also, the extension program could be reconciled with the empirical evidence for point particles. The reinterpretation of the charge distribution might also provide a fresh look on the nature of what was thought to be cohesive forces holding the electron together. Again, I do not claim that any of this comes even close to the truth—I just tried to convey how aaad might serve as a fresh perspective to approach some of the problems troubling the extension program.

(ii) The second class of problems related to the ideal absorber and emitter is genuine to aaad theories. In order to deny any independent degrees of freedom for fields—to turn fields into derived entities—one has to postulate an ideal emitter as well as an ideal absorber that account for the emission and absorption of all fields, respectively. Thereby, the fields depend entirely on the motion of particles. In general, the existence of such ideal absorbers and emitters is difficult if not impossible to assess empirically.[15] The reason for this is quite simple: It seems impossible to prove that there are fields which have not been emitted from a material source or which will not be absorbed by a material absorber: we would have to know the matter distribution in the entire universe, in all future and all past. (It is admittedly equally difficult to prove the opposite, that every field is due to an emitter and will eventually be absorbed.) In view that nobody can

[15] For some specific versions of an absorber condition, empirical tests have been suggested: By means of the Partridge experiment the existence of an ideal absorber as postulated in the Wheeler-Feynman theory was ruled out, because a microwave source always draws the same power, no matter if it is pointed into free space or into a local absorber (Partridge, 1973; Zeh, 2001, p. 36).

ever know the positions and movements of all charges in the universe it is impossible to test in general, if charges and fields can exist independently.

However, two observations very loosely suggest that fields have no extra degrees of freedom in addition to those of the charges: (1) Almost all electromagnetic radiation and fields seem to originate in a material source, in the sun, stoves, light bulbs etc. (2) Most of the matter around us is approximately electrically and magnetically neutral, meaning that most electric and magnetic fields generated around us are in fact absorbed.

However, there is one phenomenon which squares rather badly both with claim (1) and with claim (2). The cosmic background radiation (CBR) does not have an obvious material source, much less does it seem intuitive that this radiation will be fully absorbed at some point in the future. This is an important open problem for aaad. Obviously, the issue is intimately linked with the cosmological model that one adopts. In all big bang type models, the question concerning a material origin of CBR comes down to a chicken or egg dilemma: was there at one point radiation without matter or not? But owing to the scarce interest in aaad in the last decades, the compatibility between aaad and big bang cosmology has barely been addressed.

Curiously, Fred Hoyle and Jayant Narlikar, arguably the most vocal proponents of a Wheeler-Feynman type aaad in recent decades, have intertwined this research program with their support for a steady state model. This doubly partisan view explains the CBR as "a consequence of the thermalization of starlight" (Hoyle et al. 1994, p. 1014; also Kragh 1999, p. 387), drawing on a rough coincidence of the temperature of CBR with the temperature of stellar light. Because the spectrum of starlight is much different from the blackbody CBR, steady state theorists have to go a long and stony way in arguing for the identity of both. Whatever the relation between aaad and cosmology, these controversies need not worry too much a proponent of aaad. As long as we are restrained to the tiny space-time spot in the universe that we currently inhabit, cosmology will remain an extremely speculative science and as such will provide good arguments neither for nor against aaad.

In total, due to the rather non-empirical nature of the question, if all radiation is emitted and absorbed, it seems implausible that the absorber-emitter postulate is the reason for rejecting aaad electrodynamics. As we will see, the main reasons for rejecting aaad are deep-lying intuitions about the way physical theories should be construed.[16]

(iii) This leads us to the third class of objections against aaad theories, which concerns metaphysical intuitions about locality and conservation laws. As a first remark of caution, there is much historical evidence that these intuitions change and it is not very plausible to assume that we have finally arrived at the correct metaphysics governing the world. Since these intuitions constitute the main reason for rejecting aaad (as is also noted by Frisch 2005, pp. 30-31), the rest

[16] Somewhat analogously, Faraday in the 1830s set out to verify, if every charge was inductively related to an opposite charge. For a while he believed he had found a counterexample in a spherical copper mirror facing the sky and connected with a Leyden jar. But the fact that the inner walls of a large hollow conductor can never be charged eventually convinced him that in fact induction through air can take place around the corner. This led him to deduce that there is no absolute charge, i.e. that every positive charge is related to an equal and opposite negative charge (Darrigol, 2000, pp. 86-88). This law implies that in the universe there are just as much positive as negative charges, which essentially is a weak version of an absorber condition. Considering the mathematical equivalence of field theories and aaad theories at the time it is of course not surprising that pure field theories incorporate some versions of ideal absorbers just as aaad theories. On the other hand, modern particle-field theories have not adopted such a law concerning absolute charge, which by the way is just as difficult to prove or disprove empirically as the existence of an ideal absorber and emitter.

of the article will broadly examine, how our concepts of locality and energy conservation could be adapted in order to account for aaad.

Before moving on let us address a final critical remark. There seems to be quite strong evidence for the *physical* existence of fields: Consider a light mill[17], where electromagnetic waves 'push' the blades of a rotor, or consider solar cells that produce energy from electromagnetic waves. Another example of the seemingly physical reality of light lies in the observation, that light rays are diverted under the influence of gravitation. However, all these phenomena do not prove the existence of fields *independently* of the existence of electric charges. As long as in principle all electromagnetic fields can be explained by the movement of charges, fields can be considered a secondary, non-fundamental ontology—making possible an aaad version of electrodynamics.

Nevertheless, it remains odd that distant charges should be responsible for the movement of the blades in a light mill. The intuition behind such a judgment is twofold: First, physical action should only be transferred locally through direct contact. Second, the energy which moves the blades should be stored somewhere when it travels from one place to the other—otherwise energy conservation seems to be violated. These two arguments against the aaad view will be discussed in the remaining two sections.

5. Locality

Field theories seem to grant some type of contact locality, while aaad fails on any account.[18] The reasons for believing in contact locality, i.e. in the idea that all physical interaction must be mediated by direct contact, fall into three categories: there are (i) reasons based on facts, on what we actually observe and experience. There are (ii) pragmatic reasons, according to which a non-local description of the phenomena would just not be useful. Finally, there are (iii) metaphysical reasons inferring from certain conceptions of matter and interaction that something cannot act where it is not. In this section it will be argued that reasons (i) and (ii) are satisfied not only by contact locality but also by a somewhat weaker constraint, which will be called 'aaad locality' because it is satisfied by aaad theories. Concerning (iii) it will be suggested, that metaphysical intuitions, though essential for doing science, are nevertheless often unreliable and should certainly not be prioritized in relation with (i) and (ii).

Let us first address the three different motivations for endorsing contact action. (i) That we can only act upon things that we touch is an experience we make again and again in daily life. This observation is at the core of the intuition, that contact locality is a fact about the world. Phenomena that seem to violate this condition, like the magnetic powers of lodestone or the electrostatic powers of amber, were long considered miraculous enough to be shown off at fairs. There is however another case of apparent aaad which is much too frequent in daily experience to be considered a miracle, the fall of bodies under the gravitational influence of the earth. In total, the evidence in favor of contact locality from direct observation is ambiguous: While many classes of interaction—notably collisions—seem to require physical contact between the interacting bodies there are important exceptions that do not fit the picture, at least prima facie.

(ii) On the epistemic side, when it comes to structuring observations about the world, there are strong pragmatic reasons for assuming some kind of locality. If objects could interact

[17] This example refers to light mills with an extremely good vacuum, such that effects on the blades from gas particles can be excluded.

[18] For detailed discussions on which types of particle-field theories actually satisfy which type of contact locality see Frisch (2005, Ch. 4) and Lange (2002, Ch. 1).

with any other object in the universe just as well as with their immediate neighbors, it would be impossible to establish any reliable regularities in our knowledge about the world. Locality is indispensable in that it limits the search for regularities to a manageable amount of possibilities. However, if locality is only a pragmatic virtue then it is not clear why it must necessarily be the strong concept of contact locality, where objects actually have to *touch* each other in order to interact. Some weaker condition may well suffice.[19]

(iii) Certainly, the metaphysical intuitions of philosophers and physicists have mostly been in favor of contact locality. However, especially in response to Newton's physics several philosophers have also taken the opposite stance. Here is Immanuel Kant replying to the claim that something cannot act where it is not: "[This] is so far from being contradictory, that one might rather say: everything in space acts on another thing in a place where the acting thing is not. For if it acted in the place where it was itself, the thing on which it acted would not be outside it; for outside signifies presence in a place, where the other is not." (Kant, 1883, p. 188)

Similarly, John Locke describes in a letter to the Bishop of Worcester how he changed his metaphysical attitude in response to Newton's *Principia*: "But I am since convinced by the judicious Mr. Newton's incomparable book, that it is too bold a presumption to limit God's power, in this point [concerning aaad], by my narrow conceptions. The gravitation of matter towards matter by ways inconceivable to me, is not only a demonstration that God can, if he pleases, put into bodies, powers and ways of operation, above what can be derived from our idea of body, or can be explained by what we know of matter, but also an unquestionable and every where visible instance, that he has done so." (cited in Hesse, 2005, p. 167) Locke's conversion suggests, that metaphysical intuitions and arguments, although essential for doing physics, should be handled with great care and certainly never dogmatized or even prioritized in relation to physics.

Having addressed the various reasons for believing in contact locality let us now look at the considerable historical evidence, that contact locality is too strong a requirement for scientific theories. In the last part of this section, I will then suggest aaad locality as a weaker constraint, which is in accordance with the historical evidence, but also with the factual and pragmatic reasons for postulating locality.

Some of the most successful theories in the history of physics could not have been accepted under the premise of contact locality—including of course Newton's theory of gravitation, the early aaad versions of electrodynamics but also (somewhat surprisingly) Maxwell's electrodynamics. Both Newton and Maxwell refrained from formulating a detailed local mechanism that could account for the transfer of physical action. Newton's famous 'hypotheses non fingo' referred to hypotheses about the mechanical connection between interacting bodies. In the same manner Maxwell wrote in the *Treatise* (1873): "I have not been able to make the next step, namely, to account by mechanical considerations for these stresses in the dielectric [i.e. for the electric fields]." (§111)

To classify Maxwell's theory as a non-local theory contradicts the common wisdom, that it is one of the main virtues of field theories to restore contact locality for physical interactions. On close inspection, however, it turns out that the conception of contact locality has changed in the times since Maxwell. Maxwell's theory in fact violated the locality requirement of his days,

[19] In *Quantenmechanik und Wirklichkeit* (1948), Einstein also stresses that some version of locality is a necessary condition for doing physics and employs this as an argument against the non-locality of quantum mechanics. However, as long as the quantum mechanical non-locality remains a microscopic one, Einstein's argument does not necessarily get through. (cp. the various versions of aaad locality elaborated on below).

which demanded a *mechanical* explanation for the local propagation of action—and thus a mechanical theory of the dielectric and the ether as the electromagnetic media. In the following decades the assumption that contact locality must necessarily involve a mechanical process was abandoned. Therefore Albert Einstein could justly claim, that field theories restore contact locality for physical interaction: "[Maxwell's equations] do not, as in Newton's laws, connect two widely separated events […] The field *here* and *now* depends on the field in the *immediate* neighbourhood at a time *just past*." (Einstein and Infeld, 1938, pp. 152-153; their italics)

However, it is not obvious how this revised version of locality can be reconciled with the factual reasons (i) for contact locality described at the beginning of this section. What we actually observe is, that pieces of *matter* must touch in order to interact, not that the interaction between pieces of matter is mediated by different physical entities like the fields. As long as fields cannot be explained mechanically in terms of matter, as Maxwell had in mind, or conversely matter in terms of fields, as Einstein had planned for his unfinished unified field theory, the supposed contact locality of field theories remains a dubious achievement. The historical success of Newton's and Maxwell's theories as well as the ambiguous empirical evidence for contact locality suggest that locality should largely be seen as a pragmatic virtue that reasonably limits the search for regular patterns in the observations. But then, there may well be acceptable notions of locality that are weaker than the strong requirement of contact locality.

In the remaining part of this section, a notion of locality is proposed that is in accordance with aaad theories while at the same time satisfying the historical evidence just mentioned, the factual requirements (i), and the pragmatic virtue (ii) that the relata of a regularity must be reasonably close to each other—both in spatial and temporal terms. The idea behind 'aaad locality' is very simple: *The interaction between two material objects must diminish reasonably fast with growing (spatio-temporal) distance between them.* Two types can be further distinguished: (1) The action and reaction themselves become smaller with growing distance. (2) While action and reaction are independent of the distance, the probability for an interaction becomes smaller with growing distance.

Examples for the first type are Newton's law of gravitation or Coulomb's law in electrostatics. An example for the second type is the electromagnetic interaction between an isotropic light source and its absorber, where the intensity of the light falls off with an inverse square of the distance. Here, intensity is a macroscopic notion—on the microscopic level, atomic processes in the source are correlated with similar processes in the absorbing material. The processes in the source and absorber (quantum jumps of the electrons) do not depend on the distance between them—this distinguishes case (2) from case (1). However, the larger the distance between absorber and source, the less probable is the interaction between a specific atom / electron in the absorber and a specific atom / electron in the source.

In both cases, the pragmatic need for locality is satisfied at least for macroscopic processes. Aaad locality also fits well the historical evidence from Newton's mechanics and from aaad electrodynamics and it satisfies the observed locality gathered from daily experience. The latter can be seen as follows: What is in fact observed in daily life is not exclusive contact locality in all interactions, but only in those cases, where the interacting bodies are electrically and magnetically neutral and where they have small masses (and that is the majority of all cases). The first condition assures that electric and magnetic interaction can be neglected, the second warrants the same for gravitation. This explains why aaad is *experienced* only for the exceptions mentioned at the beginning of this section. Finally, even the apparent contact action observed in collisions can be explained in terms of aaad, because when bodies come very close to each other, then on the microscopic scale the bodies are not electrically neutral anymore and electromagnetic aaad interaction (on small scales) becomes relevant.

6. Conservation of energy

There is a widespread view on conservation of energy which rules out aaad: “In fact, whenever energy is transmitted from one body to another in time, there must be a medium or substance in which the energy exists after it leaves one body and before it reaches the other, for energy, as Torricelli remarked, is a quintessence of so subtile a nature that it cannot be contained in any vessel except the inmost substance of material things.” (Maxwell, 1873, §866) Apparently, energy is considered here something like a substance, which is literally carried from one place to the other. In this view, energy conservation implies that *the energy content of a closed system is the same at all times.* In the following, the constancy of energy content over time will be referred to as the '*substantial* view' on energy conservation, no matter if energy is actually considered a substance or not.

Obviously, the substantial view is incompatible with *retarded* aaad, where the interaction between two bodies is delayed by a certain period of time. Classical electrodynamics can be construed in terms of such retarded interactions by relying on the retarded results for the electrostatic potential φ and the vector potential $\boldsymbol{A}$. These retarded potentials, that depend on both the positions and the movements of charges at earlier times, are known as the Liénard-Wiechert potentials (e.g. Jackson 1999, Ch. 14.1).

Einstein argues against such a representation of electrodynamic phenomena: “What distinguishes the Maxwell-Lorentz differential equations from other forms [e.g. the Liénard-Wiechert potentials], which contain retarded functions, is the fact that the former yield, for every instance and relative to every non-accelerated coordinate system, an expression for the energy and the momentum of the considered system. In a theory that operates with retarded forces the current state of a system cannot be described without referring to earlier states of the system.” (Einstein, 1909, 185; my translation) From the substantial view on conservation of energy, on which Einstein's argument relies, the verdict is quite clear: Field theories must be preferred to aaad.

Drawing on some of the same reasons, Lange (2002) gives an original and insightful argument for preferring fields to aaad. Lange's first point is that the inverse-square dependence of gravitational and electrostatic forces as well as the time delay in the interaction can be explained by the fields spreading out isotropically from the source, but only under the assumption that these fields really exist (p. 96). Lange concedes that this argument is not conclusive, since in aaad such characteristics could still be taken as brute facts. In the end, it is not even clear why with sufficient ingenuity there could not be some kind of explanation for these characteristics within aaad.

In his second and in my view most important objection against aaad, Lange takes up the criticism by Maxwell and Einstein and refers to the difficulties of formulating energy conservation within retarded aaad (pp. 123-125). In this context, Lange distinguishes three senses in which energy can be understood: energy as a substance or stuff, energy as a property of some thing, and energy as a mere bookkeeping variable for a system. Obviously, the first and the second notion are not reconcilable with energy conservation in retarded aaad. The third notion works for aaad, but only entails a very weak and largely unsatisfying rendering of energy conservation. Crucially, Lange fails to consider energy as a relational quantity, an account which goes back at least to Ernst Mach's relational interpretation of inertia. If energy is interpreted in such a way, energy conservation is metaphysically more meaningful than a mere bookkeeping formula while at the same time remaining compatible with aaad.

Thirdly and finally, Lange argues that the fields possess a Lorentz-invariant quantity, namely rest mass, and therefore must be real (p. 247). Here, many assumptions are involved which are far from being self-evident and universally accepted: e.g. the crucial role of rest mass for turning entities into 'stuff', the inference from invariance properties to the reality of entities etc. In this article, I have preferred to speak of the fundamentality of quantities in relation to a theory and to avoid all commitments concerning the actual reality or unreality of entities.

Let us return to the '*relational* view' on energy conservation, which is the crucial concept overlooked in Lange's argument against aaad. Relational quantities must always be defined by means of the relations between *material* objects[20]. When the interaction of bodies is described relationally, only those quantities should play a role which can be stated in terms of relational quantities between the interacting bodies (spatio-temporal distances, relative velocities etc.) and of intrinsic properties of the interacting bodies (e.g. charge).

Relationality as a physical concept is intimately linked with aaad. Potential energy, which is an aaad quantity par excellence, fits a relational description in the above sense. Kinetic energy can be interpreted relationally as well, if the particle velocities are interpreted relationally. From relationality follows, that any absolute velocity ascribed to the whole system of particles has no influence on and is not affected by the interaction between the particles. It only yields an additional constant kinetic energy.

If potential and kinetic energy can be interpreted relationally, then the most basic version of energy conservation, stating that the sum of both types of energy is always constant for closed systems, can also be interpreted relationally: *There is a fixed functional dependence between the distances of the particles in a closed system and their relative velocities.* If for example a system consists of only two interacting particles, then conservation of energy requires that the mutual velocity must be recovered once the original distance is recovered.

From all theories of classical physics, electrodynamics proves the most difficult case for the relational view on conservation of energy. Both field energy and field momentum need to be reformulated in terms of relations between charges. A simple example how this works is the connection between the (non-relational) electrostatic field energy $\varepsilon \int |\boldsymbol{E}|^2 dV / 2$ and the (relational) electrostatic potential energy $\sum_{i,j} Q_i Q_j / 8\pi \varepsilon r_{ij}$, where in both cases the energy due to the same arrangement of charges Q_i is considered. As can be seen in any standard textbook, both expressions can be derived from each other and thus represent the same physical quantity. If only electrostatic interaction is considered, a relational energy law can be formulated by means of the electrostatic potential. A relational version of electro-*dynamic* conservation of energy has never been fully worked out, but it would presumably rely on the Liénard-Wiechert potentials.

For *instantaneous* interaction the relational view on conservation of energy matches the substantial notion of constant energy content: in this case, the energy content at any moment is given by the sum of the potential and kinetic energies, and this sum will stay the same for all times. For *retarded* interaction, the energy content cannot be specified anymore for a given moment, because the potential energies depend on the respective locations and motions of the interacting particles at different times (compare Einstein's quote at the beginning of this section). Therefore, retarded aaad is incompatible with the substantial notion of energy conservation.

However, retarded aaad poses no essential problem for the relational view on conservation of energy—only, what used to be spatial distances in the case of instantaneous

[20] The term 'material' here always refers to particles, never to fields.

interaction refers now to spatio-temporal distances. Relational conservation of energy in the case of retarded aaad means, that *there exists a functional dependence between certain* spatio-temporal *distances of the interacting particles and their mutual velocities (possibly time-derivatives of higher order must also be included)*. For example, if a certain spatio-temporal distance is recovered between two particles making up a closed system, then the mutual velocity is recovered as well.

In most situations, the substantial view of constant energy content and the relational view of a fixed functional dependence are pragmatically equivalent due to the enormous size of the interaction speed for electromagnetic and gravitational phenomena. While the substantial view is in fact conceptually incompatible with retarded aaad electrodynamics, the relational reformulation seems quite adequate for retarded aaad.

7. Conclusion

We have evaluated the prospects of action-at-a-distance interpretations for solving some of the conceptual issues, that have recently surfaced in discussions on the foundations of electrodynamics. It was shown, that currently action at a distance is the only player in the game that can avoid both the riddles of extended particles and the divergences in the field energy. Technically, action at a distance is not much distinct from particle-field formulations of electrodynamics. It involves just the additional assumption, that fields have no genuine degrees of freedom. In order to guarantee this, action at a distance must amend particle-field theories with the additional postulate of an ideal absorber and an ideal emitter—an assumption which is extremely difficult, if not impossible, to verify or falsify empirically.

The reason that action-at-a-distance electrodynamics is generally rejected and particle-field theories are preferred lies not in any specific characteristic of such theories. Rather the rejection of action-at-a-distance theories is due to strong metaphysical intuitions about locality and the conservation laws. As was suggested, these concepts can be altered to allow for action at a distance without compromising any of the pragmatic and factual content of these concepts.

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