Hidden underdetermination – a case study in classical electrodynamics

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Abstract:
In this article, I present a case study of underdetermination in 19th-century electrodynamics between a pure field theory and a formulation in terms of action at a distance. A particular focus is on the question if and how this underdetermination is eventually resolved. It turns out that after a period of overt underdetermination, during which the approaches are developed separately, the two programs are merged. Based on this development, I argue that the original underdetermination survives in hidden form in ontological and methodological redundancies of the subsequent particle-field electrodynamics. Implications regarding criteria for theory choice and the realism debate are briefly addressed.

Keywords: underdetermination, electrodynamics, action at a distance, field theory

1 Introduction

As is frequently acknowledged, debates on underdetermination suffer from a lack of genuine examples that are both historically important and methodologically relevant. Only about a handful of such examples are regularly cited, including the equivalence of Euclidean and non-Euclidean formulations of geometry and the equivalence of orthodox non-relativistic quantum mechanics with Bohmian mechanics. In this essay, a novel[1] case study will be introduced which examines a historical episode of underdetermination in classical electrodynamics concerning the relation between a pure field theory and an action-at-a-distance formulation. Furthermore, we will look at the criteria governing theory choice following the period of explicit underdetermination and argue that the underdetermination vanishes only superficially while actually persisting in redundancies of the resulting theory. We will call this phenomenon *hidden underdetermination*.

In Section two, a brief taxonomy of underdetermination will be provided. In particular, the distinctions between transient and permanent as well as between deductive and ampliative underdetermination will be introduced. As will be argued, historical episodes of underdetermination generally concern transient and ampliative underdetermination. Note however, that in the way we define transient underdetermination, it can be compatible with an implicit permanent underdetermination. In particular in instances of hidden underdetermination, the underdetermination is transient since the explicit underdetermination eventually vanishes. However, it may well be permanent, since the hidden underdetermination may not be eliminable even when taking into account ampliative criteria.

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[1] Some authors (e.g. Bonk 2008, pp. 79-82) discuss the equivalence of Wheeler-Feynman electrodynamics with particle-field electrodynamics, which is however only remotely connected to the case study in this essay. A further case of underdetermination in electrodynamics is discussed in Pitts (2011).

Section three will then introduce the historical situation of electrodynamics in the 19th century, which was developed both in terms of action at a distance and as a field theory. The main differences between these two formulations are found to concern all characteristics of scientific theories, from ontology to the mathematical framework, to the experimental focus.

Building on the historical sketch, Section four establishes that we are faced with a genuine case of underdetermination, as was acknowledged also by James C. Maxwell and William Thomson. It does not fall into any of the categories to which there exist quick realist replies. In particular, it is implausible that we are dealing merely with variant formulations of the same theory in view of the enormous differences sketched in Section three.

Section five further emphasizes the relevance of the case study by showing that 19th-century electrodynamics played a central role in Duhem's thinking about underdetermination. Arguably, Duhem was puzzled by the success of the English research style in electrodynamics, especially that of Thomson and Maxwell with its emphasis on models and analogies. To some extent, Duhem's underdetermination thesis can be interpreted as an attempt to provide a methodological explanation for this specific historical situation.

Section six examines the subsequent development in electrodynamics at the end of the 19th and the beginning of the 20th century. At first, the discovery of electromagnetic waves by Heinrich Hertz made field theory appear the sole victor, but then the discovery of charge quantization in terms of elementary particles like the electron led to a considerable revival of the action-at-a-distance framework. This return to action at a distance was acknowledged by several leading figures of the emerging electron theories, e.g. by Hendrik A. Lorentz or Emil Wiechert. It can therefore be said that the two 19th-century programs both survived in the resulting particle-field theory, which dominated classical electrodynamics in the 20th century.

Section seven identifies the situation in classical electrodynamics following the explicit underdetermination as a situation of hidden underdetermination. Though we are formally dealing with a single theory, the two original frameworks persist in considerable redundancies of this theory. We will require three criteria to establish hidden underdetermination: (i) The original underdetermination can be recovered from the final theory by introducing constraints which eliminate the redundancies. These constraints must not be empirical in nature, i.e. pure observation should not be able to rule them out. (ii) There are important pragmatic reasons for introducing the redundancies. (iii) A considerable number of conceptual problems of the final theory can be traced back to the merging of two frameworks that were originally designed to function independently.

In our case study, the hidden underdetermination can be most clearly perceived in the double ontology of the subsequent particle-field electrodynamics. We will argue that this doubling has enormous pragmatic advantages but also lies at the root of many conceptual problems that plague classical electrodynamics. Thus, the story of hidden underdetermination sketches the genesis of some of the conceptual problems or even inconsistencies in classical electrodynamics that were recently discussed by Mathias Frisch (2005).

Section eight concludes with some reflections how the case study is relevant to the realism debate. The most important features are: (i) underdetermination can persist in single theories and thus may be present in situations where it has traditionally not been suspected; (ii) for an assessment of realist or antirealist intuitions it is not sufficient to observe that in almost all examples from the history of science the underdetermination is eventually resolved—as the possibility of hidden underdetermination proves. Rather, the criteria for theory choice are crucial. While scientific realists would expect theory choice to be largely driven by the accumulation of evidence, antirealists would allow for a much wider range including all kinds of pragmatic and even sociological criteria.

Traditionally, scientific realists have considered transient underdetermination as unproblematic since, like a bad cold, it is annoying but will quickly go away. This view has recently been challenged by Kyle Stanford's Problem of Unconceived Alternatives (2006, 2009). The hidden underdetermination of our case study provides further and distinct evidence that transient underdetermination should be taken seriously. In particular, there is much to learn from a detailed examination of the various ways in which situations of underdetermination can end.

2 A brief taxonomy of underdetermination

Let me first provide a broad classification of underdetermination that will allow us to identify the type of underdetermination encountered in the case study. The core idea is always the same: Theory is underdetermined with respect to evidence. Distinctions can be drawn by specifying the involved concepts, notably what we understand by evidence and according to which methodological toolbox the underdetermination is established.

(a) The distinction between *permanent* and *transient* underdetermination refers to the evidence with respect to which the considered theories are underdetermined. In the case of permanent underdetermination, no evidence can ever distinguish between the alternative theories, i.e. we are dealing with empirically equivalent theories. Thus, the theories are underdetermined by all possible evidence. By contrast, transient underdetermination refers to the actual evidence in a specific historical context. In our usage of the term, transient underdetermination also requires that the underdetermination eventually vanishes. However, we do not impose any restrictions with respect to the reasons which lead to the end of underdetermination. For example, these might well be of pragmatic or even sociological nature. Thus, transient underdetermination in our usage of the term is *compatible* with permanent underdetermination as might be the case in hidden underdetermination.

(b) The second distinction concerns the scientific method with respect to which a theory is underdetermined. In *deductive* underdetermination, the alternative approaches are underdetermined with respect to a purely hypothetico-deductive methodology. In addition, *ampliative* underdetermination takes into account epistemic virtues like simplicity as well as inductive methods.

Historical case studies generally concern transient and ampliative underdetermination. Such episodes are transient, because underdetermination is always assessed on the basis of the available evidence in the historical context. Also, it is a historical fact that in most cases underdetermination eventually vanishes with possible exceptions, when a more or less trivial equivalence relation between the different approaches can be established. However, let me emphasize again that even in cases of transient underdetermination, there might be a case of permanent underdetermination in the background. If this is the case depends crucially on the criteria of theory choice according to which the underdetermination situation is eventually resolved. Historical episodes generally concern ampliative underdetermination, because scientists certainly take epistemic virtues and inductive considerations into account when evaluating underdetermination. This “historical view on underdetermination” is further developed and defended in Pietsch (2011a, 2011b). According to this perspective, a genuine case of underdetermination concerns competing frameworks that rely on different metaphysics which provide the scientists with different research agendas. The historical view on underdetermination shares many characteristics with the work of Kyle Stanford, which has triggered the rising interest in transient underdetermination in recent years (2001, 2006, 2009). Stanford built on some earlier work by Lawrence Sklar, who had originally introduced the term in the following way: “[In transient underdetermination] we allege merely that there can be incompatible alternatives between which no rational choice can be made on the basis of a priori plausibilities, strength, simplicity, inductive confirmation, and so forth, relative to present empirical evidence. In this case future data might very well make one of the alternatives uniquely most preferred on the basis of these other ‘non-conservative’ grounds. It is only now, given our present evidential basis, that the theories are underdetermined relative to current observational considerations.” (Sklar 1975, pp. 380-381)

Stanford argues for taking transient underdetermination seriously and uses it as a backdrop for his novel challenge to scientific realism. He argues that the historical record makes it plausible that there are always *unconceived alternatives* to presently accepted theories. In other words, transient underdetermination is highly likely to be recurrent. Again and again, we will be faced with the emergence of alternatives which account equally well for all known phenomena. In opposition to scientific realism, we find no convergence to truth in the evolution of science (Stanford 2006).

3 A tale of two electrodynamics

To set the stage for the considerations concerning hidden underdetermination, let us sketch the historical development. Throughout much of the 19th century, two approaches compete for the adequate description of the wide range of electrodynamic phenomena: one formulated in terms of action at a distance, the other field-theoretic. The two approaches differ in a variety of aspects, most notably in their notion of interaction, their fundamental ontology and the mathematical framework. These differences are all related to one another.

3.1 Differences between action at a distance and field theory

One can begin to distinguish the field view from action at a distance by the different accounts of interaction. While in field theory action can only be mediated by contact, action at a distance does not impose such a constraint. These different notions of interaction immediately manifest themselves in the respective fundamental ontologies. Field theory requires the existence of a continuous medium that permeates space and allows for the strictly local transfer of physical action. Action at a distance on the other hand presupposes discrete or even point-like pieces of matter which are distributed in an empty space devoid of other fundamental entities. Not surprisingly, a pure vacuum is often held to be impossible in field theories, while in action-at-a-distance theories a vacuum, across which matter can interact, is naturally assumed.

Pure field theories like the electrodynamics formulated in Maxwell's *Treatise* (1873) or Einstein's unified field theory deny the existence of discrete fundamental entities altogether. In such theories, particles are only secondary or derived concepts that should be definable in terms of continuous fields. In the Schilpp-volume, Einstein sketches his notion of a rigorous field theory in the following way: "continuous fields are to be viewed as the only acceptable basic concepts, which must also be assumed to underlie the theory of the material particles" (Schilpp 1949, p. 675). Einstein tried to derive the apparent 'existence' of particles from extremely dense regions or even singularities in the field.

In both cases, the fundamental ontologies and notions of interaction suggest a natural mathematical framework for the formulation of the fundamental equations. The natural form in field theory is in terms of partial differential equations as is aptly illustrated by Maxwell's set of fundamental equations for electrodynamics. The reason is quite simple: Partial differential equations allow following the transfer of action from one point in space-time to an, informally speaking, immediately adjacent point, which is only an infinitesimal distance away in terms of space $\mathrm{d}\vec{r}$ and time $\mathrm{d}t$.

By contrast, the natural language of the fundamental equations in action at a distance employs proportions. A good example is Newton's law of gravity describing a force between two particles, which is *proportional* to the amount of matter of the interacting particles and inversely proportional to the distance square between them. Generally, the fundamental equations in action at a distance refer to finite (as opposed to infinitesimal) distances—mainly in spatial terms but sometimes also in spatio-temporal terms as in the case of retarded action at a distance. The prime example for the latter is given by the Liénard-Wiechert potentials in electrodynamics. Of course, these different languages are in the end mathematically equivalent, but they convey a difference in perspective and ontological commitment.

Finally, the difference in methodology is not restricted to the theoretical domain, but concerns also experimental methods and tools. In short, while action at a distance will put the experimental focus on discrete pieces of matter, field theory will be mainly concerned with determining the behavior of the medium in between. For example, to follow the field lines by means of iron filings is certainly a natural thing to do in field theory—it is not that obvious within action at a distance. Coulomb's torsion balance is an obvious experimental setup in action at a distance, much less so in field theory.

Thus, the differences between action at a distance and field theory pervade so crucially all constitutive characteristics of scientific theories—the two approaches are "so completely opposed in their first principles" (Maxwell cited in Hesse, 2005, p. 216) that one is confronted with much more than just different readings or interpretations of the same formalism. The actual physics is different—ranging from the metaphysical presuppositions concerning ontology and interaction to the theoretical methods employed in formulating the theory and finally to the experimental outlook on the world.

3.2 Achievements of the two programs

Both programs contributed enormously to the development of electrodynamics. For the larger part of the 19th century, the predominant approach was action at a distance treating electrodynamic phenomena broadly in the framework of a Newtonian theory of interaction. Within this tradition, Coulomb developed the force law for two charges at rest (1780s), and Ampère his law for the interaction of two current elements $i\mathrm{d}s$ and $i'\mathrm{d}s'$ (1822):

$$\mathrm{d}^2 f = ii' \frac{\mathrm{d}s\mathrm{d}s'}{r^2}\left(\sin\alpha\sin\beta\cos\gamma - \frac{1}{2}\cos\alpha\cos\beta\right). \qquad (1)$$

This law is certainly a departure from the pure Newtonian paradigm, since the force f depends not only on the distance r between the interacting current elements but also on the angles between them: α is the angle between the line connecting the two current elements and β the angle between the directions of the current elements $i\mathrm{d}s$ and $i'\mathrm{d}s'$; γ denotes the angle between the two planes spanned each by the connecting line and one of the current elements.

Still, the essential characteristics of action at a distance, as described in the last section, are preserved by Ampère's law. They can also be found in the arguably most sophisticated account of the action-at-a-distance tradition, namely the general law of electrodynamics developed by Wilhelm Weber (1846), in which forces between moving charges Q and Q' depend not only on the mutual distance but also on the mutual velocity dr/dt and acceleration $\mathrm{d}^2r/\mathrm{d}t^2$:

$$f = \frac{QQ'}{r^2}\left[1 - \frac{1}{C^2}\left(\frac{\mathrm{d}r}{\mathrm{d}t}\right) - \frac{r}{C^2}\frac{d^2r}{\mathrm{d}t^2}\right]. \qquad (2)$$

C is a velocity constant, whose meaning will be discussed further below.

Given that action at a distance was the dominant paradigm in electrodynamics for large parts of the 19th century, the merits of this tradition are of course various. It produced the fundamental laws of electrostatics by Coulomb and of electrodynamics by Ampère. Also, several important unifications were achieved within this framework. Early on already, Ampère had suggested unifying magnetism and galvanism by interpreting magnets in terms of electric currents and decades later, electrostatic and electrodynamic interaction found a common theoretical framework in Weber's law (2).

Maybe most surprisingly, crucial hints pointing toward a unification of electrodynamics with optics were discovered within the action-at-a-distance tradition. Notably, the velocity constant C in Weber's law is linked through a simple relation with the velocity of light c: $c = C/\sqrt{2}$. Furthermore, significant attempts were made to include optical phenomena into action-at-a-distance type theories by means of retarded potentials—among those pursuing such research were Bernhard Riemann, Carl Neumann, and Ludvig Lorenz (Darrigol, 2000, p. 212).

In comparison with action at a distance, Michael Faraday's field theory was much the work of an outsider. Even when many of his experimental results received broad attention, the underlying theoretical framework was long neglected. It was mainly due to William Thomson and James Clerk Maxwell that Faraday's conceptual ideas were eventually taken from obscurity. Like action at a distance, field theory provided the starting point of many significant novelties in electromagnetism: for example induction, or the theory of electric and magnetic media. Most of these discoveries were intimately linked with the shift in focus from interacting particles to the space or medium between them. Besides the formulation of a definite mathematical framework for electrodynamics in terms of Maxwell's equations, the most impressive successes of field theory were of course the inclusion of optics into electromagnetic theory and the prediction of electromagnetic waves beyond the visible.

To sum up, the two conceptually very distinct approaches coexisted as successful research programs for several decades in the 19th century. Both were at some point in time the preferred framework of a wide majority of physicists and both led the way to exciting new experimental results and were successful in the explanation of phenomena that had previously not been well understood.

4 The two electrodynamics and underdetermination

It happens only rarely that situations of underdetermination are explicitly acknowledged and fruitfully exploited by working scientists. More often than not, it is left to historians and philosophers of science to trace underdetermination in a specific scientific controversy. It is therefore remarkable that James Clerk Maxwell himself acknowledges the underdetermination between action-at-a-distance electrodynamics and the field view in the preface to his *Treatise*, and thus in one of the most prominent locations of all his work[2]:

> "In a philosophical point of view, moreover, it is exceedingly important that two methods [i.e. action at a distance and field theory] should be compared, both of which have succeeded in explaining the principal electromagnetic phenomena, and both of which have attempted to explain the propagation of light as an electromagnetic phenomenon, and have actually calculated its velocity, while at the same time the fundamental conceptions of what actually takes place, as well as most of the secondary conceptions of the quantities concerned, are radically different." (Maxwell, 1873, p. xii)

Maxwell adds that William Thomson had once convinced him that the differences between action at a distance and the field view "did not arise from either party being wrong" (p. x).

In short, both Maxwell and Thomson considered the situation in 19th-century electrodynamics as ampliatively underdetermined by the available evidence. The two approaches are claimed to be roughly equally successful in the explanation of those electrodynamic phenomena which were known at the time. Nevertheless, they rely on "radically" different fundamental concepts. The ontology is different as are the mechanism of interaction and the mathematical framework.

It must be emphasized, that the underdetermination of the two electrodynamics does not belong to any category of examples that can be quickly dismissed as philosophers' games. This example cannot be reconstructed by a straight-forward algorithm as in the case of so many pseudo-examples of

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[2] It has of course been a long-standing tradition for scientists to discuss methodological questions in the preface to their works. Maxwell is no exception in this respect.

underdetermination pervading the literature, e.g. invoking redefinition of terms, hallucination or the like. Rather, we are dealing with a situation involving "the sort of difficult conceptual achievement that demands the sustained efforts of real scientists over years, decades, and even careers" (Stanford, 2006, p. 15).

For much of the same reasons, the example of the two electrodynamics is not affected by the objection that in many alleged cases of underdetermination we are only dealing with variant formulations of the same theory (Magnus, 2003; Norton, 2008). In our case, the metaphysics, i.e. the claims what really exists in the world, and the methodology of the two electrodynamics is so different that nobody could plausibly consider them to be merely variant formulations. This assessment is further consolidated by the observation that the differences between the two accounts are intimately connected with the respective successes of these accounts—as we had seen in the last Section 3.2.

Furthermore, the development of electrodynamics profited a lot from attempts to work out the connections between the two frameworks, in particular in the work of William Thomson. For example, the potentials φ and $\vec{A}$ were proposed in this context as neutral quantities that allow for the translation of one framework into the other (Darrigol, 2000, Ch. 3.5-3.7). These quantities can be employed both in action at a distance, where they are relational quantities between different particles, and in field theory, where they describe the state of the electromagnetic medium. The immense practical usefulness of these quantities can be seen in any modern textbook on electrodynamics. Historically, such neutral quantities allowed for the transfer of advances from one framework to the other. If we were merely dealing with variant formulations, it would be surprising that sketching the connection between the two programs could lead to actual progress in electrodynamics.

In summary, there is overwhelming evidence that the two electrodynamics constitute a genuine and methodologically instructive example of underdetermination by the available evidence.

5 The electrodynamic roots of the underdetermination thesis

The relevance of the case study is further underlined by the fact that Duhem's view on scientific method in general and underdetermination in particular was shaped decisively by his reflections on classical electrodynamics. As Roger Ariew and Peter Barker have remarked: "Duhem's most sustained examination of a contemporary case is his critique of Maxwell's science and scientific methodology" (Ariew & Barker 1986, p. 145). Electrodynamics was one of Duhem's main study fields as is evidenced by his volume on Maxwell's theory (1902). Also, an early essay on scientific method, namely "L'école anglaise et les théories physiques" (1893), makes ample reference to Maxwell and Thomson and is later reworked into the crucial chapter IV of part I in *The Aim and Structure of Physical Theory*. This chapter contains a detailed exposition of the underdetermination thesis—much more so than the ubiquitously cited and reprinted chapter VI of part II. In summary, an understanding of the role of the underdetermination thesis in Duhem's work should profit considerably from a thorough grasp of the development in electrodynamics at the turn of the 19th century.

At least as far as I am aware, Duhem nowhere explicitly acknowledges a case of underdetermination between the Newtonian tradition of Coulomb, Poisson and Ampère and the field approach of Faraday, Thomson, and Maxwell. Rather, Duhem's thinking is deeply rooted in the French school and he does not seem to consider Maxwell's electrodynamics a coherent research program at all. Too numerous are in his eyes the contradictions and inconsistencies in Maxwell's work including the *Treatise*. Still, Duhem does not hold that Maxwell's approach can be ruled out in principle, neither on empirical nor on epistemic grounds. His main objection against Maxwell's program is that he does not comply with conservativeness in theory change and thus does not guarantee historical continuity in the evolution of physics: "No logical necessity pressed Maxwell to imagine a new electrodynamics." (Duhem 1902, p. 8) For Duhem, it is rather Helmholtz's electrodynamics, which naturally continues the Newtonian tradition while accounting for the same phenomena as Maxwell's theory.

Duhem's underdetermination thesis is very much a product of his quarrel with the method of the English physicists. This is further corroborated by the fact that the mentioned chapter IV of part I of *Aim and Structure*, which arguably contains his most explicit statements of the underdetermination thesis, frequently refers to Maxwell and Thomson. Here is his reaction to the English method:

> "If we confine ourselves strictly to considerations of pure logic, we cannot prevent a physicist from representing by several incompatible theories diverse groups of laws, or even a single group of laws; [...] Logic evidently imposes on the physicist only one obligation: not to confuse or mix up the various methods of classification he employs. [...] Logic does not, therefore, furnish any unanswerable argument to anyone who claims we must impose on physical theory an order free from all contradiction. Are there sufficient grounds for imposing such an order if we take as a principle the tendency of science toward the greatest intellectual economy? We do not think so." (Duhem, 1954, pp. 101-102; my italics)

Duhem states clearly that theories are not only underdetermined by logical considerations, but also by those epistemic criteria that contribute to the 'economy of thought' in scientific theories. In addition, Duhem's well-known critique of inductivism indicates that for him inductive methods cannot provide an answer to underdetermination, either. Because Duhem takes into account epistemic virtues and inductive methods, he argues for ampliative underdetermination. There remains of course Duhem's notorious concept of good sense, which is supposed to resolve most cases of underdetermination. But according to Duhem, 'good sense' refers to a "confused collection of tendencies, aspirations, and intuitions" and cannot be stated in terms of explicit rules of rationality (1954, p. 104). Notably, neither inductive methods nor epistemic virtues can account for good sense. But plausibly, the requirement of historical continuity which was mentioned above should be considered as an example for a rule of good sense. Good sense then has a crucially pragmatic dimension.[3]

If Duhem's theory of good sense proves that he was in general not very sympathetic to the underdetermination thesis, then why did he propose it at all? My suggestion is that the underdetermination thesis constitutes a concession to the style of the English physicists with its focus on models and analogies, especially in the works of Thomson and Maxwell:

> "It is the English physicist's pleasure to construct one model to represent one group of laws, and another quite different model to represent another group of laws, notwithstanding the fact that certain laws might be common to the two groups. To a mathematician of the school of Laplace or Ampère, it would be absurd to give two distinct theoretical explanations for the same law, and to maintain that these two explanations are equally valid. To a physicist of the school of Thomson or Maxwell, there is no contradiction in the fact that the same law can be represented by two different models. Moreover the complication thus introduced into science does not shock the Englishman at all; for him it adds the extra charm of variety. His imagination, being more powerful than ours, does not know our need for order and simplicity; it finds its way easily where we would lose ours." (Duhem, 1954, p. 81)

The mechanical models, to which Duhem refers here, played a most prominent role in the development of electrodynamics, especially when it came to accounting for the behavior of the electromagnetic medium. These models succeeded to an extent that is deeply miraculous from the

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[3] The fact that Duhem distinguishes English, French and German research styles in physics, somewhat suggests that Duhem might even allow for sociological influences in physics.

perspective of modern electrodynamics, which has given up all attempts at mechanically accounting for the transmission of action via fields.

Consider for example Maxwell's well-known 'idle wheel'-model for the electromagnetic field. In ordinary kinematics with cranked wheels, idle wheels can be employed for transmitting rotation between two wheels with the same sense of rotation. Now, Maxwell pictured the electromagnetic field as a medium with vortices, which he modeled as cranked wheels with a thin layer of round particles in between to account for the vortices having all the same sense of rotation. Maxwell identified the stream of these round particles with the electric current, the rotational velocity of the idle wheels with the magnetic force, and the tangential action of the cell on the particles with the electric force. By allowing for elasticity of the cranked wheels, he produced a mechanical model of the basic electrodynamic equations with only few limitations. For example, it was restricted to closed currents. Even though Maxwell acknowledged the awkwardness of the model and it seemed quite obvious to him that it did not represent the true connections, he nevertheless fruitfully employed it (Darrigol, 2000, pp. 149-151). According to Maxwell, underdetermination is always lurking in such models, since "determining the mechanism required to establish a certain species of connexion [...] admits of an infinite number of mechanisms" (Maxwell cited in Nersessian, 2008, p. 50).

Duhem despises these mechanical models and leaves no doubt that he prefers the French or continental style in physics which is wary of underdetermination. However, Duhem is unable to deny the obvious successes of Thomson and Maxwell's method. Duhem's reaction to the English style is very similar to that of other continental physicists, for example von Helmholtz and Poincaré, both of whom he cites. Poincaré, for example, alleges a certain inevitability of Maxwell's methods: "We should not flatter ourselves on avoiding all contradiction. But we must take sides. Two contradictory theories may, in fact, provided that we do not mix them and do not seek the bottom of things, both be useful instruments of research. Perhaps the reading of Maxwell would be less suggestive if he had not opened so many new, divergent paths." (cited in Duhem, 1954, p. 91) Like Duhem, Poincaré finds Maxwell's approach distinctively English: "The first time a French reader opens Maxwell's book a feeling of discomfort, and often even of distrust, is at first mingled with his admiration [...] The English scientist does not seek to construct a single, definitive, and well-ordered structure; he seems rather to raise a great number of provisional and independent houses among which communication is difficult and at times impossible." (cited in Duhem, 1954, p. 85)

As in the case of the confusing variety of mechanical models for the field, so in Maxwell's assessment of an underdetermination between field theory and action at a distance, with which Duhem was certainly familiar, British physicists doing research in electrodynamics were very tolerant toward contradictory descriptions of one and the same phenomenon. Thus, in developing his underdetermination thesis Duhem did not have to resort to abstract methodological speculations, but rather he had to make sense of an actual historical situation in 19th-century electrodynamics.

6 The hybrid nature of classical electrodynamics

There is a common misconception about classical electrodynamics which is well illustrated by a quote from the classic textbook of John D. Jackson. According to Jackson, classical electrodynamics is "a subject whose fundamental basis was completely established theoretically [...] by Maxwell" (Jackson, 1999, p. vii). This suggests that classical electrodynamics originates exclusively in Maxwell's field theory. By contrast, we will now see that to a considerable extent classical electrodynamics, i.e. the theory presented in textbooks like Jackson (1999) or Griffiths (1999), owes much to action at a distance.As a preliminary remark, let me remind you that by the term 'field theory' we mean theories, in which *only* continuous fields constitute the fundamental entities, to be distinguished from the particle-field theories which dominate modern classical physics. Crucially, in genuine field theories—

like the electrodynamics expounded in Maxwell's *Treatise* or Einstein's unified field theory—discrete particles are secondary or derived concepts. In contrast, the classical electrodynamics of modern textbooks is a particle-field theory that allows for both fields *and* particles as fundamental entities. This classical electrodynamics is therefore not a field theory in the sense mentioned above.

Let us sketch briefly how charges and currents were derived concepts for Maxwell. In his theory, electromagnetic phenomena are due to mechanical stresses in the dielectric medium[4]. These stresses Maxwell calls 'polarization'. Charge represents a discontinuity in polarization at the border between a dielectric and a conductor. Conductors differ from dielectrics in that they are not able to sustain polarization. Since the concept of charge is so intimately connected with polarization in the dielectric, for Maxwell charge is *not* a property of the conductor. Rather, he takes it to 'reside' on the surface of the dielectric:

> "[A]ll electrification is the residual effect of the polarization of the dielectric. This polarization exists throughout the interior of the substance, but it is there neutralized by the juxtaposition of oppositely electrified parts, so that it is only at the surface of the dielectric that the effects of the electrification become apparent." (Maxwell, 1873, §111)

The view that charge is a property of the medium and not of the conductor was already held by Faraday, for whom charges were loosely speaking just the endpoints of the force lines.

The electric current is also a secondary concept in Maxwell's theory—again derived from polarization. Electric currents essentially consist in a change of polarization over time. This idea has broadly survived in the modern notion of displacement current, which is due to a changing electric field and which according to Maxwell's equations can act as a source of a magnetic field in the same manner as an ordinary current. Since polarization was the fundamental concept for Maxwell, in his *Treatise* there existed no genuine difference between the nature of the displacement current and that of ordinary conduction currents. Accordingly, Maxwell could claim that there are no open currents at all—thereby resolving an old quarrel in electrodynamics concerning the question how open currents should be treated, an issue which was very difficult to examine experimentally at the time. Maxwell summarizes his view on the electric current with the following sentences:

> "[W]hatever electricity may be, and whatever we may understand by the movement of electricity, the phenomenon which we have called electric displacement is a movement of electricity in the same sense as the transference of a definite quantity of electricity through a wire is a movement of electricity, the only difference being that in the dielectric there is a force which we have called electric elasticity which acts against the electric displacement, and forces the electricity back when the electromotive force is removed; whereas in the conducting wire the electric elasticity is continually giving way, so that a current of true conduction is set up." (Maxwell, 1873, §62)

The derived nature of charges and currents lies at the heart of what makes Maxwell's electrodynamics so different from the theory of today's textbooks. Olivier Darrigol, a leading historian of electrodynamics in our days, emphasizes the same point: "Maxwell's theory was a pure field theory, ignoring the modern dichotomy between electricity and field." (Darrigol, 2000, p. 173) But outside the small community of historians it is only rarely acknowledged, how different the conceptual and in particular ontological foundations of Maxwell's theory and the classical electrodynamics of textbooks like Jackson (1999) are. In a slight variation of a famous dictum by Heinrich Hertz, who said that Maxwell's theory are his equations, one could phrase, that what has survived from Maxwell's original theory are just the equations—and only few of the fundamental concepts.

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[4] What we would today call a vacuum is also a dielectric medium in Maxwell's sense.

As sketched above, two of the most important conceptual differences between particle-field electrodynamics and pure field electrodynamics concern the ontological status of charged particles and the treatment of the displacement current. Today, charged particles are considered part of the fundamental ontology of classical electrodynamics and conduction currents are thought to be very different from displacement currents, in that the former consist of charged particles and the latter do not.

Both the modern treatment of charges and that of the displacement current owe much to the action-at-a-distance tradition. The existence of charges is a postulate from action at a distance as is the non-mechanical and immaterial nature of the displacement current. In the end, rather than talking of the abandonment of action at a distance, it seems justified to say that the two theories actually merged in important respects to build the classical electrodynamics of textbooks like Jackson (1999).

One of the main reasons for the renaissance of concepts from action at a distance was the 'discovery' of charged elementary particles in the late 1890s like electrons or alpha particles. As Maxwell stresses in the *Treatise*, charge quantization does not fit easily into his field theory. At one instance, talking about electrolysis, he calls charge quantization "out of harmony with the rest of this treatise" (Maxwell, 1873, §260). Presumably, charge quantization clashes with Maxwell's concept of a continuous medium on the one hand and the derived nature of charges from the properties of this medium on the other hand. How could something discrete be possibly derived from something continuous? By contrast, for action at a distance charge quantization poses no particular problems.

Many physicists at the turn of the 20th century that were involved in developing the new 'quantized' electrodynamics acknowledged the return to concepts from action at a distance in order to accommodate the experimental discovery of elementary particles. Hendrik A. Lorentz, possibly the most important contributor to the emerging microscopic electrodynamics, readily concedes this debt to the action-at-a-distance tradition in a speech from 1904: "I have already drawn your attention to the affinity of the electron theory with older ideas. In particular, the electron theory has quite a few similarities with the theory of the two electric fluida as advocated especially by Wilhelm Weber." (Lorentz, 1905, p. 7; my translation) Emil Wiechert, another leading researcher in electrodynamics, equally admitted the return of action at a distance: "The more recent electrodynamics based on Maxwell has returned to such an extent to the viewpoints of the older school by distinguishing between ether and matter in the interior of the perceptible bodies that the original opposition does not exist anymore. The 'electric particles' of the old theories have regained their right; but we have learned to follow their interactions through the medium in between." (Wiechert, 1901, p. 667; my translation)

Thus, classical electrodynamics is neither a field theory nor is it genuinely action at a distance. It is the result of a merging of the two traditions. This is not only acknowledged by historical figures like Lorentz or Wiechert but also by modern historians of electrodynamics like Olivier Darrigol: "By analogy with Weber's [action-at-a-distance] theory, conduction became a flow of the charged particles; charge, their accumulation; polarization in material dielectrics, their elastically resisted shift; and magnetism, their microscopic cyclic motion. All of this was utterly un-Maxwellian: gone were the analogy between material dielectrics and the ether, the concept of conduction as a decay of displacement, and the prejudice against applying electromagnetic concepts at the molecular scale." (Darrigol, 2000, p. 326) Just in the moment, when Maxwell's field theory seemed to have prevailed on account of the discovery of electromagnetic waves, the action-at-a-distance tradition regained its right following the discovery of elementary charges.

As a result, a theory was constructed that merged important concepts of both the field tradition and action at a distance. The resulting theory included both the fundamental ontology of the field theory and that of action at a distance, both fields and particles. Although less pronounced, there is also a doubling in the concepts of interaction in that the Lorentz-force is added to Maxwell's equations. In addition to the field equations, particle-field theories require a fundamental force law for the action of fields on charges and currents. There is also a doubling of energy concepts which can now be ascribed to both charges and fields. Also, fundamental equations of both approaches survive: the action-at-a-distance laws of Coulomb and Ampère as well as the field equations of Maxwell.

Since our primary interest in this essay concerns the historical resolution of the specific underdetermination situation in 19th-century electrodynamics, we can let our story end around 1905. At this time, classical electrodynamics is basically formulated, while Planck, Einstein and others open the door to new research programs that originate in classical electrodynamics but go much beyond it, in particular special relativity and quantum mechanics. Of course, new interesting issues arise when quantum electrodynamics emerges in the 1920s, but addressing the highly complex relationship between classical and quantum electrodynamics would by far exceed the scope of this paper[5].

In summary, following a situation of underdetermination, none of the programs was really abandoned. Rather, the two programs were merged into a resulting theory with considerable redundancies in comparison with the original theories: most importantly a doubling of ontology, which is in turn connected with all kinds of other redundancies, e.g. regarding the mathematical framework. These redundancies were crucial in keeping the methodological advantages of the two frameworks. In the next section we will identify this as a situation of hidden underdetermination.

7 Hidden underdetermination

Hidden underdetermination is a thesis about the evolution of theories following a situation of explicit underdetermination between two (or more) approaches. It denotes one of various possibilities, how situations of explicit underdetermination might end. In a situation of hidden underdetermination, both approaches survive in considerable redundancies of the final theory. However, these redundancies are not explicitly acknowledged as such but are considered to be fundamental and indispensable elements of the theory, as the charges and fields in classical electrodynamics. Nevertheless, by eliminating the redundancies the original underdetermination could be recovered from the final theory.

Thus, we require the following criteria to establish hidden underdetermination: (i) The redundancies can be eliminated by introducing constraints into the final theory, thus recovering the original situation of underdetermination. Crucially, these constraints cannot be ruled out by direct observation and/or straight-forward inductive rules, i.e. they are not empirical in nature. (ii) Rather, the mentioned redundancies can be pragmatically motivated in terms of intuitiveness of the final theory. (iii) Finally, it is reasonable to assume that the integration of redundancies leads to conceptual problems at the interface between the two theories. After all, the two frameworks were originally designed to describe the same phenomena *independently*. Let us now show that classical electrodynamics as found in textbooks like Jackson (1999) or Griffiths (2003) fulfills criteria (i) to (iii) to be discussed in sections (7.1) to (7.3), respectively.

7.1 Absorber and emitter conditions

By introducing an ideal absorber and emitter, modern classical electrodynamics can be reduced to an action-at-a-distance theory which in turn corresponds to a pure field theory. In other words, given the absorber and emitter conditions the original underdetermination is restored. We will establish the non-empirical nature of these constraints. Also, we will look at reasons that have sometimes been brought forward against absorber and emitter conditions and will find them wanting.

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[5] The interested reader might look at Spohn (2004) or references therein.

The absorber condition states that every field is eventually absorbed by a distribution of charges. The emitter condition states that every field once originated in a distribution of charges. In a sense, both are cosmological boundary conditions. Under these conditions there are no free fields and the fields can be interpreted as mere auxiliary tools to calculate the interaction between distant particles. The state of the field can be calculated from the distribution of charges using Maxwell's equations or vice versa the distribution of particles from the state of the fields. Therefore, either the fields can be taken to have no degrees of freedom independent of the charged particles or the particles can be taken to have no degrees of freedom independent of the fields. The absorber and emitter conditions drastically reduce the degrees of freedom of the theory. As a consequence, there is no need for a double ontology. Either the particles can be taken as fundamental ontology and the fields as derived or secondary ontology resulting in an action-at-a-distance theory, or the fields can be taken as fundamental ontology resulting in a pure field theory. Graphically speaking, either the endpoints of the field lines can be taken as fundamental ontology or the field lines excluding the endpoints.

Over the twentieth century, there have been a number of attempts to formulate either pure field or action-at-a-distance theories. We need not subscribe to any of these attempts. In particular, if we argue for the possibility of an action-at-a-distance electrodynamics, we do *not* commit to the Wheeler-Feynman approach (1945, 1949) and its peculiar set of conceptual problems[6]. Rather, any formulation of classical electrodynamics including the orthodox Maxwell-Lorentz electrodynamics can be turned into an action-at-a-distance theory just by introducing the absorber and emitter conditions.

Let us now establish that the absorber and emitter conditions cannot be ruled out for empirical or conceptual reasons: (a) The absorber and emitter conditions cannot be empirically falsified. On the contrary, there is some inductive evidence which speaks in favor of them. (b) Criticism of these conditions in the contemporary literature is often only superficial. Many authors just find them "odd" or "awkward". (c) Conceptually, the absorber and emitter conditions are closely related to conservation laws. An example of an absorber (and emitter) condition which was endorsed by Maxwell and Faraday is the conservation of charge in combination with the belief that the total charge in the universe adds up to zero. (d) Arguments relying on locality and conservation of energy and momentum are not decisive against the existence of absorber and emitter conditions. (e) Finally, arguments from reversibility and the action-reaction principle speak in favor of absorber and emitter conditions.

(a) As mentioned, the absorber condition states that every field is eventually completely absorbed by charged matter while the emitter condition states that every field once originated in charged matter. Obviously, these conditions cannot be falsified through observation. After all, the emitting and absorbing charges can be arbitrarily far away both in spatial and temporal terms. Therefore, we can never prove that a certain field is *not* absorbed or *not* emitted. This seems to be general consensus, since one rarely finds statements that action-at-a-distance is ruled out empirically.[7]

By contrast, an inductive argument can be construed *in favor* of the absorber and emitter conditions just by enumerating those fields which are known to originate in charged matter and to be absorbed by charged matter. Notably, this can be established for the majority of fields and radiation. After all, most macroscopic matter around us is electrically and magnetically neutral, showing that microscopic fields on the atomic and molecular scale are to a large part absorbed. We also find that most radiation originates in some material source, e.g. the sun or a light bulb (with the possible exception of the microwave background radiation). Also, the quantization of the radiation field makes possible its full absorption, which would be less plausible if radiation were spreading out isotropically in space.

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[6] These problems are mainly inherited from Dirac's treatment of radiation reaction about which more will be said later on. It is rather unfortunate that action-at-a-distance approaches in classical electrodynamics have been tied so closely to the Wheeler-Feynman theory.

[7] Zeh (1999, p. 36) cautiously hints that under certain cosmological conditions action at a distance might be ruled out experimentally.

Finally, there are impressive instances, where electromagnetic fields and radiation are completely absorbed by surrounding matter as in the example of a Faraday cage.[8]

Of course, this inductive evidence does not prove the absorber and emitter conditions. Strong theoretical or conceptual reasons might still rule against such constraints. However, if such reasons exist then they are absent from the literature, as we will see now.

(b) Absorber and emitter conditions are in general not well-regarded among modern physicists, with the exception of those few that propagate action-at-a-distance electrodynamics in the Wheeler-Feynman tradition, e.g. Fred Hoyle and Jayant Narlikar (1995). Many just find these conditions awkward and odd. However, the history of science teaches us that one should be wary of such assessments since they are often subject to change.

Let us briefly examine some of the major monographs in classical electrodynamics and look at what they have to say about absorber conditions.[9] Generally, all authors presuppose a particle-field ontology, thereby implicitly rejecting the absorber and emitter conditions. Other approaches like action at a distance, which requires an ideal absorber, are addressed only *en passant*. For example, Jackson (1999), in an otherwise extensive monograph of more than eight hundred pages, refers to action-at-a-distance approaches in a single paragraph without providing reasons for or against them (pp. 611-612). Griffiths (1999), another classic textbook, finds an action-at-a-distance electrodynamics "possible, though cumbersome" (p. 61). He gives no reasons for this assessment. Spohn (2002) spends two pages introducing the Wheeler-Feynman theory concluding that "agreement with the conventional theory is accomplished" (p. 41).

As a last example, Rohrlich (2007) is the only one of these four to actually give reasons why an absorber condition should not be included in modern electrodynamics. He states that ''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) Rohrlich's first argument comes close to a *petitio principii*. Surely, *if* we accept the autonomous nature of the radiation field then the elimination of fields is unjustified. But the whole point of the absorber and emitter conditions is that we need not accept this autonomy. Furthermore, it is not clear how field quantization can change this assessment. As noted above, it is easier to accept that photons will once be absorbed by point-like charges in comparison with an isotropic radiation field spreading out in space. Thus, field quantization actually makes the absorber condition more plausible.

Rohrlich's second reason is equally unconvincing. There exist a number of ways, how absorber and emitter conditions can easily be integrated into the basic assumptions of theories, for example by restricting the ontology to either particles or fields. From such a restriction, absorber and emitter conditions follow automatically. Maybe Rohrlich has in mind that absorber and emitter conditions concern boundary conditions and thus should not belong to the core of a theory which supposedly contains only laws. But if that was his intention than he is mistaken, since, again, these conditions follow from a restriction of the ontology and ontological commitments naturally belong to the core of physical theories.

(c) Also, absorber and emitter conditions bear close resemblance to conservation laws. For example, the absorber condition amounts to the statement: If a change in motion of a charged particle is observed creating a field, there must be a complementary motion somewhere else which fully absorbs the field. From this view, the absorber and emitter conditions amount to nothing else than a conservation law for the motion of charged particles (leaving unspecified the exact quantity that is conserved).

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[8] For a detailed exposition of these issues, see Pietsch (2010, pp. 73-74)

[9] Emitter conditions are generally not addressed since they do not form part of the currently most influential action-at-a-distance approach due to Wheeler and Feynman.

An example of an absorber and emitter condition, which was readily accepted by both Faraday and Maxwell, is the law of the impossibility of absolute charge (Darrigol 2000, pp. 86–88). This law states charge conservation in combination with the claim that the total charge in the universe is zero. If this were not true, then there would be an electrostatic field of the whole universe which would not be absorbed and both the absorber and the emitter conditions would be violated.

(d) Certainly, the conservation of motion, which would guarantee the absorber and emitter conditions, differs in crucial respects from other conservation laws. Most importantly, in electrodynamics we are dealing with retarded interaction: If a charge is moved here and now, another charge will move somewhere else at a later instant in time. By contrast, traditional conservation laws require that a quantity remains constant over time. Such worries are closely related to concerns regarding locality. If there is no medium between the charges, how can energy and momentum be transferred from one space-time point to the other. Even though these are serious arguments for taking the field ontology seriously, one can counter them by altering our intuitions about locality and conservation laws. For a detailed exposition just how this can be done, we must refer the reader to Pietsch (2010, Sec. 5 & 6).

(e) Finally, there are conceptual arguments that work in favor of absorber and emitter conditions, most importantly reversibility and the action-reaction principle. Plausibly, a theory fares better in terms of reversibility, if for every field-emitting process there exists a field-absorbing process and vice versa. By the way, such reasoning played a crucial and successful role in one of Einstein’s arguments for field quantization. If the radiation would spread out isotropically in space as classical electrodynamics predicts, then there would be no reverse process to an elementary emission of radiation. Therefore, on the elementary level the picture of isotropic emission must be wrong and we must assume directed emission and therefore field quantization (Einstein 1909).

Reversibility is closely related to the action-reaction principle which also appears more fully realized in action at a distance. Presupposing the absorber and emitter conditions, for every action in terms of motion of charges there is an equal reaction in terms of motion of charges. By contrast, in a particle-field ontology, action and reaction are qualitatively different: one in terms of fields, the other in terms of particles.

In the end, everything depends on how one weighs the different arguments that speak in favor or against the absorber and emitter conditions. However, there are no empirical or conceptual reasons that definitely rule out these constraints and thus pure field and pure particle approaches to electrodynamics are possible. This result is all we need to establish hidden underdetermination.

7.2 Pragmatic advantages of the particle-field approach

If the doubling of ontology was not a necessary step, why hasn’t Ockham’s razor been applied to reduce the ontology? The answer is that the particle-field ontology has important pragmatic advantages. There are a large number of problems that are treated more naturally by means of fields, others by means of particles. For example, a field ontology lends itself intuitively to problems in optics. By contrast, all interaction between charged bodies and electric currents is naturally treated in terms of a particle ontology. The particle-field ontology has the advantage that it offers an obvious justification for working both with particles and fields depending on the context.

Another pragmatic advantage of the double ontology is that physicists need not be too concerned about the full charge distributions generating or absorbing a field. For example, it is much easier to state boundary conditions in terms of both particles and fields than just in terms of particles (or fields). In addition, it requires less information, since certain fields could be generated by a variety of different charge distributions.

7.3 Conceptual problems resulting from the double ontology

A number of conceptual problems that have plagued classical electrodynamics for over a century are intimately related with the doubling of ontology. Many of them concern the interaction between particles and fields, and thus a question which is genuine to particle-field theories. After all, if only fields *or* particles are fundamental, then there can be no interaction between particles and fields. As of today, a number of these problems remain unsolved: (a) There is no agreement on the exact expression for the force of a field acting on particles. (b) No plausible account exists regarding the physical origin of the recoil force that charged particles experience when they are accelerated. (c) There are open questions in how energy and momentum must be distributed between particles and fields, which are most pressing in the divergences of point particles (Frisch 2005, Ch. 3).

(a) As already noted, the doubling of ontology entails a doubling of interaction. Only in particle-field theories, one is confronted with two distinct laws, one for the action of a particle on the field, the other for the action of the field on a particle. In classical electrodynamics, the first kind can be calculated from the two inhomogeneous Maxwell equations and thus constitutes no problem. By contrast, there is no universally accepted force law for the action of a field on a particle. Crucially, this issue does not come up in action-at-a-distance theories which know only an interaction between distant particles, as in Coulomb's, Ampère's, or Weber's laws. Similarly, in pure field electrodynamics, there is just one set of equations describing the dynamics of the fields, of which charges are only the endpoints. In a pure field theory, the 'action' of a field on a particle must be derivable from the dynamical equations of the field.

In classical electrodynamics, the action of fields on particles is of course described by the Lorentz force. Certainly, the attribution to Lorentz is not surprising given that he was the father of the electron theory, i.e. the first major particle-field approach. Today, most physicists believe that the simple Lorentz force must be supplemented by an additional force term accounting for radiation reaction. However, what exactly this additional term should look like remains an open question. The two main contenders are the Lorentz-Abraham-Dirac equation (LAD) and the Landau-Lifshitz equation (LL).[10]

LAD has long been considered the correct force law, though with some unease since it is notoriously plagued by unphysical solutions that exhibit preacceleration and self-acceleration (also known as runaway solutions). In the former case, the particle accelerates prior to the action of the force on the particle. In the latter case, the particle accelerates towards the speed of light in the limit of time $t \rightarrow \infty$, even if *no* external force is acting on the particle. These unphysical solutions have puzzled physicists for over a century. Griffiths *et al.* (2010) refer to them as "the skeleton in the closet of classical electrodynamics" (p. 391). Jackson (1999) writes: "a completely satisfactory classical treatment of the reactive effects of radiation [on the radiating particle] does not exist. […] Although partial solutions, workable within limited areas, can be given, the basic problem remains unsolved." (p. 745). There have been several attempts to rule out unphysical solutions, e.g. by appropriate boundary conditions, but most of them remain rather *ad hoc*.

By contrast, the Landau-Lifshitz equation does not exhibit unphysical solutions and it is currently favored by several physicists working on classical electrodynamics (e.g. Rohrlich 2007, Spohn 2004). Rohrlich, who is one of the most outspoken supporters of LL, goes as far as claiming that they represent "the physically correct dynamics" (p. 257). However, such statements have not remained undisputed. For example, Griffiths *et al.* (2010) stress that both LAD and LL are only approximations.

(b) A related problem concerns the physical cause of the radiation emitted by accelerated particles and thus of the recoil term by which the Lorentz force must be supplemented. Unfortunately, the two programs that address this question from the particle-field perspective are both plagued with notorious difficulties. Muller (2007) refers to the approaches as the *extension* and the *renormalization* program.

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[10] For details, confer Rohrlich (2007).

The former approach tries to account for radiation reaction in terms of the structure of an extended particle, the latter in terms of the fields that accumulate around a point charge.

The extension program, which dates back to Lorentz and Max Abraham, tries to account for the emitted radiation in terms of the action of an extended charge on itself. Fundamental charges are modeled as relativistically rigid spheres. Since the times of Lorentz and Abraham, such models have reached an enormous degree of sophistication with the most elaborate modern account to be found in Yaghjian (2006). Until very recently, major advances have happened and crucial problems of the extension program have been solved. For example, the original calculations led to an inconsistency between the force equation and the power equation by a factor 4/3 in one of the terms. Also, an extended charge should be expected to 'explode' due to the repulsion by Coulomb forces. Surprisingly, both issues were resolved simultaneously by an ingenious suggestion of Poincaré to introduce binding forces, which both counter the repelling forces and remove the mentioned inconsistency. Another remarkable success of the extension program is its consistency with relativity theory before the latter was even formulated.

Unfortunately though, scattering experiments have failed to reveal an extension of the electron in the order of magnitude of the classical electron radius nor has any internal structure of electrons been detected at all. Notoriously, the electrostatic self-energy diverges in the limit of a vanishing radius implying an infinite mass that cannot be convincingly dealt with. Also, the nature of the binding forces remains unclear. Yaghjian (2006, Ch. 4) speculates that they result from electromagnetic polarization but has to postulate an insulator material to which this polarization is attached. However, there are no plausible candidates for this insulator material. In summary, while the extension program has yielded impressive successes, its conceptual layout is deeply rooted in 19th century physics and largely at odds with modern knowledge about fundamental particles.

The renormalization program starts from opposite assumptions. Most importantly, point particles are taken as fundamental. Also, advanced forces are interpreted as physically meaningful, while the extension program works only with retarded forces. The renormalization program essentially dates back to a paper of Dirac (1938), which suggests a new derivation of the LAD equation. The name originates in the fact that Dirac deals with infinities, such as divergences in the field, by means of a clever omission ('renormalization') of terms. The crucial observation is that half the difference between retarded and advanced fields results in the radiation reaction term of the LAD equation. There is much to criticize in the renormalization program, in particular the very peculiar treatment of advanced fields, which remains essentially mysterious. Dirac's derivation is justified mainly by the fact that it leads to the correct results, as he himself readily acknowledged (1938, p. 149).[11] In summary, both the extension and the renormalization programs are beset with considerable problems.

(c) A final issue concerns the exact distribution of energy and momentum between particles and fields. Of course, this is again closely related with the problems regarding the interaction between particles and fields. As long as the exact force laws have not been determined, the transmission of energy and momentum between particles and fields must also remain unclear.

Thus, we have established the conditions (i)-(iii) that we required for a situation of hidden underdetermination. We have seen that action-at-a-distance and pure field approaches can both be recovered from the modern particle-field theory by introducing the absorber and emitter conditions. We have also shown that the motivation for merging the original approaches was essentially pragmatic. Finally, a number of conceptual problems result from the merging, in particular when the interaction between particles and fields is considered.[12]

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[11] A more detailed critique of the Dirac program is left for another occasion.

[12] Of course, this is not to claim that pure particle and pure field approaches are without problems.

7.4 Some 20th-century historical perspectives

The assessment of hidden underdetermination in classical electrodynamics is corroborated by the fact that throughout the 20th century, we find several quite successful attempts to reduce the ontology of classical electrodynamics to either fields or particles. Of course, this would be striking if the doubling of ontology had been necessitated on the basis of new evidence in connection with charge quantization. Examples are the Wheeler-Feynman action-at-a-distance electrodynamics (1945, 1949)[13] and its various precursors including the theories of Jakow Frenkel, Karl Schwarzschild, Hugo Tetrode, and Adriaan Fokker. To some extent, these theories have influenced the development of physics in the 20th century. For example, Tilman Sauer has argued that Feynman's work on action-at-a-distance electrodynamics provided fruitful ground for some of his later contributions to physics, e.g. his space-time approach to non-relativistic quantum mechanics (2008).

Or consider the work on unified field theory by Einstein and his coworkers—certainly a field theory very different from Maxwell's but nevertheless an attempt at reducing the ontology. The existence of these projects is testimony that several leading figures in 20th-century physics did not see the step to a particle-field ontology as a necessary one.

8 Conclusion: Hidden underdetermination and realism

The relevance of this essay to the realism debate consists in an elaboration of some aspects of the underdetermination thesis, which is usually construed as a central argument against realism. To which extent underdetermination really poses a threat to the different versions of scientific realism remains a difficult and by no means trivial question that is beyond the scope of this essay[14]. There are two main lessons to be drawn from the case study: First, underdetermination can be hidden in the redundancies of a single theory and thus single theories can pose a threat to realism insofar as the corresponding explicit underdetermination would threaten realism. Second and relatedly, if underdetermination does not necessarily vanish when explicit underdetermination ends, then a thorough examination of the criteria governing theory choice is essential to assess realist and antirealist intuitions about the evolution of science. Let us now address these issues in turn.

The fact that underdetermination can be hidden in single theories implies that it may lurk in situations where it has traditionally not been suspected and thus it may be much more widespread than usually supposed. Certainly, not every redundancy in a scientific theory automatically implies a corresponding situation of hidden underdetermination which could threaten realist intuitions. For example, there is a considerable literature on "surplus structure" in physical theories—a term originally introduced by Michael Redhead (1975)—and how to make sense of this phenomenon from the perspective of structural realism (e.g. French 2011, Lyre 2011). The focus in this literature is on how to distinguish mathematical surplus structure from the physically relevant structure of a theory in order to make structural realism work. This perspective on redundancies is fundamentally different from the role that redundancies assume in an instance of hidden underdetermination, namely to implicitly carry on a former explicit underdetermination. Surplus structure concerns redundancies that are explicitly recognized, whereas redundancies in hidden underdetermination are usually not

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[13] Although in his later years Feynman largely abandoned the theory, he nevertheless continued insisting on the possibility of action-at-a-distance electrodynamics, e.g. in his Nobel lecture: "The fact that electrodynamics can be written in so many ways—the differential equations of Maxwell, various minimum principles with fields, minimum principles without fields, all different kinds of ways, was something I knew, but I have never understood." (Feynman, 1972)

[14] For a recent discussion see for example Worrall (2009).

acknowledged as such and are commonly taken to be fundamental and ineliminable elements of the theory (e.g. when both fields and charges are taken to belong to the fundamental ontology).

For comparison, let us briefly examine the classical example from the literature on surplus structure, the gauge-invariance of various physical theories. Clearly, there is redundancy in the sense that any choice of gauge already implies all relevant empirical consequences. However, just as clearly this is not a case of underdetermination according to the criteria given in Section two. Essentially, we are just dealing with equivalent descriptions that differ with respect to the conventional choice of gauge. Notably, we are not faced with frameworks that are metaphysically distinct enough to substantiate different research programs. A change in gauge does not change the ontological commitments of the theory, it much more resembles a change in coordinate system. Therefore, the existence of surplus structure in general does not imply hidden underdetermination.

By contrast, the hidden underdetermination of our essay fulfills the criteria of Section two—mainly because it results from a genuine historical episode of underdetermination. It thus undermines a realist attitude regarding the fundamental entities posited in classical electrodynamics, i.e. charges and fields, just because an underdetermination concerning these entities can be recovered from the resulting theory. In this manner, the case study raises doubt about a version of realism along the lines of Psillos's epistemic thesis: "Mature and predictively successful scientific theories are well-confirmed and approximately true of the world. So, the entities posited by them, or, at any rate, entities very similar to those posited, inhabit the world." (Psillos, 2000, 706) Such a statement seems irreconcilable with our case study, where we have three empirically equivalent formulations that fare similarly well in terms of epistemic virtues but work with very distinct fundamental ontologies: the orthodox particle-field account plus two frameworks with one additional posit (the emitter and absorber conditions) that reduces the ontology either to fields or to particles. Thus, the predictive success seems to be largely independent of the ontology.

The second moral I want to draw from the case study is that it exemplifies how the realism debate can profit from a detailed historical study regarding the criteria of theory choice resolving situations of underdetermination. Emphatically, realists should not be satisfied by the mere fact that the explicit underdetermination eventually vanishes. Rather, they must also examine the *kind* of criteria that govern theory choice, as the possibility of hidden underdetermination proves.[15] This crucial role that criteria for theory choice play for the issue 'realism vs. antirealism' is not so often acknowledged. It is, for example, implicit in Kuhn's classic "Objectivity, Value Judgment, and Theory Choice" (1977). It is also extensively discussed in McAllister (1993). As a rule of thumb, scientific realism would require that theory choice is generally driven by the accumulation of evidence in combination with some objectifiable epistemic virtues like accuracy, consistency, scope, simplicity, and fruitfulness (Kuhn, 1977, 322). Realists would also expect that eventually these criteria in combination with the accumulation of evidence narrow down the list of possible candidates to the single true theory or at least to a framework exhibiting the true structure of the phenomena. By contrast, antirealists of various stripes would allow for a much broader range of all kinds of pragmatic and even sociological criteria that determine theory choice.[16]

Let us briefly examine if theory choice in the case study strikes the best balance between simplicity and a criterion of strength combining accuracy and scope? We had seen in the previous section that any particle-field theory can be turned into an action-at-a-distance theory (or a pure field theory) by adding non-empirical emitter and absorber conditions. Therefore, if strength is construed as informativeness of a theory, as suggested by David Lewis (1994, p. 478), the three frameworks are

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[15] A further separate issue in this regard is Stanford's problem of recurrent, transient underdetermination (2006).

[16] As the discussion of surplus structure shows, structural realists do acknowledge pragmatic criteria like heuristic fruitfulness in theory choice. However, in such instances the surplus structure which serves the pragmatic means should be clearly identifiable

equally strong. After all, these different frameworks all have the same observable consequences. Simplicity then seems to favor either the pure field or the action-at-a-distance approach since both surpass the particle-field approach in terms of ontological sparseness. The realist then must plausibly require that idle ontologies should be discarded. But the very opposite happens. Ontologies that could in principle be eliminated are accepted for what seem to be largely pragmatic reasons and nebulous worries about absorber and emitter conditions.

What drove theory choice in this historical episode is arguably the pragmatic criterion of ease of applicability, which is crucially different from strength. While the later refers to the range of phenomena that are covered by a theory, the former refers to the intuitiveness with which a theory can be applied to the phenomena. Due to strong subjective connotations, pragmatic criteria like intuitiveness do not fit easily with realist accounts of theory choice. Finally, the particle-field view is the most natural continuation of *both* successful paradigms in 19th-century electrodynamics. Somewhat ironically then, we find Duhem's pragmatic criteria of historical continuity and of conservativeness at work, though not in favor of the French tradition and thus not quite in the way that Duhem had imagined.

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