Foundations of Science
https://doi.org/10.1007/s10699-020-09663-3

Local Selective Realism: Shifting from Classical to Quantum Electrodynamics

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Abstract

This article elaborates local selective realism in view of the shifting from classical to quantum electrodynamics. After some introductory remarks, we critically address what we call global selective realism, hence setting forth the background for outlining local selective realism. When examining the transition from classical to quantum electrodynamics, we evaluate both continuities and discontinuities in observational features, mathematical structures, and ontological presuppositions. Our argument leads us to criticise the narrow understanding of limiting-case strategies, and to reject the claim that we need a fully coherent theoretical framework to account for the transition from one theory to its successor in the case of electrodynamics. We close with a few remarks on the scope of local selective realism.

Keywords Selective realism · Localism · Pluralism · Electrodynamics · Observational features · Mathematical structures · Ontological presuppositions

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This article is a partial result of research carried out within the framework of governmental funded Grants FONDECYT de Iniciación No. 11160324, "The Physico-Mathematical Structure of Scientific Laws: On the Roles of Mathematics, Models, Measurements and Metaphysics in the Construction of Laws in Physics", responsible investigator: Dr. Cristian Soto; and FONDECYT Regular No. 1150661, "Masa, emergencia y realismo estructural", responsible investigator, Dr. Diego Romero-Maltrana. We thank their financial support. Likewise, we are deeply grateful to two referees for Foundations of Science. They helped us work through the details of our own views, providing invaluable feedback on ways to improve our argument.

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1 Introduction

Recent developments in the philosophy of science have called *naive scientific realism* into question for several reasons. An uncharitable reading of realism about science would tell us that naive scientific realism recommends us to interpret current best scientific theories at face value (as a whole, as it were) as approximately true. Of course, it is hard to find advocates for such a claim, especially since—as some have neatly argued—counterarguments like the pessimistic-meta induction (hereafter, PMI) (Laudan 1981) would forcefully deliver an unquestionable reason to do away with the naive construal of realism. In fact, the PMI gathers evidence for the successive abandonment of theories that were once believed to be approximately true in their fields, thereby suggesting a reason for us to think that current best theories are likely to face a similar fate. Furthermore, others have yet pointed out the flaws of an unrestricted realist interpretation of scientific theories, suggesting that a variety of epistemic attitudes is to be considered in view of specific elements of theories, such as models, abstractions, and mathematical idealisations, among others (Maddy 1995).

Over the recent years, rather than this caricature of naive scientific realism, various forms of *selective realism* have come to advance a live alternative within the realist programme. In particular, the selective strategy aims at delivering an account of scientific practice that acknowledges the success of science, although this time imposing a limit on the realist interpretation of theories. At present, the much-debated question to be asked is, where shall we draw such limit?[1]

We suggest distinguishing between *global* and *local* forms of selective realism. Available articulations of selective realism are generally framed in terms of one or another version of *global selective realism*, being semirealism, epistemic structural realism, and the divide et impera strategy among the most well-known developments. A key feature of global selective realism is that it is committed to a single selection criterion that purportedly allows us to identify those elements of theories that have survived, or are likely to survive, theory change. Not only is this single selection criterion supposed to work globally across various scenarios of theory change, but it is also expected to be applied prospectively, hence anticipating future cases of abandonment or replacement of theories in future steps of scientific research. The three forms of global selective realism aforementioned have largely employed this strategy in the analysis of the Fresnel–Maxwell case of theory change.

Here is our main point. Further work needs to be done in the defence of the realist stance. Contrary to global selective realism, we argue for *local selective realism* (hereafter, LSR). Importantly, LSR submits that our choosing of selection criteria is to be guided by local considerations of specific scenarios of theory change. Among those that we shall consider, LSR remains pluralistic about the adoption of such selection criteria as observational features, mathematical structures, and ontological presuppositions, showing that they all partially contribute in their own ways to make sense of local continuities and discontinuities through theory change.

A few remarks on LSR are crucial for our argument to work. First, LSR is pluralist because in different scientific settings it can apply different criteria for assessing (dis)

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[1] Among others, Saatsi (2017) observes that selective versions of scientific realism dominate the debate. Saatsi develops his own *exemplar realism*, which takes realism to be an attitude that should be applied locally by specifying the exemplar in each case. Below, differences between local selective realism and other forms of selective realism will become clear.

continuity through theory change, such as observational features, mathematical structures, and ontological presuppositions.[2] Second, LSR mitigates the optimism of forms of global selective realism, since it aims at applying such selection criteria only in a retrospective fashion, hence illuminating past scenarios of theory change and giving us a hint about the way in which theorising evolves in specific situations. And third, as a strategy for defending the realist stance, the tenability of LSR relies on securing local conservation across theory change taking place in the historical transition from one theory to its successor in a specific field. Since elaborations of global selective realism have largely focused on the Fresnel–Maxwell case, the natural step to follow consists in examining whether continuity falls apart when moving from classical electrodynamics to quantum electrodynamics (or, CED to QED, for short). LSR, we contend, is in a position to tell us something about current best science, represented in this case by QED. It should be noted that, among others, Lyre (2004) has addressed similar issues in view of debates concerning holism and structuralism in U(1) gauge theory.

The structure of our argument is as follows. Section 2 addresses global selective realism. Section 3 outlines LSR, putting this view to work concerning (dis)continuities in the transition from CED to QED. In this regard, we separately look into the details of Sect. 3.1 observational features, Sect. 3.2 mathematical structures, and Sect. 3.3 ontological presuppositions. Section 4 argues against what we call *a narrow understanding of limiting-case strategies*, which has broadly been assumed in debates concerning the transition from CED to QED. And Sect. 5 rejects the view that we need a fully coherent theoretical framework to account for partial continuities from CED to QED. Section 6 closes with some concluding remarks.

2 Global Selective Realism

Let us briefly look at the current debate on global selective realism. As has been amply documented, an early-modern instance of theory change is the shifting from the *particle* to the *wave* theory of light (see Darrigol 2012, Chapters 2–6). Particle theorists described light in terms of corpuscles, i.e., tiny material particles emitted in all directions from a source, explaining such phenomena as simple refraction and prismatic dispersion, although leaving unaccounted for such observed phenomena as two beams of lights crossing paths and the interference patterns of light discovered by Young's double-slit experiments in 1807. The latter problems, among others, called for the gradual abandonment of the particle theory, which was later on replaced by the wave theory that was differently articulated in Fresnel's luminiferous ether theory and Maxwell's ether-based electromagnetic field theory. According to Fresnel, light consists of vibratory motions set up by luminous bodies that are carried over by the luminiferous ether, the latter being conceived as an all-pervading, mechanical medium. Nevertheless, after various attempts at constructing a mechanical model representing the dynamics of the luminiferous ether, Maxwell came to articulate the theory in terms of a set of equations from which wave-like changes taking place in an ether-based electromagnetic field could be derived (Morrison 2000, Chapter 3).

A main point that has been made in the literature consists in showing that in the transition from Fresnel's theory to Maxwell's, the latter kept on the belief in the luminiferous

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[2] We greatly thank one of the referees for helping us to make this point clear throughout the article.

ether. Here is Maxwell: “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 subtle a nature that it cannot be contained in any vessel except the most inmost substance of material things’. Hence, all these theories lead to a conception of a medium in which the propagation takes place, and if we admit this medium as an hypothesis, I think it ought to occupy a prominent place in our investigations” (Maxwell 1873, p. 438).[3]

Let us see now how global selective realism has concentrated on the Fresnel–Maxwell case of theory change. Worrall (1989) firstly highlighted that the following set of equations represents an attractive avenue to endorse the continuity claim from Fresnel to Maxwell:

$$\begin{aligned}
\frac{R}{I} &= \frac{\tan i - r}{\tan i + r} \\
\frac{R'}{I'} &= \frac{\sin i - r}{\sin i + r} \\
\frac{X}{I} &= \frac{2 \sin r \cos i}{\sin i + r \cos i - r} \\
\frac{X'}{I'} &= \frac{2 \sin r \cos i}{\sin i + r}
\end{aligned} \tag{1}$$

As Chakravartty explains: “Consider an ordinary beam of unpolarized light. [...] The polarization of such a beam can be resolved into two component planes, at right angles to each other. One of this is called the plane of incidence, and contains the incident, reflected and refracted beams. [...] The other component is polarized in a plane at right angles to the incident plane. I^2, R^2 and X^2 represent the intensities of the incident, reflected, and refracted components respectively, polarized in the plane of incidence. I'^2, R'^2 and X'^2 represent the intensities of the components polarized at right-angles to the incident plane. i and r represent the angles made by the incident and refracted rays with a normal to the plane of reflection” (Chakravartty 2007, p. 49) (see figure in Chakravartty 2007, p. 35).

With Psillos (1999, p. 158), we identify three levels of interpretation for this set of equations, namely: observational features, mathematical structures, and ontological presuppositions. It should be noted that the levels of interpretation go hand in hand with the three criteria examined thus far in the three main articulations of global selective realism. Indeed, semirealism highlights observational features; epistemic structural realism appeals to mathematical structures; and then the divide et impera strategy focuses its analyses on ontological presuppositions. Be that as it may, global selective realism faces the following challenge, viz., advancing a reason to decide the extent to which we should promote a realist interpretation of the Fresnel–Maxwell transition, while at the same time making sense of the shifting from CED to QED. Here is what each view has to say in turn:

Observational features. In the Fresnel–Maxwell case, we find observational features of light, which are the physical quantities expressed by the variables of the mathematical equations, such as the amplitude, intensity (incident, reflected and refracted), and direction of propagation. A minimal form of global selective realism is in order regarding this, namely, *semirealism* (Chakravartty 2007). Indeed, semirealism endorses realism about only first-order detection properties. Such properties, it is argued, are those with which we have causal contact by means of either our unaided senses or other technological devices.

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[3] We thank one of the referees for directing our attention to this passage from Maxwell.

Hence, a realist interpretation, it is argued, could be secured about such first-order detection properties. Nevertheless, semirealism need not extend its realist stance to Maxwell's ether-based electromagnetic field, even though the latter was *somehow* carried over in current QED. We shall return to this issue in Sect. 3.3.

Mathematical structures. Motivated by the fact that Fresnel's equations re-appeared intact in Maxwell's theory, *epistemic structural realism* argues that we have a reason to hold realism about the mathematical structures in question (Worrall 1989). Accordingly, conservation of mathematical structure, it is claimed, is all there is left for defending the realist programme.[4] Problems for this view, nevertheless, come from different angles, some of them highlighted by Worrall (1989) himself, who acknowledges that complete conservation of equations is a rather unusual fact in the history of science. Furthermore, as has been pointed out, the sole conservation of mathematical structure is not enough to answer the PMI, granted that the mathematics may fail to correctly pick out relevant features of physical systems (Pincock 2011; Psillos 1995).

Ontological presuppositions The Fresnel–Maxwell case introduces ontological presuppositions concerning the wave-like nature of light and the nature of the carrier of light (be the latter the mechanical luminiferous ether, or an ambiguous elastic, disembodied electromagnetic field modelled by a set of equations). At this point, the evident issue emerges as to the ontological presupposition of the luminiferous ether, which was ultimately abandoned in QED. For one thing, the *divide et impera* proposes that we should be realists about only those mechanisms and laws that are causally responsible for (or indispensable to) relevant phenomena. This view, however, may be too permissive. Not only would it submit that we should be realists about the electromagnetic field assuming that it contributes to causally explain observable phenomena of light in current QED, but it would go as far as to contend that some form of semantic realism could account for the partial conservation of Fresnel's luminiferous ether. Fresnel's luminiferous ether, after all, played similar causal roles in explaining the observable behaviour of light in the early version of the wave theory (Psillos 1999).

These three articulations of global selective realism draw our attention in the right direction, representing a substantial refinement of old-style naive scientific realism. Nevertheless, they face the following three boundaries:

(i) *Commitment to a single selection criterion* The three forms of selective realism outlined above endorse a single, global selection criterion, be it first-order detection properties, mathematical structures, or ontological presuppositions under the form of causally explanatory laws and mechanisms. Each such selection criterion is supposed to work globally across diverse scenarios of theory change. We shall show that the complexities of theory change in the transition from CED to QED invite us to abandon global approaches in favour of local ones.

(ii) *Prospective strategy* At least one of the three versions of global selective realism (Chakravartty 2007) contends that the selection criterion should work prospectively, thereby anticipating future scenarios of theory change, whereas another one (Worrall

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[4] Note that beyond the variables of the set of equations above, the mathematics in the Fresnel–Maxwell case involves various theoretical assumptions: (a) the minimal mechanical assumption that the velocity of the displacement of molecules of ether is proportional to the amplitude of the light wave; (b) the principle of conservation of energy during the propagation of light in the two media; and (c) the geometrical analysis of the configuration of the light-rays in the interface of two media (Psillos 1999).

1989) implies that mathematical structure should perform a similar predictive role. Contrary to this, we shall argue for the benefits of retrospective approaches in our elaboration of LSR.

(iii) *Shifting from CED to QED* None of the three forms of global selective realism aforementioned have attempted to address so far the ulterior transition from CED to QED, which is the historical continuation of the Fresnel–Maxwell case. We develop this argument in Sect. 3, keeping in mind our responses to (i) and (ii). In brief, further evidence is to be provided as to whether selective realism stands on its feet regarding QED.

3 LSR at Work

Contrary to global selective realism, LSR embraces a local stance towards the adoption of selection criteria that may help us evaluate the (dis)continuity in the shifting from CED to QED in a context-sensitive fashion (Asay 2019; Henderson 2017). LSR contends that we should abandon the search for a global selection criterion which purportedly applies across various scenarios of theory change in science. By contrast, it asks us to remain pluralistic as to the application of various criteria. Likewise, LSR is expressly designed as a retrospective strategy. Philosophical reflection upon past scenarios of theory change can teach us about features of the various elements involved therein, as well as about the various epistemic attitudes we should adopt with respect to each theoretical element. The investigation of past scenarios of theory change has the means to deliver morals that serve as heuristic strategies when it comes to interpreting current theories (Rohrlich and Hardin 1983).

In what follows, we examine the strengths of LSR analysing the transition from CED to QED. We look into Sect. 3.1 observational features, Sect. 3.2 mathematical structures, and Sect. 3.3 ontological presuppositions, highlighting both continuities and discontinuities *in each such level*. In a nutshell, along with global forms of selective realism, LSR recognises parcels of the theories in question where continuity is undeniable, while at the same time acknowledging discontinuities. Neither thorough continuity (as a caricature-like naive scientific realism would suggest) nor complete discontinuity (as the PMI may want to suggest) are tenable options. Yet, moving beyond global selective realism, LSR emphasises both localism (i.e., specific elements of a single theory are to be taken into consideration in scenarios of theory change) and pluralism (in different context of theory change different selection criteria could be applied). Although our analysis of the transition from CED to QED is not intended to be exhaustive, we believe that what we have to say suffices to make a case for LSR.

3.1 Observational Features

Forms of global selective realism that focus on the preservation of observational features broadly appeal to measurable quantities that were, and generally still are, present in experimental setups concerning relevant phenomena. In view of our case study, electric and magnetic field intensities, charge, light intensity, light frequencies, energies and the electromagnetic spectrum, among others, fall under the category of measurable quantities.

When it comes to operationally defined measurements, discontinuities are highly unlikely to be found. Methods and techniques may improve or change, and the same seems to be the case for the interpretation and comprehension of the measured properties. The properties, which are responsible for the physical interactions leading to measurements, are largely independent from theories, therefore remaining unaffected by theory change.

However, discontinuities in observational features from CED to QED are easy to point out. Some methods and properties were unknown at early stages of the transition from CED to QED. The quantum version, indeed, was designed to deal with double-slit experiments performed with electrons and single photons, and the theory was expected to explain the photo-electric effect. Additionally, QED had to come to grips with phenomena related to black-body radiation. In this regard, it can be claimed that growth of knowledge regarding observational features amounts to a form of discontinuity. Think of black-body radiation: even though what is measured does not change across the transition from CED to this early version of a quantized theory, granted that both the phenomena under study (i.e., the radiation spectrum) and the measurement procedures remain unchanged, knowledge of what is observed radically changes.

Another important difference can be identified if we consider double-slit experiments, given that the appearance of interference patterns leads to a weave interpretation of phenomena that were previously considered particles. However, interference patterns make their appearance only once the experiment is preformed several times, and it still would work under the assumption that particles are the ones that hit the screen. Statistical analysis is relevant for our comprehension of these phenomena, thereby introducing a change in experimental methods, growth of observational knowledge, and discontinuity in observational terms.

Advocates of semirealism may recommend us endorsing a form of realist stance on first-order detection properties resulting from measurement procedures only. Such detection properties, it would be claimed, are preserved from Maxwell's repertoire of observations to the new observational findings that led to the construction of an early version of QED. Nevertheless, the growth of observational evidence does not fully back up the continuity claim *simpliciter*. Among other things, difficulties in providing understanding of data obtained in QED in terms of the theoretical framework of CED preclude us from holding full continuity from one theory to its successor.

3.2 Mathematical Structures

From the perspective of LSR, we can assess whether the mathematical structures expressing the theoretical assumptions underlying CED can be obtained from the mathematical framework of QED. There is a significant correspondence in mathematical terms when passing from CED to Planck's early contributions in the transition from CED to QED.[5] Planck's use of Boltzman's probability distributions rather than energy equipartition theory was a step forward against the background of the standard approach leading to the Rayleigh-Jeans law, which had the known flaw of predicting a divergent amount of energy emitted by any body at any non-zero temperature within the ultraviolet regime. The classical theory would inevitably fail to explain the so-called *ultraviolet catastrophe*, which was the target of Planck's efforts. Nevertheless, such improvement did not really break with

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[5] Although neither Planck's work on black-body radiation nor Einstein's on the photoelectric effect amount to complete theories of electromagnetism, they certainly provided new theoretical elements that played a crucial part in the transition from CED to QED. Such elements could also be targets of the PMI against a smooth transition from CED to QED. Taking these elements into consideration helps us point out traces of continuities or discontinuities in a piecemeal fashion in the present case.

tradition. By contrast, it can straightforwardly be accommodated within the classical picture. In structural (mathematical) terms, the most radical change was brought about by the energy quantization and the dependence of light's energy on light's frequency. Planck's contributions preserve most of the mathematical structure of previous theories in the field. Energy becomes continuous under the appropriate limit ($\lim(h \to 0)$), thereby granting continuity with the preceding theory.

It is possible to re-obtain Maxwell's equations from QED. We now present one such way. Our goal is not to show all steps involved in the derivation, but only to highlight the main arguments leading to Maxwell's results, hence demonstrating that the mathematical structure of QED bears enough structural richness as to encompass results from CED.[6]

To begin with, there is more than one way of deriving Maxwell's equations. One strategy consists in arriving to the photon (a massless excitation) from a massive vector field by taking the limit of very low masses. The usual construction of a massive vector field within quantum field theories is by means of annihilation and creation operators. However, the limit $m \to 0$ cannot be applied to any such massive fields because the projection matrix on the space orthogonal to the four-vector p^μ, that appears in the commutation relation of the annihilation and creation operators, corresponds to $\Pi^{\mu\nu}(p) = \eta^{\mu\nu} + p^\mu p^\nu / m^2$, and the rate of production of spin-one particles turns out to be proportional to $\Pi^{\mu\nu}(p)$. Therefore, the emission rate of such massless particles blows up in the limit $m \to 0$.

The problem is the lack of coefficient functions satisfying rotations and boosts for general representations of the homogeneous Lorentz group. Therefore, no four-vector field can be constructed from annihilation and creation operators for massless particles and helicity ±1. However, the antisymmetric tensor field for such particles can be built, and its general form is $f_{\mu\nu} = \partial_\mu a_\nu - \partial_\nu a_\mu$, where a_μ satisfy:

$$\begin{aligned} \Box a^\mu(x) &= 0 \\ a^0(x) &= 0 \\ \nabla \cdot \mathbf{a}(x) &= 0 \end{aligned} \tag{2}$$

Therefore, $f^{\mu\nu}$ satisfies the vacuum Maxwell equations $\partial_\mu f^{\mu\nu} = 0$, $\varepsilon^{\rho\sigma\mu\nu}\partial_\sigma f_{\mu\nu} = 0$.

Furthermore, Maxwell's equations for interactions can be obtained in a theory of interactions of matter and radiation once one ensures that the part of the action describing such interactions remain invariant under a general gauge transformation of the electromagnetic potential.

Note that here we follow the notation used in (Weinberg 2005), who distinguishes between a free four-vector a^μ and the interactive field A^μ which is the electromagnetic potential. A Lorentz-invariant theory can be constructed by coupling the vector field A_μ to the conserved current $J^\mu(x)$ if such current is proportional to the variation of the matter action I_M with respect to the vector field

$$\frac{\delta I_M}{\delta A_\mu(x)} = J^\mu(x) \tag{3}$$

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[6] The following lines summarise ideas taken from Weinberg (2005). Similar approaches appear in Greiner (2000), Sect. 15.5, pp. 364–366, Frisch (2005), p. 16 and Rohrlich (1988).

The conserved quantity associated to the current J^{μ} is the electric charge. And the unique gauge-invariant functional that is quadratic in the field strength tensor $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$, without higher derivatives,[7] that can be used as action for photons is

$$I_{\gamma} = -\frac{1}{4}\int d^4x F_{\mu\nu}F^{\mu\nu} \tag{4}$$

Taking into account Eqs. 3 and 4, the field equations for electromagnetism are

$$\frac{\delta}{\delta A_{\nu}(x)}[I_{\gamma} + I_M] = \partial_{\mu}F^{\mu\nu} + J^{\nu}(x) = 0 \tag{5}$$

which are the usual in-homogeneous Maxwell's equations with current J^{ν}. The homogeneous Maxwell's equations ($\partial_{\mu}F_{\nu\rho} + \partial_{\rho}F_{\mu\nu} + \partial_{\nu}F_{\rho\mu} = 0$) follow from the definition of the field strength tensor in terms of the electromagnetic potential $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$.

This shows that QED, as a mathematical framework dealing with the description of electromagnetic phenomena, possess enough resources to encompass Maxwell's equations, which are the hallmark of CED. This contributes to our argument demonstrating, first, that continuity claims concerning structure are tenable; though, second, it also stresses that such continuity cannot be achieved by taking the limit of a single variable to a fixed variable.

Contrary to our analysis, some conclude with negative results when it comes to the possibility of bridging the transition from CED to QED (Valente 2011). Pincock (2011) argues for similar negative results. A general concern for both of them has to do with the viability of construing Maxwell's equations as a *limiting case* of the mathematics of QED. Pincock, for one, claims that "taking limits on the equations of the contemporary theories is said to recover Maxwell's equations" (2011, p. 68), but later on he expresses his scepticism regarding such endeavour; whereas Valente promotes pessimism about the limiting case strategy insofar as CED and QED do not form a *a fully coherent theoretical framework* (Valente 2011, p. 55). We shall return to these issues in Sects. 4 and 5, respectively, arguing that such contentions impose unnecessarily stringent requirements for advocating continuity.

3.3 Ontological Presuppositions

The continuity claim can be evaluated regarding the ontological presuppositions involved in the theories. Cases in point are the electromagnetic field and the nature of light, which CED and QED describe in different ways.

Think of the classical and quantum versions of the electromagnetic field. One may be led to believe that each theory purports to describe the same unobservable posit under the label *electromagnetic field*, despite the fact that CED conceives it as continuous, whereas QED adds to the continuous nature of the field the existence of a discrete number of excitations in electromagnetic phenomena.

Things, however, are not that simple. Stances on the ontological status of the electromagnetic field diverge, as the scientific literature illustrates. Although some consider the electromagnetic field to be "more than a calculational device" (Tipler 1976, pp. 705–706), others are inclined to claim that ascribing physical reality to the electromagnetic field lacks

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[7] Any term with higher derivatives or higher order in $F_{\mu\nu}$ can be included in the matter action I_M.

justification. Some claim that “the electromagnetic field itself is an invention and is never subject to direct observation” (Bridgman, as quoted in Lange 2002). Here is another passage: “the assertion [of the field’s reality], taken by itself apart from the quantitative law-force, is scientifically otiose. It is merely the physically irrelevant statement of a metaphysical conviction” (O’Rahilly 1965, vol. II, pp. 653–654).

Concerning the nature of light, CED and QED deliver separate, not easily compatible conceptions: the former describes light as a series of wave-like changes in a disembodied electromagnetic field, whereas the latter depicts light in terms of quantized photons showing both wave- and particle-like behaviour.

Recent global selective realist examinations of the Fresnel–Maxwell case would fall short if it is demonstrated that the classical conception of the electromagnetic field is not conserved in QED. In this latter domain, physical theories seem indeed to have moved substantially ever since Maxwell, up to the point that some are inclined to claim that “there is simply nothing in contemporary physics that corresponds to the entities that were supposed to bear those properties [of light according to Maxwell’s view]” (Ladyman et al. 2007, p. 90, fn. 18).

There is yet room to contend that the classical view of the electromagnetic field has been partially conserved in current photon theory in QED. The general intuition on this side of the road is broadly alive, some asserting that the Maxwellian theory outlined for the first time the layer of the fundamental constituents of the world, which consists of fields satisfying simple linear equations, thereby setting the prototype for twentieth-century physical theories such as Einstein’s relativity theory and quantum mechanics (Dyson 2007). In a similar vein, in the second of his 1905-papers, Einstein claims that the Maxwellian wave-like theory of light “will probably never be replaced by another theory” (Arons and Peppard 1965 [translation of Einstein 1905], p. 368), although he was giving in that same paper the initial steps for what others consider among the best reasons for abandoning the same theory.

Let us move back again to the consideration of discontinuity. There is a sense in which continuity is broken between the two theories due to the Planck-style picture of the discrete nature of energy . In formal terms, not only does the quantization of energy pose a problem regarding the known wave-nature of light, but it also forces us to reevaluate the very notion of energy. Interpreted in ontological terms, the quantization of energy marks a point of discontinuity that cannot be overlooked. The comparison between CED and Planck’s ideas demonstrates that only the latter was suitable to be further on developed to deliver a story that successfully accommodated experimental evidence emerging from the problem of the black-body radiation spectrum. CED and QED (the latter one incorporating Plank’s contributions) are committed to different characterisations of the nature of light that explains both observable and unobservable phenomena. Although Planck’s theoretical progresses in his seminal work are largely silent regarding the nature of the electromagnetic field, his ideas contained the seeds that led to positing *photons*, a key addition to the ontology of an early version of QED with no precedent in the classical theory.

This is closely related to Einstein’s explanation of the photoelectric effect, which exemplifies some of the issues aforementioned. In observational terms, the situation is akin to the black-body case already discussed, namely: observational features remain unchanged, and they only experience growth of evidence. Likewise, some ontological elements are present in both CED and Einstein’s explanation of the photoelectric effect, such as light and induced electric potentials, thereby granting continuity in this regard. Others, like electrons and photons, do not appear in CED. Einstein articulates a different conception of the nature of light, according to which energy is not only quantized, but it is also absorbed/transmitted instantaneously. Hence, even though there is a sense in which continuity can be outlined, the case for discontinuity is compelling given that CED and Einstein's photon theory radically differ with respect to the nature of light, which is the bedrock for later developments of QED addressing the interaction between photons and electrons. Accordingly, although some features of relevant unobservable posits playing an important role in scientific explanations are preserved across theory change from CED to QED, LSR acknowledges other aspects where radical discontinuities take place from one theory to another.

4 On the Narrow Understanding of Limiting-Case Strategies

In this section, we further develop LSR addressing the issue of whether the transition from CED to QED is to be articulated in terms of a narrow understanding of limiting-case strategies. When examining the viability of *limiting-case strategies*, Pincock suggests that we need *the continuous change of a single parameter* to a defined value, perhaps inspired by the case of special relativity, where the Lorentz transformations become the Galilean transformations, hence classical mechanics being recovered in the limiting case of an infinite speed for light ($\lim c \rightarrow \infty$). The case of quantum mechanics and classical mechanics provides a similar example, since in the limiting case of Planck's constant going to zero ($\lim \hbar \rightarrow 0$), energy becomes continuous just as it is conceived in classical mechanics.[8] We call the search for a unique variable allowing the passage from one theory to another *the narrow understanding* of limiting-case strategies.

We grant that CED cannot be fully recovered from QED by varying a single parameter continuously to a fixed value. As argued in Sect. 3.2, the conditions for re-obtaining Maxwell equations are not trivial, especially since they do not correspond to the limiting case of the Proca equation in the limit of zero mass, granted that no four-vector field can be constructed from annihilation and creation operators for massless particles and helicity ±1.

When considering limiting-case strategies, it is possible to deductively move from one theory to another by changing a single parameter into a limiting value. The aforementioned paradigmatic examples (i.e., $\lim c \rightarrow \infty$ or $\lim \hbar \rightarrow 0$) are ones in which *the special case* (classical mechanics) is *a limiting case* (of Special Relativity or Quantum Mechanics). That, however, is a narrow construal of limiting-case strategies. It misses the point when it comes to the possibility of deducing the equations of one theory from the mathematical framework of another, regardless of the fact that such deduction could be performed in just one step (changing a single parameter into a limiting value). As our case study shows, the set of Maxwell's equations can be re-obtained from QED in a series of mathematical steps, thereby the former counting as *a special case of* the latter, though not for any continuous change of a single variable to a particular value.[9]

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[8] It is not possible to re-obtain the whole of classical mechanics from quantum mechanics by taking the limit of $\hbar$ to zero. The latter claim is true for only a—limited—number of results. More to the point, as quantum field theory is a perturbation theory where calculations are performed by means of expansion in powers of the fine structure constant (which is inversely proportional to $\hbar$), the limit $\hbar$ to zero cannot be performed in quantum field theory. We thank one of the referees for bringing our attention to this point.

[9] Note that the previous discussion overlaps with the larger debate concerning theory reduction. The limiting-case strategy belongs to a case of "domain preserving reduction" (Nickles 1973). Yet, this is not the only form of theory reduction, as other cases of theory reduction would involve the explanation of one theory by another (or domain combined reduction, following (Nickles 1973) once more). The case at hand is a complex one of "domain combined reduction" *that includes* "domain preserving reduction" as well. It is not our intention to dive into the theory reduction debate. But the point we want to make is that a narrow

Valente stresses the worry that the reconstruction of a classical theory in terms of a non-classical one through a long series of mathematical manipulations may risk overlooking the actual physical interpretation of the formalism of the theories in question, given that classical and quantum theories conceive the electromagnetic field and the nature of light in different ways (Valente 2011, p. 58). Attempts at building bridges between theories may be of philosophical interest, Valente contends, but they may come at the price of not paying attention to the purported physical detail, especially in view of ontological presuppositions. That is, even if continuity from CED to QED can be outlined in terms of mathematical structures deriving Maxwell's equations from QED, this would not warrant continuity at the level of the physical interpretation of unobservable ontological presuppositions.

Let us give a step further. After examining the consequences of Dirac's equation, Valente suggests the conclusion that CED and QED do not form a fully coherent theoretical framework (we return to this in Sect. 5). Note, at present, that Dirac's equation is the most simple relativistic generalisation of Schrödinger equation dealing with material particles such as electrons. Hence, it is a generalisation of quantum mechanics rather than an upgrade of the electromagnetic theory. Valente's contention at least partly emerges from an analysis of theoretical developments *related to* electrodynamics, which *do not amount to a full theory of electromagnetism*. Even though it is correct that Dirac's theory can be employed to describe the interaction of radiation and matter, Dirac's original goal was to provide a relativistic version of quantum mechanics that delivers positive probabilities, a feature that the Klein-Gordon equation fails to secure (Weinberg 2005, p. 7).

There are well-known problems resulting from Dirac's formulation. (1) Dirac's approach seems to rule out the existence of particles of zero spin. At the time, compound states such as the hydrogen atom at its ground state or alpha particles were known to have zero spin. Later on, a large number of spin-zero mesons were discovered, i.e., composite systems of quarks that are more elementary than protons. Additionally, there was evidence in favour of a Higgs-like particle, a non-composed boson with zero spin. (2) The exclusion principle for fermions allows the picture of an infinite sea of negative energy that explains antiparticles as holes of such states. But given that the exclusion principle is not applicable to bosons, the picture of the infinite sea of occupied states of negative energy could not explain the existence of boson's antiparticles. And (3), although Dirac's theory correctly predicted the electron's magnetic moment, the formalism allows more than one way of calculating such magnetic moment, where not all of such elections lead to the expected result (see Weinberg 2005, pp. 13–14). It seems unfair to conclude the impossibility of recovering CED from a more refined theory if the latter is known to be incomplete. This, we believe, mitigates Valente's conclusion.

Footnote 9 (continued)

understanding of the limiting-case strategy overlooks complexities associated with exactly these considerations. As Nickles points out: "I am not advancing the simplistic view that all or even most historical reductions fit neatly into one or the other of the schemata. For one thing, many of the reductions will be partial; for another, [domain combined] reduction is rarely strictly derivational" (Nickles 1973, p. 186). We thank one of the referees for suggesting Nickles' work in view of our argument.

5 Do We Need a Fully Coherent Theoretical Framework?

When trying to find out genuine continuity from CED to QED, we may be tempted to search for a complete theory of electromagnetism. Nevertheless, to do so turns out to be highly deceptive. Take Feynman's contributions to QED, whose work was motivated by the question about how photons and electrons interact with each other. This problem was not present, of course, over the birth and development of classical electromagnetism as the idea of *photon* was not around until the beginnings of the twentieth century. In fact, most physics textbooks establish a link between the classical equations and electromagnetic waves only once the whole electromagnetism is duly summarised in Maxwell's equations.

Although not undisputed, a common interpretation of quantum field theory takes particles to be excitations of fields. *Interactions* involve the creation and annihilation of real and virtual particles. Such representation does not find room in classical theories. The kinds of phenomena successfully modelled by classical and quantum versions of theories are different. As a consequence, the problems that Dirac or Feynman had in mind, as well as the scale of phenomena properly described by their theories, are too different from the framework of CED to allow any attempt to envision a strategy for a smooth transition, let alone a complete match in a fully coherent theoretical framework.

Arguing that CED and QED are not fully coherent, Valente (2011) maintains that there is no timescale in the latter theory because free initial and final states in any interaction are treated as asymptotic in time, i.e., at infinite time before and after the interaction. The following is at the bottom of Valente's critical appraisal. On the one hand, quantum field theory does not allow a description in terms of particles when it comes to interactions. Only free states support a particle description within the formalism. In turn, this fact has led some physicists and philosophers to take fields as fundamental and particles as fictions that are useful for macroscopic treatment (see Haag 2012; French 2014; for a counterargument see Romero-Maltrana et al. 2018). However, this sort of criticism overlooks a reason that should be properly highlighted: quantum and classical physics are as different as to make any demand of full coherence a dead end. It is unclear whether the requirement of full coherence assumes that QED is incomplete, and hence that only a future, complete quantum field theory will deliver the results provided by the CED. Nevertheless, this does not represent an internal problem for QED. By contrast, it is an issue that has to do with the kind of theoretical products expected in each case.

Naturally, the outcomes and predictions expected from a quantum version of a theory are different from those of its classical counterpart, if available. In the latter, all the relevant parameters of full trajectories of related bodies can be determined. Quantum theories provide only probability distributions of final outcomes, and the kind of results expected within this framework and high-energy physics are Branching Ratios, i.e., the ratio of creation and decay of a particle into specific final particles. Predictions are corroborated after a large number of similar events, hence consisting of statistical results that do not provide a detailed account of each physical interaction in terms of fully determined trajectories at any time. Think now of CED: it describes electromagnetic forces between *charged particles*. Extended charged bodies are formally calculated as a continuous sum of charged particles. In its classical version, the theory provides an account of their trajectories. The mathematical framework for classical theories corresponds to second-order partial equations that lead to equations of motion. Outcomes expected from such theories are trajectories; the predictions they provide are the complete characterisation of the movement of the body (position, velocity, distribution of charge or density responsible for accelerations, and so forth) at any time.

We take these differences to mean that CED and QED describe phenomena at different levels. Furthermore, we would not mind accepting that CED still offers "the most successful models in the domain of classical phenomena involving charged particles" (Frisch 2005, pp. 15–16). Hence, granting that the very nature of the theoretical framework (be that classical or quantum) determines various aspects of our descriptions of phenomena, it is only natural to acknowledge that CED and QED cannot form a fully coherent theoretical framework. Furthermore, any theory in the fashion of a quantum field theory would fail to be fully coherent with its classical counterpart (and *vice versa*).

6 Concluding Remarks

LSR enables us to make sense of various continuities and discontinuities that we find in the transition from CED to QED. Neither the caricature-like naive scientific realism nor PMI-based anti-realism represent sensible positions for our case study. Concerning versions of global selective realism, no all-encompassing selection criterion is to be endorsed as if it were suitable for yielding understanding of the diverse components of successive theories across theory change in one domain, let alone across separate fields in scientific practice. In its attempts to identify a single selection criterion, global selective realism unnecessarily imposes a limit on our ability to make sense of the peculiarities of theory change.

LSR acknowledges the complexities of scientific practice, separately addressing observational, mathematical and ontological features of theorising in past scenarios of theory change. Each such element contributes to assessing the tenability of the realist stance from a local perspective. Although this move prevents us from foreseeing what elements of current theories will be preserved in future scenarios of theory change, we do not take this as a source of concern, so long as philosophical reflection upon past scenarios of theory change do teach us something about the workings of scientific theorising.

We demonstrated that the continuity claim may turn out satisfying for those leaning towards epistemic structural realism if the examination is restricted to the possibility of recovering Maxwell's equations from the mathematics of QED. Similarly, an advocate of the *divide et impera* may still be inclined to contend that we have become better acquainted with the causal mechanisms underlying electromagnetic phenomena when passing from CED to QED considering the the electromagnetic field as a label—although not in its detailed physical description—has been preserved. Even more, those who endorse semirealism may nevertheless suggest that our study exemplifies a relevant scenario of continuity, at least in the sense that there is growth and refinement of our access to first-order detection properties of several electric and magnetic phenomena, viz., not only do we know now behavioural features of light such as reflection, refraction, and else, but we also have highly controlled experimental access to the photoelectric effect, black-body radiation, and modelling of the photon-electron interaction.

Remaining pluralistic about local applications of selection criteria, LSR takes into account these various layers of theory change in the shift from CED to QED. Moreover, LSR argues that many other developments played a role in facilitating this transition, such as the possibility of recovering Maxwell's equations from the electromagnetic tensor of

QED, and the lack of a single parameter to be varied continuously making possible to recover the classical theory as a limiting case of the quantum theory.

Note that LSR avoids the threat of radical cases of PMI in the transition from CED to QED. There is no phlogiston-like replacement of theoretical entities in the scientific scenario under examination. As Frisch puts it, "[i]n the case of phlogiston theory, the theory was in fact completely abandoned; yet in the case of [CED] the idea of a certain world picture was given up, but not the belief that the theory was appropriate for modelling certain phenomena" (Frisch 2005, p. 16). Posits such as light and the electromagnetic field are targets of both the classical and the quantum versions of electrodynamics. What changes is our conception of such entities, which is largely determined by the progressive refinement of the mathematical and experimental tools available to investigate their nature. Rather than radical replacement, the present case of theory change at least partly exemplifies a substantial progression in our theoretical accounts of such entities.

We rarely find cases of radical ontological replacement across theory change. LSR challenges anti-realists to articulate local versions of the PMI, paying attention to cases of local conservation and local abandonment of *specific elements* of theories. Continuities and discontinuities at a local level are far more common in the history of modern science than radical scenarios of full-blown conservation or abandonment. From our perspective, localism concerning scenarios and pluralism concerning the application of criteria are attractive options for strengthening the defence of the selective realist stance.

The continuity claim, nevertheless, falls apart when it comes to the fact that Maxwell's equations describe electromagnetic phenomena in terms of accelerations and full trajectories in the context of classical physics. QED, by contrast, speaks of the interaction of photons and electrons in terms of instantaneous creation and annihilation of particles. Within the context of QED, anti-realist spirits may want to put pressure on ontological inconsistencies arising from the wave-like or particle-like behaviour of light, which is ultimately context-dependent. As a result of the introduction of photons, the electromagnetic field ceased to be exclusively viewed as a dynamical, continuous entity, and came to be the ground for discrete quanta emerging as excitations of the field.

We are aware that other elements of CED and QED can be addressed along the lines of our argument. However, we hope that what we have said thus far suffices to illustrate the benefits of the local approach in the recent defence of the realist stance, which naturally moves from naive scientific realism, through global selective realism, to LSR.

Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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