Two electrodynamics between plurality and reduction

Comparing action-at-a-distance electrodynamics in the tradition of Coulomb and Ampère with electromagnetic field theory of Faraday and Maxwell provides an example for a relation between theories, that are on a par in many respects. They have a broadly overlapping domain of applicability, and both were widely successful in explanation and prediction. The relation can be understood as an inhomogeneous reduction without a clear distinction between reducing and reduced theory. It is argued in general, when a clear hierarchy between competing theories cannot be determined, the plurality of standpoints should be preserved and the bridge laws carefully developed.

1 Introduction: electrodynamics and reduction

The reduction of optics to Maxwellian electrodynamics belongs to the few standard examples in intertheoretic reduction. While this is certainly an excellent example for the virtues of reductive approaches, it is perhaps not the most interesting case of a reduction in electrodynamics. Electrodynamic phenomena are at the heart of a wide range of scientific knowledge: in chemistry, physics, and biology. In chemistry, the number of charged particles in the atoms partly determines the layout of the periodic table or the strength of chemical reactions. In macroscopic classical physics, electrodynamics is only one of two interactions – next to gravitation. Finally, many phenomena in molecular biology can be traced back to an electromagnetic origin: the chemical production of energy in cells or the propagation of information through nerves via electrical currents.

Due to this wide range of phenomena, electrodynamics offers a rich field for case studies in reduction – far beyond the reduction of optics. The issue I will address is the relation between action-at-a-distance electrodynamics and field theory in the 19th century. It is central for the understanding of modern classical electrodynamics, which owes to both predecessors, as well as for the historical reconstruction, how electrodynamics has become the theory of today's textbooks.

2 The reduction of the two electrodynamics

To set the stage for the considerations concerning intertheoretic relations, let us first sketch the historical development. Throughout much of the 19th century, two electrodynamic theories competed for the adequate description of the wide range of electrodynamic phenomena. For a long time, the dominant view was the action-at-a-distance electrodynamics, which treated electrodynamic phenomena largely in the framework of a Newtonian theory of interaction. In this tradition, Coulomb developed the force law for charges at rest, and Ampère his law for the interaction of current elements. The most sophisticated account in the action-at-a-distance tradition is arguably the force law developed by Wilhelm Weber, in which forces depend not only on the distance between particles but also the mutual velocity and acceleration.

In comparison, Michael Faraday's field theory employing electromagnetic force lines was much the work of an outsider and 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 ideas were taken from obscurity to eventually yield the foundations of electromagnetic theory as it is known today. Over the decades Faraday's framework was the origin of many significant novelties in electromagnetism: amongst others induction, diamagnetism, or the theory of dielectrics. The most impressive success was of course the inclusion of optics into electromagnetic theory and the prediction of electromagnetic waves. Eventually, this rang the death knell of the action-at-a-distance view as a *fundamental* perspective on electrodynamics. Certainly, Coulomb's law and to a lesser extent Ampère's original law are still widely in use. But the Newtonian electrodynamics, from which these laws emerged, is not cultivated anymore.

For a few decades in the 19th century, the two conceptually very distinct approaches coexisted as successful research programs. Both lead the way to exciting new experimental results and were successful in the explanation of phenomena, that had previously not been well understood. Both were at some point in time the opinion of a wide majority of physicists. But as history seems to be written mostly by the victors, in spite of the enormous successes action-at-a-distance is today largely neglected. However, even a seemingly clear-cut case in favour of the field view like the prediction of electromagnetic waves turns out much more difficult to establish, when the details of the historical development are taken into account.

Already in the 1850s, decades before Maxwell's seminal *Treatise on Electricity and Magnetism*, significant attempts were made to include optical phenomena into the action-at-a-distance view by means of retarded potentials. There were promising attempts for example by the mathematicians Bernhard Riemann and Carl Neumann. In the end, neither the integration of optics nor the prediction of electromagnetic waves beyond the visible seems to be a conclusive reason for the rejection of the action-at-a-distance view. Of course, early attempts in the action-at-a-distance tradition failed, while the field view succeeded very fast. Soon after, the former was largely abandoned.

However, in the preface to his *Treatise*, Maxwell still considered both approaches to electrodynamics as of approximately equal merit: "In a philosophical point of view, moreover, it is exceedingly important that two methods 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."[1] At the same place, Maxwell considered himself an "advocate" of the field view rather than a "judge" between both views.

Most people would probably interpret the relation between the two electrodynamics as a falsification of one of two competing theories and not as a reduction. However, this seems not appropriate for a variety of reasons. First, a theory, that was as empirically successful as the action-at-a-distance view of electrodynamics, is not falsifiable as a whole. Only certain elements of the theory can be falsified, while the large chunk that was empirically successful must be kept and subsequently reduced to the preferred view of a field theory.

A second reason, why it is more useful to think of the case as a reduction rather than a falsification, lies in the empirical and theoretical significance of the quantities and laws, that were explicitly developed as bridge quantities and bridge laws. The most famous example is William Thomson's electromagnetic potential ϕ, another one is the vector potential $\vec{A}$. Thomson considered both action-at-a-distance and field view as viable alternatives and was concerned with developing the connection between both standpoints. One of the quantities that turned out most useful in this endeavour was the electromagnetic potential.

A third reason lies in the hybrid nature of modern electrodynamics itself. Although the common perception is, that modern electrodynamics takes its root exclusively in field theory, a detailed historical study reveals a very different picture. Olivier Darrigol, the historian of electrodynamics, writes: "Maxwell's theory was a pure field theory, ignoring the modern dichotomy between electricity and field."[2] Outside the small community of historians it is only rarely acknowledged, how different the conceptual foundations of Maxwell's theory and modern electrodynamics 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 only the equations – Maxwell's equations.

Maybe the two most important conceptual differences between Maxwell's theory and modern electrodynamics concern the ontological status of charged particles and the treatment of the displacement current. Regarding the former, for Maxwell as for Faraday charge was a derived concept denoting the endpoint of a force line. Today charges are considered ontologically on a par with electromagnetic fields. This difference is not only of philosophical concern, but has empirical consequences. While the former point of view necessarily links the existence of charges to the existence of fields, the latter point of view allows for an independent existence of charges and fields.

Concerning the displacement current, in the view that Maxwell formulates in the

[1] Maxwell, James C. (1873), *A Treatise on Electricity and Magnetism.* Oxford: Clarendon Press, p. xii
[2] Darrigol, Olivier (2000), *Electrodynamics from Ampère to Einstein.* Oxford: OUP, p. 173

Treatise, a displacement current is very similar to an ordinary current. This view is closely linked with Maxwell's belief in the existence of an ether, which would be the mechanical medium for the displacement current. Today, even though both displacement current and ordinary current serve as sources of a magnetic field, displacement currents and ordinary currents are considered of very different nature. While one consists of charges, the other does not. While one is the result of moving matter, the other results from fields permeating a matter-free vacuum.

The aspect, I want to stress here, is that both the modern treatment of charges as that of the displacement current owes much to the action-at-a-distance tradition. The independent existence of charges is a postulate from action-at-a-distance as is the non-mechanical nature of the displacement current. Then the lesson seems, that modern electrodynamics owes important traits to the action-at-a-distance view. To what extent is surely arguable. But in the end, rather than talking of a falsification of the action-at-a-distance view, it seems justified to say, that both theories actually merged in important respects to build the modern electrodynamics known today. In the next section, it is shown how this merging can be broadly described as a reduction.

3 The reducing theory reduced

In the previous section we have sketched a symmetrical picture, where the distinction between reducing and reduced theory seems to some extent arbitrary. This is largely explainable in the framework of Nagel's inhomogeneous reduction, where two theories are connected by *empirical* bridge laws. Consider two theories 1 and 2 and the bridge laws X, that connect both theories for the overlap in domains. Then, every phenomenon in this overlap can be described by 1 plus X or alternatively by 2 plus X.

This reduction enables the explanation of each one of the theories through the other for the overlap in the domains. In the example of the two electrodynamics the distribution of the charges in the action-at-a-distance picture would determine the distribution of the force lines in field theory, and vice versa. The laws that describe the movement of the charges would correspond to the laws that describe the evolution of the force lines.

Also, the merging of the theories into modern electrodynamics is a symmetrical process with respect to both theories. It is not only the reduced theory that has to be corrected, as for example Kenneth Schaffner has argued, but the reducing theory as well has to be adjusted. This corresponds quite well with the historical picture described in the previous section, where we have seen that both elements from action-at-a-distance and from the field view have been implemented in modern electrodynamics.

There are of course a whole range of criteria, that can break this symmetric picture. In principle, all characteristics that determine the value of a theory can be used to establish a hierarchy between two theories. There is for example the domain of applicability, which historically decided the case between the two electrodynamics, since the domain of field theory turned out considerably larger. While action-at-a-distance failed at describing optical phenomena, field theory succeeded. Also, for the reduction of thermodynamics to statistical physics, the latter is seen as more fundamental, because it can also describe mesoscopic and microscopic phenomena. Then, other theoretical virtues like simplicity, and explanatory or predictive power have to be taken into account. It seems, that in this respect both electrodynamics are largely on the same level in the 19th century.

We have already stressed that in cases as that of the two electrodynamics one should refrain from calling one theory falsified. On quite similar grounds Ernest Nagel defended his view of reduction against Paul Feyerabend's attack, that theories are rather replaced than reduced. Nagel answers basically, that two theories that are empirically successful, must be commensurable in the overlap of their domains. Thus, a reduction is always feasible.

Also, inconsistency is not a very useful category, when two theories are empirically successful in the same domain. This is linked with Nagel's insight, that the connection between theories in an inhomogeneous reduction is of empirical or synthetic nature. Consequently, a logical term like inconsistency is largely out of place. Consider the following example: One theory yields the value 1.63 for an observable, the other theory yields 1.65, while the measured value is 1.64. Although these theories are logically inconsistent, they can both be empirically useful and the inconsistency does not imply that one theory should necessarily be abandoned. Similarly, the term incommensurable is not helpful, because there should always be a way to understand, why two theories are successful in the same domain.

So far we have argued, that cases like the historic example of the two electrodynamics can broadly be understood in the framework of Nagel's inhomogeneous reduction, but without the clear distinction between reducing and reduced theory. We have argued against understanding the reduction of both theories in terms of theory replacement or of incommensurability. In the final section, I will argue, that even when such a reduction is successful, the plurality of standpoints should be preserved.

4 Conclusion: Reduction and plurality

An important methodological question at stake is, under which conditions competing viewpoints should be kept. Action-at-a-distance electrodynamics in the Newtonian tradition is not an active research field anymore. To a lesser extent thermodynamics has vanished from the topics in physics research. While reduction is an important and useful tool, it does not necessarily imply, that one of the viewpoints has to be abandoned. Consider the debate regarding the nature of light, where one group of scientists including Newton, Laplace, and Biot defended the particle nature, while the other including Huygens, Young, and Fresnel favoured the wave picture. The case is quite analogous to that of the two electrodynamics. Both theories about the nature of light could account for considerable empirical successes and they had a large overlap in their respective domains. As is well known, the particle view of light was abandoned for a long time until it was revived by Einstein in the beginning of the 20th century. Historically speaking the long abandonment of the particle picture seems a mistake.

There are in principle three options, how one can deal with a situation, where theories on a par compete with each other. Both theories can be merged, one of the theories can be abandoned, or both theories can be kept, while at the same time the bridge laws are developed. It seems that the third option is generally preferable. Against merging the theories can be brought forward, that this bares the risk, that redundant elements are included in the resulting theory compromising simplicity. What are really two descriptions of a phenomenon might become just one very redundant description. An example, where merging of theories or at least of some aspects of competing theories may have compromised simplicity, was described in the historical overview. The traditional field view considered only fields as fundamental entities, action-at-a-distance only charges. However, today's 'classical' electrodynamics allows for both, a standpoint which cannot be empirically contradicted but which may easily contain redundancies.

Abandoning one of two competing viewpoints altogether is problematic as well, because it is difficult to decide, which of the viewpoints should be kept, since both theories were assumed largely on a par. Also, there is some danger in abandoning a research program which at least once used to be very successful.

To the contrary, if both viewpoints are kept, a wide range of problems can be tackled – no matter if they are more easily understood from one point of view or from the other. If the bridge laws are developed carefully, each of the theories can also serve as a corrective to the development of the other. It seems, that in cases as regarding the nature of light or the formulation of electrodynamics a pluralistic approach might well prove the most fruitful. To hold this viewpoint for electrodynamics seems somewhat odd from a modern perspective. On the other hand, the most productive time for classical electrodynamics arguably falls into the short period of time up to the publishing of Maxwell's *Treatise*, during which both viewpoints coexisted. And there are also examples from recent history. After all the young Richard Feynman together with John Wheeler developed an action-at-a-distance electrodynamics as an alternative to the dominant field view – the same Feynman, who later got a Nobel prize for his contributions to quantum electrodynamics.