HEINRICH HERTZ (1857–1894) – PHILOSOPHY OF SCIENCE

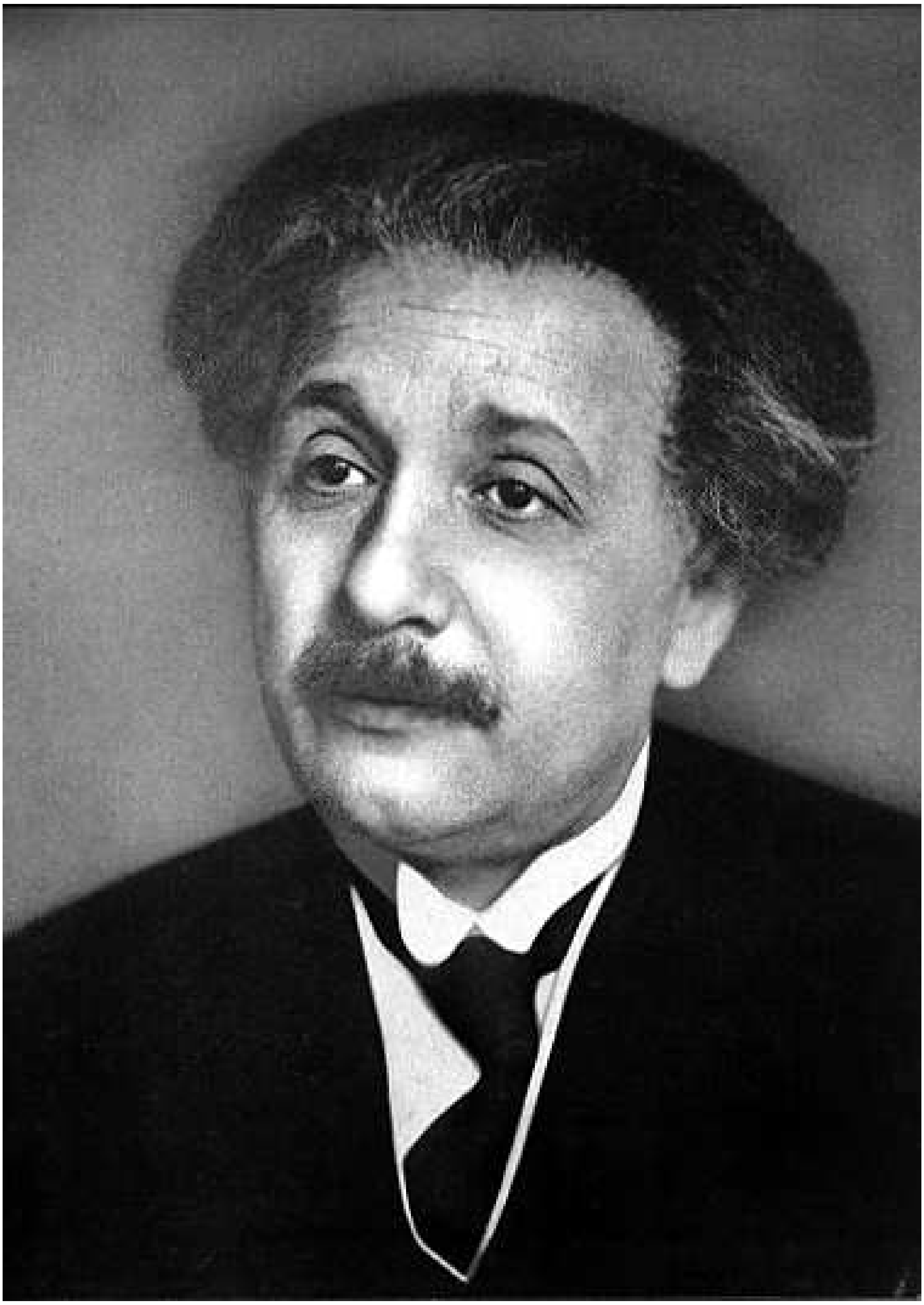

Figure 5.1:
Albert Einstein (1879–1955)

Hamburger Sternwarte

Hertz's methodology and its influence on Einstein

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Abstract: Die Methodologie von Hertz und sein Einfluß auf Einstein

1884 publizierte Hertz genaue und kritische Analyse von Maxwells Gleichungen. Hertz versuchte in seinem Beitrag die Gültigkeit der Maxwellschen Gleichungen zu zeigen, sogar wenn man mit der Prämisse sich widersprechender Theorien beginnt. Hertz charakterisierte explizit Maxwells Theorie als asymmetrisch, eine Eigenschaft, die ihn nicht befriedigte. Deshalb veränderte er die Gleichungen für die elektrischen und magnetischen Kräfte mathematisch, indem er sie symmetrisch umformte und so erreichte, daß die beiden Beschreibungen der Kräfte austauschbar wurden. Jedoch als Folge seiner experimentellen Arbeit über elektrische Wellen akzeptierte Hertz nicht länger die Gültigkeit seiner Ableitung der Gleichungen; stattdessen wählte er die axiomatische Methode. Einsteins Entscheidung, die zwei Prinzipien seiner Relativitätstheorie von 1905 zu fordern, erinnert an Hertz' Entscheidung, die Gleichungen zu fordern. Aber dieser Einfluß wirkte sich nicht auf Einsteins Anschauung bzgl. der Asymmetrie aus, weil sie aufgrund physikalischer Argumente entfernt werden mußte, nicht aufgrund mathematischer Kunstgriffe wie Hertz es getan hatte. Für Einstein war *Ununterscheidbarkeit* das Schlüsselkonzept, nicht die *Vertauschbarkeit.* Nichtsdestoweniger bildete Hertz' bahnbrechender Versuch, mit der asymmetrischen Natur von Maxwells Theorie zu ringen, die Grundlage, die Einsteins sorgfältige physikalische Vorgehensweise zu diesem Problem verdeutlichte.

In 1884 Hertz published a detailed and critical analysis of Maxwell's set of equations. Hertz attempted in this paper to show the validity of Maxwell's set of equations even if one starts with the premises of opposing theories. Hertz explicitly characterized Maxwell's theory as asymmetrical, a feature with which he was not satisfied. He therefore manipulated the equations for the forces of electricity and magnetism mathematically, recasting them symmetrically, thus making the two descriptions of the forces interchangeable. However, in the wake of his experimental work on electric waves, Hertz no longer accepted the validity of his derivation of the equations; instead, he opted for the axiomatic approach. Einstein's decision to postulate the two principles of his theory of relativity of 1905 is reminiscent of Hertz's decision to postulate the equations. But this line of influence did not affect Einstein's view of asymmetry, for it had to be removed by physical arguments, not by mathematical manipulations as Hertz had done. For Einstein *indistinguishability* was the key concept, not *interchangeability*. Nevertheless, Hertz's pioneering attempt to grapple with the asymmetrical nature of Maxwell's theory formed the background against which Einstein clarified his thoroughly physical approach to the problem.

Heinrich Hertz died at the early age of 37; nevertheless, in this short lifetime he became a leading classical physicist and an outstanding philosopher.[1] Indeed, his contributions are highly regarded both for his experimental originality and for his theoretical insights. In 1884 Hertz embarked on a detailed and critical analysis of Maxwell's set of equations: "On the Relations between Maxwell's Fundamental Electromagnetic Equations and the Fundamental Equations of the Opposing Electromagnetics." This major undertaking preceded his famous *tour de force*: proving experimentally that electric waves exist. Hertz attempted in this paper

> to demonstrate the truth of Maxwell's equations by starting from premises which are generally admitted in the opposing system of electromagnetics, and by using propositions which are familiar in it.[2]

That is, Hertz sought to show the validity of Maxwell's set of equations even if one starts with the premises of opposing theories, perhaps alluding to the viewpoint of his mentor, Hermann von Helmholtz. In so doing, Hertz did not introduce the ether in the derivation of the equations. Hertz distanced himself from the assumption of an ether or, at least, he did not ascribe to it the importance it had in Maxwell's original theory. At stake then was the issue of derivation.

Hertz's wish to construct a "bridge" between the opposing views is expressed in the principle that guides him throughout the paper, namely, "the principle of the unity of electric force". He then elaborated another principle, that of "the unity of magnetic force".[3] Thus, according to Hertz, "the essential step in this reasoning is the assumption

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[1] Baird, Hughes, and Nordmann 1998.

[2] Hertz 1896, 289; *idem* [1884]/1895, 313: *"Ich habe im Vorhergehenden versucht, die Gültigkeit der Maxwell'schen Gleichungen nachzuweisen auf Grund von Prämissen, welche auch von der gegnerischen Elektrodynamik zugegeben werden und unter Benutzung von Schlussreihen, welche dieser Elktrodynamik geläufig sind."* Cf. Buchwald 1994, 198.
By "opposing system" Hertz meant any electrodynamics which could accommodate Neumann's potential law: see Hertz 1896, 276 n. 1 and *idem* [1884]/1895, 298 n. 2. On Neumann's potential law, see Archibald 1989.

[3] Hertz 1896, 274; *idem* [1884]/1895, 297: "... der Einheit der elektrischen und ... der Einheit der magnetischen Kraft ... bezeichen könnte ..."

that only *one* kind of magnetic force exists."[4] Hertz distinguishes between the electric and the magnetic force, claiming, however, that each force is unified in the sense that different sources yield the same kind of force.

Perhaps the clearest statement of Hertz's intentions appears in a paper which he published in the following year. Hertz explicitly writes that his motivation is to "make the magnetic and electrostatic systems change places [*Platz vertauschen*]."[5] He sought to establish, first theoretically and then experimentally, that electrostatic force and electromagnetic induction are interchangeable. Thus, he writes,

> in the laws of electric induction we need only interchange the words "electric" and "magnetic" throughout in order to obtain the inductive actions in magnetic circuit.[6]

Notice that Hertz sought a scheme in which the elements are interchangeable, though they still keep their separate identities as magnetism and electricity.

Against this background, Hertz remarks that the two forces, namely, electric and magnetic, have usually been deduced in an asymmetrical manner. Given the two principles announced at the outset of the paper, it is not surprising that he was dissatisfied with the common approach. He therefore proceeds – by purely formal, mathematical means – to eliminate the asymmetry between the forces and to render them interchangeable.

In order to obtain a symmetrical structure for the equations, Hertz eliminated the vector-potentials. He did so by differentiating the equations with respect to *time* by which he obtained the set of equations that do not contain components of the vector-potentials. An examination of the resulting set of equations reveals that the structure is symmetrical in the sense that the components correspond to each other in the same manner and are readily interchangeable – *vertauschbar*.[7]

Hertz is explicit about his move: his intention is to eliminate the asymmetry between the forces and to render them interchangeable. He expected the forces and their governing laws to be interchangeable; indeed, he tried to capture this idea in his new formalism, but nowhere – to the best of our knowledge – does he suggest that the two distinct elements should be united. Symmetry for Hertz appears to embody the notion of interchangeability, and Maxwell's equations ought to be recast to exhibit this feature. Thus, in Hertz's case, the elimination of asymmetry establishes symmetry in the mathematical form of the equations.

The experiments on electric waves, which made Hertz world-renowned, appear to have changed his views. Presumably, Hertz needed an ether to account for the transmission of

[4] Hertz 1896, 273 (italics in the original); *idem* [1884]/1895, 295 (italics in the original): "Das wesentliche Glied in dieser Schlussfolge ist die Annahme, dass es nur *eine* Art magnetishcer Kraft gebe ...."

[5] Hertz 1896, 292; *idem* [1885]/1895, 316: "... das magnetische und das elektrostatische System genau ihren Platz vertauschen."

[6] Hertz 1896, 277; *idem* [1884]/1895, 300: "Wir brauchen nur in den Gesetzen der elektrischen Induktion konsequent die Namen 'elektrisch' und 'magnetisch' zu vertauschen, um zu den hier gesuchten Induktionswirkungen magnetischer Stromkreise zu gelangen."

[7] Hertz 1896, 286–287.

Ueber die Grundgleichungen der Elektrodynamik für ruhende Körper.

Von

H. Hertz.

Das System von Begriffen und Formeln, durch welches Maxwell die elektromagnetischen Erscheinungen darstellte, ist in seiner möglichen Entwicklung reicher und umfassender als ein anderes der zu gleichem Zwecke ersonnenen Systeme. Es ist gewiß wünschenswerth, daß ein der Sache nach so vollkommenes System auch der Form nach möglichst ausgebildet werde. Der Aufbau des Systems sollte durchsichtig seine logischen Grundlagen erkennen lassen; alle unwesentlichen Begriffe sollten aus demselben entfernt und die Beziehungen der wesentlichen Begriffe auf ihre einfachste Gestalt zurückgeführt sein. Die eigene Darstellung Maxwells bezeichnet in dieser Hinsicht nicht das erreichbare Ziel, sie schwankt häufig hin und her zwischen den Anschauungen, welche Maxwell vorfand, und denen, zu welchen er gelangte. Maxwell geht aus von der Annahme unvermittelter Fernkräfte, er untersucht die Gesetze, nach welchen sich unter dem Einfluß solcher Fernkräfte die hypothetischen Polarisationen des dielektrischen Aethers verändern und er endet mit der Behauptung, daß diese Polarisationen sich wirklich so verändern, ohne daß in Wahrheit Fernkräfte die Ursachen derselben seien [1]). Dieser Gang hinterläßt das unbefriedigende Gefühl, als müsse entweder das schließliche Ergebniß, oder der Weg unrichtig sein, auf welchem es gewonnen wurde. Auch läßt dieser Gang in den Formeln eine Anzahl überflüssiger, gewissermaßen rudimentärer Begriffe

1) Die gleiche Bemerkung trifft die durch v. Helmholtz im 72. Bande des Crelleschen Journals gegebene Ableitung, nicht zwar allgemein, aber doch für diejenigen besonderen Werthe der Constanten, welche in den Endresultaten die Fernkräfte verschwinden lassen, welche also auf die hier vertretene Theorie führen.

Figure 5.2:
Heinrich Hertz: *Ueber die Grundgleichungen der Elektrodynamik für ruhende Körper* (1890).

Nachrichten von der Königlichen Gesellschaft der Wissenschaften und der Georg-August-Universität zu Göttingen aus dem Jahre 1890, p. 106.

the newly discovered electric waves in space. The assumption of the ether plays a central role in Hertz's second phase of theoretical studies which begins right after the completion of his experimental work in 1888, for the ether offered a physical interpretation (or model) to account for the electric waves. As an adherent of Maxwell's theory, Hertz then gives the set of equations a new status.

> Maxwell arrived at [the equations] by starting with the idea of action-at-a-distance and attributing to the ether properties of a highly polarisable dielectric medium. One can also arrive at them in other ways. But in no way can a direct proof of these equations be deduced from experience. It appears most logical, therefore, to regard them independently of the way in which they have been arrived at, to consider them as hypothetical assumptions, and to let their probability depend upon the very large number of natural laws which they embrace.[8]

In contrast to his earlier view, Hertz now considers the equations axiomatically. His point is that it is better to take these equations as postulates rather than claiming that they can be proved or derived from principles and observations. The Einsteinian spirit of this methodological "inversion" is startling. But, of course, historically it is the other way around: Hertz's change of heart, namely, abandoning the attempts at deriving the equations and turning them instead into the axioms on which the theory is based, is similar to the move that Einstein makes in the introductory section of the relativity paper where he raises two conjectures to the status of postulates.

We have reached an intermediary conclusion: Hertz recognized an asymmetry in Maxwell's set of equations and sought to present them in a symmetrical form. His motivation was a commitment to the interchangeability of electric and magnetic phenomena. He then manipulated the equations mathematically in order to give them a symmetrical structure. However, in the wake of his experimental work on electric waves, Hertz no longer accepted the validity of his derivation of the equations; instead, he opted for the axiomatic approach, turning the equations into postulates.

At the outset of his relativity paper Einstein called into question Maxwell's theory which includes Maxwell's original set of equations and then, later in the paper, invoked these equations in their Hertzian form, namely, in the symmetrical form that Hertz presented for the first time in his paper of 1884. Einstein is explicit about this: he appeals to the "Maxwell – Hertz equations".[9] In fact, Einstein postulates these equations in the same spirit as Hertz did in 1890, implicitly agreeing with Hertz on the axiomatic status

[8] Hertz [1893]/1962, 138 (slightly modified); *idem* [1889a]/1892, 148: *"Maxwell gelangte zu [diese Aussagen], indem er von Fernkräften ausging und dem Aether die Eigenschaften eines in hohem Grade dielektrisch polarisirbaren Mittels beilegte. Man kann auch auf anderen Wegen zu denselben gelangen. Auf keinem Wege kann indessen bislang ein director Beweis für jene Gleichungen aus der Erfahrung erbracht werden. Es erscheint deshalb am folgerichtigsten, dieselben unabhängig von dem Wege, auf welchem man zu ihnen gelangt ist, als eine hypothetische Annahme zu betrachten und ihre Wahrscheinlichkeit auf der sehr grossen Zahl an Gesetzmässigkeiten beruhen zu lassen, welche sie zusammenfassen."*

[9] Einstein 1905, 907, 908. Einstein presented a modified version of Hertz's symmetrical form of Maxwell's equations (Hertz 1890, 111), as had been done by some of his predecessors. For example,

of the equations. However, he did not comment on their symmetrical form – thereby implying that this feature was not essential to the argument of the theory. Einstein's decision with respect to postulating the two principles of his theory (thus giving it an axiomatic basis) is reminiscent of Hertz's decision to postulate the equations. But these lines of influence do not affect Einstein's view of asymmetry, for it has to be removed by physical arguments and not by mathematical manipulations. Nevertheless, Hertz's pioneering attempt to grapple with the asymmetrical nature of Maxwell's theory formed the background against which Einstein clarified his thoroughly physical approach to the problem. Hertz was a most effective interlocutor for Einstein: in Hertz's work Einstein found the quintessence of 19th-century physics and it served as his point of departure for inaugurating the physics of a new era.

Einstein begins his relativity paper of 1905 by calling attention to the fact that Maxwell's electrodynamics – "as usually understood at the present time" – leads, when applied to moving bodies, to asymmetries which do not correspond to anything in the phenomena. We may be tempted to think that Einstein directs his criticism, right at the outset of the paper, at the formalism of Maxwell's theory, for this formalism is responsible for these asymmetries. Thus it would seem that one needs to address the form of the equations, either to modify it or replace it, with the goal of making it correspond faithfully to the phenomena. But we take Einstein's expression "as usually understood at the present time" to mean that the fault lies in the way the theory had been understood, not in the equations. After all, later in the paper Einstein introduces the Maxwell – Hertz equations lock, stock, and barrel, and does not question their validity in any respect. The formalism is taken to be correct without comment. The expression "Maxwell's theory", or "Maxwell's electrodynamics", refers then not merely to the equations but to the equations together with a host of assumptions, derivations, and interpretations. Indeed, the evidence in support of Maxwell's equations at the turn of the 20th century was overwhelming; they satisfactorily described a large number of phenomena. Einstein, to put it bluntly, "buys" the formalism, that is, the equations, but he rejects the interpretation(s) outright. The fact that at the very beginning of the paper Einstein calls attention to an *asymmetry* that results from a theory is an important clue that attention should be directed to the physical interpretation of the formalism.

What was the motivation for Einstein to drive a wedge between the theory and its formalism, to see so clearly that the system of equations could be retained despite a radical change in the interpretation of Maxwell's theory? Einstein read Hertz closely and he appears to be an adherent of Hertz's methodology.

Although Hertz was motivated by physical reasoning, he sought analogous treatment of the equations for electricity and magnetism. He observes that Maxwell's equations are deduced in an asymmetrical fashion and so he manipulates the equations formally in order to make them display the symmetry he sought.

Drude (1894, 315) presented the equations in their symmetrical form (with the partial derivative symbol) and referred, *inter alia*, to Hertz ([1890]/1892). Further, Drude (1894, 316 n. 4) noted that the algebraic sign depends on the choice of direction of the coordinate system. Wiechert (1898, 90) also invoked Hertz's symmetrical presentation of the equations in much the way that Drude had done.

Hertz first derives the equations; he does not regard them as having an axiomatic status. Once the formalism was in place, the equations allowed Hertz to deduce consequences that are experimentally testable. The formalism, as Hertz noted, takes on a life of its own. In 1889, in an essay on light and electricity, Hertz revealed the extent to which Maxwell's set of equations had impressed him:

> It is impossible to study this wonderful theory without feeling as if the mathematical equations had an independent life and an intelligence of their own, as if they were wiser than ourselves, indeed wiser than their discoverer, as if they gave forth more than he had put into them ....[10]

In 1892 Hertz reported in the theoretical part of the Introduction to his *Electric Waves* that

> I ... endeavoured to form for myself in a consistent manner the necessary physical conceptions, starting from Maxwell's equations, but otherwise simplifying Maxwell's theory as far as possible by eliminating or simply leaving out of considerations those portions which could be dispensed with, inasmuch as they could not affect any possible phenomena .... The common significance of the different modes of representation ... appears to me to be the undying part of Maxwell's work. This, and not Maxwell's peculiar conceptions or methods, would I designate as "Maxwell's Theory." To the question, "What is Maxwell's theory?" I know of no shorter or more definite answer than the following: – Maxwell's theory is Maxwell's system of equations.[11]

Having stated his belief in the formalism of the equations as the core of the theory, Hertz proceeds to spell out the different interpretations given to the formalism, claiming that the difficulty is not necessarily of a mathematical nature. And he cautions the reader that

[10] Hertz 1896, 318; *idem* [1889b]/1895, 344: "Man kann diese wunderbare Theorie nicht studieren, ohne bisweilen die Empfindung zu haben, als wohne den mathematischen Formeln selbständiges Leben und eigener Verstand inne, als seien dieselben klüger als wir, klüger sogar als ihr Erfinder, als gäben sie uns mehr heraus, als seinerzeit in sie hineingelegt wurde."

[11] Hertz [1893]/1962, 20–21; Hertz 1892, 22–23: *"Ich versuchte deshalb mir die unentbehrlichen physikalischen Vorstellungen widerspruchsfrei selbst zu construiren, indem ich von den Maxwell'schen Gleichungen ausging, im Uebrigen aber die Maxwell'sche Theorie so viel wie möglich vereinfachte durch Elimination oder einfache Fortlassung aller derjenigen Elemente, welche ich nicht verstand und welche entbehrlich waren, da sie auf keine möglichen Erscheinungen einen Einfluss üben konnten .... Die Darstellung der Theorie in Maxwells eigenem Werk, die Darstellung als Grenzfall der Helmholtz'schen Theorie und die Darstellung in den vorliegenden Abhandlungen sind also wesentlich verschiedene Formen für einen wesentlich gleichen gemeinsamen Inhalt. Dieser gemeinsame Inhalt der verschiedenen Formen, für welche gewiss noch viele andere Formen gefunden werden können, erscheint mir als der unsterbliche Theil der Maxwell'schen Arbeit, diesem Inhalt und nicht den besonderen Vorstellungen oder Methoden Maxwells möchte ich den Namen 'Maxwell'sche Theorie' vorbehalten wissen. Auf die Frage, 'was ist die Maxwell'sche Theorie' wüsste ich also keine kürzere und bestimmtere Antwort als diese: Die Maxwell'sche Theorie ist das System der Maxwell'schen Gleichungen."*

> scientific accuracy requires of us that we should in no wise confuse the simple and homely figure, as it is presented to us by nature, with the gay garment which we use to clothe it. Of our own free will we can make no change whatever in the form of the one, but the cut and colour of the other we can choose as we please.[12]

Hertz wished to strip from the theory everything (which he calls "garments") but the equations, and then recast them in a symmetrical form.

Einstein refers to asymmetry at the beginning of the relativity paper: "Maxwell's electrodynamics ... when applied to moving bodies, leads to asymmetries that do not seem to adhere to the phenomena."[13] He argued that, on the one hand, from Maxwell's theory one would expect asymmetries in the descriptions of the phenomena but, on the other, no such asymmetries are to be found in the phenomena. For Hertz, the issue of symmetry does not concern the phenomena directly; rather, it concerns the structure and the derivation of Maxwell's equations. Not so for Einstein.

There is a clear difference here between Hertz and Einstein. Hertz identifies and addresses a different problem from the one Einstein states at the outset of his relativity paper. In Hertz's case the problem lies in the way Maxwell's equations are set up and derived: the distinct phenomena of electricity and magnetism are analogous and the formalism ought to exhibit a correspondence between them; hence the equations should be symmetrical in the sense that analogous elements have to correspond and be interchangeable. Einstein, by contrast, argues that the fault is not in the equations – be they symmetrical or asymmetrical – but in their interpretation, that is, in embedding them in an ether. Curiously, Einstein seems to arrive at this position on the basis of Hertz's own methodology:

1. The equations are valid regardless of the way they were originally determined;
2. The validity of the equations depends on their successful accounting for a wide range of phenomena; and
3. The equations are valid independent of any specific interpretation of them.

The third item is of particular interest for us here: Einstein indicated that an interpretation which distinguishes electric and magnetic forces of moving bodies is false, for there is only one kind of force involved, and it is simply electromagnetic. But, despite the radical change in interpretation, the equations are still valid.

Einstein took Hertz's methodology to heart, but with a twist: in some respects he is more Hertzian than Hertz. The theory with its interpretative baggage could, and

[12] Hertz [1893]/1962, 28; Hertz 1892, 31: "Aber die Strenge der Wissenschaft erfordert doch, dass wir dies bunte Gewand, welches wir der Theorie überwerfen, und dessen Schnitt und Farbe vollständig in unserer Gewalt liegt, whol unterscheiden von der einfachen und schlichten Gestalt selbst, welche die Natur uns entgegenführt und an deren Formen wir aus unserer Willkür nichts zu ändern vermögen." See also *idem* [1893]/1962, 195, and *idem* 1892, 208.

[13] Beck 1989, 140 (slightly modified); Einstein 1905, 891: *"Daß die Elektrodynamik Maxwells – wie dieselbe gegenwärtig aufgefaßt zu werden pflegt – in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt."*

should, be separated from its purely formal-mathematical representation. Hence, according to Einstein, seeking symmetrical equations – in the sense that the relations between the symbols that comprise the equations support some structure that exhibits correspondence among the symbols – may not affect the actual physical issue at stake, thus adding an unnecessary "garment" that has led physicists astray. The problem that Einstein presents at the outset of his relativity paper is that the theory leads to two descriptions related to the same phenomenon, and that these descriptions are different. To be truly Hertzian, one has to come up with a physical argument to account for this disparity of one phenomenon with two contrasting descriptions. And we claim that in all likelihood this is the way Einstein read Hertz.

In sum, Hertz's work is part of the background to Einstein's thinking on issues in electrodynamics. Hertz explicitly used the term *asymmetry* in his essay of 1884. However, for Hertz this asymmetry is purely formal and he then derived Maxwell's equations in a symmetrical form. After his successful experimental demonstration of the existence of electric waves, Hertz opted for the ether as presented in Maxwell's theory but retained the equations in their symmetrical form.

Hertz showed the way to a critical examination of Maxwell's theory. In particular, he insisted that the equations should only concern physically meaningful magnitudes, not artifacts of the theory. One could say that Einstein followed Hertz in his recognition that something was wrong in the theory, but Einstein had a different "diagnosis" and eventually came up with a different "cure".

The formalism, the core of Maxwell's theory stripped of all its "garments", does not include the ether. For Einstein the issue is not the symmetry or the asymmetry of the equations – which was a central theme for Hertz, Heaviside, and some other notable physicists[14] – but the removal of asymmetries that are "artifacts" of the theory and have no objective reality.

We suggest that Einstein was, as it were, in conversation with Hertz. On this view, Einstein opens the relativity paper with a critique of Hertz's approach to electrodynamics. Using Hertz's own methodology, Einstein implicitly responded to Hertz that his attempt at recasting Maxwell's equations into a symmetrical form was ill-conceived: asymmetry is deeply embedded in Maxwell's theory and a formal modification of the equations does not suffice to render the theory symmetrical; in any event, this deep-seated asymmetry is an artifact that has no counterpart in the phenomena. A radical solution is called for: recasting the fundamental postulates of the theory.

We submit that in Einstein's view Hertz did not address the right problem. The issue for Einstein concerned the theory, not just the equations; thus, formal solutions were not in fact solutions, for they were merely manipulations of formulas. This interpretation is supported by Einstein's explicit reference in the opening sentence of the paper to Maxwell's theory and not to its equations (to which he refers later in the electrodynamic part of the paper). The problem is that the theory distinguishes between electricity and magnetism whereas, in fact, these phenomena are different manifestations of the same thing – the electromagnetic field. This is where Einstein focuses his

[14] See Hon and Goldstein 2005.

attention: the distinction between electricity and magnetism has to be dropped in favor of "electromagnetic phenomena". In other words, the contrast is between Hertz's interchangeability and Einstein's indistinguishability; while the former calls for a symmetrical structure, the latter seeks unity. The asymmetries of which Hertz and Einstein speak are therefore conceptually different and ought not to be conflated.

This is connected with the ether hypothesis and, if one rejects the ether, as Einstein already did in 1899, it seems that one has rejected Maxwell's theory at the same time. But the equations are well confirmed – so how to resolve this dilemma? Einstein takes Maxwell's equations in Hertz's form since they do not depend on the ether hypothesis (despite Hertz's later views on this issue). The question is then, has Hertz eliminated the asymmetry as he claimed to have done? And Einstein replies, No – asymmetry still remains in the theory even though it has been removed from the equations. For this argument to work, Einstein has to adhere to Hertz's terminology, at least to some extent.

But what term should be used to express the problem that remains in Maxwell's theory? Einstein chose *asymmetry*, the very term which Hertz used to refer to problems in Maxwell's theory in the derivation of the equations which, according to Einstein, Hertz did not succeed in removing. The particular difficulty is that, within the framework of Maxwell's theory, one can generate an electric field, and not generate it, by means of the same experiment (seen in two different ways). That is, the term *asymmetry* in Einstein's account is an artifact of his response to Hertz. Einstein's vocabulary is often idiosyncratic and here it reflects his engagement with the ideas expressed in Hertz's publications that led to his critique of Maxwell's theory. For Hertz the removal of asymmetry results in symmetry, but for Einstein the contrary of asymmetry – symmetry – is not an issue: symmetry has become irrelevant. Unity was the key to revolutionizing 19th century physics.

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