Chapter 2
Sorting Things Out: Drude and the Foundations of Classical Optics
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2.1 Introduction

> My goal will be reached if these pages will strengthen in the reader the view that optics is not an old, worn-out domain of physics, but that also here a fresh life pulses, the contribution to whose further nourishment should be enticing for anyone.[1] (Drude 1900a, vi)

With these stimulating words Paul Drude aimed at engaging physicists, in 1900, in the reading of his textbook *Lehrbuch der Optik*. More than one hundred years later, in this paper I will try to clarify historically these inspired words: In what sense could optics have been considered old? In which aspects did Drude's new account of optics "pulse with fresh life"? How could the further "nourishment" of optics take place in Drude's view? To what extent did Drude succeed in achieving his goal?

In fact, in 1985 Jed Z. Buchwald already spoke of Drude's *Lehrbuch der Optik* in his thorough account on the complex and gradual transition between the macroscopic outlook of Maxwell's electrodynamics and Drude's microscopic approach to electromagnetic optics (Buchwald 1985). *Lehrbuch der Optik* was Buchwald's finale. I share with Buchwald the viewpoint that *Lehrbuch der Optik* was the first encompassing work in which a microscopic approach to optics was established. For this reason, the book is a particularly interesting subject of study. However, in this paper, instead of analyzing Drude's work against the background of the general history of electrodynamics, I will explore the articulation of the book with other contexts.

First, I understand *Lehrbuch der Optik* not only as a singular point in Drude's career, but as the result of a long process, started in the early 1890s, through which he reflected upon and changed his understanding of what optics should be. Moreover, *Lehrbuch der Optik* not only had an impact on the physics community; the endeavor to write a comprehensive book on optics was also important for Drude as a way to organize his knowledge, strengthen his views on the field, and revamp his career. I will thus follow the story of *Lehrbuch der Optik* through the development of optics, and not electrodynamics. Second, to understand better the distinctiveness of Drude's decisions for a redefinition, both ontological and epistemological, of optics, I will follow Drude in his conversation with his contemporaries, in particular his mentor and dissertation advisor Woldemar Voigt, and in relation to other views about optics conveyed in coetaneous textbooks. Third, after I arrive at Drude's construction of *Lehrbuch der Optik*, I will then go further to ask about the impact the book had in setting the tone for future generations, especially in stimulating further research in the field. To answer

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[1] All translations are done by the author.

the above mentioned questions, I have divided the paper into five sections corresponding to different periods of Drude's life and career.

In the first section, I will follow Drude's early career at the University of Göttingen, from 1887 until 1894, under Voigt's supervision. My concern will be to identify those aspects of the Göttingen approach to optics that were unsatisfactory for Drude and, at the same time, to unfold Drude's gradual shaping of an alternative view. A choice between the mechanical and the electromagnetic theory of light, together with the criteria upon which to rely in making such a decision, were both at stake for Drude in this period. His first textbook, published in 1894, *Physik des Aethers*, embodied his decisions on these matters, and thereby marked an important turning point in his life and career.

From 1894 to 1900, Drude served as full professor at the University of Leipzig, where he could develop in depth his own standpoint on optics, hinging completely upon the electromagnetic theory of light. In the years after 1894, Drude managed the incorporation of matter into the electromagnetic picture of light. By 1900 he envisioned a unified theoretical approach for a variety of optical phenomena stemming from different kinds of interactions between light and matter. In his second textbook, *Lehrbuch der Optik*, published in 1900, Drude displayed his own, programmatic view, which merged the electromagnetic theory of light with the dynamical action of the microstructure of matter. I will give an account of Drude's development between 1894 and 1900 in the third section.

Lehrbuch der Optik was not a compendium of well-established knowledge in optics. New optical phenomena were explored experimentally at the end of the nineteenth century, which led to a revitalization of theoretical discussions about the interaction between light and matter. For this reason, many textbooks had become rapidly outdated. Drude's *Lehrbuch der Optik* was very innovative in attempting to encompass both old and new phenomena, through his personal strategy of merging electromagnetism and matter. But Drude's textbook was original also for other reasons. Most European textbooks on optics evinced a special concern for the nature of the ether, because light presumably amounted to the perturbation of that substance. In *Lehrbuch der Optik*, instead, Drude relinquished questions about the constitution of the ether, taking the electromagnetic equations of light as the starting point for his account of optical phenomena. Actually, Drude did not eschew mentioning the ether as the substratum for light, but in starting from the light equations, Drude completed a radical shift in the kind of questions textbooks had addressed so far: from the relation between the nature of the ether and its mathematical expression, to the relation between the microstructure of matter and the modification of the light equations that captured this new dimension of optical phenomena. I will describe the content, organization, and main points of *Lehrbuch der Optik* in the fourth section.

In the fifth section, I examine Drude's work, between 1900 and 1906, concerning the relation between optical phenomena and the microstructure of matter. Important outcomes stemmed from the incorporation of the electron into the previous picture of optics, which allowed Drude to network optics with other fields in science, like chemistry. Such modifications were included in a second edition of his book in 1906.

All in all, Drude not only provided readers with explanations of new phenomena, but also with new questions to ask and a new methodological approach to optics. Advancing into almost virgin terrain, Drude's claims in *Lehrbuch der Optik* had a strong impact, which I will analyze in the epilogue of the paper. Without criticizing directly previous works in optics, Drude redefined them as part of a past that should be overcome. He simply reorganized optical knowledge in such a way that these older traditions were not mentioned or were re-understood through "Drude's lens." *Lehrbuch der Optik* remained influential for years to come, in part through Woldemar Voigt's 1908 *Magneto- und Elektrooptik*, in which he extended Drude's take on optics to the explanation of new features of optical phenomena. Both theoretical and experimental physicists used Drude's and Voigt's accounts as points of reference in the early twentieth century. Later physicists started to juxtapose such approaches with the emerging quantum theory, particularly after Bohr's 1913 quantum model of the atom. Most importantly, what came to be considered classical optics, as opposed to quantum physics, was not simply what came before quantum optics. This is another reason it is important to analyze Drude's *Lehrbuch der Optik*: Drude's selection and reorganization of nineteenth-century optics became the paradigm of "classical optics," against whose backdrop physicists constructed the quantum understanding of optical phenomena.

2.2 Göttingen 1887–1894: From the Optics of Ether to the Electromagnetic Equations

2.2.1 On Voigt's Footsteps

Paul Drude was born on 12 July 1863 in Braunschweig, where he lived until he completed his studies at the local Gymnasium in 1882 (Hoffmann 2006; Goldberg 1990). Thereafter, he studied mathematics, first at Göttingen and then at Freiburg and Berlin. In the sixth semester, he decided to return to Göttingen and devote himself to theoretical physics, under the guidance of Woldemar Voigt, director of the Physics Institute at Göttingen. Drude's early research was very much influenced by Voigt in terms of subject matter, guidelines, and research procedures. Voigt, in turn, was a faithful heir of Franz Ernst Neumann's approach to physics. Thus it is of key importance to trace the scientific genealogy from Neumann to Drude, in order to understand the specific tradition within which Drude grew up.

Neumann, one of the founding fathers of German theoretical physics, was *Privatdozent* for physics and mineralogy starting in 1826 at the University of Königsberg. To supplement his lectures, in 1833, he inaugurated the German mathematical-physical seminar, through which he trained his students, including Voigt, in his particular approach to theoretical physics. Optics was one of the principal topics of interest in Neumann's seminar. At that time, it was commonplace to think that light consisted of elastic perturbations propagated through a transparent substance filling everything, called the ether. An optical theory amounted to the set of differential equations and boundary conditions describing the behavior of the ether, which were to be derived from the application of general mechanical principles to that hypothetical elastic substance. Gaining optical knowledge meant then to obtain the most complete set of equations and boundary conditions, which, on the one side, were supposed to manifest the true properties of the ether, and on the other side, had to describe mathematically optical measurements. The phenomena of reflection and refraction through crystals were the main target of optical theories.

In such a dualist scheme, Neumann pursued a very specific methodology, which Kathryn Olesko dubbed the "ethos of exactitude" (Olesko 1991). The key to Neumann's approach lay in mastery of the relations between the mathematical equations describing the ether and experimental measurements, which required the development of numerical techniques to fit accurate empirical data into theoretical formulas, the improvement of strategies to eliminate the possible experimental sources of error, and the identification of the key parameters for a better comparison between theoretical and observable quantities. As Olesko pointed out, following the ethos of exactitude, experimental reenactment was stimulated only by the desire to check theory, while the creative task of enhancing optical theories was restricted to the addition or modification of differential terms in the mathematical equations describing the ether. No additional hypotheses on the underlying interaction between ether and matter were called for. Thus, no new level of physical explanation beyond the principles of mechanics and the mathematical completion of the ether equations was added. This dynamics of knowledge indeed led to an effective exploration of the limits of the present theories of ether, but not necessarily to new conceptual frameworks.

Voigt completed his dissertation in 1874, expanding upon one of the most frequently recurrent topics in optics tackled at the Königsberg seminar: the behavior of light reflected by or refracted through crystals. On the one hand, Voigt worked with optical constants, which were the measurable quantities that accounted for the behavior of light at the border between ether and matter, i.e. the refractive index and the coefficient of reflectivity of the crystal. Voigt literally spent hours in the laboratory measuring the optical constants of manifold crystal samples. On the other hand, Voigt enhanced Neumann's initial set of differential equations and boundary conditions so that the most satisfactory mathematical expression for the optical constants that fit into his measurements could be derived from them. In general, Voigt aimed to go a step further in the theoretical understanding of optics: the "causal nexus" between the kind of substance explored (different crystals in this case) and the modification of the properties of the ether, represented in a set of differential equations. It is important to notice that, within this framework, the role of matter was solely to *modify* the ether's properties: ether, whether filling the interstices of matter or surrounding it, was considered the only substratum of light propagation. Matter did not play a role in the production of light. From this point of view, the mathematical description of optical phenomena should be a mirror of the ether's behavior.

Voigt brought the Königsberg tradition to the Göttingen Physics Institute in 1883 (Olesko 1991, 412–414). Four years later, Drude finished a dissertation in Göttingen that was a continuation of Voigt's own. Equally driven by the ethos of exactitude, Drude set out to study the optical constants of crystals, although he focused on one very specific class of crystals: those that not only refracted and reflected light, but also partially absorbed it (Drude 1887). For several years after his dissertation, Drude continued to work and publish on this problem, extending his research from crystals to metals. To be sure, Drude's close faithfulness to Voigt's guidelines turned out not to be very beneficial for him. Precisely because he was often regarded, among German theoretical physicists, as unduly dependent on his teacher, from 1887 until 1894 Drude found it very difficult to obtain a job outside of Göttingen (Jungnickel and McCormmach 1986). But his reputation improved in 1894, with the publication of his first textbook *Physik des Aethers*, where he clearly distanced himself from Voigt's agenda and started supporting the electromagnetic theory of light. However, Drude's change of heart did not happen overnight and involved much more than a substitution of one theory of light with another.

2.2.2 Towards a New Way to Optical Knowledge: *Practical Physics*

In 1887–1888, in his laboratory in Karlsruhe, Heinrich Hertz observed that electromagnetic disturbances of the ether exhibited wave-like characteristics and propagated through the ether at the speed of light (Hertz 1888).[2] It is common wisdom that Hertz's experiments provided physicists with a strong argument for the unification of electromagnetism and optics and were a breakthrough for the dissemination of the electromagnetic theory of light in Continental Europe. In 1888–1889, Voigt's students discussed the electromagnetic theory of light in connection with Hertz's experiments in the mathematical-physical seminar in Göttingen (Olesko 1991, 412). From then onwards, Drude divided his interest between the Neumann-Voigt mechanical theory of light and Maxwell's electromagnetic theory. At the beginning, he made no choice between them. In fact, he made up his mind only after a long process of reflection during which he carefully examined and compared both approaches. What was at stake was not simply which theory to choose but, above all, which criteria to use to decide the most satisfactory theory. The conclusions Drude eventually arrived at, in 1894, were significantly different from Voigt's conservationist position at that time.

Drude's first open demonstration of a radical departure from Voigt's standpoint was his provocative 1892 paper (Drude 1892a). There Drude addressed one of the most puzzling consequences of comparing electromagnetic and mechanical theories of light: the various sets of differential equations derived from considering the ether as an elastic substance were mathematically equivalent to Maxwell's electromagnetic equations. In fact, in addition to Neumann's mechanical theory of light, there existed others that also described the phenomena of refraction and reflection of light satisfactorily, most significantly Fresnel's. What differentiated them were specific properties ascribed to the elastic ether. In particular, Neumann considered ether an incompressible substance, while Augustin Fresnel regarded it as a compressible material.[3] Nevertheless, these theories of light all led to equivalent mathematical equations and boundary conditions, including electromagnetic equations. This was, according to Drude, a powerful reason to discount optics altogether:

> Since many different theories, which derive from very different basic assumptions, can account for scores of observable features in the same way without contradictions, the theoretical research on optical phenomena has been discredited to the extent that one tries to understand these phenomena through mathematical and almost philosophical speculations, from which new knowledge about the true properties of nature cannot be extracted, for the same properties are explained differently in the different theories. (Drude 1892a, 366)

What Drude described was an epistemological dilemma. The only criteria the ethos of exactitude offered to evaluate the validity of an optical theory was the precision of the numerical agreement between experimental data and theoretical predictions. Now, given the mathematical equivalence between mechanical and electromagnetic theories of light, it was clear that numerical exactitude could not be the only way to mediate between optical experiments and the physical properties of the ether. How to proceed in this situation? Drude's way-out involved a twofold break with Neumann's and Voigt's tradition.

First of all, Drude endorsed a more radical phenomenological standpoint: theories of light he reduced to just the differential equations and the imposed boundary conditions. He called the combination of these two ingredients an *Erklärungssystem* (explanatory system).

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[2] For a general account of the dissemination of the electromagnetic theory of light in Continental Europe, see (Darrigol 2000; Buchwald 1985). More specifically about Hertz's contribution, see (Buchwald 1994).

[3] The story of the various theories of the lumiferous ether in the nineteenth century is rather intricate. A good overview can be found in (Whittaker 1910).

The point of departure for optics was then the *Erklärungssystem*. Questions about the true nature of the ether became irrelevant for the mathematical construction of an optical theory, while the physical system to be studied was reduced to the mathematical parameters making up the *Erklärungssystem*. The choice of an optical theory was thus a choice of language: either density, elasticity, and velocity of ether perturbations, or magnetic permeability, dielectric constant, and magnetic field strength.

Secondly, since the ethos of exactitude had exhausted its potential for revealing new knowledge about the ether, Drude hinted at other possible criteria to help one choose among the different theories of light. More specifically, he claimed that

> the adoption of the electromagnetic theory of light seems to be a significative step in the true understanding of nature, since the velocity of light in vacuum or through air derives directly from electromagnetic features. (Drude 1892a, 366)

In other words, Drude promoted a unification of optical and electromagnetic theories from below. Given that experiments proved that optical and electromagnetic waves propagated at the same velocity, one was inclined to extend this coincidence to the rest of the optical and electromagnetic features. Unification would then mean, according to his radical phenomenological move, the adoption of a single physical language to describe the mathematical equations accounting both for optical and electromagnetic phenomena.

Voigt was also aware of the mathematical equivalence between mechanical and electromagnetic theories. Nevertheless, for years he did not sympathize with this idea of unifying optics and electromagnetism from below. For him, the only way to strive for unification was the determination of the properties of a general ether, from which the equations of optical and electromagnetic phenomena could be derived. Thus, adopting an electromagnetic language would mean, for him, losing generality, and restricting oneself to only one possible nature for the ether. In fact, Voigt had conveyed his own point of view in a paper published just one year before Drude's paper (Voigt 1891). In it, Voigt maintained a "mathematical viewpoint" in the development of optical theories. That is to say, like Drude, he decided to work directly with differential equations. But unlike his disciple, for the sake of generality, Voigt concealed any decision about the physical interpretation of mathematical terms. This eventually implied continuing to rely on the "incontestable principles of mechanics" (Voigt 1891, 411). Voigt upheld such a mathematical viewpoint until the publication of the second volume of his ambitious *Kompendium der Theoretischen Physik* (Voigt 1896).

The break with his master notwithstanding, Drude was not alone in his positivistic move, which he dubbed "practical physics." As he mentioned in his 1892 paper, Drude found inspiration in Hertz's treatment of electrodynamics. In 1890 Hertz had stated that Maxwell's equations contained everything that was essential in Maxwell's theory, so that any attempt to derive them from mechanical models of the electromagnetic ether, as had been done in the past, overshot the mark (Hertz 1890). In his paper, Hertz simply postulated the electromagnetic equations, which he obtained by simplifying Maxwell's formalism and detaching it from any physical assumptions concerning the nature of the electromagnetic forces. The electrical polarizations of the medium were, for him, the only things truly present. To look for their origin in some essential quality of the ether was futile.[4] In fact, such a reformulation of Maxwell's equations became very popular in Europe thanks to its clarity and synthetic

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[4] In fact, the British physicist Oliver Heaviside had been working on a similar reformulation of Maxwell's equations since 1885, as Hertz rightly acknowledged in his paper. For more information about the developments of

value. Thus immediately after Hertz, other physicists, like Hermann von Helmholtz and Hendrik Antoon Lorentz, adopted it.

Despite Drude's clear alignment with Hertz's approach, he still pondered for some time the definitive adoption of the electromagnetic theory of light. The theory was troubled by one important difficulty: Maxwell's equations accounted well for the phenomena of reflection and refraction of light, but not for those optical phenomena in which matter was assumed to contribute directly to the generation and absorption of light waves. Ever since the early 1870s, it had become clear to physicists that ether waves were not sufficient to describe optical phenomena, like optical dispersion. In these cases, differential equations referring to the ether had to be combined with differential equations accounting for the action of matter. While there were attempts to interweave the action of ether and matter in the framework of the mechanical theories of light, Maxwell's electromagnetic equations applied only to the ether. To fill this gap, Drude suggested that "in order to fix the facts rightly, also this theory [the electromagnetic one] must be built upon enlarged assumptions [incorporating the action of matter], at the expense of the advantage of its simplicity and evidence" (Drude 1892a, 366). Hence, in the ensuing two years, Drude worked on the possibility of extending the scope of the electromagnetic theory of light to other optical phenomena apart from reflection and refraction. Namely, he wanted to find the *Erklärungssysteme*[5] for these other phenomena, and relate them to Maxwell's *Erklärungssystem* for ether. In particular, he dwelled upon the Kerr effect (Drude 1892b) and optical dispersion (Drude 1893). I will concentrate on the last example, because of its persistence and its special significance to the story.

2.2.3 Optical Dispersion and the "Practical Physics" at Work

Beginning in the seventeenth century, optical dispersion was understood as the continuous spread of white light into different colors when passing through a prismatic medium. The ensuing order of colors was always: red, orange, yellow, green, blue and violet, as observed in rainbows. One parametrized this phenomenon through n, the index of refraction, which referred to the change in the direction of light propagation with respect to the initial beam. Each color corresponded to one frequency of light waves, thus optical dispersion amounted to the dependence of n on the light frequency ν. The continuity of the analytical function $n(\nu)$ stood for the observed order of colors mentioned above.

In the early 1870s, though, a series of circumstances changed radically the understanding of this phenomenon, both from the experimental and the theoretical perspective. On the one hand, it was found that when light passed through certain substances (actually, liquid dyes), the normal succession of colors appeared reversed. The reversal implied that the function n was discontinuous with respect to ν at some point. More interestingly, it was acknowledged that the discontinuity in the behavior of n took place around those colors of the spectrum whose frequency coincided with the frequency at which the liquid dyes typically absorbed light. That is to say, when interacting with these substances, one color component of the light was absorbed, while the others passed through and were dispersed into a spectrum. Absorption and dispersion of light became two complementary features of the same

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Heaviside and, in general, the work of the so-called "Maxwellians" (George Francis FitzGerald, Oliver Lodge, Oliver Heaviside) in the 1870s and 1880s, see (Hunt 1991).

[5] The *e* marks a German plural.

light-matter interaction. But if this was the case, matter should not just modify the properties of ether, but should play an active role in the production and absorption of light waves.[6]

On the other hand, almost simultaneous with these experimental findings, a radically new optical theory was put forward, in which both the action of matter and ether were taken into account.[7] It was assumed that hypothetical microscopic matter particles vibrated around fixed positions under the action of elastic forces. When light interacted with them, the particles were set in *Mitschwingungen* (co-vibrations) with ether waves. Only when the frequency of light coincided with the proper frequency of the matter particles did these absorb the light, by resonance, in analogy with a tuning fork. For the other colors, light was transmitted through the material, but with a certain phase delay, whose empirical counterpart was the change of direction of light propagation, parametrized through the index of refraction n. According to the *Mitschwingungen* model, the phase delay depended on the color of the light. Thus the new optical theory accounted for a dispersion of light over the whole spectrum, interrupted at resonance frequencies, which occured when the microscopic particles of matter were assumed to absorb light. If the experimentally determined points of color reversal coincided with the natural frequencies of the hypothetical particles of matter, the *Mitschwingungen* model would explain perfectly the phenomenon of optical dispersion, as complementary to the absorption of light.

Even after the adoption of the electromagnetic theory of light, the *Mitschwingungen* model was considered the most satisfactory account of this phenomenon, and generally, a paradigm for the way in which matter and light should interact at the microscopic level. Yet, the *Mitschwingungen* represented light as consisting of mechanical perturbations of the luminiferous ether and not of electromagnetic fields. How could one account for optical dispersion and for processes of light-matter interaction in general, on the basis of the electromagnetic theory of light? For several theoretical physicists in the early 1890s, most significantly Hermann von Helmholtz, Hendrik Antoon Lorentz, and also Paul Drude, answering this question meant developing an electromagnetic version of the *Mitschwingungen* model.[8]

Von Helmholtz's, Lorentz's, and Drude's approaches to optical dispersion were rather different. The first two physicists sought a mechanical foundation for Maxwell's electromagnetic theory via general principles of mechanics. Once they had given a mechanical form to the electromagnetic equations, both von Helmholtz and Lorentz, almost simultaneously, but independently, incorporated the positions and velocities of the hypothetically vibrating particles of matter, as if they performed *Mitschwingungen* with light. But to form a complete electromagnetic version of the model, one additional hypothesis had to be added: if matter particles are going to respond to the electromagnetic ether, these particles should

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[6] Christian Christiansen was the first to measure the discontinuity of light dispersion through fuchsine (Christiansen 1870). Drawing on Christiansen's experiments, August Kundt systematized the anomalous behavior depending on the kind of substances (dyes), the position of the discontinuity and its relation to other properties of the materials, such as the absorption of light (Kundt 1871a; 1871b; 1871c; 1871d). As a result of these observations the term "anomalous dispersion" was coined.

[7] Wolfgang Sellmeier was the theoretician who took the first steps (Sellmeier 1872a; 1872b; 1872c; 1872d). Other physicists, most significantly, Hermann von Helmholtz (1875), Eduard Ketteler (1874), and Eugen von Lommel (1878) subsequently elaborated on Sellmeier's theory.

[8] About von Helmholtz's and Lorentz's electromagnetic theories of optical dispersion, on the basis of the *Mitschwingungen* model, see (Buchwald 1985, 237–239) and (Darrigol 2000, 321–325). About Drude's developments in this direction there is no comprehensive secondary literature.

be electrically charged. In turn, when both ether and charged particles were in co-vibration, the microscopic motions of matter provoked a periodic change in the electrical polarization of the substance. The total electric polarization amounted then to the sum of the ether and matter contributions, the first still being determined by Maxwell's equations.[9] In this way, von Helmholtz and Lorentz reproduced the formalism of the *Mitschwingungen* model, while giving it an electromagnetic meaning: light waves were electromagnetic waves and matter particles were charged particles (von Helmholtz 1892; 1893; 1897; Lorentz 1892). Furthermore, both von Helmholtz and Lorentz identified the hypothetical charged particles with another kind of charged particles deployed in a very different phenomenological domain: the electrolytic ions. Ions had been hitherto understood as the moving electric charges going from one electrode to the other in electrolysis experiments. They were the only sort of moving charged particles postulated in physics at that time, but they had never been attributed optical properties. Thus, the connection between electrolytic ions and the dispersive charged particles pointed at a possible unification of electrical and optical phenomena through the same hypothetical microscopic agents.[10]

Drude's analysis of optical dispersion in 1893 was different from von Helmholtz's and Lorentz's (Drude 1893). He relinquished abstraction, drawing a novel boundary between electromagnetism and mechanics. The reduction of Maxwell's electromagnetic theory to mechanics went far beyond the pure formal analysis required for the practical physics. What was important for Drude was to find the differential terms that complemented Maxwell's equations to give the same functional expression for $n(\nu)$ given by the *Mitschwingungen* model. Any other physical hypotheses on the constitution of the system were unnecessary for the time being, including the mechanical foundation of ether. Moreover, Drude also referred to the microstructure of matter in very different terms from von Helmholtz and Lorentz, without committing himself to the nature of the charged particles.

In his 1893 paper, Drude conducted a formal analysis, comparing the mathematical expression for $n(\nu)$ derived from the *Mitschwingungen* model with the definition of n according to Maxwell's equations. Regarding this comparison, it was important that, in the case of the simplest phenomena of reflection and refraction, when the change of direction of light did not depend on the frequency, the mathematical equivalence of mechanical and electromagnetic theories of light entailed the equivalence of optical and electromagnetic parameters. As in both cases the differential equations referred solely to the behavior of the ether, either luminiferous or electromagnetic, that is $n^2 = \epsilon_0$, ϵ_0 being the dielectric con-

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[9] Lorentz published his electromagnetic theory of optical dispersion as early as 1878, but his results remained unnoticed until the mid-1890s. Buchwald and Olivier Darrigol argue that it was most probably because he wrote in Dutch and, at that time, he did not enjoy international connections. In the case of his 1892 theory, however, the situation did not differ much, due to the use of very complicated mathematical tools such as retarded potentials and the ongoing lack of international connections. On the deep differences between Lorentz's account and the rest of European physicists', see (Buchwald 1985, 198–199) and (Darrigol 2000, 322–330). The situation changed when a systematic account in German appeared in 1895 (Lorentz 1895). Also it must be emphasized that, although Lorentz had made use of a mechanical principle in 1892, he was not dogmatic in this respect and soon abandoned general principles, which, on the other hand, were driving von Helmholtz's approach.

[10] In fact, Lorentz first identified charged particles with electrons in the 1895 German translation of his 1892 paper (Lorentz 1895). As Theodore Arabatzis has remarked, the identification of Faraday's ions with charged particles presupposed the conviction that electricity had an atomistic structure, as was the case for von Helmholtz (Arabatzis 2006, 72–73). In this direction, by 1881 von Helmholtz had already suggested a possible connection between the concept of ions in electrolysis and the notion of a moving singular charge in electromagnetic theory (von Helmholtz 1903). Ions acquired optical properties only later. See also (Darrigol 2000, 272–274) for further details on this connection.

stant of the ether. Now, for optical dispersion and other phenomena involving the action of matter, the equality $n^2 = \epsilon_0$ only held in the limit of very low frequencies, i.e. $n_\infty^2 = \epsilon_0$. Drude aimed at determining the differential terms of the *Mitschwingungen* model responsible for the difference between the dispersion formula $n(\nu)$ and its limit n_∞. This would tell him how to complement mathematically Maxwell's equations to fill the gap between $n_\infty^2 = \epsilon_0$ and $n(\nu)$.

His reasoning developed through several steps. The starting point was the mechanical *Erklärungssystem* corresponding to the model of *Mitschwingungen*.[11] By comparing it with Maxwell's equations, Drude arrived at a very interesting conclusion: the difference between n—derived from the *Mitschwingungen Erklärungssystem*—and its limit at very low frequencies n_∞ corresponded to the ratio r of the sum of the masses of all matter particles to the mass of ether contained in the same volume. Therefrom Drude surmised that $n^2 - n_\infty^2 = n^2 - \epsilon_0$ amounted to the contribution of the hypothetical microparticles that composed matter. The problem was that, within the electromagnetic framework, the masses did not relate to the efficacy of those particles in interacting with the ether. To overcome this difficulty, Drude assigned to each particle an electrical polarization χ_h, so that the total electrical polarization of the system, ether-matter, χ, was a sum of the ether and matter contributions $\chi = \chi_0 + \sum \chi_h$, χ_0 being the polarization of the ether. By assuming that χ_h could vibrate at natural frequencies, analogously to the massive particles in mechanical theories of dispersion, one could emulate the formalism of *Mitschwingungen* for χ and therefore pursue a schema of co-vibrations between χ and the electric field of the ether. Using these equations, one obtained χ as a function of the frequency of light, ν, that was obviously the same as $n(\nu)$. In the last step, Drude put forward that, in the same way as the electrical polarization of ether was characterized by the dielectric constant, ϵ_0, the polarization of each matter particle was characterized by a new dielectric constant, ϵ_h. In these terms, the divergence $n^2 - \epsilon_0$ coincided exactly with $\sum \epsilon_h(\nu)$, which played the same role as the ratio r mentioned above.[12]

Through this ingenious method of combining the *Mitschwingungen* model, electromagnetic variables, and new electromagnetic parameters, Drude reached a twofold goal: first, he restored the equivalence between optical and electromagnetic constants, so that $n(\nu)^2 = \epsilon_0 + \sum \epsilon_h(\nu)$; and second, he outlined a procedure to modify Maxwell's equations in cases where the action of matter had to be taken into account, without making general claims about the unification of electromagnetism and mechanics. More specifically, χ_h followed the equations of motion of matter, to wit the *Mitschwingungen*, and in this way contributed to the behavior of the general system. Maxwell's equations remained formally untouched if one considered ϵ instead of ϵ_0. Effectively, Drude had extended to optical dispersion the possibility of switching from the mechanical to the electromagnetic framework through a simple choice of language. Two other assumptions about matter were brought in with the *Mitschwingungen* model: its microstructure and the independence of each particle in giving rise to macroscopic effects, which hence boiled down to the simple sum of indi-

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[11] It is remarkable that Drude took von Helmholtz's set of mechanical equations for dispersion, laid down in 1875, as a basis for comparison (von Helmholtz 1875), but not von Helmholtz's 1893 electromagnetic theory. Limiting himself to a formal comparative analysis, Drude chose von Helmholtz's 1875 mechanical theory, "since it supplied the form of the differential equations in the most precise and *anschaulichsten* [clearest, most intuitive] way" (Drude 1893, 537).

[12] In fact, in his 1893 paper, Drude mentioned an inspiring exchange of letters with Hertz.

vidual actions. No hypothesis about the nature of those particles was offered, as for example their identification with electrolytic ions.

2.2.4 *Physik des Aethers* and Drude's Advocacy of the Electromagnetic Theory of Light

In his first textbook *Physik des Aethers* (1894), Drude decisively sided with the electromagnetic theory of light. The book was the result of his lectures on electromagnetism at the University of Göttingen between 1892 and 1894. In the first part of the volume, Drude analyzed the properties of the electromagnetic field. His goal was "to derive, on the basis of fundamental experiments, the strictly necessary formulas for the mathematical characterization of observable features" (Drude 1894, vi). In this way, Drude passed over completely the ethos of exactitude of his masters. He did not aim at the determination of the *Erklärungssysteme* from hypotheses on the ultimate nature of ether, but from below, namely from electromagnetic phenomena. Further, he explicitly restrained himself from any attempt to base electromagnetism on mechanical principles, a task that, according to him, was "only justified [...] as a necessity of the natural philosophers" (Drude 1894, vi).

In the second part of the book, Drude tackled optical phenomena from the point of view of the electromagnetic theory of light. Drude pushed for the adoption of this theory in view of the unification of optical and electromagnetic phenomena through the common *Erklärungssystem* and the coincident manifestations of optical and electromagnetic phenomena in experiments. In particular, Hertz's discovery that electromagnetic waves propagated at the velocity of light was key to Drude's advocacy of such a unification:

> The fact that the equivalence of the properties (of lumiferous and electromagnetic ether) is not serendipitous, but something deeply entrenched in the nature of the thing, was already an idea that Maxwell articulated in 1865, when one was not so far away from possessing the resources, with which Hertz has proved this analogy in such an evident way. (Drude 1894, 482)

Hence Drude's unification of electromagnetism and optics implied that the optical ether was electromagnetic in nature, which, for him, meant that the mathematical terms in optical equations should be interpreted using the language of electromagnetism. Drude's unification of electromagnetism and optics eventually resulted in a divide between electromagnetism and mechanics: the ether was electromagnetic in essence, while mechanics only served to model the dynamics of material objects. If there was nothing beyond equations and the language to describe them, such as mechanical principles, there was no way to unify the two domains of mechanics and electromagnetism. Drude's move thus went precisely in the opposite direction of Voigt's attempt to preserve the generality in optics through the "incontestable principles of mechanics."

After endorsing the electromagnetic theory of light, Drude turned to optical phenomena that called for the combination of electromagnetic waves with the motion of microparticles of matter: optical dispersion and the natural rotation of light. The second phenomenon consisted in the change in the direction of light polarization when light passed through certain transparent media, e.g. quartz. This change of direction, measured by the angle δ, was dependent on the color of the light, hence it showed features similar to dispersion, expressed through the functional relation $\delta(\nu)$. Following his 1893 reasoning, Drude argued that the action of matter particles modified Maxwell's equations through their contribution to the electromagnetic constants. But contra 1893, Drude now related the microdielectric constants, ϵ_h, to electrical microcurrents, u_h, that crossed each matter particle of kind h. Thus, on the one hand, one had the current density, u_0, of the ether, which followed Maxwell's equation, $u_0 = \frac{\epsilon_0}{4\pi c}\frac{dX}{dt}$, X being the external electric field of light. On the other, one had the microcurrents, u_h, which were themselves subject to the particle motions. In the case of optical dispersion, the motion consisted in harmonic oscillations. Hence, under the influence of an external electric field, X, coming from light, the microcurrents followed the equation:

$$u_h + a_h \frac{du_h}{dt} + b_h \frac{d^2u_h}{dt^2} = \frac{\epsilon_h}{4\pi c}\frac{dX}{dt}, \tag{2.1}$$

a_h and b_h being two coefficients related to frictional and vibrational terms, respectively. In the same fashion, to explain the natural rotation of light, Drude assumed that the microcurrents underwent a spiral motion. This other kind of *Mitbewegung* (co-motion) with the ether was also in good agreement with observable facts.[13]

Drude concluded his book with a programmatic section, in which he called attention to the state of the art concerning magneto-optical phenomena. As in the case of optical dispersion and the natural rotation of light, these phenomena stemmed from a process of light-matter interaction, the difference being that an external magnetic field was applied. The Kerr effect, mentioned earlier, and the magneto-rotation of light polarization (nowadays called the Faraday effect) were the two most common instances of magneto-optical phenomena then known. The latter consisted of the rotation of light polarization when light passed through a transparent material under the influence of a magnetic field, and it had been first produced by Michael Faraday (1846). The Scottish physicist John Kerr observed a similar phenomenon (1877): polarized light reflected by a magnetized material experienced a change in the direction of polarization. In fact, as early as 1892, Drude had already dealt with the Kerr effect in the vein of practical physics; he undertook a comparative analysis of the various *Erklärungssysteme* suggested hitherto for the Kerr effect, relinquishing any physical hypothesis regarding the microscopic mechanism that could give rise to the corresponding mathematical description (Drude 1892b). In 1894, however, Drude regarded such a mathematical approach as insufficient. He lamented that

> so far one has only been able to establish one satisfactory *mathematical Erklärungssystem* for the optical features of magnetically active bodies, without being able to give a physical justification of the *Erklärungssystem*, in such a way that it would be possible beforehand to compute theoretically the magneto-optical features on the basis of other physical properties of bodies. (Drude 1894, 585–586)

As a matter of fact, Drude did not attempt to give a physical explanation of magneto-optical phenomena, at least not for the time being. But his programmatic claim epitomized a shift in his heuristic strategy: from ether properties to the behavior of microscopic matter

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[13] It must be emphasized that Drude's phenomenological approach entailed an important conceptual difference from Lorentz's and von Helmholtz's electromagnetic constructions of optical dispersion: while for the latter two the electrical force exerted on each particle comprised both the electric field of ether and the electrical polarization of the particles, Drude identified external force with the electric field of the ether. I used the term *Mitbewegung* for brevity's sake.

particles. Also the phenomena of fluorescence and phosphorescence called for an optical theory based on a physical model of the behavior of molecules in his opinion. In *Lehrbuch der Optik*, Drude elaborated at length on this lack of a physical interpretation of optical phenomena. But much was still to come between 1894 and 1900.

2.3 Leipzig 1894–1900: From *Physik des Aethers* to *Lehrbuch der Optik*

2.3.1 *Physik des Aethers* and Drude's Program in Leipzig

Physik des Aethers was very influential in introducing Maxwell's electromagnetism and electromagnetic optics into German Universities (König 1906), and more specifically, in introducing Drude's own view of the field. In comparison to the most prominent books on electromagnetism at the time, especially Ludwig Boltzmann's *Vorlesungen über Maxwells Theorie der Elektrizität und des Lichtes* (1893) and Henri Poincaré's *Electricité et optique* (1890), *Physik des Aethers* (1894), Drude's book, contained a great deal of innovative material, in particular about optics. It presented the first systematic electromagnetic account of optics. Actually, Boltzmann's book was radically different from Drude's. Boltzmann derived electromagnetic equations by classifying the ether as a complicated mechanical system, and he did not deal with optical phenomena beyond refraction and reflection. In contrast, Poincaré's approach was very similar to Drude's, for Poincaré stuck to Maxwell's equations for representing electromagnetic phenomena, and avoided giving them any mechanical foundation. Drude acknowledged Poincaré's influence in the introduction of *Physik des Aethers*. In particular, he followed Poincaré in certain derivations of electromagnetic equations from observable features (e.g. the induction law). However, Poincaré did not explore the consequences of the electromagnetic theory of light in its interplay with the microstructure of matter. He confined himself to accounting for the reflection and refraction of light. In this regard, Drude went further than his French colleague.

Physik des Aethers was also crucial for Drude in promoting his career. In August of the year it was published he was offered an extraordinary professorship for theoretical physics in Leipzig, and it was precisely the appearance of *Physik des Aethers* that tipped the balance in his favor (Jungnickel and McCormmach 1986, 166). Also in 1894, Drude married Emilie Regelsberger, the daughter of a Göttingen jurist. Thus, shortly after the wedding, the couple moved to Leipzig to start a new life, as well as a new chapter in Drude's career.

Drude's inaugural speech, held at the University of Leipzig on 5 December 1894, was a clear, programmatic presentation of the approach to optics he had been forging and wanted to pursue in the ensuing years (Drude 1895). Drude's decision to reduce the physical system to physical language describing the mathematical equations, what he called practical physics in 1892, was reinvigorated and reiterated:

> You see, the goals of the current research on theoretical physics are not so extensive as the goals of the old natural philosophers. Today one does not ask about the so-called true essence of things, which goes beyond what is perceptible, not about the ultimate cause of phenomena. The goal of a theory is simply the description of the phenomenal world.[14] (Drude 1895, 4)

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[14] "Phenomenal world" is the usual translation of the German philosophical term *Erscheinungswelt*. Hereafter, the German word will be used.

Drude sided explicitly with Ernst Mach, whom he found an "excellent advocate" of the cause. These words acquired special significance in connection with Drude's description of the ether. According to Drude, "the word 'Ether' does not involve a new hypothesis, but it is only the epitome of space free of matter, which possesses certain physical properties" (Drude 1895, 9), thus it was only the embodiment of Maxwell's equations.

The subsequent shift from ether to matter as the new heuristic around which to develop optical theories was also clearly reflected in Drude's Leipzig speech. On the basis of the phenomenon of dispersion, Drude argued that "the electromagnetic theory of light calls for the concept of molecules in order to describe the optical properties of *matter* in the easiest way. I emphasize: of matter, not ether" (Drude 1895, 12). Here, the molecular structure of matter was by no means to be regarded as an ad hoc hypothesis, but was unequivocally associated with observable phenomena. This hypothesis also led to a re-categorization of optical properties: these were properties of matter, not ether, whose traits were already well-fixed by Maxwell's equations. In light of this, research efforts in optics should focus on the elucidation of the properties of molecules that lead to the proper description of phenomena. Physics of matter and physics of the ether should be combined, without being reducible, one to each other.

No sooner said than done, Drude devoted his research in Leipzig to examining in more detail issues relating to the program he advanced in his inaugural talk, while he persisted in his missionary task to spread his own view of electromagnetism in Germany. His work made significant progress through a 1899 paper in which he produced a consistent and encompassing account of optical dispersion and magneto-optical phenomena (Drude 1899), deriving the *Erklärungssysteme* from physical hypotheses. Two important events led Drude to work in this direction. On one side were novel developments in magneto-optics that changed the field in the period between 1897 and 1899. On the other side was Drude's plan to write a textbook on optics, *Lehrbuch der Optik*, during the elaboration of which he was forced to deal with a broader spectrum of insights into the field. Drude had become one of the most prominent figures in the fields of optics and electromagnetism by that time.

2.3.2 Magneto-optics and the Ion Hypothesis

A new magneto-optical phenomenon had been characterized experimentally, which led to a general revamping of the search for optical theories in magneto-optics. In 1897 Pieter Zeeman, Lorentz's student in Leiden, had detected that the spectral D line at which sodium vapor emitted light split into different components when a magnetic field was applied (Zeeman 1897a; 1897b). Zeeman used the theoretical insights of his master to analyze how the split of spectral lines could be related to the microstructure of sodium atoms. Fundamental in Lorentz's account was the hypothesis that ions emitted light at the frequencies of their mechanical motions, in the same fashion as in the *Mitschwingungen* model. The only difference was that, in the case of dispersion, light was absorbed at specific frequencies, while in the case of spectral lines, it was emitted at specific frequencies. Further, Lorentz put forward that, upon the application of a magnetic field, the initial motion of the ions was decomposed into three components, leading to different frequencies: one linearly polarized oscillation and two circularly polarized in opposite directions. Exploiting this physical model, Zeeman could use the experimental data to calculate the charge-to-mass ratio, e/m, of the ions, which had previously only been assumed. It was indeed the first calculation of ionic properties outside the field of electrolysis.[15]

After 1897, Woldemar Voigt also became very active in discussions of magneto-optics. He had recently "converted" to the electromagnetic theory of light, and his contributions to magneto-optics were well appreciated by Drude, in both the 1899 paper and the 1900 *Lehrbuch der Optik*. Actually, Lorentz, Voigt, and Drude attended the 70th Meeting of German Natural Scientists and Physicians in Düsseldorf, held in 1898, and they could probably have exchanged opinions on the new, fashionable topic of magneto-optics. In 1899 Voigt also laid down a comprehensive theory of magneto-optical phenomena, taking "the system of equations that Drude had developed on the basis of Hertz's work as his starting point" (Voigt 1899, 345). In particular, he built upon Drude's 1893 paper on dispersion and his solution of modifying the electromagnetic constants in order to integrate the actions of matter into optics. Voigt also adopted Drude's language of *Erklärungssystem*. Light equations were complemented by different vectors, P_h, accounting for the action of matter. Nevertheless, Voigt did not interpret the vectors P_h physically, sticking for the time being, to the mathematical form of *Erklärungssysteme*. Drude acknowledged Voigt's *Erklärungssysteme* for the Zeeman and Faraday effects in his own 1899, overarching account of magneto-optical phenomena. But in this paper he went a step further than Voigt: Drude related each magneto-optical *Erklärungssystem* to one hypothetical kind of motion of the microscopic particles in their interaction with the ether, which could explain its specific set of differential equations. The incorporation of a new element, the ion, into Drude's picture of the microstructure of matter was instrumental in achieving the new account. Drude replaced his earlier language of microcurrents with the new language of ions, arguing that "the easiest foundation of the theory of dispersion is embodied in v. Helmholtz's assumption of moving and electrically charged ions" (Drude 1899, 107). Both Drude's maneuver and his theoretical justification deserve close scrutiny. Did Drude's change of mind mean that now he agreed with von Helmholtz's 1892–1893 strategy to reduce electromagnetism to mechanical principles when figuring out an electromagnetic theory of optical dispersion?

Drude borrowed von Helmholtz's ion hypothesis but not von Helmholtz's overall approach. Drude found inspiration for his approach in the work of Richard August Reiff, who, in 1896, had published a book titled *Theorie molekular-elektrischer Vorgänge* (Reiff 1896). The standpoint Reiff developed there was similar to Drude's. For Reiff had

> [a]bove all avoided those developments that only had mathematical interest. I have not used the principle of least action for the derivations of equations, but I have derived the motion equations of ions from molecular considerations, in order to attain the easiest interpretation of the equations. For this purpose I use the language of atomism. (Reiff 1896, vii)

Reiff's procedure consisted in stating first of all the equation of motion of ions of charge density e and mass density m under the influence of the electric field of light X. For example, in the case of dispersion, the ions being presumably subject also to elastic forces, the electrical moment ξ of the ions could be expressed in the following way:

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[15] For more information about the interplay between theory and experiment in Zeeman's route to his experiments and analyses, see (Arabatzis 1992; Hentschel 1996; Kox 1997).

$$\frac{1}{4\pi\theta}\xi + r\frac{d\xi}{dt} + \frac{m}{4\pi e^2}\frac{d^2\xi}{dt^2} = X, \tag{2.2}$$

r being the coefficient of the frictional force, and θ the coefficient for the elastic force. By supposing that both X and ξ were wave functions having the frequency of light ν, the latter with a phase delay characterized through the index of refraction n, one easily obtained an expression for n depending on ν identical to the one derived from the *Mitschwingungen* model. Thus the motion of ions in Reiff's picture worked very similarly to the motion of microcurrents in Drude's picture. At any rate, the ether persisted in being an embodiment of Maxwell equations, thus it was only the motion of microparticles of matter which modified optical constants. In this sense, Drude's adoption of the ion essentially implied a replacement of the microcurrents, u_h, in his earlier accounts by ions, and therefore the identification of the motion of the charge with the motion of the mass of the ions.

Apart from their vibrations, which explained optical dispersion, in 1899 Drude assumed that ions underwent two other, different kinds of motion: spiral motions and also translations perpendicular to the magnetic field. Drude related the first kind of behavior to the Kerr effect. Then Drude argued that the *Erklärungsysteme* for the Zeeman and Faraday effects could be obtained by assuming ions performed the second kind of motion. Altogether, with the 1899 paper, Drude laid down the first comprehensive account of magneto-optical phenomena on the basis of a systematic combination of electromagnetic equations and the ion hypothesis. *Lehrbuch der Optik* consisted of a full-fledged expansion of this "ion turn" into book form, from optical dispersion to all varieties of magneto-optical phenomena known at that time, together with fluorescence and phosphorescence. We can say that with *Lehrbuch der Optik* Drude fulfilled the programmatic aims presented in the last chapter of *Physik des Aethers*.

Although his appropriation of the ion hypothesis supplemented nicely Drude's approach and fulfilled his requirements for a physical interpretation of optics, it must be emphasized that the particular adoption of the ion cannot be justified fully from the point of view of practical physics. The molecular structure of matter and the possibility of particles generating time-varying electrical polarizations was enough for that purpose. Polarizations and frequencies were the measurable quantities in optical phenomena. Hence, assigning an active role in optics to ions, which were characterized by a mass, m, and an electrical charge, e, determined through electrolytic experiments, independent of optical phenomena, was a kind of "external hypothesis" to the dynamics of practical physics. While the ether was reduced to the physical language necessary for Maxwell's equations, matter was not reduced to the minimal physical language necessary to give a meaning to the differential terms accounting for the motion of particles. In a way, Drude overstepped the bounds for theoretical physics he himself had established in 1895. Assuming the existence of ions meant asking oneself about the essence of the microparticles of matter, beyond the description of the *Erscheinungswelt*. What could have happened for Drude to make such a decision?

I think that *Lehrbuch der Optik* could have played a catalyzing role. As Drude wrote in the preface, the endeavor to write a book motivated him to sharpen his own view of the field. Indeed he accepted the offer to write a book from the publishing house because, among other reasons, "I wished for myself the development of new ideas through the deepening of my own view of the field, which is compelling in writing a book" (Drude 1900a, iii). Between 1894 and 1900 Drude worked on various topics related to optics, but it was only at the end, in 1899, that he saw in the adoption of the ion hypothesis the possibility of an overarching account of optics. He never mentioned von Helmholtz's ion hypothesis or Reiff's work until 1899, although they were already published in 1892/1893 and 1896, respectively. At that moment, Drude was concentrating on his experimental and theoretical work on electric waves and the nature of actions at a distance. He also published on magneto-optical phenomena, but only from the point of view of the *Erklärungssystem*.[16] So it is plausible to think that Drude's prompt advocacy of the ion hypothesis originated in the reexamination and comparison of different sources necessary for the purpose of writing the textbook, which allowed him to see the ion hypothesis as a means to articulate optical knowledge in a unified way, without giving up his own approach to optics.[17]

Since the advantage of dealing with ions instead of microcurrents was not the possibility of explaining the optical properties of matter, I think that the adoption of the ion offered Drude another kind of advantage: a new heuristics. In fact, the incorporation of the ion into Drude's picture not only had consequences on an ontological level (e.g. the ions as the specific particles that were optically active), but also epistemologically. For the ion hypothesis allowed Drude to explore new ways to gain knowledge in optics, apart from seeking the right mathematical description of phenomena and the unification of ether theories from below (e.g. adoption of the electromagnetic language). As we will see in the following section on *Lehrbuch der Optik*, the ion hypothesis allowed Drude to network different domains of knowledge (optics and beyond) through the specific properties of charge e and mass m of these particles, which should manifest in different phenomena.

2.4 The *Lehrbuch der Optik*

2.4.1 *Lehrbuch der Optik* as a Novel Program in Optics

The year 1900 began very productively for Drude. In January he became the new editor of the most prestigious German scientific journal, *Annalen der Physik*, and he published his second textbook, *Lehrbuch der Optik*, which was soon translated into English and became

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[16] More specifically, between 1894 and 1899, Drude's research had been especially fruitful in three directions: electric waves, magneto-optical phenomena and actions at a distance. Concerning the first topic, Drude found experimentally that electric waves, whose frequency lay outside the optical range of the spectrum, also displayed dispersion, and indeed anomalous dispersion through certain liquids. Furthermore, in line with his 1895 claims at his inaugural speech in Leipzig, he immediately related the dispersion behavior to the chemical constitution of the liquids examined (Drude 1896; 1897a; 1898). In 1897 he addressed the Kerr effect again from a theoretical point of view, but without daring to give it a physical interpretation in terms of the properties of matter, as he had himself suggested at the end of the *Physik des Aethers* (Drude 1897c). The paper was the continuation of an old controversy he had been engaged in since the early 1890s with D. Goldhammer, concerning the best *Erklärungssystem* for the Kerr effect and which kind of optical constants best described it. For more details about the controversy, see (Buchwald 1985, 215–232). Eventually, Drude also explored the theoretical possibility of reducing actions at a distance such as gravitation, to local actions, mediated by the electromagnetic ether (Drude 1897b).

[17] It is very remarkable that Drude did not mention Lorentz's account of the Zeeman effect either in 1899 or in 1900; although, he referred to Zeeman's papers and met Lorentz in 1898 at the conference in Düsseldorf. At that time, Lorentz had already published his theoretical account (Lorentz 1897; 1898). In the 1899 paper, Drude indeed resorted to Voigt's 1899 *Erklärungssystem* for the Zeeman effect, but Voigt did not allude to Lorentz either. Darrigol (2000, 331–332) is of the opinion that Drude, and also Voigt, became advocates of the microscopic view of optics abruptly, possibly as a consequence of Lorentz's presence at that meeting. But the absence of Lorentz in Drude's 1899 paper and 1900 book, in the context of magneto-optics, hints at another explanation. Possibly Lorentz had an influence on them, but he was not the only reason for Drude's adoption of the ion. Drude developed, as early as 1893, a microscopic outlook to explain optics, in his contribution to dispersion.

the reference book for optics in many European universities. Drude was asked by the publishing house S. Hirzel to write the textbook "because a modern book covering the whole field was lacking" (Drude 1900a, iii). Since he was considered one of the greatest specialists on optical physics at the time, Hirzel "could really not have contacted any one better than Drude for this request" (König 1906). Woldemar Voigt, Walter König, and Max Planck highlighted precisely this point in their recollections of Drude after his tragic death in 1906 (Voigt 1906; König 1906; Planck 1906).

In fact, *Lehrbuch der Optik* became the first textbook on optics to make use of only the electromagnetic theory of light and to combine it systematically with a microphysical view of matter (in this case the ion hypothesis). Moreover, Drude did not have much concurrence in Germany. At that time, German students of theoretical optics would resort to compendiums on the subject, written by prominent professors at universities. Famous examples were penned by Ketteler (1885), Voigt (1896), and von Helmholtz (1897).

Ketteler's book responded to very different questions than Drude's. Ketteler had been very active, in the 1870s and 1880s, in the further elaboration of optical theories based on the groundbreaking hypothesis that the ether and matter particles were in *Mitschwingungen*. But he obviously did not discuss how to deal with the electromagnetic theory of light in the context of mechanical theories of ether, and he subsequently left magneto-optics out of his analysis altogether. These topics flourished first in the early 1890s, when Ketteler died.

By contrast, Voigt was well aware of the difficulties that had arisen in optics due to the spread of the electromagnetic theory of light in Continental Europe by the time he wrote his *Kompendium*. But he decided to approach optics in the second volume of his *Kompendium der theoretischen Physik* from a mathematical viewpoint, without committing himself to any hypothesis on the nature of the ether, thus leaving the final decision about the nature of the ether to the readers. He just stuck to the mathematical formulation of phenomena, which in turn meant that he took mechanical principles as undisputed bases. Only for optical dispersion did Voigt introduce additional mathematical terms, P_h, into the differential equations for the ether. Magneto-optical phenomena were simply omitted in his account of optics. Ironically, Voigt was the first one to go beyond his own work. From the late 1890s, he advocated the electromagnetic theory of light and devoted himself precisely to the only domain of optics that was absent from his *Kompendium*, namely, magneto-optics, as mentioned earlier. In that field, Voigt soon became an authority.

Von Helmholtz's posthumous collection of lectures thus would have been the most immediate competitor to Drude's *Lehrbuch der Optik* in Germany, for von Helmholtz clearly embraced the electromagnetic theory of light, and he was a pioneer in introducing the concept of ions into optics. However, the hot topic at the end of the 1890s, namely magneto-optics, was also missing in von Helmholtz's book.

Outside Germany, Drude's book was compared with the works of the British physicists Thomas Preston, *The Theory of Light* (1890), and Alfred B. Basset, *A Treatise of Physical Optics* (1892). The style of the English books was rather different from that of the German ones, specifically in their way of approaching and organizing theoretical optics. As Preston expressed well in his book, his goal was to "furnish the student with an accurate and connected account of the most important researches from the earliest times up to the most recent date […] without entering into complicated mathematical theories" (Preston 1890). That was exactly the opposite of what Drude was trying to do in his *Lehrbuch der Optik*. Drude, as well as the above mentioned German authors, normally tried to convey a unified program that could explain all optical problems in a consistent way. The guiding principle of each textbook was expressed in its introduction and was always closely related to the strategy each author chose to describe and manipulate mathematically both optical phenomena and hypothetical physical mechanisms. There was thus not much space for historical accounts in this kind of textbook. Alternatively, both Preston's and Basset's books provided the reader with very precise accounts of optical experiments, the types of instruments used to perform them, and various techniques to manipulate data, without hesitating to stick to diverse European sources and compare different historical accounts from Newton onwards. The reader was conducted smoothly through a manifold of approaches, each one teaching something about the characteristics of optical phenomena and the way in which they were disclosed at specific historical moments, almost chronologically, up to the Faraday and Kerr effects (the Zeeman effect was published later than their books). The electromagnetic theory of light only appeared as the most recent development in optics, in connection with Hertz's experiments, although the authors, especially Preston, had been closely related to the main developers of the electromagnetic theory in Great Britain. In particular, Preston was a junior colleague of George FitzGerald in Dublin. Nevertheless, the point was not to advocate either theory of light, but to give the reader an overview of the state of affairs. In fact, at the moment the books were published, the electromagnetic theory of light did not suffice to account for phenomena stemming from the interaction of light with matter, like optical dispersion or the Kerr effect.

Thus Drude was offered, by the publishing house S. Hirzel, the great opportunity to pioneer the exploration of essentially virgin territory, in a moment when the questions to ask in optics were changing rapidly. In the 1870s and 1880s, optical theoreticians engaged in a honing of the *Mitschwingungen* model. In the early 1890s, the main issue in Germany became how to choose between electromagnetic and mechanical theories of light, and the implications of this choice in relation to the ultimate nature of the ether, alongside the translation of the *Mitschwingungen* model into electromagnetic language. Eventually, in the late 1890s, the field of magneto-optics offered itself as the new boiling pot. Thus Drude arrived at the right moment to take up the most fashionable questions and lay down his own answer.

2.4.2 *Lehrbuch der Optik* Piece by Piece

The textbook was divided into two parts: geometrical optics and physical optics. Geometrical optics dealt with the optical features of light propagation and came down to four essential laws: linear propagation of light (light rays), the geometrical laws of refraction and reflection, and the possibility that a light ray splits at any point of its trajectory. These laws could be expressed by simple geometrical relations and they sufficed to describe the functioning of most optical instruments: lenses, microscopes, telescopes, and prisms. The second part of the textbook was devoted to physical optics, where geometrical laws did not suffice. One had to introduce hypotheses on the nature of light and the physical mechanism of light-matter interaction in order to account for optical phenomena more complex than reflection and refraction. This part was divided into three big sections: the first, about the general properties of light, in which the constitution of matter did not play a role (such as the interference and diffraction of light); the second about the optical properties of bodies measured when light was reflected by or passed through transparent media (principally, optical dispersion and magneto-optical phenomena); and the third about the emission of radiation from matter, which boiled down to the thermodynamics of radiation.

Drude's programmatic claims are to be found in the second part of the book. The first part helpfully provided the reader with the necessary knowledge about how to produce and measure optical phenomena with optical instruments, but it did not contain much new knowledge. In fact, Drude constantly referred the reader to the existing literature on geometrical optics to which he himself had resorted.[18] Drude devoted the longest and most involved section of the introduction to justifying his approach to physical optics in the second part, namely, the adoption of the electromagnetic theory of light and the ion hypothesis.

The first notion from physical optics that Drude introduced in the main text was that of the constant velocity of light in vacuo, c. To support it, Drude put forward a detailed overview of the interferometric experiments to measure c. Thereafter, the phenomenon of interference led Drude to introduce the wave nature of light. The mathematical translation of this physical concept was the wave function, with the velocity of light being one of its parameters. Hence, the second step subsumed the first one. In what followed, Drude explored the different ways in which wave functions could be superposed, thus giving rise to different patterns of interference (such as Newton's rings) and to the diffraction of light (depending on the experimental set up).

Next, to describe the features of the double refraction of light, Drude introduced the concepts of light polarization and transverse waves. With these notions clearly formulated, an indeterminacy in the mathematical formulation appeared. Different conventions concerning the relative orientation of the wave amplitude, its polarization, and the direction of propagation could be adopted. For example, according to Neumann's mechanical theory of light, the wave amplitude coincided with the direction of light polarization, while in Fresnel's mechanical theory the amplitude was perpendicular to the polarization. These differences notwithstanding, in both cases amplitude and polarization were considered to be perpendicular to the direction of wave propagation. From this point of view, the two theories of light were mathematically equivalent.

The electromagnetic theory of light concealed these indeterminacies, for the perpendicularity of the two light vectors (electric and magnetic field) to the direction of propagation was inherent to the formulation of the theory. The adoption of the electromagnetic theory of light led one, therefore, to overcome the conflict, but not to resolve it. But beyond this isolated advantage, Drude's justification of his preference for the electromagnetic theory of light lay in the possibility of unifying optics and electromagnetism through the identification of the velocity of light with the velocity of electromagnetic waves. Because of this, Drude deemed the adoption of the electromagnetic theory of light "one step further in knowledge about nature, since this way two initially parallel domains of knowledge, like optics and electricity, are treated together in a close and measurable relation" (Drude 1900a, 248). With no further explanation, Drude identified the electromagnetic theory of light with Maxwell equations and boundary conditions.

Whereas Maxwell equations accounted well for all the phenomena Drude had described so far, the behavior of light in absorbent media called for additional terms related to the microphysical action of matter. Drude justified this very clearly in his introduction:

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[18] More specifically, to Winkelmann's *Handbuch der Physik* (1894) and Müller and Pouillets's *Lehrbuch der Physik und Meteorologie* (1897).

> First of all, in this way one succeeds in providing an explanation of the phenomenon of dispersion, since the purely electromagnetic experiments only suggest, I would say, macroscopic properties of bodies. To explain optical dispersion it is necessary to make hypotheses on the microphysical properties of bodies. In this sense I have used the ion hypothesis introduced by v. Helmholtz, because it seems to me the easiest, clearest [*anschaulichste*] and most consequent one to characterize, apart from dispersion, also the absorption and natural rotation of light polarization, and also the magneto-optical properties and properties of bodies in motion. (Drude 1900a, v)

In the following four chapters, Drude developed in detail his programmatic approach to the optical properties of matter. First of all, he tackled the phenomena of optical dispersion and of the rotation of light polarization, both of which he had already dealt with in *Physik des Aethers*, but now, he used the novel perspective of the ion hypothesis. Then he explained the singular features of the reflection of light in metals, and expanded upon the magneto-optical phenomena. Let us look again at the example of dispersion to get a better glimpse of Drude's developments in this direction.

The physical system responsible for the optical properties of matter consisted of the electromagnetic ether, N_1 positive ions, and N_2 negative ions, both kinds being characterized by natural frequencies of vibration. For the case of optical dispersion, when the electromagnetic waves impinged upon matter, these ions were supposed to be set in vibration at the same frequencies as the impinging light. The displacements of the ions from their equilibrium positions, ξ_1 and ξ_2, caused the polarization of the material medium, whereas the ether polarization corresponded to the electric field, X, of the light. Drude's idea for incorporating the polarization of the medium into Maxwell equations was the following: the displacement of the ions gave rise to two electric currents, j_1 and j_2, of opposite sign, which could be expressed as the product of the respective number of ions, N_1 and N_2, their charges, e_1 and e_2, and their velocities, $\frac{d\xi_1}{dt}$ and $\frac{d\xi_2}{dt}$. The total electrical current amounted to the sum of the ion currents and the ether current, $\frac{1}{4\pi}\frac{\partial X}{\partial t}$. By assuming that ions were subject to elastic forces $-\frac{4\pi {e_1}^2}{\theta_1}\xi_1$ and $-\frac{4\pi {e_2}^2}{\theta_2}\xi_2$, while acted upon by electromagnetic light, Drude eventually obtained this expression for the total electric current:[19]

$$j = \frac{1}{4\pi}\frac{\partial X}{\partial t}\left(1 + \frac{\theta_1 N_1}{1 - \frac{b_1}{\nu^2}} + \frac{\theta_2 N_2}{1 - \frac{b_2}{\nu^2}}\right). \tag{2.3}$$

The factor 1 within the brackets corresponded to the action of the ether, whereas the other two terms referred to the influence of the positive and negative ions. The expression depended on the electric field of light, X, its frequency, ν, two parameters, b_1 and b_2, and the elastic constants of the two types of ions, θ_1 and θ_2. Drude had thus managed a combination, in one mathematical expression, of both electromagnetic parameters (electric fields and frequencies) and mechanical parameters (elastic constants). Subsequently, if one defined the dielectric constant, ϵ', of the joint system of matter and ether as the sum of the dielectric constant of the ether, $\epsilon = 1$, and the two ionic terms written above, one could eventually return to Maxwell's expression for the electric current $j = \frac{\epsilon'}{4\pi}\frac{\partial X}{\partial t}$, with a modi-

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[19] For simplicity's sake, I have approximated Drude's formula to the case of no frictional force.

fied dielectric constant. This is the way in which the equations of motion of the ions entered Maxwell equations, and the relation $\epsilon' = n^2$, between optical and electromagnetic constants, remained untouched.

Following the same strategy of modifying constants, Drude continued to account for the other optical properties of matter and magneto-optical phenomena, providing a full derivation of the differential equations for magneto-optics by attributing to each phenomenon a specific kind of ionic motion. While for optical dispersion ions vibrated, for metallic reflection ions were supposed to translate across the metal, and in the phenomenon of rotation of light polarization (through quartz) ions were assumed to combine vibrations and rotations, tracing out helicoidal trajectories. Under the influence of a constant magnetic field, Drude suggested two possible motions for ions, which could modify both the dielectric and the magnetic constants: first, ions could go through proper vibrations and small rotations, resulting in helicoidal motions. Drude argued that the correspondingly modified Maxwell equations led to satisfactory agreement with the features of the "inverse" Zeeman effect through sodium gas.[20] The second possible motion of ions was a superposition of their natural vibrations parallel to the electric field of light and a translation perpendicular both to the electric and magnetic fields (as in the Hall effect). With the differential equations corresponding to these motions, Drude could explain the Zeeman effect in sodium vapor, and the Kerr and Faraday effects, as manifested through the use of nickel, cobalt, and iron vapors.

In the last chapter devoted to the subject of physical optics, Drude eventually referred to the optical properties of bodies in motion. In this case he referred substantially only to Lorentz's *Versuch* (1895). Drude reconsidered his formulation of certain optical phenomena, such as optical dispersion, in light of the possibility that not only could ions move from their equilibrium positions inside molecules, but also the molecules themselves could move. In this case, the frequency of light $\nu = \frac{1}{\tau}$ appearing in the dispersion formula should be replaced, using instead:

$$\frac{1}{\tau'} = \frac{1}{\tau}\left(1 - \frac{p_1 v_x + p_2 v_y + p_3 v_z}{c}\right), \tag{2.4}$$

p_1, p_2, p_3 being the normal components of the direction of wave propagation; v_x, v_y, v_z the components of the molecule's velocity throughout the space and c the light velocity in vacuo. In fact, this was the only occasion in which Drude resorted to Lorentz's theoretical works. It is very remarkable that Drude reduced Lorentz's contribution to the special case in which equilibrium positions of ions inside molecules were not fixed, since Lorentz had founded his whole approach to optical phenomena on the relative motions of ions, making them responsible for the local changes in the properties of the static electromagnetic ether. As Buchwald and Darrigol claimed in their respective books, Lorentz's approach, calling for such complicated mathematical tools as retarded potentials, was almost certainly not well

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[20] This effect was observed one year after the Zeeman effect (Macaluso and Corbino 1898), for which Voigt had already provided an *Erklärungsystem* in 1898 and 1899 (Voigt 1899). Damiano Macaluso and his assistant Orso Mario Corbino took a sample of sodium gas and applied a constant magnetic field, as in arrangements that exhibited the Zeeman effect. But in constrast to Zeeman's experiment, Macaluso and Corbino did not examine the light emitted by the gas. They made white light pass through the gas and measured the change of polarization of the transmitted light. They observed a continuos change of the angle of polarization for the whole spectrum, interrupted only by sharp discontinuities at the D spectral lines of sodium.

understood in Germany, in its broader scope (Buchwald 1985; Darrigol 2000). Drude was, in this regard, no exception.

Eventually, in the third part of the book, Drude wrote about the thermodynamics of radiation. It is very significant that Drude devoted more than fifty pages to this matter, for this was the first time that the topic was so thoroughly treated in a textbook on optics. To date, it had been scarcely considered part of optics, since it seemed to have nothing to do with the explanation of light propagation, either through the ether or matter. Thermodynamics of radiation dealt instead with the generation of radiation by matter and the distribution of its energy over different spectral frequencies at different temperatures. The thermodynamics of radiation required, therefore, a very different set of concepts (i.e. distribution of energy, black-body radiation), physical laws (i.e. the second principle of thermodynamics), mathematical procedures (i.e. those of the kinetic theory of gases), and experimental sources (i.e. spectroscopy) than the ones discussed hitherto. In fact, Drude relied on accounts from others, basically Gustav Kirchhoff, Boltzmann, and Wilhelm Wien, to expand upon this issue. However, in the very last section of this part, which was about the emission of radiation by gases and vapors, Drude presented his own insights in a very revealing way. The ions were presumed to be the cause of the light emission in luminescence, fluorescence, and spectral lines, in a way analogous to the way covibrations of ions with light caused optical dispersion and magneto-optical phenomena. The key difference was that now the ions were not supposed to modify the behavior of the already propagating light. They were instead supposed to vibrate and to emit radiation at the same frequency as their vibration. Actually, Drude did not expand at length upon the various manifestations of these phenomena, for which there was, so far, no systematic theory. His description of the phenomenon was rather superficial in comparison with the section on physical optics. Rather, the important point is Drude's extension of the fruitfulness of the ion hypothesis to optical phenomena beyond dispersion and magneto-optics.

All in all, the ion hypothesis seemed to provide Drude with an insightful way to describe mathematically all kinds of optical phenomena involving light-matter interactions from the standpoint of the motion of particles at the microscopic level. Yet, the ion hypothesis also allowed Drude another route to new knowledge.

2.4.3 The Ion Hypothesis as a New Heuristics

Drude justified the adoption of the ion hypothesis in *Lehrbuch der Optik* on the grounds that it provided the most *anschaulich* description of the optical properties of matter, namely, the clearest, most demonstrative, most graphic description. It is true that a moving ion is much easier to picture than a moving particle being crossed simultaneously by an electric microcurrent, which Drude suggested in 1894. But the ion offered much more than a more concrete physical picture; other advantages contributed to its being *anschaulich*.

On the one hand, the ion hypothesis worked well as a heuristic tool, to model the interaction between light and matter in a more approachable way. On the other hand, the ion had an ontological status as the physical agent of optical phenomena, whose specific properties could be measured through different sorts of experiments. Nevertheless, ions could not be directly viewed or detected. Their properties (such as mass and charge) could be calculated from experimental data only by analyzing these data under the previous assumption that measurable phenomena were caused by the hypothetical ions. Through the sharing of ions as both heuristic tools and physical agents in this way, Drude figured out a new way to network different domains of knowledge.

In the second part of his book, Drude placed special emphasis on Zeeman's experiments and the first measurement of the charge-to-mass ratio of ions obtained from them. Drude relied on Zeeman's interpretation of the experimental split of the D lines of sodium under the influence of a magnetic field, as a direct consequence of the decomposition of the natural motion of ions, and he reproduced Zeeman's relation between the frequency difference, $g = D_1 - D_2$, and the mass, m, and charge, e, of the hypothetical ions:

$$g = \nu_1 H \frac{e}{m}, \tag{2.5}$$

H being the magnetic field applied and ν_1 the frequency of the original D line. This approach offered an exceptional opportunity to obtain a numerical value of e/m for the hypothetical ion from optical experiments. But Drude did not stop there. Drude compared Zeeman's value with other values for e/m obtained in other experimental contexts outside of optics, like the production of cathode rays and the process of electrolysis. If it were not for their shared reliance on the ion as a hypothetical cause, it is rather unlikely that such diverse phenomena would have been put together in a textbook on optics:

> It is remarkable that, from the deviation of cathode rays, Kaufmann has derived […] almost the same value […] for the relation of the charge to the mass of the accelerated cathode particles. For the ions appearing in electrolysis this relation is much smaller. […] One can think that either the electrolytic ion contains more positively and negatively charged components that hold together for electrolysis but move freely with light waves and in vacuum, or the electrolytic ion is composed by the bonding of a charge e of mass m (electron) with a bigger neutral mass M. (Drude 1900a, 410–411)

This text appears in a footnote, but this does not mean that it was considered ancillary by Drude. Actually, in the ensuing years, his research focused on the extension of the ion hypothesis to the most varied of fields. Most probably, Drude incorporated these insights into his text in the last moments before delivering it to the publishing house. Maybe he learned about Kaufmann's experiments only in 1899, as Walter Kaufmann gave a talk on the topic in the same session of the 1899 meeting of the German Physical Society as Drude spoke. This would explain why Drude only mentioned Kaufmann in relation to cathode rays. For, in fact, almost simultaneously, Joseph J. Thomson in Cambridge (1897a; 1897b), Kaufmann in Berlin (1898), and Emil Wiechert in Königsberg (1897a; 1897b) performed experiments with cathode rays and measured similar values for e/m. Cathode rays were emitted by the cathode of a vacuum tube during an electrical discharge. If the rays were interpreted as streams of electrically charged particles, then by measuring their deviation in a magnetic field one could obtain a numerical value of their hypothetical e/m.[21]

Some further aspects of this triangular comparison of e/m values should be highlighted. First, only after the same hypothesis of moving charged particles was applied to several different phenomena were ions differentiated into different sorts. Then only the particles

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[21] The secondary literature on cathode ray experiments in the late 1890s is huge, especially on Thomson. Representative examples include (Falconer 1987; Robotti 1995), the first four papers of (Buchwald and Warwick 2001), and (Navarro 2012). For the taxonomy of the electron, see (Arabatzis 2006).

responsible for cathode rays seemed to coincide with the ones measured by Zeeman. Remarkably, Drude referred to them as "electrons." This was the first time that Drude made the distinction between electrons and electrolytic ions, a dichotomy that became very fruitful in his research in the ensuing years. Thus the value of e/m obtained in experiments signified that electrolytic ions were much more massive particles than electrons. Second, only after this dichotomy arose could one begin to wonder about how electrons could be combined with electrolytic ions in the constitution of matter, as Drude did. He envisioned two possibilities: either ions were composed of a manifold of positive and negative elementary charges, or a charge e was attached to a bigger mass M. Now, rather than Drude's answer, what is important here is the fact that Drude asked *this* question. The ion turned out to be not only productive in providing him with a clearer physical picture, ions also offered Drude the ability to interrelate different phenomena through the different ways in which they manifested the properties acknowledged as dependent upon ions, and then to speculate on a more general picture of the constitution of matter. That is to say, pieces of information obtained from different experimental contexts, once interpreted as a consequence of the same microscopic agent, could contribute to the disclosure of a new and exciting puzzle: the microstructure of matter.

Drude's appropriation of the ion also impacted the third part of the book, specifically when he dealt with the phenomenon of luminescence. According to Drude, luminescence was produced when ions vibrated and emitted radiation at the same frequency as their vibrations. To support this hypothesis, Drude put forward the following argument: he assumed that the number of vibrating ions coincided with the chemical valence number of the material, and that the charge associated with a valence was a universal constant.[22] Using these hypotheses, together with experimental values for the amount of light energy emitted per second, he calculated a value for the hypothetical amplitude l of the vibrations of the ions, if regarded as ideal Hertz resonators. Finally he pointed out that l was various orders of magnitude smaller than the size of the molecule, which was fully consistent with the general picture of ions as vibrating inside molecules. Thus Drude found support for his initial hypothesis in the plausibility of the results generated by his network of assumptions: ions being Hertz resonators, applicability of the kinetic theory, and valence numbers representing sites for universal charges.

In this manner, exploitation of the ion hypothesis led to a new way to generate knowledge: this was not the ethos of exactitude, nor physical unification through mathematical equivalence, but a networking of different physical domains through a shared hypothesis. In this case, precise numerical agreement between theory and experiments could not help in checking whether the hypothesis was correct. One had to presume the ion in order to calculate e/m from experimental data. The only way to check the ion hypothesis was the consistency of the speculative picture on the microstructure of matter constructed through the network of insights dependent upon it (electrochemistry, spectroscopy, cathode rays, physical optics, heat radiation).

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[22] The valence number was related to the number of other atoms that one substance required to form molecules. Hence valence was related to empty positions in the atom, not yet to the number of elementary particles—electrons—to be shared in forming molecules. Drude calculated the charge associated with a valence position from electrolysis, using the kinetic theory of gases, thus it was acknowledged that, in electrolysis, the electrolytes of one substance—ions—always transported the same number of valences from one electrode to the other. Drude happily observed that this charge almost coincided with the charge of the electron measured by Thomson. But Drude did not go further in relating the charge of one electron with the charge of valence.

2.4.4 Content and Narrative in *Lehrbuch der Optik*

The way in which Drude organized his book is inseparable from the way in which he understood the study of optics, the nature of electromagnetic light, and the role attributed to matter in the production of optical phenomena. From the previous two sections it follows that Drude's starting point in accounting for physical optics was always the description of an optical phenomenon. Then he gave a mathematical description of the phenomenon, and at the same time identified each mathematical term with its physical meaning. Since the physical system had been reduced to the physical language to describe the formalism, mathematical and physical accounts of optical phenomena mirrored each other (I call it a *mathematical-physical* approach). Thus there was no space for physical speculation beyond the bounds set out by the formal description of the phenomena. The introduction of phenomena followed a strict order: from those with the simplest mathematical-physical description to those with the most complex, hence from light propagation to magneto-optics. Each step subsumed the former one, both in terms of mathematics (from the parameter of light velocity to complex *Erklärungssysteme*) and in terms of the physical concepts used (from wave propagation to the interactions of electromagnetic light with ions). There were only two detours on this route. First, when Drude claimed the unification of electromagnetism and optics by introducing an external criterium: the experimental coincidence of the velocities of light and electromagnetic waves. Second, when, for the first time, Drude decided to introduce a speculative element: the ion. A clear gap was apparent between the physical description of mathematical terms (dielectric constants, refractive index, electric currents, light velocity, phase delay, light frequencies, and characteristic frequencies of selective absorption) and the supposition that the motions of ions were the cause of the optical properties of matter. Thus, the ion hypothesis enlarged the physical system beyond the interpretation of the mathematical formalism. Drude called this strategy of organizing the book the "synthetic route."

From the perspective of a physicist today, the synthetic route might seem a very obvious way to organize a book. Nevertheless, this was not necessarily the case. Ketteler, for example, articulated his book around the principle that light and matter interacted through *Mitschwingungen*. Thus he organized the chapters according to the type of medium within which the *Mitschwingungen* were performed, from the simplest to the most complicated media (first isotropic media, then anisotropic, then those having natural properties to polarize light). Preston, instead, put the emphasis on how optical phenomena were produced experimentally. He described some fundamental experiments, like Newton's refraction of light, for which he even reproduced passages of Newton's works. Preston thus combined chronology with experimental simplicity in organizing his account.

Drude's particular approach to optics clearly reflected another explicit goal, expressed in the introduction of his book: "To preserve a close contact with experiment, aiming at the simplest characterization possible of the field, I have chosen the synthetic route" (Drude 1900a, iii). Thus Drude's synthetic route aimed at "simplicity," where simplicity meant using the least number of physical hypotheses to support the mathematical formalism. In this sense, Drude's strategy can be regarded as a realization, for the field of optics, of the positivistic move he initiated in 1892. Indeed, it is hard to imagine another strategy, different from the synthetic route, that could articulate the existing knowledge into a unitary and consistent view of optics following the basic simplicity principle. Another option would have been seeking to unify the field around, for example, mechanical principles, as von Helmholtz did, but Drude had already relegated those principles to natural philosophers years before.

The synthetic route implied a very particular kind of trafficking between the simplest account in principle and the older sources. Previous papers entered the narrative for two principle reasons: first, to provide support for Drude's unitary view (in the case of experiments); second, as components naturally incorporated into his overall picture. As a matter of fact, he commented with regard to his own previous works on optical dispersion and the Kerr effect that they were subsumed by the new account in *Lehrbuch der Optik*. The implication was that previous papers could not give us more information about optics, unless we wanted to go beyond the simplest description of phenomena. The synthetic route blocked, in this way, direct contact with the scientific past. This contrasts clearly with Preston's and Basset's books, where older works entered the story by teaching us something about optics, conveying instead an accumulative process of knowledge acquisition.

Through the synthetic route, Drude concealed not only older versions of electromagnetism and the ion hypothesis but also the kind of questions that led to alternative conceptions of these subjects, viz. whether electromagnetism and mechanics related to each other in a manner beyond the system of Maxwell's equations. Simplicity, as characterized above, worked as a self-evident criterion for selecting knowledge and possible ways of generating knowledge in *Lehrbuch der Optik*. But simplicity had not always been such an obvious way to justify choices in physics. As Poincaré argued eloquently in the introduction of his 1891 book on electricity and optics:

> How can we make a decision among all these possible explanations [he is speaking of the various mechanical and electromagnetic theories of light, mathematically equivalent], if the experiments do not help us? [...] Our decision can only be founded on considerations in which our personal views play a big role; in that there are solutions that someone can refuse due to their oddity and other solutions that are preferred due to their simplicity. (Poincaré 1891, 6–7)

Thus, what for Poincaré was a matter of personal taste in the selection of theories, for Drude was a distinguishing factor between physics and natural philosophy.

In Drude's synthetic route, the new questions to be posed appeared almost at the end of the narrative, when the introduction of the ion hypothesis produced a gap between the mathematical formalism and its physical interpretation, breaking in this way the simplicity rule. The "fresh life pulsing" in optics was to be found, as Drude prognosticated in the introduction, in the interplay between optical properties of matter, the corresponding *Erklärungssysteme*, the physical hypotheses about how ions behaved, and insights coming from other physical fields.

2.4.5 *Lehrbuch der Optik* as a Modern Book on Optics

Drude's textbook rapidly became influential in Germany, in the rest of Europe, and even in the United States. An English translation by Charles R. Mann and Robert A. Millikan was published in 1902 (Drude 1902), and a second and third edition of the German version appeared in 1906 and 1912 (Drude 1906; 1912).[23]

Reviews of *Lehrbuch der Optik*, both of the 1900 German and 1902 English editions, highlighted the modernity of the book, describing it as an advanced text that contained a lot of novel knowledge, upshots of the fast developments in optics in the preceding decades, and never included in textbooks up to that point. For example, Max Abraham wrote, in a review of 1900: "as a result of the fast progress that optics has made in the last years, the *old* books are obsolete. Drude's *Lehrbuch der Optik*, built on *modern* considerations, is therefore welcome"[24] (Abraham 1900, 415–416). And Albert A. Michelson commented in the preface to the 1902 English edition: "There does not exist to-day in the English language a general advanced text upon Optics which embodies the important advances in both theory and experiment which have been made within the last decade" (Drude 1902, iii). Even in comparison to famous English textbooks on optics, *Lehrbuch der Optik* was highly praised:

> It is a satisfaction to note that there has appeared a translation of this work, which received such instant recognition at the hands of physicists the world over upon its appearance in Germany. [...] Descriptively, the book is fully on a par with Preston's *Theory of Light* and mathematically more valuable, as well as more lucid and attractive, than Basset's *Treatise on Physical Optics*. (Kent 1903, 75–76)

The aspect of Drude's account that most satisfied reviewers was his treatment of the electromagnetic theory of light together with the ion hypothesis, well expressed in this English review of the first German edition:

> Textbooks of optics, it is true, are numerous, and the reviewer is apt to think that of the making of many books there is no end. Professor Drude's book, however, contains much that is novel (at any rate, to English books) and the student will find up-to-date information on many points of interest. [...] In all this work Prof. Drude has been most successful; the electromagnetic theory, supplemented by the one additional hypothesis of the moving electrons, serves to coordinate in a satisfactory way very many of the phenomena of light. (Anonymous 1900)

Now the question is: in what did the modernity of the book lay? Or put it in another way, what knowledge was left behind as old, once modern knowledge arrived?

In my opinion, the modernity of the book lay not only in the adoption of the electromagnetic theory of light and the introduction of the ion hypothesis, but also in what these decisions implied for the conception of optics as a whole. That is to say, the modernity lay also in the way electromagnetism and the ion hypothesis were redefined in their articulation as part of the synthetic route. Electromagnetic theory was reduced to the Maxwell's equations and optical phenomena were pictured as manifestations of ions, favored for both being *anschaulich* enough to derive optical theories and being embedded in a broader network of experimental practices from which to characterize their properties. Drude's viewpoint on optics was also modern in its way of breaking with the optical debates of the past. Discussions

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[23] Moreover, two further editions of the English version appeared in 1959 and 2005. Besides them, there was one French translation in 1912 and another into Russian in 1935 (Cardona and Marx 2006).

[24] Italics are mine.

of the nature of the ether were abandoned for simplicity; the philosophical conflicts about the coincidence of electromagnetic and mechanical *Erklärungssysteme* were out of place. At the same time, *Lehrbuch der Optik* revealed a new domain for speculation in optics regarding the connection between ions and their optical manifestations, and the construction of a consistent microscopic picture of matter through the combination of the properties of ions from different experimental contexts. Drude had conceived a modern book, also because it posed modern questions, which then shaped research in optics in the ensuing years. Drude is the first, best example of the fruitfulness of these new questions. Drude not only wrote a book under their guidance, but the task of writing such a book also opened for him new pathways for further research.

2.5 Giessen 1900–Berlin 1906: Development of *Lehrbuch der Optik*'s Program up to the Second Edition

2.5.1 Ions vs. Electrons: the Sharpening of Drude's New Heuristics

The ion hypothesis turned out to provide great gains for Drude in a short time. On 21 April 1899, Drude presented his work on magneto-optical phenomena in the annual meeting of the German Physical Society, in which he used the ion hypothesis for the first time. On 14 December, Drude submitted a paper on the ion theory of metals, in which he accounted for the optical properties of metals by assuming that there existed a kind of light ions (as opposed to massive ions) that could travel freely across the metal (Drude 1900b).[25] In January 1900 Drude sent off the preface of *Lehrbuch der Optik*, where optics was built upon the ion hypothesis. Finally, in February, he sent off a very long paper to *Annalen der Physik*, in which he extended his optical program to other fields, specifically, to the thermal and electric properties of metals (Drude 1900c; 1900d). From December 1899 to February 1900, in these last papers, the dichotomy between light and massive ions had transformed into a dichotomy between electrons and ions.

In the same span of time, Drude was offered a position as full professor at the University of Giessen and directorship of its Institute of Physics, results of his being "known through his sound and comprehensive works on the field of optics and electric waves" (Lorey 1941, 123). He accepted immediately, and in April 1900 he and his family were already in Giessen, where he spent the five most productive and happy years of his professional life (König 1906; Planck 1906; Voigt 1906; Lorey 1941). He founded the *Physikalisches Kolloquium* and succeeded in creating a very lively research atmosphere among the doctoral students, resident researchers, and visitors. At the forefront of this research were ions and electrons. As one of his doctoral students, Karl Hahn, recalled: "The electron and ion theories were in the foreground in Giessen in that period. Drude himself worked on his electron theory of metals. In second place came everything that was associated with electric waves and radiation" (Lorey 1941, 123).

In terms of effects, the electron was the most significant acquisition of Drude's research in Giessen, and it enhanced the fruitfulness of the electromagnetic theory and ion hypothesis

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[25] Drude's inspiration for writing this paper was a work published by Wilhelm Giese in 1889, in which he suggested that electrical conduction through metals was connected to ions (Giese 1889). It must not be just a coincidence that Lorentz, in his 1895 *Versuch*, grounded his adoption of the ion hypothesis on Giese's work, among other things. Drude never mentioned Lorentz's works before *Lehrbuch der Optik*, where he had to read them to provide a comprehensive account of the field.

overall. Analogously to the previous discussion of the various ways in which ions could be productive in *Lehrbuch der Optik*, we also see several different forms of fecundity for the electron in Drude's ways of articulating it. Drude's appropriation of the electron occurred in two steps. First, Drude employed the electron in his electron theory of metals, mentioned previously (Drude 1900c; 1900d). Rather than just the definition of the electron as a universal charged particle, what was useful for Drude was establishing a contrast between the lightness of the electrons and the massiveness of the ions, now relegated to "aggregates of electric cores and ponderable masses that refer to electrolytes" (Drude 1900c, 566). For in this way, Drude could distinguish conceptually between two kinds of microscopic behavior in metals: under the action of an electric field, ions were assumed to be practically at rest, whereas electrons moved freely across the material. This assumption enabled Drude to treat electrons as the particles of an ideal gas, and thereby to make use of the kinetic theory of gases to predict the thermal and electric properties of metals. For a concrete check on his results, he then resorted to Thomson's measurements of the charge, e, of the electron. The value of the mass of electrons, however small it was, played no role in Drude's 1900 theory of metals.

In 1904 Drude turned again to the electron, to give a more precise interpretation of optical phenomena in terms of the microstructure of matter (Drude 1904a; 1904b). In this case, the electrons had both mass and charge. Another post-1900 event also led Drude to reinforce the idea that the electrons and ions had well-differentiated roles in optics. In 1902, another student of Lorentz in Leiden, Lodewijk Siertsema (1902), calculated a value for e/m from his experiments on the Faraday effect in sodium gas, which was almost the same as the value calculated by his colleague Zeeman five years earlier in Leiden, and as the one measured in cathode rays. A sharper dichotomy between electrons and ions was established: electrons were the light charged particles characterized by the universal value e/m, while ions were characterized by the values e'/m' obtained in experiments on electrolysis, which did not all agree with one another, but depended on the substance explored. This dichotomy was very useful for Drude in various senses. First of all, Drude envisioned the vibration of electrons as the origin of natural frequencies in the ultraviolet region of the spectrum, while the motion of ions, being much more massive, caused natural vibrations in the infrared region. This assumption was especially useful in the cases of optical dispersion and the Faraday effect. Let's again follow Drude's reasoning for the example of dispersion.

Given the assumption that macroscopic effects were the sum of the microactions of either ions or electrons, Drude rewrote, in 1904, the formula for dispersion obtained on the basis of the *Mitschwingungen* model, in terms of the ratio of charge to mass of the hypothetical particles. The dependance of the index of refraction on ν of light had the same generic form as in 1872:

$$n^2 = 1 + \sum \frac{K_i {\nu_i}^2}{\nu_i^2 - \nu^2}. \tag{2.6}$$

Now Drude found the following expression for the parameter K_i as a function of the number N_i of electrons/ions with each proper frequency, ν_i, e being their charge and m their mass:

$$K_i = \frac{4\pi e^2 N_i}{m}. \tag{2.7}$$

Applying this expression to already-existing empirical data on dispersion in fluorite, Drude showed the plausibility of his hypothesis. He did it in the following way. He used the two values of K_i obtained by fitting experimental data on dispersion through fluorite into the generic formula, which corresponded to two proper frequencies ν_i (or the inverse of two wavelengths λ_i) at which the hypothetical microscopic particles vibrated. One frequency turned out to be in the ultraviolet region, the other in the infrared. As Drude observed, $\frac{K_{ultrav}}{\lambda_{ultrav}}$ was much larger than $\frac{K_{infrar}}{\lambda_{infrar}}$. By relating this piece of information to the fact that the value e/m of electrons was much smaller than e'/m' of ions, Drude proved the plausibility of his hypothesis that electrons vibrated at ultraviolet and ions at infrared frequencies.

On the whole, the parameters K_i and ν_i of $n(\nu)$, which could be computed by fitting macroscopic observations into the formula, turned out to provide an exceptional window into the invisible microstructure of matter: on the one hand, ν_i were identified directly with the frequency of the natural vibrations of the corresponding charged particles. On the other, by using either the universal value for e/m of the electrons or the varying ones obtained in electrolysis experiments, one could derive, from the empirical value of K_i, the number N_i of charged particles involved in producing optical phenomena. Thus optical dispersion became a means to *count* microscopic particles. In this way, the inner structure of molecules could be further characterized through Drude's interpretation of optical phenomena, while until then this inner structure had remained practically restricted to the domain of chemists.

The electron hypothesis led Drude to suggest another bold connection between optics and an outside scientific domain. In 1904 Drude suggested that the electrons counted in dispersion calculations coincided with valence electrons, to wit the same entities revealed both physical and chemical properties depending on the circumstances. To make this connection between optics and the periodic properties of the elements, Drude relied upon Richard Abegg's recent theory of valence. Just that year Abegg (1904), the theoretical chemist, had laid down the first electron theory of valence, according to which the chemical valence number corresponded to the number of negative electrons loosely bound to the atom that tended to be shared with other atoms in order to form molecules. In the case of fluorite, the identification between dispersion and valence electrons worked, while Drude left the stage open for checking the hypothesis with other substances.

In the end, the electron hypothesis showed itself fecund in two ways: first, through the conceptual differentiation between electrons and ions, grounded in their mass difference, and second, through the possibility of calculating the charge-to-mass ratio, e/m, and number, N_i, from experiments. A network of heterogeneous domains of knowledge was spanned through the connection of the values of e/m, N_i, and chemical valence: cathode rays, Zeeman effect, optical dispersion, chemistry. Thus in these years, Drude deepened his commitment to the new ion heuristics he had introduced in 1900.

2.5.2 Dispersion Electrons and the Second Edition of *Lehrbuch der Optik*

The significance of these novel insights for Drude's program of optics was demonstrated by their incorporation into the second edition of *Lehrbuch der Optik*, as Drude highlighted in the introduction to the 1906 edition. The electron was indeed the essential modification with respect to the first edition of the book:

> In the six years that have elapsed since the publication of the first edition of this book, a fast development of the whole field of physics has taken place through the experimental and theoretical display of the electron theory in a way that is hitherto unique. In optics, this advancement is naturally noticeable in the chapters that, as in the case of dispersion of bodies and their magnetic activity, are built on the ion hypothesis. Basically, the progress consists in replacing the ion hypothesis by the electron hypothesis, namely, by the knowledge that from certain optical phenomena one can derive the same characteristic universal constant as in the case of cathode rays and generally when free electrons appear. (Drude 1906, v)

In 1906 Drude assumed that the charged particles producing optical dispersion, as well as the Zeeman, Kerr, and Faraday effects were indeed electrons. Only when the proper frequencies of the hypothetical charged particles were situated in the infrared, as mentioned earlier, did he work with ions. As a matter of fact, Drude reworked the analytical expressions for the Kerr and Faraday effects in a similar way to his reworking of the dispersion formula. More specifically, he rewrote the variation of the polarization angle, δ, with respect to the frequency of light, ν, in terms of the number, N_i, of electrons, characterized by the natural frequency, ν_i, and the universal constant e/m. Thus, not only from experiments on optical dispersion, but also on the Kerr and Faraday effects, one could calculate the number of dispersion electrons that hypothetically gave rise to measurable features.

In this way the network of phenomena established through the electron hypothesis extended to the whole field of magneto-optics. In the new edition, one question seemed to "pulse fresh life" more than ever: how optical phenomena, taken as a whole, could help us in characterizing the structure of specific chemical substances, once we assumed that electrons were the microscopic causes of their macroscopic features. One important assumption was implicit in Drude's reformulation of optics, which turned out to be problematic a decade later: in order for macroscopic phenomena to result from the arithmetic sum of N_i microscopic resonances, each electron should interact with light independently of all the other electrons.

2.5.3 Last Year in Berlin

As he was writing the preface to the second edition, Drude and his family were living in Berlin. In 1905 he was offered a full professorship in physics and the directorship of the Berlin Physics Institute, replacing Emil Warburg. This was a big promotion, so despite certain reservations about leaving his pleasant life in Giessen, Drude accepted. But soon the situation in Berlin became very demanding. The first year he invested almost all his energies into the reorganization of the Institute, and this kept him away from research. He came to the point where he felt so anxious that, at the end of a talk he gave on 28 June in the Prussian Academy of Sciences, he declared: "I have a feeling of oppression, whether, by the exertion of all my strength, I will be up to the tasks assigned to me"[26] (Lorey 1941, 127).

Just one week after he uttered these dreadful words, Drude committed suicide. Planck, who had worked with him in Berlin, remembered the last weeks of Drude in this way:

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[26] "Ich empfinde ein Gefühl der Beklemmung, ob ich durch Anspannung aller meiner Kräfte den an mich gestellten Aufgaben gewachsen sein werde."

> He retained his usual permanently jovial character in his everyday life, inside and outside home, until the last day. While the work at the Institute made its regular progress, he devoted himself with enthusiasm and success again to his scientific activity. He never expressed any idea about drastic relief. On 27 June he wrote the preface to the second edition of his *Lehrbuch der Optik* [...] and on 28 June, just one week before the catastrophe, he gave his inaugural talk at the Academy of Sciences, [...] in which he portrayed his scientific career and immediate plans for the future.
>
> He had already complied with the most important duties of the semester, holidays were close. The application to leave on vacation was already signed, his substitution by the assistants arranged, a tour in the Karwendel mountains with his colleague and friend Willy Wien agreed upon, from the equipment to the last detail of the garderobe prepared for this purpose. (Planck 1906, 628–629)

2.6 Epilogue: Following the Traces of *Lehrbuch der Optik*

2.6.1 *Lehrbuch der Optik* at Universities and in Other Textbooks

Drude's *Lehrbuch der Optik* became one of the reference books for teaching optics at universities, in particular German universities. For instance, Rudolph Minkowski, who worked as assistant to Rudolf Ladenburg, before and after WWI, said, concerning the University of Breslau, in an interview with Thomas Kuhn and John Heilbron for the Archive for History of Quantum Physics:

> Electro-magnetic theory I think the book most widely used would have been Abraham's. To some extent, although that was not translated into German that I know of, Lorentz's theory of electrons. Optics? I think Drude's was probably the commonly used book. Mechanics? I do not quite remember. But this were, in general, lectures tailored after some book. You may read Boltzmann or Kirchhoff....[27]

Further Drude's approach was also influential for other textbooks, in particular Voigt's second textbook, devoted almost exclusively to magneto-optics, titled *Magneto- und Elektro-Optik* (Voigt 1908). Voigt started by describing the simplest Zeeman effect and Lorentz's theoretical account of it, and continued by extending these initial insights to a manifold of new possible varieties of the Zeeman effect and further magneto-optical phenomena, such as the Faraday effect. To do so, Voigt relied upon Drude's strategy of deriving the optical formulas through the modification of constants. Voigt's departure point was actually Drude's formulation of optical dispersion as produced by N_i electrons each vibrating at a proper frequency ν_i. Voigt acknowledged Drude's impact both in the introduction of the book and throughout the text:

> Concerning treatments of magneto-optics in general textbooks on optics the one by P. Drude deserves special mention (Lehrbuch der Optik, Leipzig 1900 and

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[27] See page 6 of the interview of Minkowski by Thomas Kuhn and John Heilbron in April 1962, AHQP, APS, M/f No. 1419-04-minkowski-r-002.

> 1906), which has a singular hue due to the strong emphasis on the electron theory. Drude confines himself to the easiest case of the Zeeman effect, namely to the easiest sort of magnetically excitable bodies, and thereby the license for rounding and completing the theory lies in his characterization, which does not correspond completely to the real state. (Voigt 1908, 4)

All in all, Drude's *Lehrbuch der Optik* and Voigt's *Magneto- und Elektro-Optik* had a resounding impact on the ensuing years of optical research in various laboratories in Germany, where experiments on optical phenomena were deemed an appropriate means to explore the microstructure of matter. Most significantly, on the basis of these two works, students of Voigt in Göttingen, Rudolf Ladenburg in Breslau, Christian Füchtbauer in Leipzig, and Dmitri Roschdestwensky in St. Petersburg did a very good job of calculating the number of optical electrons in gaseous substances from measurements of the Faraday effect, anomalous dispersion, and the intensity of dispersed spectral lines.[28] In this context, the electrons that were supposed to be optically active in the production of these phenomena were dubbed "dispersion electrons." Questions about the nature of the ether or the possibility of unifying mechanics and electromagnetism simply disappeared. The strategy of combining matter and ether by means of the electron hypothesis was taken for granted. The main new concern in the measurement of optical phenomena became the analysis of matter, where dispersion electrons acquired a life beyond the specificities of each phenomenon. The Faraday effect, optical dispersion, and the spread of the spectral lines all became a means to calculate the number and properties of dispersion electrons. The heuristics shift from the nature of ether to the nature of matter had been completed. Precision was a precondition of fitting experimental data to the formulas, but knowledge came from the networking of phenomena and different domains of knowledge through the sharing of concepts like dispersion electrons (e.g. cathode rays, optical phenomena, chemistry, and gas theory).[29]

Drude's *Lehrbuch der Optik*, in particular its English edition, was also influential for the American physicist Robert Wood in the writing of his textbook *Physical Optics* (1905). In contradistinction to Drude's and Voigt's books, and more in line with the English tradition, Wood payed more attention to the experimental realization of optical phenomena in their old and new variations, his book being an outstanding reference work from this point of view. However, "no pretence at originality in the mathematical treatment was made" (Wood 1905, 5). Instead, in this regard, Wood relied mostly on Drude's work: "The excellent theoretical treatment, based upon the electro-magnetic theory, given by Drude, has been followed very closely, and it is hoped that this acknowledgment may serve in place of the numerous quotation marks which would otherwise be necessary" (Wood 1905, 5). Mention of the other two English books, by Basset and Preston, Wood omitted. In this way, the audience for Drude grew larger still in English speaking countries.

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[28] See especially (Geiger 1907; Ladenburg and Loria 1908; Ladenburg 1911; 1912; Füchtbauer and Schell 1913; Füchtbauer and Hofmann 1913; Roschdestwensky 1912).

[29] Lorentz also wrote a very influential book drawing upon the electron theory (Lorentz 1909), containing features on the various domains of physical knowledge that were hypothetically explained through different behaviors of electrons, such as optics and heat. Nevertheless, Lorentz's was not a book on optics, and it lacked a systematic approach to the field, which included the description of instruments and experiments, from the simplest to the most complex phenomena, separate from a theoretical account of the actions of the electrons.

2.6.2 From a Modern Book to Classical Optics

Drude's textbook was also referred to in research papers. Eventually, in the context of the emerging quantum theory, Drude's modern *Lehrbuch der Optik* was redefined as "classical." This transition is particularly well-revealed through Sommerfeld's 1915–1917 attempts to lay down a quantum theory of optical dispersion. In the 1910s, Drude's account of optical dispersion suffered a big theoretical blow. In 1913 Niels Bohr postulated that atoms consisted of a nucleus orbited by electrons and that specific trajectories existed along which electrons did not radiate energy (Bohr 1913a). The crux of the contradiction between Bohr's atom and Drude's dispersion theory was that in the quantum model electrons orbited, not vibrated, and that atoms emitted or absorbed light only through electrons jumping between orbits, not through the mechanical co-vibrations of electrons with light. In this way, Bohr explained the emission process of discrete spectral lines. At the same time, he also attempted to keep Drude's theory of dispersion and the identification between dispersion electrons and valence electrons by allowing orbits to be, under very specific circumstances, perturbed around their stationary states (Bohr 1913b; 1913c).

The theoretical physicist Arnold Sommerfeld singled out this conceptual conflict, and during various years he grappled with the possibility of restoring the correspondence between light frequencies and mechanical vibrations as a way to account for optical dispersion in the context of Bohr's model of the atom (Sommerfeld 1915; 1917). Sommerfeld followed the same direction hinted at previously by Bohr, and he developed at length the analytical problem of stationary orbits being mechanically perturbed under the external influence of the electric field of light. Thus *Mitschwingungen* between light and matter persisted in accounts of optical dispersion, although now electrons vibrated harmonically around their quantum orbits, instead of oscillating around fixed positions. In this way, Sommerfeld recovered the classical theory of optical dispersion, which he directly identified with Drude's *Lehrbuch der Optik*.[30] Eventually, Sommerfeld put forward the following conceptual dichotomy, in order that the whole picture held: the phenomena of spectral lines should be considered quantum in nature, therefore following Bohr's quantum jumps, while optical dispersion persisted in being accounted for by classical physics, namely, *Mitschwingungen* between electromagnetic radiation and matter. Drude's theory of optical dispersion instantiated the classical case (Sommerfeld 1915, 575-577).

In the late 1910s, Sommerfeld's dream faded for various reasons, but the important point here is the redefinition of Drude's previously modern approach as classical, within this context. What made Drude's dispersion theory a classical theory, as opposed to the quantum theory? Was it simply that it was non-quantum? The reason Bohr's atom became problematic in relation to Drude's theory of dispersion in 1913 was in fact a very specific and restricted one: the causal relation between the hypothetical resonance process at the particular mechanical frequencies of electrons and the macroscopic production of optical dispersion as it was observed in the laboratory. But as we have seen, such a causal relation was far from being obvious to Drude in the beginning. It was rather the result of a process extending from 1892 up to 1900, through which Drude, in conversation with his contemporaries, made numerous decisions that affected his and others' conceptions of optics as a whole, both at the epistemological level (from ethos of exactitude to simplicity, and then to networks of insights through the electron hypothesis), and ontological level (from a me-

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[30] For more information about this episode, see (Jordi Taltavull 2013).

chanical ether to an electromagnetic ether, irreducible to mechanics). Thus, in the end, it was one of the features that made *Lehrbuch der Optik* a modern book, in the context of its composition, which led it to be considered classical years later: the articulation of vibrating electrons and electromagnetic light through the analysis of optical dispersion as representative of manifold magneto-optical phenomena.

As a matter of fact, it was the experimentalist Ladenburg who, in 1921, first ventured a new interpretation of optical dispersion, which would turn out to be in better agreement with the conceptual requirements of the emerging quantum theory (Ladenburg 1921). Ladenburg's difficulties with Drude's account originated in the counting of dispersion electrons and became apparent in the early 1910s, having, at the beginning, nothing to do with quantum physics. The problem was that the number of dispersion electrons did not coincide with the valence number, and most importantly, the numbers computed from experiments hinted at the possibility that dispersion electrons were actually not independent from each other in their interactions with light. Now, to interpret K_i in terms of N_i, thus $K_i = \frac{4\pi e^2 N_i}{m}$, one had previously to assume that electrons interacted with light, each one independent of the other. In other words, Drude's counting of dispersion electrons led to a dead end, for the results of the counting undermined the conditions for the dispersion electrons to be counted. Thereafter, in 1921, independently from Sommerfeld, Ladenburg suggested a new interpretation of K_i, resorting to new quantum tools and Bohr's atomic model. Ladenburg relinquished the proportion between macroscopic features and microscopic electrons underpinning Drude's theory of dispersion, and suggested a new proportionality: between the measurable parameter K_i and the number of quantum transitions corresponding to the frequency ν_i. In this way, optical dispersion became a quantum phenomenon. But at the same time, the *Mitschwingungen* model persisted in supplying the mathematical expression for $n(\nu)$ used to fit the experimental data and calculate the value of K_i, albeit reduced merely to a formal device. Thus what Ladenburg left behind with his quantum interpretation of optical dispersion was not classical physics altogether, but the identification of the abstract particles resonating with light in the model of *Mitschwingungen* with very specific charged particles, electrons, whose properties could be calculated from a heterogeneous network of phenomena. The *Mitschwingungen* (and *Mitbewegungen* in general) persisted in describing mathematically optical phenomena, though devoid of physical meaning. For the *Mitschwingungen* were conceptually incompatible with quantum transitions. Drude's modern heuristics, developed from 1900 until 1906 to network heterogeneous phenomena through their sharing of the same hypothetical microscopic agent, namely, electrons, was left behind. The new features with physical meaning were quantum transitions, instead of dispersion electrons.

Overall, what was modern in Drude's textbook, including and beyond the blending of the electromagnetic theory of light and electrons, was also what allowed it to become classical, when its differences from the emergent domain of quantum physics were made apparent. Negotiations of the boundary between classical and quantum physics took place precisely at the points of articulation of knowledge that had been ascribed "fresh life" in Drude's account: causal relations between moving, independent electrons and macroscopic features, disclosure of the microstructure of matter through the interrelation of phenomena hypothetically manifesting electron properties. But at the same time, this "modernity" of the book was itself the result of an arduous process that was by no means less challenging or innovative than its later development in relation to quantum physics. Classical physics had been constructed through other distinctions both on the epistemological and ontological levels, which were left behind as optics took on a modern form: mathematical formalism vs. the nature of ether, mechanics vs. electromagnetism. Only a long-term analysis enables us to understand the specific "classical" physics with which physicists grappled in the first decades of the twentieth century, and avoid oversimplifying it to mean all of non-quantum physics. Classical optics, and more specifically Drude's *Lehrbuch der Optik*, established the field of possibilities, the exploration of whose limits, defined the cognitive space within which the boundary with quantum physics was negotiated.

Abbreviations and Archives

AHQP	Archive for History of Quantum Physics. American Philosophical Society, Philadelphia

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