The Vortex Theory of Atoms

— pinnacle of classical physics —

Thesis for the master's degree in History and Philosophy of Science, by
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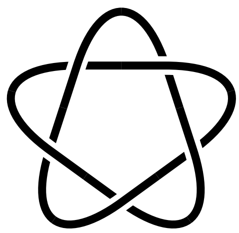

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Abstract

Investigation into a nineteenth century atomic theory that assumed atoms to be vortices in an ether. Originally an idea of Kelvin, the vortex atom theory enjoyed great popularity in England, roughly form 1870 to 1890. In this thesis, the popularity of the vortex atom theory is explained through four values in nineteenth century English physics. Furthermore, it will be argued that the (surprising) fact that the theory was virtually ignored by German scientists can be explained by a German critical attitude towards scientific theories. An attitude that was a reaction to the Romantic philosophy of *Naturphilosophie*.

Acknowledgements

Without the support of my supervisor, Jeroen van Dongen, this masterthesis would have been nothing of what it is in its current form. Not only did he teach me a lot about doing history of science and writing academic texts in general, he also broke my habit of cutting corners while doing research.

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Contents

CHAPTER 1

Introduction to the vortex theory of atoms

The wreckage of rejected theories is appalling; but a knowledge of what actually goes on behind what we can see or feel is surely if slowly being attained.

— Hicks

In this first chapter the vortex theory of atoms is introduced together with an overview of its history. After that I will pose my research questions and give an outline of the structure of this work.

1.1 Ether and atoms

In the course of the history of science there is one concept that is notoriously connected to failed scientific theories: the concept of the *ether*. Although the ether was already present in ancient Greece where it was to fill the vacuum of space, and kept alive in the work of Descartes and Newton, the nineteenth century can be regarded as the golden age for the ether. It has to be said that scientists always remained somewhat suspicious towards the unfathomable ether, but during the second half of the nineteenth century the existence of the ether was close to being undeniable. This was largely due to the development of theories of light by Augustin Fresnel in 1818 and James Maxwell in 1861. It was through these theories that scientists became convinced that light was a wavelike phenomenon rather than a stream of particles. If light was a wave, then, it needed a medium through which it could undulate. As water waves needed water and sound waves needed air, light also was thought to require some substance as its carrier; the undulation of nothing was regarded as an unthinkable idea.

Next to the acceptance of the ether, the nineteenth century also was a deciding period for atomism. Although the idea of matter being composed of minute, finite building blocks is as old as the ether, it also always had been conceived with suspicion. Yet in the nineteenth century science progressed to the point where its theories could reach the dimensions of the atoms and enabled scientists to deduce some of their actual properties. As these properties were being revealed, physicists used them as reference points to construct atomic models that could account for, and describe the composition of matter. Three of these models were: the atomic model of Dalton, the theory of force-centers of Boscovich, and the vortex theory of atoms of William Thomson, better known and henceforth referred to as Lord Kelvin.

1.2 The vortex theory of Kelvin

It is the vortex theory of atoms which is the subject of the current investigation. Not because the other two theories are less interesting but because of the little attention Kelvin's theory has been given until now. Besides minor references to the theory in studies of the history of atoms or ether, there are only three studies dedicated to the vortex theory of atoms. First is a paper of Robert Silliman from 1963, which is only a very general account of the theory but it nevertheless became the standard reference because it was the only account of the vortex theory available. In 1994 the dissertation of Alfons Alkemade appeared which contains a more thorough account of the history of the vortex theory of atoms, mainly to introduce the second part of the dissertation about the technical aspects of vortices in fluids. Finally, the most complete and recent work has been published in 2002 by Helge Kragh which also became a chapter in his book "Higher Speculations", published in 2008. The title of Kragh's paper, "The Vortex Atom: A Victorian Theory of Everything", gives a good characterization of the theory.

The idea of the vortex atom theory was to explain *everything* just with some equations of fluid dynamics. To quote the English physicist George Fitzgerald about the ambition of the theory: "If it be true, ether, matter, gold, air, wood, brains, are but different motions."[1] In short, the vortex theory pictured atoms as small vortices in an ideal, i.e. frictionless fluid, which was often identified as the ether. Kelvin first published the idea in 1867 and kept working on it until the theory was abandoned around 1890. He was not the only physicist spending his time elaborating the theory. In particular together with J.J. Thomson, who discovered the electron, and William Hicks, another English physicist, Kelvin formed the core group of the vortex theory. Around these three men stood a group of scientists that partly participated and published from time to time on the theory. Amongst these scientists, about a dozen, were names like Peter Tait, George FitzGerald, Joseph Larmor, and Karl Pearson. Other British

[1] FitzGerald 1970, p. 25.

scientists like James Maxwell did mention the vortex theory occasionally, sometimes favorable, but always somewhat doubtful.

1.3 History of the vortex theory of atoms

Kelvin had occupied himself with the idea of a hydrodynamical theory of everything already in the early 1850s,[2] but there were two events that gave him the inspiration for the vortex theory of atoms. First was the appearance of a paper on hydrodynamics in 1858 from the German physicist Herman von Helmholtz. Although the derived equations in this paper were a huge step forward in the theory of hydrodynamics, it gained little attention at the time of its publication in Germany. One person who did appreciate the work of Helmholtz was Peter Tait, a Scottish mathematician who in many projects was in close collaboration with Kelvin. Immediately after its publication Tait translated Helmholtz's paper into English for his personal use. Kelvin, a close friend of Helmholtz, read the paper as well in 1858, but he did not see the significance of it until Tait published his translation in the English 'Philosophical Magazine' in the summer of 1867.

Vortices

The mathematical theory of vortices in a fluid was until then still very much in its infancy. It had already occupied the minds of Descartes, Euler, and some lesser known natural philosophers, but it was through the hands of Helmholtz that vortex theory became established as a serious branch in fluid mechanics.[3] In his paper, Helmholtz assumed an ideal fluid, that is, an incompressible fluid without friction. In this ideal fluid, Helmholtz derived that portions of the fluid that are stationary will remain stationary and, vice versa, portions of the fluid that are in rotational motion will keep their rotation. This was an expected result: since the fluid did not allow for friction, there was no action available to change the fluid's momentum. As a result, a vortex, which is a portion of fluid in rotational motion, will always exist out of the same portion of fluid and would be immune to dissipation, i.e. would exist forever. Helmholtz also showed that the 'strength' of a vortex, defined as the product between the local circumference and rotational velocity, is constant over the entire length of the "vortex tube", see figure 1.1.

[2]Smith & Wise 1989, p. 396.
[3]Alkemade 1994, p. 6.

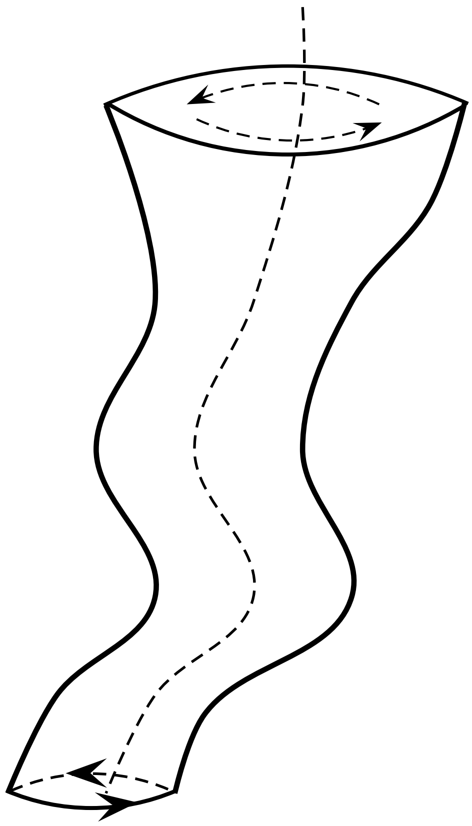

Figure 1.1: A vortex tube. The "strength" of the vortex is defined as the local circumference of the tube multiplied by its rotational velocity at that point. Helmholtz showed that this strength is constant over the length of the tube.

Consequently, a vortex tube could not end inside the fluid, for then either the rotational velocity or the tube's circumference would be infinitely large. However, in a fluid enclosed by a wall, a vortex tube could end on that wall. More interesting for the subject of atoms is the circumstance that the tube could also end on itself, forming a continuos loop. In the simplest case, the vortex tube would be circular and is commonly known as a 'vortex ring', see figure 1.2. As an illustration of these rings, Helmholtz remarked that they are easily studied by pulling a spoon through a cup of coffee.[4]

[4]Helmholtz 1867, p. 512.

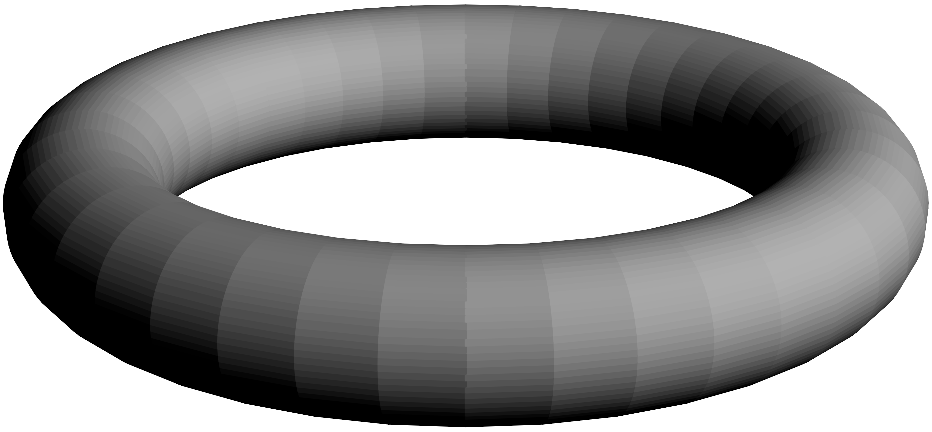

Figure 1.2: Representation of a vortex ring.

From theory to experiments to enthusiasm

After reading Helmholtz's paper, Tait devised an experiment to create these vortex rings out of smoke in a controlled way. Witnessing this experiment was the second event that supposedly gave Kelvin the inspiration for his vortex theory. Kelvin's enthusiasm becomes clear in a letter to Helmholtz describing the experiment:

> Just now [. . .] *Wirbelbewegungen* have displaced everything else, since a few days ago Tait showed me in Edinburgh a magnificent way of producing them. Take one side (or the lid) off a box (any old packing box will serve) and cut a large hole in the opposite side. Stop the open side [. . .] loosely with a piece of cloth, and strike the middle of the cloth with your hand. If you leave anything smoking in the box, you will see a magnificent ring shot out by every blow.[5]

When Kelvin characterized the behavior of a single vortex ring as "magnificent", then the interaction between two rings rightly can be called spectacular. Helmholtz showed in his paper how two rings in vicinity of each other would interact and Tait's smoke rings confirmed these interactions, to the approximation of a non-ideal fluid, perfectly. For instance, Helmholtz calculated that two identical vortex rings with opposite direction of rotation would slow down and both increase in size upon directly approaching each other in such a way that they would never come into contact with one another. Two vortex rings heading in the same direction,

[5]Kelvin to Helmholtz 1867, Smith & Wise 1989, p. 418.

the one chasing the other, exhibit even more curious behavior. The ring in front will expand and slowed down by the rear ring, which in turn speeds up and becomes smaller. If the initial conditions are right, the chasing ring can actually intercept the front ring, going through the middle of it and become the front ring. Then the whole process starts over again, leaving the rings to play a game of leap-frogging.

In the non-ideal laboratory these rings showed a remarkable stability. Kelvin and Tait tried to dissolve the rings by cutting them in half with a knife and tried to let the rings violently collide with each other or with the walls.[6] Yet the vortices let the blade go through, quickly uniting again and bounced off each other and the walls with apparent perfect elasticity. These experiments certainly made a big impression on Kelvin and with the knowledge that in an ideal fluid the rings really would be indestructible and really would collide elastically, hypothesizing was very tempting indeed.

Back to theory

The prime property, or better, the definition of an atom always had been its indestructibility. The commonly accepted atomic model viewed atoms as tiny indestructible spheres: the billiard ball model. Kelvin called this "the Lucretian Atom", after the ancient Greek philosopher Titus Lucretius, and he was not content with this representation of the atom. In his first publication on the vortex theory of atoms, "On Vortex Atoms", he severely criticized it: "For the only pretext seeming to justify the monstrous assumption of infinitely strong and infinitely rigid pieces of matter, [. . . is], that it seems necessary to account for the unalterable distinguishing qualities of different kinds of matter."[7] Kelvin's main objection to the billiard ball model was that its solidity prevented a natural explanation for properties like elasticity.

Where "On Vortex Atoms" was a very qualitative paper, a year later in 1868 Kelvin published his second text on vortices: "On Vortex Motion", which was much more technical. It also becomes clear from this paper that the development of the theory of vortex atoms was accompanied with major progress in hydrodynamics. Kelvin started this paper by stating that "the mathematical work of the present paper has been performed to illustrate the hypothesis that space is continuously occupied by an incompressible frictionless liquid, acted on by no force, and that material phenomena of every kind depend solely on motions created in this liquid."[8] Yet what follows are fifty-three pages of hydrodynamical equations that do not mention

[6]Silliman 1963, p. 463.
[7]Kelvin 1867, p. 15.
[8]Kelvin 1868, p. 217.

"atoms" once. In the following years, for most scientists working on the vortex atom theory, this would be the general template for texts about the vortex atom theory: an initial remark about vortex atoms and how incredibly beautiful such a theory would be, followed by an investigation in some hydrodynamical problem. The reason for this approach is twofold. Firstly, as already mentioned, hydrodynamics was in need for a more thorough investigation, it was still somewhat in its infancy as a field of science. Secondly, the mathematics needed to describe the behavior of vortices promised to be extremely complex. Whereas Kelvin in 1867 typified the mathematical difficulties to be "formidable",[9] Maxwell described the difficulties with the not so optimistic term "enormous"[10] while reviewing the vortex atom in 1875 for the Encyclopedia Britannica.

A good example of this formidable mathematics is found in "A Treatise on the Motion of Vortex Rings" (henceforth referred to as Treatise), published in 1882 by J.J. Thomson. Thomson was at the time just finishing his study in Cambridge which was home to some of the world's best mathematicians, where every year the best students in mathematics were awarded the Wrangler titles. Although Thomson was not awarded the title of Senior Wrangler of his year (he finished second best), he did get the even more prestigious Adams Prize for his Treatise, a prize for the best mathematical research, given every year by the University of Cambridge to a junior student. In his Treatise, Thomson followed the template of first making a few remarks about vortex atoms followed by an impressive piece of hydrodynamical mathematics examining the behavior of single vortex rings, vibrating vortices, and the interaction between multiple vortex rings. What mostly makes the Treatise interesting, though, is the final chapter that deviates from the rest of the text in that it contains little mathematics and a lot of hypothesizing. The title of the chapter: "The Vortex Atom Theory of Gases", gives a good idea of what the chapter is about. Although the vortex theory of atoms was too much of a working hypothesis to give a clear idea of how Kelvin and his followers pictured vortex atoms, the final chapter of Thomson's Treatise provides the closest thing to it. The Treatise also marks the high point of the vortex theory of atoms. Around its appearance, Kelvin and others published a great number of papers on the theory and many prominent physicists spoke in awe of the idea of reducing matter to a few hydrodynamical equations; in the same sentence where Maxwell called the mathematical difficulties of the vortex atom to be "enormous", he admitted that "the glory of surmounting them would be unique".[11]

It was at this high point that research on the vortex theory was more or less taken over by

[9] Kelvin 1867, p. 17.
[10] Maxwell 1875, p. 45.
[11] Maxwell 1875, p. 45.

the younger generation of English physicists, like Karl Pearson, Georg FritzGerald, and William Hicks. Because the vortex theory was proposed by such an eminent figure as Kelvin and that the theory promised to be a theory of everything just based on fluid mechanics, it could expect to capture interest from most physicists. To arouse more than just interest, though, the theory had to deliver some results: explain known phenomena or predict new ones. Yet this was lacking from the research on vortex atoms. Kelvin and his followers made much progress in hydrodynamics itself but from the start in 1867 until the mid 1880's they could not deliver a satisfactory kinetic theory of gases, a theory of gravitation, or a theory of electromagnetism based on vortex atoms.

Vortex sponges

Around 1885 a new type of vortex theory emerged, the so-called 'vortex sponge theory'. Instead of viewing atoms as consisting out of small, separate vortices, this type of theory supposed that the ether was completely filled with tiny vortices. These tiny, close-packed vortices made up large sponge-like structures, which gave this category of models its name. The difference with Kelvin's original idea was that in the vortex sponge theory atoms were thought to be constituted of these larger sponge structures instead of single vortices. The motivation for the sponge theories was to have one ether for both atoms and electromagnetism. It is important to keep in mind that the vortex theory was partly motivated by the need for an ether from other theories of physics like theories of light and electromagnetism: the ether was presupposed to be existent. Kelvin, though, did not at first speak of vortices in the ether, he rather spoke of an "universal plenum", but the ether would of course be the single best candidate for this plenum. Until the eighties of the nineteenth century, Kelvin and his followers were more or less allowed to freely speculate about vortices in such an universal plenum. Yet the ether was originally a child of the theories of light and electromagnetism and in some way the ether of the vortex atoms had to be reconciled with the ether of these theories: two ethers was in the context of unification regarded as undesirable. An ether containing sponge-like structures could, according to Hicks, FitzGerald, and Kelvin, account for the transmission of light and other electromagnetic waves, something that was problematic in the early atomic theories of ether. In his 1888 lecture to the 'British Association for the Advancement of Science', FitzGerald discussed the state in which the vortex theory was at the time. Although he still spoke hopefully about the theory, reading it with hindsight makes clear that the idea of the vortex atom was already in decline. At the time the vortex theory of atoms was over twenty years old and over a hundred papers had been published on the topic so it could be expected that FitzGerald was going to report some of the progress that had been made over the years. Yet, it appears from FitzGerald's speech as if he started from scratch with the vortex atom. The text resembles much of Kelvin's first paper from 1867, it contained no details of how certain phenomena could be explained, FitzGerald only gave a general talk about how great and attractive a vortex theory of matter could be. The following quote may illustrate this: "Hard particles are abominations. Perhaps the impenetrability of a vortex would suffice".[12] That is all, no mention of any of the work by Kelvin or Thomson who tried to a develop a kinetic theory of gases from the vortex theory. Apart from that, the term "abominations" resembles strongly the "monstrous assumption" which was used earlier by Kelvin.

William Hicks, on the other hand, made more progress in the vortex theory. He repeatedly published new ether sponge theories and went into a fair amount of detail to model an electromagnetic theory based on vortex sponges. In 1895, he also gave a lecture for the British Association on the vortex theory of atoms, although it had already long been abandoned by Kelvin, Thomson, and most other members of the scientific community. At the beginning of his lecture, Hicks stated that to him there were two ways of dealing with a theory that is in trouble: "one is to give up the theory, the other is to try to see if it can be modified to get over the difficulty".[13] From the rest of the speech it became very much clear that with the vortex theory of atoms Hicks was willing to allow much modification to keep it out of trouble. To cover up all of the problems, and to include electromagnetism and gravity into the theory, Hicks proposed a new type of vortex sponge theory: the "cell theory of ether". In short, the proposal was to assume that ether was divided into have tiny rectangular boxes, each containing a vortical current: further details will be a topic in the second chapter.

Decline of the theory

No noteworthy paper was published on the theory after 1895, and from the foregoing history of the vortex atoms I think it has become clear that from Kelvin's original idea of 1867 the vortex theory of matter evolved into a collection of many ideas concerning single rings, multiple rings, vortex-sponges, and vortex-cells. For Ludwig Boltzmann, the Austrian physicist and fierce promoter of the atomic model, this variety of different ideas was certainly not a blessing: "every second-best [physicist] felt himself called upon to devise his own special combination of atoms and vortices, and fancied, having done so, that he had pried out the ultimate secrets

[12] FitzGerald 1888, p. 561.
[13] Hicks 1895, p. 596.

of the Creator."[14] Whether this harsh statement is justified or not, it is one of the very few continental reactions on the vortex theory. This highlights an interesting historical fact about the vortex theory of atoms: the theory was almost exclusively an English affair. This is remarkable because although historians of science have given the vortex atom theory little attention, in the second half of the nineteenth century the theory was a significantly large research program in England. The book "A history of European Thought in the Nineteenth Century", by the English nineteenth century historian John Merz, also contains this remark:

> The vortex theory is the most advanced chapter in the kinetic theory of matter, the most exalted glimpse into the mechanical view of nature. Though suggested by Helmholtz, it has, as already stated, been limited almost exclusively to [England]. If science still shows international differences and patriotic predictions, this affords one of the few remaining examples.[15]

From this quote, written in 1904, it also becomes clear that some people, like Merz, remained hopeful about the theory long after it had been abandoned by the scientific community.

Besides a handful of papers and a dozen or so notes on the vortex atom, scientists in the United States, France, and Germany practically ignored the theory. Helge Kragh also finds this "most remarkable".[16] He concludes that the theory was developed only by British scientists mainly because of the "Zeitgeist of Victorian Britain", which he characterizes by mathematical guided research with an accent on hydrodynamics and a desire for mechanical explanations of natural phenomena, combined with "extra-scientific ramifications" in a theory.[17] Whether it was due to the absence of this 'scientific spirit' in Germany that the vortex theory was ignored by German physicists is a conclusion Kragh does not draw.

1.4 Research question

Why was the vortex theory of atoms ignored by German scientists? Next to England, Germany was in the second half of the nineteenth century a major center of scientific research and also home to many prominent physicists who worked on various hypotheses surrounding the atomic theory. Furthermore, the English interest in vortex rings was instigated by the paper of Helmholtz, who was one of Germany's most important scientists of the nineteenth century. Both

[14] Boltzmann 1895, p. 414.
[15] Merz 1965a, p. 66.
[16] Kragh 2002, p. 94.
[17] Kragh 2002, p. 95.

Silliman and Kragh do not attempt to explain the lack of German interest in the vortex theory. Alkemade does give a hint of an explanation, suggesting that the vortex theory of atoms did not fit into the nineteenth century mainstream philosophical movement of Neo-Kantianism.[18] To find whether Alkemade's suggestion is correct and, if it is not correct, to look for for other explanations of why the vortex theory of atoms was ignored in Germany is the main goal of this thesis.

However, before these explanations can be given, the reason for the success of the vortex theory in England has to be further explored. Kragh points for this reason at the Victorian Zeitgeist, which he defines by its main properties as noted above. To me, though, this is an unsatisfactory and incomplete answer. The character of nineteenth century English physics has been investigated by many historians and numerous books have been written in which the characteristics of mechanical based theory, fluid dynamical research, and spiritual-guidance are summed up as the aspects of Late-Victorian science. Yet, these books are mostly focussed on the development of Maxwell's theory of electromagnetism. To draw conclusions about every theory in physics that was developed in England during the second half of the nineteenth century solely based on a general scientific culture does not, I think, deliver a precise answer. Therefore, I will go through the lives of Kelvin, Thomson, and Hicks, the three main players in the vortex atom theory, together with the lives of FitzGerald, Tait, and Maxwell, who stood somewhat farther away from the theory. In doing this, I will try to create a more precise picture of nineteenth century English physics, which is specifically about the vortex theory of atoms. Then I can conclude which characteristics of the vortex atom theory appealed to the above listed scientists and thus explain the popularity of the vortex atom.

In this introductory chapter, a brief history of the vortex atom theory has been given, which came with a sketch of what the theory was about. Yet this sketch is not sufficient to explain why the vortex theory's characteristics matched the characteristics of Late-Victorian science, or to explain why German scientists almost completely ignored the theory. This is why the following chapter is about the vortex atom theory itself, in which I will give a more detailed picture of vortex atoms. After I have acquired a good grip on the concept of the vortex atom theory, I will move on to chapter three in which I investigate the scientific culture in which the vortex theory of atoms was being developed in. The fourth and final chapter of this thesis explores the German scientific culture around the time of the vortex theory of atoms, to formulate an answer to the main question of this work.

[18] Alkemade 1994, p. 36.

CHAPTER 2

The Vortex Theory of Atoms

It is only within the last few years that man has won the battle of old, has snatched the thunderbolt from Jove himself and enslaved the all-pervading ether.

— FitzGerald

This chapter will give an as complete as possible overview of the vortex theory of atoms. How did Kelvin, Thomson, and other scientists picture the atoms as vortices in the ether? That will be the main question to be answered here.

2.1 Properties of gases and molecules

As noted in the introductory chapter, the nineteenth century was a decisive moment for both the concepts of atoms and the ether. While the ether got support from theories about light and electromagnetism, atoms were a crucial assumption in another two important theories that emerged during the nineteenth century: the kinetic theory of gases and the chemists's law of definite proportions. Where the kinetic theory of gases reached its more complete form at the end of the century thanks to Boltzmann, its foundations were laid by David Bernoulli, Rudolf Clausius, and Maxwell with his formulation of the Maxwell distribution. The law of definite proportions, originally from the Frenchman Joseph Proust, states that a chemical compound always contains exactly the same proportions of elements by mass. Although in its original form the law was independent of any hypotheses about the atomic structure of matter, it suited Dalton's atomic theory very well, which appeared around the same time. The point is: the kinetic theory of gases and the law of definite proportions were, unlike electromagnetism, favorable to the belief in the existence of atoms or, in the terminology of the scientists back then, 'molecules'.

2.2 Requirements made to atoms

One could speculate about the origin or shape of these molecules, but in order to make the kinetic theory of gas work, and to be in agreement with the chemists's law of definite proportions, the ultimate building blocks were required to have some particular properties. Maxwell formulated in 1878 three essential conditions which the atoms of whatever atomic theory had to satisfy: "permanence in magnitude, capability of internal motion or vibration, and a sufficient amount of possible characteristics to account for the difference between atoms of different kinds."[1] The first requirement came from the law of definite proportions: one atom of oxygen has the same weight as every other atom of oxygen. The second requirement is imposed by the kinetic theory of gases which assumes atoms in a gas to collide elastically with the walls of the container and with each other. The last requirement comes from the everyday observation of the variety of matter in the macroscopic world. Although Maxwell posed these requirements after Kelvin had introduced his vortex theory of atoms, historian of science Silliman noted that it is likely that Kelvin had the same properties in mind for vortex atoms while constructing his theory.[2] To see how the vortex atom would account for these requirements is a good starting point to get a grasp of the vortex theory of atoms.

"Permanence in magnitude"

Helmholtz showed in his paper that a vortex ring in an ideal fluid would always consist of the same portion of fluid. So a vortex atom would always preserve its mass. The mass of one vortex atom would then be invariable, which was favorable because then mass in general would be conserved. However, this does not explain why all atoms of one element are of the same mass. This required the assumption that all the vortex atoms were constructed in an identical way.

"Capability of internal motion or vibration"

The requirement of elasticity was one of the main reasons why Kelvin was critical about the Daltonian atom. "The clash of atoms", as Kelvin called the elastic collision between atoms, "has been invoked by his modern followers to account for the elasticity of gases".[3] According to Kelvin, the vortex atom did not need such an ad-hoc hypothesis. Although he could not prove that two vortices would collide elastically in a perfect fluid, he justified the assumption in his

[1] Maxwell 1875, p. 45.
[2] Silliman 1963, p. 469.
[3] Kelvin 1867, p. 16.

first paper with the behavior of smoke-rings in the experiments of Tait: "the elasticity of each smoke-ring seemed no further from perfection than might be expected in a solid india-rubber ring of the same shape". To assume that in an ideal fluid like the ether vortex rings were completely elastic was "at least as good a beginning as the 'clash of atoms' to account for the elasticity of gases."[4]

Spectral phenomena

The elasticity of vortex rings also promised a very natural explanation of a newly discovered phenomenon. Spectral analysis of elements was one of the most important discoveries in physics of the nineteenth-century. It allowed for identification of every element only by looking at the light it emitted at a certain temperature or the absorption of certain wavelengths of light by the element. For the emission spectrum, it was thought that the atom of an element had certain vibrational modes, with a frequency corresponding to the wavelength of the emitted light. This capability of internal vibration was another property that had to be given to the Daltonian atom on an ad-hoc basis. Even worse, many elements possess more than one spectral line, which led Kelvin to conclude that Daltonians had to assume that, to account for its emission spectrum, "the molecule of sodium, for instance, should be not an atom, but a group of atoms with void space between them."[5] This arrangement of atoms could, according to Kelvin, in no natural way be stable and conform to the first requirement of Maxwell.

The vortex atom, on the other hand, already possessed the ability to vibrate. In his first paper, "On Vortex Atoms", Kelvin acknowledged that he did not have a complete mathematical analysis of a vibrating vortex column, but he was working on it. Kelvin regarded the natural explanation of this new, exciting, science of spectral analysis to be a great merit of his theory. However, Kelvin knew that to convince the scientific community, he had to give an analytical description of the vibration of vortex rings; he had to prove that the rings would remain stable during this vibration. Yet vortex mechanics is a very difficult mathematical subject. This is why he returned to the problem only in 1880, in a paper titled "Vortex Statics". There, he derived from an analogy with bent elastic wires the first four fundamental modes of vibration of a single vortex.[6]

J.J. Thomson, in his 1882 Adams price winning Treatise, also gave an elaborate, and impressive, mathematical analysis of the equation of motion of a deformed vortex ring. He found

[4]Kelvin 1867, p. 16.
[5]Kelvin 1867, p. 17.
[6]Kelvin 1880a.

that the frequency of a vibrating vortex ring is given by[7]

$$f = \frac{2\pi}{\sqrt{n^2(n^2-1)}}\frac{a}{V}, \tag{2.1}$$

where n is a measure of how much the vortex ring deviates from a perfect circle during the vibration, a the radius of the vortex-tube, and V the translational velocity of the ring as a whole. From this he concluded quantitatively that "the time of vibration is 0.289 times the time taken by the vortex ring to pass over a length equal to its circumference." And qualitatively that "these equations show that the circular vortex ring is stable for all small displacements of its central line of vortex core."[8]

Going back to Kelvin's paper, "On Vortex Atoms", Kelvin suggested what the sodium-atom would look like in his theory. To account for the two spectral lines of this element, he argued that it would be very natural to assume that sodium did not consist of one but of two vortex rings, both having a vibrational mode corresponding to one spectral line. The stability of this configuration could be explained by letting the two rings be intertwined with one another.

"Characteristics to account for the difference between atoms of different kinds"

This brings us to the third requirement of an atomic model: the ability to explain the variety of elements. Up until the last paragraph, we have only discussed single circular vortices as a model for the atom, but there is no reason for a restriction to this shape. Single vortices could be intertwined in every possible way and infinite configurations of multiple, knotted, vortex rings were thinkable.

How these rings could be knotted was a mathematical subject taken up by Kelvin's friend Peter Tait, who was one of the first to investigate the mathematical theory behind knots. Knot theory, today an important topic in various fields of modern mathematics and physics, is thus largely an offspring of the vortex theory of atoms.

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[7] Thomson 1883, p. 35.
[8] Thomson 1883, p. 35.

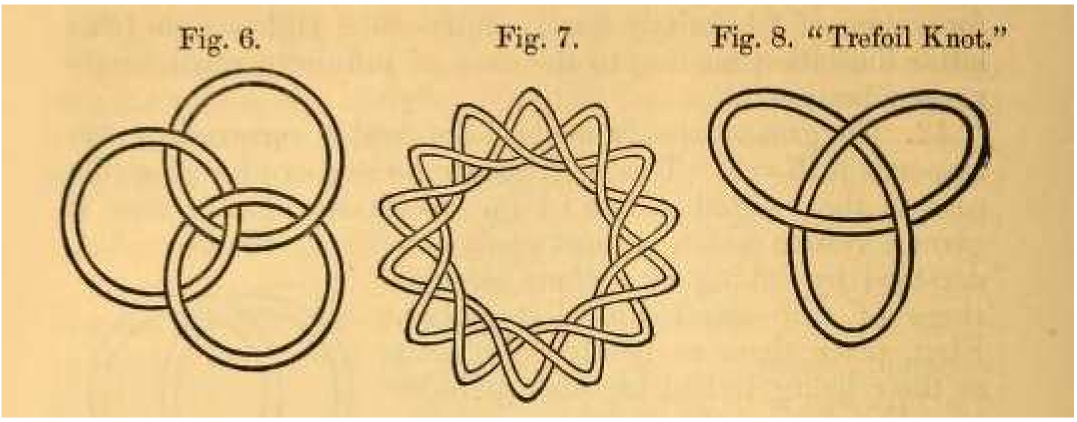

Figure 2.1: Different types of vortex rings, from Kelvin's 1880 paper "Vortex Statics". This is how Kelvin thought different elements were possible in the vortex theory of the atom. Every element would be represented by a particular type of configuration. (Kelvin 1880a, p. 104)

Yet the problem that Kelvin faced with these exotic forms of vortex rings was that he could not mathematically show that they were stable configurations, as the first of Maxwell's requirements demanded. That his vortex atoms would be stable configurations was a very important aspect for Kelvin, mostly because of religious arguments, a theme that will be treated in chapter three. Kelvin went through quite some effort in his later papers to prove that several of these configurations were stable; this was for instance the main goal of the paper "Vortex Statics".[9]

2.3 Vortex theory of gases

Now that the three main requisites of an atomic model, to Kelvin's idea, could be met, he had to show that the main equations of physics could be derived from the vortex theory if it was to transcend the level of an hypothesis. As already noted above, the second half of the nineteenth-century was an exciting time in physics with new and successful theories of electromagnetism, thermodynamics, and, at issue here, the kinetic theory of gases. The kinetic theory of gas gave scientists a picture of how and why the laws of thermodynamics worked, assuming that the atomic hypothesis was correct.

[9]Smith & Wise 1989, p. 431.

Pressure

A gas exerts pressure. To explain this phenomenon with the assumption that a gas consisted out of vortex atoms was a good first step towards a full vortex theory of gases. Kelvin's first and only attempt to do this was in 1881 with the publication of the article "On the average Pressure due to impulse of Vortex-Rings on a Solid". In the kinetic gas theory, pressure is explained by gas particles colliding with the walls of a container. The problem with vortex rings is that, as Helmholtz had shown,[10] a vortex ring upon collision with a wall would not bounce back but rather slow down upon approaching and increase in diameter, elongating along the sides of the wall. How a pressure would follow from this behavior was something that had to be explained and this was what Kelvin tried to do in his paper. He first assumed a vortex ring in a cylindrical container, the ring traveling along the central axis towards one of the ends of the cylinder. Upon approaching the end, the ring would slow down and expand, but, as Kelvin argued, this would be limited by the circular walls of the cylinder. As a result, the ring would bounce back and deliver a part of its momentum to the wall of the cylinder. Kelvin then switched from a cylinder to the wall of a randomly shaped container of gas. This wall would be under a constant bombardment of approaching vortices, which elongated along the sides the wall. Yet in the case of a large number of bombarding vortices, Kelvin claimed that "for every vortex-ring that gets entangled in the condensed layer of drawn-out vortex-rings another will get free."[11] A large collection of vortices that elongated on the wall of a container would interact with a newly approaching ring in such way that the new ring travelled towards the wall as if it was traveling along the axis of a cylinder, being bounced back and thus delivering momentum on the wall. "In the statistics of vortex-impacts", Kelvin concluded, "the pressure exerted by a gas composed of vortex-atoms is exactly the same as is given by the ordinary kinetic theory, which regards the atoms as hard elastic particles."[12]

The most elaborate attempt to explain pressure and some other relations of kinetic gas theory was done in Thomson's Treatise. To show that a gas of vortex atoms could account for pressure, Thomson tried to derive Boyle's law, $pV = \frac{1}{3}T$, from the equation of motion of a vortex ring. His end result did not match Boyle's law exactly, though. It had an extra term which predicted that the product between pressure and volume was "a little less than the value

[10] Helmholtz 1867, p. 510.
[11] Kelvin 1881, p. 47.
[12] Kelvin 1881, p. 47.

given by Boyle's law":[13]

$$pV = \frac{1}{3}T - \frac{1}{6}\rho \iint (u^2 + v^2 + w^2)(xdydz + ydxdz + zdydx) \tag{2.2}$$

where ρ is the density of the fluid and u, v, w the velocities of the fluid at coordinates x, y, z. Thomson explained the deviating term as representing the flow of gas along the walls of the container. This deviation from Boyle's law did not discourage Thomson, on the contrary. It was shown by Henri Regnault, Kelvin's mentor, that Boyle's law was an approximation, and experimental values were slightly less then the predicted values. Thomson could happily conclude that "in this respect [the vortex atom] compares favorable with the ordinary theories, for if we assume the molecules to be elastic spheres we cannot explain any deviation from Boyle's law".[14]

Temperature

Besides pressure, temperature is also an intrinsic property of a gas. Again, Thomson's Treatise provides us with the most complete account of the property of temperature based on the vortex atom theory. In the ordinary Daltonian atomic model, temperature is equivalent to the mean kinetic energy (or velocity) of the individual atoms. This relationship between temperature and velocity is not that simple for vortex atoms. Thomson showed in his Treatise that the radius of a vortex ring will increase if its energy increases and, as Kelvin had already shown in a note added to Helmholtz's paper,[15] the radius of a vortex ring is inversely proportional to its translational velocity: $V \propto \frac{1}{R}$. In short: contrary to the standard atomic model, an increase of temperature in a vortex-gas meant a decrease in the mean velocity of the vortex atoms.

"The difference between the effects produced by a rise in temperature on the mean velocity of the molecules will probably furnish a crucial experiment between the vortex atom theory and the ordinary kinetic theory of gases,"[16] so argued Thomson after he had remarked the foregoing result. This crucial experiment was based on the phenomenon of thermal effusion, i.e. the behavior of two gases separated by a porous wall. If the densities on both sides of the porous wall are equal and sufficiently small, then the rate at which the atoms flow from one side to the other will depend only on the temperatures of the two sides. If the temperature on side A is higher then on B's side, more atoms will go from A to B than vice versa. In the vortex

[13] Thomson 1883, p. 112.
[14] Thomson 1883, p. 112.
[15] Helmholtz 1867, p. 512.
[16] Thomson 1883, p. 112.

atom hypothesis, where a higher temperature means lower velocities, the net flow of vortex atoms will be the other way, from the low to the high-temperature side. To decide between the standard atomic model and the vortex atom theory, one simply had to check the rate at which the atoms flow from A to B and B to A in the experiment described above. If the execution of this experiment had been easy one would never have heard about the vortex theory of atoms anymore, but as Thomson writes: "These experiments would, however, be difficult to make accurately."[17] In addition, Thomson notes that this inverse relation between temperature and velocity only holds for single vortex rings, equivalent to a monoatomic gas. For a gas consisting out of diatomic molecules, Thomson argued, the temperature-velocity relation is the same as in the standard atomic model.

2.4 Vortex theory for chemistry

The best picture of what the atomic model of vortices would look like can be found at the end of Thomson's Treatise. Here, he applied the vortex theory to explain the chemical theory of valence and thus explained why molecules are composed of the number of atoms in the way that they are. For reasons of simplicity, Thomson assumed that all vortex rings were of the same strength, i.e. the product of rotational velocity with the radius is equal for every vortex ring. Atoms were made of these rings; the most simple element could be pictured as a single ring. Other elements could be represented by single rings that were knotted and again other elements could be composed out of multiple, chained rings. Thomson had derived earlier that the highest number of linked rings that would form a stable configuration was six, so it can be said that atoms in the vortex theory consisted of one to six rings, all of the same strength, which could be knotted, intertwined, or both, in such a way that they could not be separated without cutting a vortex tube, which is impossible in an ideal fluid.

Molecules, then, were pictured as multiples of these atoms in the vicinity of each other. Through mutual interaction they remained together. There were some restrictions on the formation of molecules. A molecule consisted of various components or, as Thomson called them, "primaries". Every primary could consist out of one or more atoms, which were called "secondaries". For a stable molecule, every primary had to be of the same strength or, recall that all vortex rings were supposed to be of the same strength, had to have the same number of rings. An atom of two linked rings for instance could then only form a stable molecule together with another atom of two rings, or of two atoms of a single ring.

[17] Thomson 1883, p. 113.

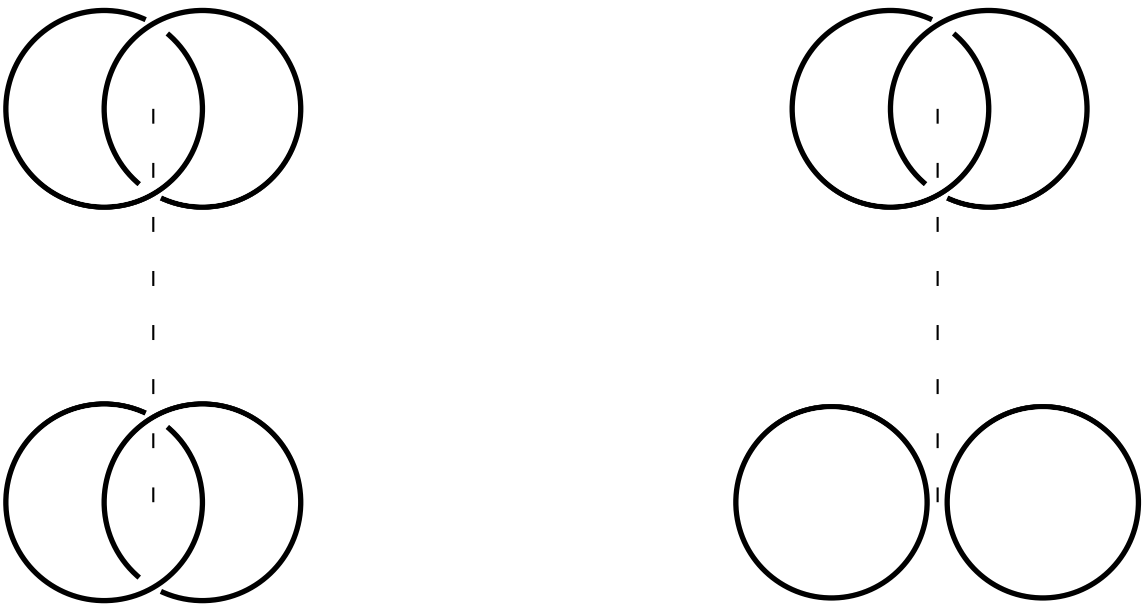

Figure 2.2: An atom consisting of two rings could only form a stable molecule together with another molecule of two rings or with two atoms of one ring. The molecule on the left could be a representation of dioxide, with two oxygen atoms. The one on the right then could be water, the two single rings representing hydrogen.

As already mentioned, Thomson proved that the highest number of linked rings together in a stable configuration was six. Six was thus the maximum number of rings out of which an atom could consist. This largest atom possible could form a molecule with six atoms of another element that consisted out of one ring. Therefore, it would not be possible for any atom to form a stable molecule with more than six atoms of another element. This result was very favorable to the vortex theory because at the time it was held that there was only one molecule which was composed in such a way, namely tungsten hexachloride (WCl_6), and no molecule was known which had more than seven primaries.

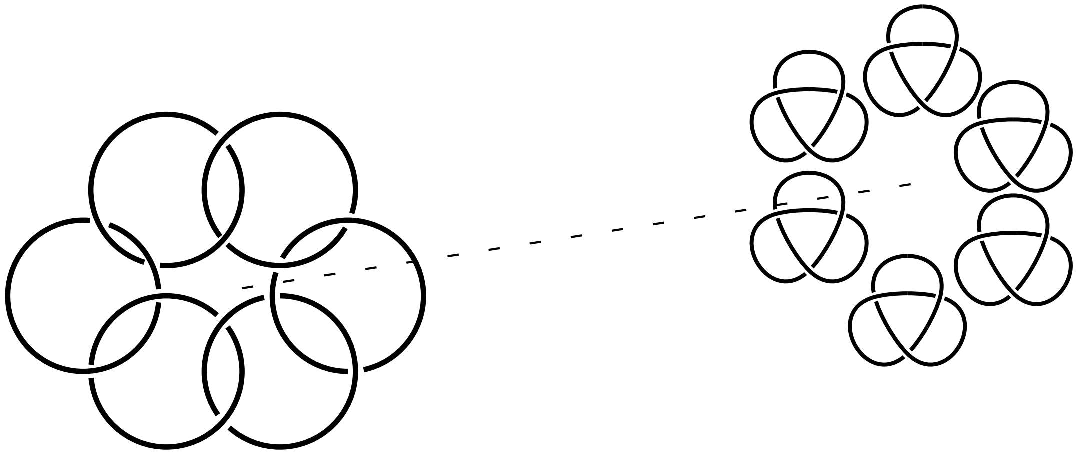

Figure 2.3: A possible model for tungsten hexachloride, the only molecule at the time known to be composed of one element together with six others. The tungsten atom on the left represent the maximum number of linked rings. Notice that the chloride atoms represented on the right are made out of one vortex ring, just like the hydrogen in figure 2.2, but that they are knotted.

Already in his Treatise, Thomson acknowledged that without some arbitrary assumptions he could not account for every molecule in this way. The various compounds of nitrogen, for instance, conflicted in the determination of the number of knots in the nitrogen atom. The composition of ammonia, NH_3, could either consist of two primaries: N—H_3, in which case nitrogen had three times as many rings as hydrogen. In the other case, nitrogen could have the same number of rings as hydrogen so that ammonia has four primaries: N—H—H—H. However, nitric oxide, NO, was also known as a molecule and this implied nitrogen to have the same number of rings as oxygen. Yet, as seen in figure 2.2, oxygen was thought to have twice as many rings as hydrogen, which determined nitrogen also to have twice as a many rings as hydrogen. It is worth reading how Thomson tried to fix this inconsistency:

> It is however conceivable that an atom might go through a process that would cause it to act like one with twice as many links. To illustrate this take a single circular ring and pull the opposite sides so that they cross at the center of the ring, forming a figure of eight, then bend one half of the figure of eight over the half, the continuous ring will now form two circles whose planes are nearly coincident. If the circular ring represented a line of vortex core the duplicated ring would behave like one with twice as many links as the original ring.[18]

This 'flexibility' of vortex rings is characteristic for the vortex theory of atoms itself: if a

[18]Thomson 1883, p. 123.

problem arose it could be solved just by bending and twisting vortices or, as we will see next, fabricating whole structures of vortices in the ideal fluid, completely designed to account for every natural phenomenon thinkable.

2.5 Vortex sponges, vortex cells, and hollow vortices

Through the work of Thomson it might appear as if the general idea of vortex atoms was clear and that details would determine whether the theory was successful or not. In reality, around 1880 a completely different approach on a vortex theory of matter was instigated which developed parallel to the vortex theory pictured in Thomson's Treatise.

Central to this research was the so-called 'vortex-sponge', first introduced by Kelvin in a general paper on vortex motion in 1880:

> what may be called a vortex sponge is [...]; a mixture homogenous on a large scale, but consisting of portions of rotational and irrotational fluid, more and more finely mixed together as time advances.[19]

Apparently, though, Kelvin did not put as much effort in the vortex sponge as he did in his original vortex atoms. Two well-known physicists did spent a lot of their time constructing vortex-sponge theories: Georg FitzGerald and William Hicks.

The vortex sponge theory was, amongst other things, an attempt to bring vortex atoms into the picture of the e electromagnetic theory of Maxwell. It has to be remembered that initially Kelvin did not, out loud, identified the luminiferous ether as the ideal fluid in which he pictured his vortex atoms. Originally, the ether served to transport electromagnetic phenomena and it was very much desirable to have the atoms in the same ether. This is why Hicks in 1885 published a short paper, a note rather, with the pertinent title "On the Constitution of the Luminiferous Ether on the Vortex Atom Theory". Short as it was, Hicks posed the problem he saw in the first sentence of his paper: "The simple incompressible fluid necessary on the vortex atom theory is quite incapable of transmitting vibrations similar to those of light."[20] To resolve this, Hicks argued that if the fluid, or ether, would contain tiny, close-packed vortex rings, smaller than the wavelength of light, these rings would make the propagation of light possible by allowing transverse vibrations in the ether. Ten years later, at the 65th meeting of the 'British Association for the Advancement of Science', Hicks presented a detailed picture

[19] Kelvin 1880b, p. 474.
[20] Hicks 1885, p. 930.

of his vortex sponge theory. Although the vortex atom theory was already in decline, Hicks nevertheless enthusiastically proposed a "cell theory of the ether". Hicks hypothesized that the entire ether was divided into "rectangular boxes", every one containing a circulation of ether. These "cells", smaller then the wavelength of light, could be partly deformed and thus account for the propagation of (light)waves. The cells are what Hicks called the 'primary medium', the gross motion of the cells he called the 'secondary medium'. Having already wandered this far into hypothetical cell structures of ether, Hicks decided that whether atoms are the circulation of the primary medium on a small scale or rather vortical motions of the ether on a large scale "is a matter to be left open in the present state of the theory".[21]

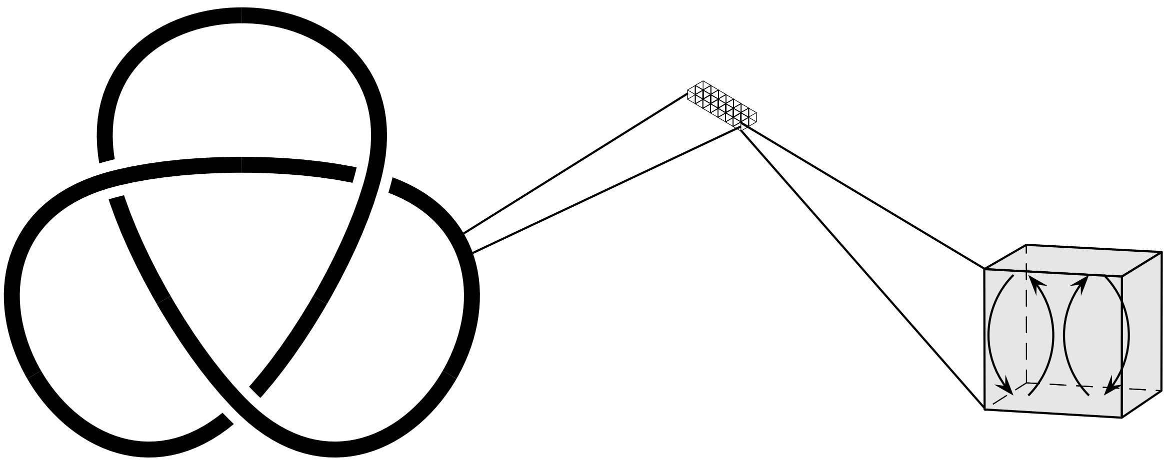

Figure 2.4: A possible picture of Hick's vortex-sponge theory. The larger vortex atom ring would consist out of small cells, made up out of the circulation of ether. In the case of this representation, atoms are made up out of the motion of the "secondary medium", which on the whole was thought to attain a sponge-like structure.

FitzGerald's largest contribution to vortex sponges was his paper titled "On an Electromagnetic Interpretation of Turbulent Liquid Motion", published in the spring of 1889.[22] The goal of this paper was not so much to incorporate the vortex atoms into a light-carrying ether as it was to give a sponge-model of Maxwell's electromagnetic theory. Initially, the paper was received enthusiastically. Especially by Oliver Lodge, British physicist and developer of wireless telegraphy, who praised FitzGerald's sponge theory as "not only optically, but also electrically, sufficient."[23] Yet the enthusiasm quickly faded, largely because Kelvin pointed out to FitzGer-

[21]Hicks 1895, p. 601.
[22]FitzGerald 1889.
[23]Lodge 1889, p. xii, Hunt 1984, p. 178.

ald that his paper contained many mistakes which, when solved, undermined the stability of the vortex structures that FitzGerald proposed.[24]

Returning to Hicks, besides vortex sponges and vortex cells he occupied himself also with so-called "hollow-vortices". In the original idea of vortex atoms, vortex rings were thought to be 'solid' portions of ether that were circulating around an axis. Yet in this original idea, in which the ether as a whole had a constant density, Hicks could not see how the different densities of macroscopic objects were to be explained. To solve his problem, Hicks started to investigate in the beginning of the 1880s vortices in a fluid which had a different density than its surrounding medium. Including these investigations, Hicks considered vortex rings that had a vacuous core. It turned out that these hollow vortices could account for spectral phenomena in a very elegant manner, even better than Kelvin's solid atoms. As Kragh remarks, these hollow vortices present a good example of how quick the mathematical work on the vortex theory could get independent of physical considerations.[25] Following from the investigation of vortices with varying densities, vacuous vortex atoms gave no explanation for the densities of macroscopic objects. Yet once it was found these hollow atoms were mathematically convenient to handle, the physical motivation to develop the theory further was not as important anymore.

2.6 Vortex theory of gravity

In modern terminology, the vortex theory of matter can be labelled as a 'theory of everything'. As with contemporary attempts at such theories, the vortex theory was also expected to give an explanation of gravity. In fact, Peter Tait proclaimed that "the theory of vortex-atoms must be rejected at once if it can be shown to be incapable of explaining this grand law of nature".[26] When we follow the historian van Lunteren, the explanation of gravity by means of vortex atoms can be divided into two categories: corpuscular- and hydrodynamical models.[27]

The corpuscular models were inspired by the eighteenth century theory of gravitation of Georges-Louis Le Sage. In short, Le Sage hypothesized the existence of tiny particles that fly through space and, upon colliding with a mass, deliver a portion of their momentum to that mass. A single mass floating through space would be in equilibrium because it is hit by the particles on all sides equally. Two masses, then, would shield each other from particles traveling along the line connecting the two bodies and hence, the two bodies are being pushed

[24] Hunt 1984, p. 182.
[25] Kragh 2002, p. 45.
[26] Tait 1879, p. 298.
[27] Lunteren 1991, p. 276.

towards each other due to the net momentum delivered by the particles on the far sides of both masses. Kelvin himself suggested such a vortex theory of gravity in 1873,[28] but it was most extensively worked out by the telegraph engineer Samuel Tolver Preston.[29] Perhaps because of his profession, Preston developed a theory that missed the spirit of the original vortex theory and therefore it was not appreciated by Kelvin and the other physicists. It assumed, for instance, the unwanted assumption of two ethers, one for gravity and one for other phenomena.[30]

More successful was the category of hydrodynamical models which were closely related to the vortex sponge theories. The two most notable physicists working in this direction were Karl Pearson and, not surprisingly, Hicks. In 1879, Hicks investigated the work of the Norwegian mathematician Carl Anton Bjerknes on the motion of a sphere in a fluid. Hicks concluded that if hollow vortex atoms would pulsate with a constant period, it could be shown that every atom would attract other pulsating atoms in accordance with the law of gravity, i.e. inversely proportional to the square of their mutual distances.[31] However, Hicks' theory was not received very enthusiastically either, mostly because it required every atom to pulsate at the same rate, which was conceived as an unnatural assumption. Furthermore, Hicks' hollow vortices in general, although from a mathematical point appealing, did away with the philosophically preferred homogeneity of the ether.[32]

At first, Pearson also investigated the possibility of pulsating atoms as an explanation of gravity but in 1889 he turned to another hydrodynamical approach. It was around this time that the vortex theory of atoms was discarded as a serious scientific theory and was left to the realm of metaphysical discussions. Pearson proposed to see atoms as ether-squirts, tiny 'holes' in space from which ether flowed. These ether-squirts would attract each other like the pulsating spheres. The difference in elements was then due to a variable ether flow from these squirts; every element had a specific flow of volume ether per unit of time. To prevent the universe from overflowing with ether, Pearson speculated about ether-sinks or 'negative matter' which would be repulsed by the ether squirts. Following along this line of speculation, our part of the universe would consist of one kind of atoms, squirts or sinks, while the other kind of atoms, sinks or squirts were pushed away long ago to the other corner of the universe, but this is a topic outside the scope of this thesis.[33]

[28]Kelvin 1873.
[29]Preston 1877.
[30]Lunteren 1991, p. 279.
[31]Hicks 1880a.
[32]Kragh 2002, p. 45.
[33]Pearson 1892.

2.7 Conclusion and reason for decline

The goal of this chapter was to present an as complete as possible picture of the vortex theory of atoms. If the reader of this text would by now describe the vortex atom theory in short as a nineteenth century alternative to Dalton's atomic theory, which grew into a wild array of theories of everything, based on fluid-dynamics, then I have reached that goal

When Kelvin first published his vortex theory in 1867, the idea was simple: an atom was nothing more then a swirl in a fluid. Next to its almost irresistible character to most physicists, the vortex atom also promised to yield natural explanations of phenomena like spectral lines and the wanted elasticity of atoms. Yet, as with many other scientific theories, after closer investigation the prospected merits of the theory turned out to be much harder to obtain. The general idea of a theory of everything is to account for all natural phenomena with a single theory. However, in the case of the vortex theory, almost for every phenomena a different model was developed. FitzGerald acknowledged this flexibility and therefore concluded that "with the innumerable possibilities of fluid motion it seems impossible but that an explanation of the properties of the universe will be found in this conception."[34] A good example of this is how Thomson solved the inconsistency in the number of rings of nitrogen. The unlimited flexibility of the theory allowed Thomson to bend and twist atoms in any way he liked and thus model the theory exactly after the needs of nature. This adaptability of the vortex theory, which enabled it to serve as a basis for virtually all scientific theories, was at the same time the reason why the theory eventually was abandoned. The vortex theory of atoms lacked internal constraints and FitzGerald was probably right in his quote that it is impossible not to explain everything with the flexibility of a perfect ether. Kragh draws the same conclusion and summarized the reason for the abandoning nicely: "the theory explained too much – and therefore too little."[35]

[34]FitzGerald 1888, p. 561.

[35]Kragh 2002, p. 92.

CHAPTER 3

English physicists and physics

We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.

— Duhem on nineteenth century English electromagnetism, 1914

The vortex theory of atoms was thought to be a potential candidate for a theory of everything for about twenty years in England. Because the theory did not yield any experimental confirmation there has to be another reason for its endurance. In this chapter I will go through the lives of the main figures behind the vortex theory of atoms to find out why they were so interested in developing this theory.

It is fair to say that the vortex theory of atoms was a medium sized research program in England. For a select group of scientists it certainly superseded the level of scientific Spielerei: vortex atoms were the subject of a large number of publications in the most distinguished journals. My estimation on the actual number of publications in prominent journals like the Philosophical Magazine is about one hundred. About sixty of those were written by one of three members of the core group around the vortex theory: Kelvin, J.J. Thomson, and William Hicks. It is not the case, though, that these three men devoted the majority of their time to the theory. Kelvin was occupied with numerous other activities in science, like the theory on heat and electromagnetism, but also practical research on marine compasses and telegraph lines. Thomson had many duties as the head of the Cavendish laboratory and most of Hicks' time went into his occupation as the principal of Firth College, which he helped transform into Sheffield University. Of the group of a dozen scientists around this core group, Fritzgerald was the most productive when it came to publishing papers on vortex atoms. He published about ten papers in various journals. For people like Maxwell, the vortex atom theory remained somewhat of a curiosity, although he could at times be enthusiastic about vortices.

Why did the vortex theory of atoms attract so much attention in nineteenth century England? Because it was, according to Helge Kragh, "in deep harmony with the Zeitgeist of Victorian Britain."[1] To give a clear definition of the concept of Zeitgeist itself is already difficult and often result in definitions such as "the spirit of the time; the taste and outlook characteristic of a period or generation"[2] which adds little understanding and makes it clear that Zeitgeist is mostly an intuitive concept. To explain why a theory was popular during a certain timespan, it is more useful to find out what the believes, ideas, motivations, and convictions of the individual scientists were and match these values to the characteristics of the theory. After carefully reading Kragh's text, it appears that four values can be listed which were important for the popularity of the vortex atom theory: an interest in mathematical theory building; making use of mechanical models to visualize natural phenomena; hydrodynamics was a popular topic at the time, not in the least because of Helmholtz' work; and many of the English physicists strove after a unified theory of everything, which, especially for Kelvin, was motivated by a religious component in their thinking

In this chapter I will evaluate the above mentioned values and their influence on the development and perseverance of the vortex theory of atoms. A good start would be to first examine the three members of the core group. To see whether Kelvin, Thomson, and Hicks were indeed guided in their research after vortices by their religion, their aim to have a unified theory of everything, or an interest in mechanical models and hydrodynamical equations. Afterwards I will give short accounts of Tait and FritzGerald, who did not contribute as much as Kelvin, Thomson, and Hicks to the theory, but were nonetheless important for the development of the vortex atom. This last part also includes an account of Maxwell who did not believe so much in the reality of vortex atoms, but his work on electromagnetism is exemplary for Victorian scientific culture and he is therefore, also on account of his status as a scientist, worthwhile to include him.

3.1 Kelvin as a scientist

Kelvin is by far the most important contributor to the idea of vortex atoms. Therefore his motivations will be most telling about the success and endurance of the theory. To give only a rough sketch of Kelvin's motivations and widespread interest is all I can hope for in here because he was active in a large number of various scientific topics. Kelvin wrote his first publicized paper at the age of sixteen, which defended Fourier's theory of mathematics, and was followed over the years by papers about waves, thermodynamics, tide-prediction, fundamental

[1] Kragh 2002, p. 95.
[2] The free dictionary, Wiktionary.

mathematics, geology, technology, astronomy, and the origin of matter, which was also the topic of his final paper, entitled “On the Formation of Matter from Atomic Origins”, published posthumously in 1908.

For a large part, Kelvin was very much a true empiricists who, despite his skills in mathematics (his father was very disappointed when Kelvin only became Second Wrangler[3]), was only interested in numbers and symbols when they had physical meaning: he called the newly introduced number system of quaternions “an unmixed evil”.[4] Kelvin was at times more an engineer than a scientists as he spent a lot of his time thinking up inventions. Examples of these inventions are the quadrant electrometer, which is a device to measure electric charge, and a new type of compass which could be used on ships made out of iron. He also participated in the project to construct the first transatlantic cable which was to bring messaging time between Europe and the United States from several weeks down to minutes. Between 1854 and 1866, most of Kelvin’s time was occupied by designing this telegraph cable, for which he had to spend long periods of time on the Atlantic Ocean. After 1866, Kelvin was freed from his duties aboard the cable-laying ship (although he apparently had enjoyed it enough to buy himself a massive 126 tonne sailboat from the money he earned with his patents[5]) and he could focus his attention on projects like the vortex theory, on which he first published in 1867.

Now that Kelvin’s dedication to applied science has been mentioned, the vortex theory had its origin in a very different sphere of his interests. The vortex atom was not the only of Kelvin’s ideas which was of a highly speculative nature. He is also known for his hypothesis about the heat death of the universe, a conclusion at which he arrived after applying the second law of thermodynamics to the whole universe. Further doomsday speculations included the prediction that the supply of oxygen on Earth would run out in a couple of hundred years and that the Sun would not be shining “for many million years longer”.[6] Kelvin also tried to determine the age of the Earth and the Sun, and he was one of the first to suggest the theory of ‘panspermia’: that life had arrived on Earth by meteorites. Kelvin was not afraid to participate in ambitious speculative theories about the origin of life and matter itself. These speculative theories had a common ground. Judging from Kelvin’s work, it appears that his religion was a strong motivation for many of these ideas.

With his determination of the age of the Sun and the Earth, respectively hundred million years and thirty million years, he came not only to clashes with geologists, but his predictions

[3]McCartney 2002, p. 26.
[4]Kelvin to R.B. Hayward 1892, S.P. Thomson 1910, p. 1138.
[5]Smith & Wise 1989, p. 735.
[6]Kelvin 1862, p. 393.

also conflicted with the biologists' new theory of evolution. It was certainly not the case that Kelvin was after a literal interpretation of the Bible with his predictions. Most important for him was that such conclusions were reached through the use of good science.[7] In fact, Kelvin had no objections to the theory of evolution itself, stating in his 1871 opening address to the 'British Association for Advancement of Science' that "all creatures now living on Earth have proceeded by orderly evolution from some such origin."[8] Meteorites is where Kelvin was referring to with "some such origin". It is here that his religious beliefs conflicted with the biologists theory of 'abiogenesis': the theory that biological life on Earth has arisen from inorganic matter. At these points, Kelvin argued, science has its limits and has to admit that behind these boundaries there is such a thing as a "Creator": "purely mechanical reasoning", he said, "teaches us that our own bodies, as well as all living plants and animals [. . .] are organized forms of matter to which science can point no antecedent except the Will of the Creator."[9] So, because Kelvin was thoroughly convinced that "life proceeds from life, and from nothing but life", life in its most basic form had to be the result of some divine creation.[10] If life had not been created on Earth, then the theory of panspermia could according to Kelvin explain why there is life on Earth. Where the meteorites with those "seeds of life" came from was left open by Kelvin.

As for the apocalyptic heat death of the universe, Smith & Wise conclude in their biography of Kelvin "that the full strength of that commitment derives from [Kelvin's] theological view that God had not created the universe –or solar system– as an eternal entity, and that only He could restore the initial sources of energy."[11] Indeed, Kelvin's papers on the second law of thermodynamics contain numerous references to a Deity. For example: "a creative act",[12] "overruling creative power",[13] and "an overruling decree".[14]

When we turn to the vortex atom theory we see that Kelvin stressed in his works that the creation of vortex rings was, just as life, a privilege of a Deity who operated outside the natural laws. To be reassured by this, Kelvin corresponded with Helmholtz to ask him wether it was indeed the case that the creation of vortices in an ideal fluid was impossible from a physical point of view.[15] Besides the creation of vortices, atoms in the natural world were also expected

[7] McCartney 2002, p. 28.
[8] Kelvin 1871, p. cv.
[9] Kelvin 1854, quoted from Sharlin 1979, p. 169.
[10] Kelvin 1894, p. 199.
[11] Smith & Wise 1989, p. 501.
[12] Kelvin 1851, Sharlin 1979, p. 112.
[13] Kelvin 1862, p. 392.
[14] Kelvin 1862, p. 388.
[15] Kelvin to Helmholtz 1868, Smith & Wise 1989, p. 419.

to be indestructible. This was why, as noted in chapter two, Kelvin put so much effort in trying to show that vortex rings were stable. Kelvin was certainly not shy about the influence of religion on his work. On the first page of his paper "On Vortex Atoms", the paper that started the vortex atom theory, he gave as an argument in favor of his idea that "to generate or to destroy 'Wirbelbewegungen' in a perfect fluid can only be an act of creative power".[16]

Kelvin's religious beliefs were an important argument for him to work on the theory of vortices, but it was not his only motivation. The nature of vortex atoms also exemplified how Kelvin tried visualize every natural phenomenon by means of a mechanical model. English physics from the nineteenth century is known for its model-like representations of physical theories. Maxwell's ether models of electricity are famous and scientists like FritzGerald made ingenious models consisting of all kinds of wheels and bands, just to be able to give a mechanical explanation of electromagnetic phenomenon. Kelvin also depended in his scientific work heavily on this practice of model-building, stating in 1884 that to him "the test of 'Do we understand a particular point in physics?' is 'Can we make a mechanical model of it?'"[17] To Kelvin, the various attributes that atoms were thought to have, like elasticity and indestructibility, seemed to follow naturally from the mechanics of the vortex atom. The atoms in Dalton's theory, on the other hand, were visualized as solid billiard balls. Kelvin objected to Dalton's atomic theory because that it was difficult, if not impossible, to visualize how these solid atoms could have attributes like elasticity and multiple vibrational modes to account for kinetic gas laws and spectral phenomena.

The vortex atom theory was a combination of Victorian model building and hydrodynamics. The latter experienced an enormous progress in the nineteenth century. Hydrodynamics was a prominent topic of research in Victorian mathematical and physical science. At the Tripos examination in Cambridge, which was one of the most distinctive mathematical examinations in the world, it was (together with mechanics and electromagnetism) one of the standard topics to be asked on the exams.[18] A thorough knowledge of the mathematics of fluids was mandatory for a career in physics in England.

The dominant field of research in England during the time of the vortex theory was electromagnetism. Yet it would be wrong to see this research independent of developments in hydrodynamics. In his book on mathematical physics in Cambridge, Andrew Warwick notes that the physicists surrounding the development of Maxwell's theory "drew heavily upon ana-

[16]Kelvin 1867, p. 15.
[17]Kelvin 1884, S.P. Thomson 1910, p. 830.
[18]Warwick 2003, p. 239.

logical arguments from heat theory and hydrodynamics."[19] Indeed, one of the collaborators of Maxwell was Horace Lamb (Warwick calls him a "first generation Maxwellian"), who is also considered as the nineteenth century authority on hydrodynamics. His book, bearing the title "Hydrodynamics" (1879), became the standard work on the subject and is still in print. This interest in the equations of motion of fluids was partly instigated by Helmholtz' work and in the years following his publication in the Philosophical Magazine in 1867, vortices took a prominent place as a subfield in hydrodynamics. In the just mentioned book of Lamb, a whole chapter is devoted to "Vortex Motion". Also, we learn from the second volume of Merz' book that vortex motion was one of the three major products of the "kinetic interpretation of matter", next to electromagnetism and the kinetic theory of gases.[20]

If we return to Kelvin's work, we see that from the amount of time and effort he put in vortex atoms, it is undeniable that he was interested in hydrodynamical equations. This interest already started early. More than ten years before he first published about vortex atoms, and one year prior to Helmholtz' paper, he wrote to Stokes that he thought that "hydrodynamics is to be the root of all science, and is at present second to none in the beauty of its mathematics."[21] For Kelvin, hydrodynamics was indeed an important part of his work.

To find the theory that was "the root of all science" was always in the background of Kelvin's mind when he conducted fundamental research, as Smith and Wise note.[22] The motivation to find a theory of everything is also the one Robert Silliman picks out as the motivation of Kelvin for the vortex atom theory. Silliman quotes that to Kelvin 'the final goal of scientific inquiry was to work out "a great chart, in which all physical science will be represented with every property of matter shown in dynamical relation to the whole."'[23]

3.2 J.J. Thomson

If we follow Kragh and typify Kelvin's motivations for the vortex theory (the reasoning by mechanical models, the interest in hydrodynamics and the influence of religious beliefs) as characteristics of "Late-Victorian" science, then the 1880s can be regarded as the culmination of that era. A high point of the vortex atom theory in itself during this decade was the Treatise of J.J. Thomson, which was all about hydrodynamics and foremost vortices, by means

[19] Warwick 2003, p. 353.
[20] Merz 1965a, p. 35.
[21] Kelvin to Stokes 1857, Smith & Wise 1989, p. 496.
[22] Smith & Wise 1989, p. 354.
[23] Kelvin 1871, p. xciii, as quoted by Silliman, p. 464.

of powerful mathematical reasoning.

Although Warwick depicts Thomson in his book as “the ideal type of high wrangler”,[24] Thomson did not make it to be the Senior Wrangler of his year. Like Kelvin, he finished second. Yet, just as Kelvin showed to the academic world that his mathematical skills were among the highest by winning the Smith’s prize, an award given annually by the University of Cambridge to its two best research students of mathematics, Thomson got the recognition he deserved by winning the Adam’s prize for his Treatise.

The vortices in his Treatise launched Thomson’s career and, since they were his only major contribution to science at the time, they were in large part responsible for his surprising nomination as Cavendish Professor of Physics at Cambridge University. Thomson’s interest in vortices would not remain limited to the subject of vortex atoms. In fact, most of the research he would conduct in his career was in some way connected to vortices. In 1895, Thomson depicted Faraday’s electromagnetic field lines as “bundles of vortex filaments”[25] and, although he already had given up on publishing about the vortex atom theory, “he attempted to combine his vortex ideas with his famous discovery of the electron in 1897”,[26] as David Topper writes in his paper about Thomson’s mechanical picture of nature. The vortices also persisted through quantum mechanics and relativity theory in Thomson’s mind: in 1931 the 73 year old Thomson still wrote that he saw a “close connection between electricity and vortex motion.”[27] This persistence, as historian of science Jaume Navarro explains, should be seen in the light of Thomson’s refusal to abandon the ether which, in turn, was embedded in his conviction that nature was ultimately continuous.[28]

Whereas religion was an important argument for Kelvin to develop the vortex atom theory, it was not so much an issue for Thomson. Thomson, on the other hand, was part of the spiritualist movement of the nineteenth century, which experienced its peak moment in the 1880s. Not only did he “attended a considerable number of séances at which abnormal physical effects were supposed to be produced”,[29] he was also a member of ‘The Society for Psychical Research’ in London.[30] Thomson’s strict scientific judgement on these psychic matters, though, eventually led him to “the Scottish verdict – not proven.”[31] Nevertheless, his scientific work did not remain within the boundaries of physics. More than occasionally he ventured into the

[24]Warwick 2002, p. 334.
[25]Thomson 1895, p. 512.
[26]Topper 1979, p. 32.
[27]Thomson to Lodge 1931, Kragh 2002 p. 77.
[28]Navarro 2005, p. 259.
[29]Thomson 1936, p. 147.
[30]Oppenheim 1986, p. 63.
[31]Thomson 1936, p. 158.

metaphysics behind the natural world. On most occasions this metaphysics was connected to the subject of the ether, which he regarded as the hidden reality behind the world which humans observe.[32] For this reason Thomson rejected the idea that atoms were indivisible billiard balls. He thought that this was an approximation to a continuous nature of matter. Thomson's ultimate aim was to reduce the theories of physics and chemistry to one theory of everything which was built on the conception of a continuous ether. This ambition already began in 1876 when he wrote his dissertation at Trinity College in Cambridge. In his dissertation he discussed the reduction of potential energy, which he thought to be an unsatisfactory concept, to kinetic energy.[33] His dissertation was followed up by his Treatise which, as described in chapter two, was in part an attempt to reduce both matter and chemistry to vortices. He would continue to maintain this quest for reduction and unification in his later years by trying to include vortices and the ether in his theories of the electron.[34]

As for the origins of Thomson's spiritual and metaphysical detours, Navarro points to Balfour Stewart, Thomson's professor at Owen's College. Together with Peter Tait, Stewart wrote the best seller "The Unseen Universe". In this book, the authors made an attempt to give a unified picture of science and religion, a picture that had been blurred by the fast progress of science in the nineteenth century. Although it diverted on some points from the conceptions of Kelvin's vortex theory and Thomson's view on the natural world, the book shared their notion of an invisible reality behind the world we humans interact with. As for Thomson, Navarro notes that "Stewart certainly exerted a direct influence on him" in his early years by inducing Thomson's later prevalence for metaphysics and the ether.[35]

Thomson definitely made use of mechanical models to explain natural phenomenon. He did not go as far as Maxwell and FitzGerald into proposing models of wheels and bands as an explanation for natural phenomena, but he was convinced that the ultimate explanation of nature was to be found in mechanics.[36] It should be noted, regarding this conviction, that Thomson was not particularly realistic about the models he proposed. He wrote that "as we do not know the nature of the mechanism of the physical systems whose actions we wish to investigate, all that we can expect to get by the application of dynamical principles will be relations between various properties of bodies."[37] Topper concludes in his paper that Thomson's philosophy of science regarding these models was "methodological": "To Thomson",

[32] Navarro 2005, p. 266.
[33] Topper 1979, p. 33 & Navarro 2005, p. 267.
[34] Topper 1979, p. 32.
[35] Navarro 2005, p. 265.
[36] Topper 1971, p. 396.
[37] Thomson 1888, p. 8.

as he summarizes, “models possessed two beneficial features”:[38] first, they enabled him to visualize how natural phenomena could occur. Secondly, Thomson noted that models “imply more than the facts justify”,[39] which he indeed thought to be a beneficial feature because the parts of the model that were not covered by empirical data could suggest further research.[40] Although Thomson had good hopes to find a theory of everything with vortices, he would refer to the vortex atom theory as an “illustration” of nature. In Thomson’s scientific biography, John Heilbron explains that when Thomson speculated about the vortex atom theory as “the ultimate account of the physical world”, he does not mean that it is an unique theory of everything, rather a “parsimonious” description of nature.[41] In Thomson’s own words: “the object of such theories is suggestions and not demonstration”.[42]

3.3 William Hicks

In contrast to the intellectual giants Kelvin and J.J. Thomson, who stand together with Maxwell and Faraday as England’s most eminent physicists of the nineteenth century, William Hicks (1850) is somewhat of a lesser know physicist. Hicks’ career lacked major achievements that Kelvin and Thomson were able to accomplish, although he did win the Adam’s prize in 1912 and made some important discoveries in the field of vortex dynamics. In a rough estimation, Hicks published about fifteen papers on the vortex theory of atoms. For the vortex atom, Hicks saw two obstacles that had to be overcome and most of the fifteen papers were attempts to tackle these obstacles.

First there was the ever stubborn gravity, which, since Newton’s theory, had the awkward status of a mysterious force at-the-distance that gave English physicists uneasy feelings. As described in chapter two of this work, Hicks sought the explanation for the force of gravity in a hydrodynamical model of pulsating spheres. This search started early in Hicks’ career. In 1880 he published the paper “On the Problem of Two Pulsating Spheres in a Fluid” in the ‘Proceedings of the Cambridge Philosophical Society’. In the introduction of this paper, Hicks remarked that the forces between such pulsating spheres “may be applied to explain gravitation and especially the gravitation of the Vortex atoms of Sir William Thomson.”[43] After five pages of calculations he indeed ended up with an inverse square force law between the two spheres,

[38] Topper 1979, p. 37.
[39] Topper 1979, p. 38.
[40] Topper 1979, p. 40.
[41] Heilbron 1967, p. 362.
[42] Thomson 1893, vii.
[43] Hicks 1880a, p. 277.

just as required by Newton's law of universal gravitation. However, as remarked in chapter two, Hicks' solution to the problem of gravity did not arouse much enthusiasm because the pulsation of vortex atoms was thought to be too much of an artificial assumption. In the following edition of the Cambridge's Proceedings, Hicks did publish a second part of his paper, but this was purely a mathematical exercise and no reference to the vortex theory of Kelvin was made.[44]

It is clear that by then Hicks' attention had shifted towards the second obstacle of the theory: how could vortex atoms explain the different densities of the elements? The hollow-core vortices, as described on page 24, which ought to explain the different densities of macroscopic objects, caused a short revival of the vortex theory of atoms but they were above all again a thorough exertion in theoretical hydrodynamics, for which he eventually was awarded the Hopkins Prize. This award, named after William Hopkins, is awarded by the University of Cambridge to scientists who had published the most original work in the field of mathematical physics during their years as a graduate student.

In the first years of his time in university, Hicks focussed purely on mathematics. Maxwell, who was his mentor, inspired Hicks to turn his attention more to physics.[45] That Hicks was "more a mathematician than a physicist" is how Kragh explains why he persevered his research on the vortex theory as late as 1895, long after Kelvin and Thomson had given up on the project.[46] The lack of empirical results after twenty years of research had caused the decline of interest in the theory at the end of the 1880s, but for Hicks, as Kragh writes, "the theory's disappointing record with regard to empirical physics did not count all that highly."[47] It is likely that Kragh based this conclusion on the 1895 address Hicks held to the 'British Association for the Advancement of Science', which he fully dedicated to the vortex theory of atoms. In this address, Hicks enthusiastically defended the theory and proposed new lines of research for it like the cell theory of ether, almost as if he was ignorant of the fact that the majority of his colleagues had ceased their research on the vortex atoms. In his address, Hicks started out by stating that in the future "all physical phenomena will be a branch of pure mathematics" and the reason that advanced theories such as the vortex theory did not yield any empirical result was because "our senses are too course grained to transmit impressions of them to our mind". As a solution to this, Hicks proposed to "make a bridge between the mechanism and

[44]Hicks 1880b.
[45]Milner 1935, p. 392.
[46]Kragh 2002, p. 78.
[47]Kragh 2002, p. 78.

our senses by means of hypotheses".[48] For Hicks it did not matter that the vortex theory of atoms could not present any directly testable results, for him it was enough that the theory provided a consistent model of how matter and forces could be visualized.

Due to the lesser status of Hicks as a scientists, compared to Kelvin and Thomson, there is not as much secondary literature available about his philosophy of science and it is therefore more difficult to judge whether Hicks' motivations reflected the characteristics of Late-Victorian science. It is clear, though, that the general interest in hydrodynamics in England was certainly part of his work because Hicks' scientific papers were, save a handful of exceptions, fully dedicated to the mathematics of fluids. Like Kelvin and Thomson, Hicks also had a reductionist view on the physical sciences, based on mathematics: "science will have reached its highest goal when it shall have reduced ultimate laws to one or two" and that these laws, as explained Hicks his point of view at the 1895 British Association address, "will be dynamical laws of the relation of matter to number, space, and time."[49]

As far as his unificatory view on science, which was to be realized by a reduction of all the physical sciences through hydrodynamics, Hicks matches the qualities of a Late-Victorian scientist. On the the other hand, the model building tradition which was so "deeply engrained in Victorian physics",[50] does not appear in the work of Hicks. Although vortex atoms can be regarded as a mechanical model, and Hicks was also of the opinion that mechanics in general would serve as the basis for the theory of everything, it appears that he did not use models as a tool to visualize the possible working of natural phenomena, not in the way Kelvin and Thomson did. An explanation for this difference between Hicks and most other physicists perhaps includes that Hicks did not participate in the development of Maxwell's electromagnetic theory, the field of research in which model-building was especially deep engraved.

Regarding the reality of vortex atoms, Hicks' writing seems not to suggest that he thought them to be merely a tool to account for the properties of atoms, like Thomson did. Kragh maintains that Hicks stopped believing in the reality of vortex atoms during the first decade of the twentieth century.[51] This is plausible considering the null result of the ether drag experiments and the rise of special relativity which did away with the reality of the ether itself. However, there is to my knowledge no statement of Hicks which supports this.

[48]Hicks 1895, p. 595.
[49]Hicks 1895, p. 595.
[50]Hunt 1984, p. 123.
[51]Kragh 2002, p. 79.

3.4 FitzGerald, Tait, and Maxwell

FitzGerald

George FitzGerald, an Irish mathematician, was one of the first scientists to embrace Maxwell's theory of electromagnetism and elaborate it after Maxwell's early death. Therefore, Bruce Hunt, in his dissertation "The Maxwellians", characterized FitzGerald as one of those early "Maxwellians". When it came to a model-like representation of natural phenomena, FitzGerald was the undisputed master and a true representative of the electromagnetic part of Victorian science. Yet the elaborate models of wheels and bands that FitzGerald proposed, which were to give a mechanical explanation of electrical phenomena like induction and magnetism, were not meant to give a realistic picture of the constitution of the ether. As FitzGerald thought, according to Hunt, "illustrative models were intended as analogies of phenomena, not likenesses; they offered a similitude of relations, not of things".[52] This instrumentalist approach of FitzGerald towards electromagnetic theories was different from his approach towards the vortex sponges he developed. The main goal he aimed at with these sponges was to combine the ether of the vortex atoms and the ether of electromagnetism. Whereas his models of wheel and bands were intended as an "illustration" of phenomena, Hunt concludes that "FitzGerald's 'vortex sponge', [was] intended to be actual 'likeness' of the ether".[53]

In his 1888 opening address to the 'British Association for the Advancement of Science', FitzGerald held that "hard particles are abominations".[54] This resembles Kelvin's attitude, who referred to Dalton's atoms as "monstrous".[55] Yet FitzGerald was critical about Kelvin's original idea of vortex atoms, which supposed the ether to be an elastic fluid. In general, FitzGerald objected to any theory that assumed the ether to be "as like a jelly".[56] For if the ether was like a thin jelly, FitzGerald argued, it could not be understood how macroscopic objects obtained their rigidity.[57]

FitzGerald shared the ambition to find a theory of everything, for which thought the vortex theory to be the best candidate. To FitzGerald, the vortex theory of atoms was worth to consider because it promised to reduce everything in the physical world to motion in a fluid, as already seen in his quote on page 2. In another review of the vortex theory, FitzGerald

[52] Hunt 1984, p. 128.
[53] Hunt 1984, p. 122.
[54] FitzGerald 1888, p. 561.
[55] Kelvin 1867, p. 15.
[56] FitzGerald 1885, Hunt 1984, p. 34.
[57] Hunt 1984, p. 170.

stated that the theory "is the most far-reaching of any that have been proposed as a ultimate structure of matter".[58]

Finally, it seems that FitzGerald also had metaphysical motivations for the vortex atom theory, like Kelvin and J.J. Thomson. FitzGerald did not confine himself to natural philosophy in his research, he also conducted metaphysical research. At times, he even led his metaphysics guide his research in physics. He offered as an argument in favor of the vortex atoms that "there are metaphysical grounds too, for reducing matter and potential to kinetic energy".[59] The origin of this metaphysical side of FitzGerald likely includes that his father, first a professor of moral philosophy, became Bishop of Killaloe, and Bruce Hunt describes him as being a "metaphysician".[60]

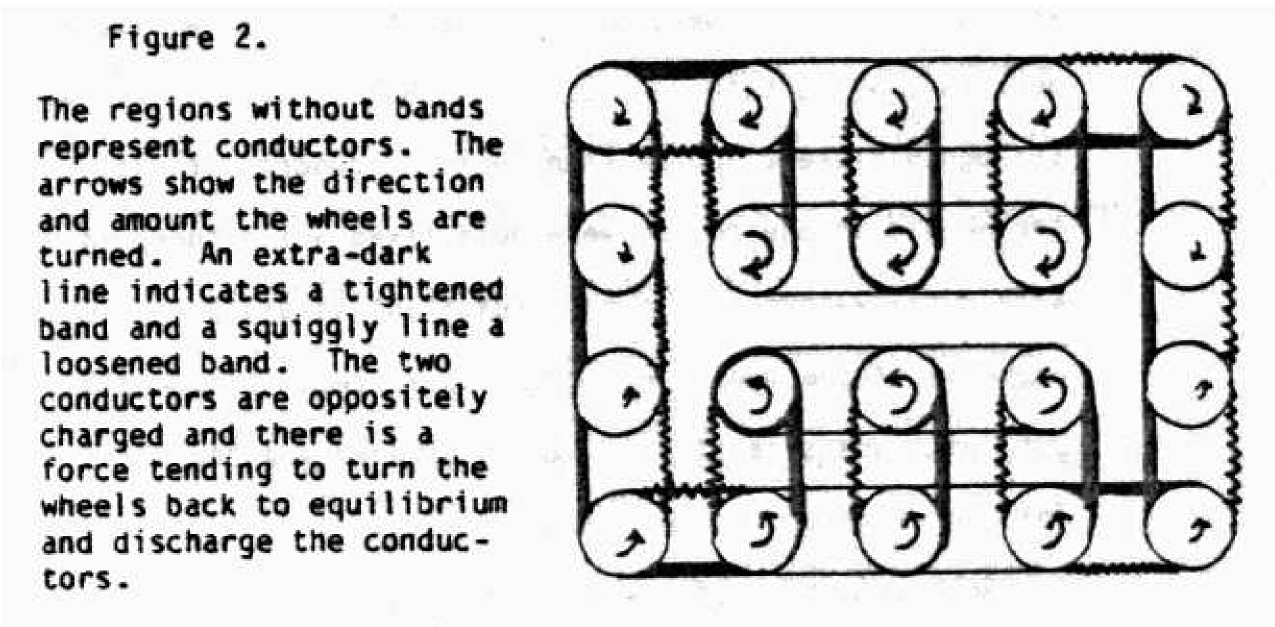

Figure 3.1: Wheels and bands model from FitzGerald's work together with commentary by Hunt. (Hunt 1984, p. 137)

[58]FitzGerald 1899, p. 13.
[59]FitzGerald 1888, p. 561.
[60]Hunt 1984, p. 11.

Tait

Peter Tait's publication record is extensive and his interest covers a large range of scientific subjects, both purely mathematical, like the quaternions Kelvin so much despised, and practical: the smoke rings he showed Kelvin were just one of the many experiments he performed on various natural phenomena.

He is best known, though, for two things. First, he was the co-author of two very popular books: "Treatise on Natural Philosophy" and "The Unseen Universe". Treatise on Natural Philosophy was written together with Kelvin and was meant to replace Newton's *Principia*, which was based on forces, by a new *Principia*, based on energy.[61] The Unseen Universe, as mentioned earlier, was an attempt to ease the controversies that existed between science and religion, and it therefore fitted very well into the already sketched metaphysical culture of the Victorian era. In the Unseen Universe, Tait positively reviewed the vortex atom although his view on the ether and the atoms in it differed from Kelvin's theory. Whereas Kelvin required the ether to be frictionless and the atoms in it thus a result of some incomprehensible creative act and immune to dissipation, Tait came to the conclusion that the ether, if it was to support vortex atoms, was not an ideal fluid, so that vortex atoms could form and disappear at any given instant. For Tait, vortex atoms could not be everlasting because this would collide with his religious beliefs or, as Kragh calls it, his "sacrosanct principle of unbroken continuity".[62] That Tait did not agree with Kelvin on such details of the theory is not of importance though, the point is that Tait, just as Kelvin, used religious motivations as a guide in his work on such theories as the vortex atom.

Tait's second work of importance was the instigation knot theory, a topic he became interested in "by Sir W. Thomson theory of vortex atoms".[63] The mathematical component which was so important in nineteenth century English physics was especially prominent in Tait's works. If Tait chose to work on a physical theory, he occupied himself mostly with the mathematical part. This was also his attitude towards the vortex theory of atoms. Stating in the Unseen Universe that even if vortex atoms did not exist, they were "very valuable from one point at least, viz. the extension and improvement of mathematical methods".[64]

As for hydrodynamics, it is not the case that Tait had no interest in the subject at all. Tait was the first scientist in England to read, translate and publish Helmholtz' paper on

[61] Smith & Wise 1989, p. 352.
[62] Kragh 2002, p. 87.
[63] Tait 1877, Kragh 2002, p. 47.
[64] Stewart & Tait 1884, p. 140, Kragh 2002, p. 46.

vortices. Yet, as Kragh points out, probably this interest was because Tait saw a useful connection between his work on quaternions and some of the mathematical results of Helmholtz.[65] Tait's bibliography does not contain a long list of publications on hydrodynamics, unlike the bibliographies of Kelvin, Thomson, and Hicks.

Tait was not a 'Maxwellian', that is, he did not participate in the development of the theory of electromagnetism. This might explain, as in the case of Hicks, why Tait did not incorporate mechanical models in his work as an aid to visualize natural phenomena, a characteristic perhaps more connected to the development of Maxwell's theory than to Victorian physics as a whole.

The reservation of Tait towards a more active engagement in the development of the vortex theory of atoms had three reasons. First, Tait did not share Kelvin's objections to Dalton's atoms, finding them "useful in explanation"[66] and therefore he did not feel the need to develop an alternative to it. Secondly, Tait had objections to the vortex theory of Kelvin itself. For example, it did not explain why matter possesses inertia: Kelvin assumed the ether to have inertia as a property. However, Tait argues, the vortex theory then "explains matter only by the help of something else which, though it is not what we call matter, must possess what we consider to be one of the most distinctive properties of matter".[67] Finally, Tait was not so much bothered about finding a theory of everything. It was not that he was against the idea of making an attempt at such a theory, yet compared to the thus far treated scientists, Tait exhibited in his work a less enthusiastic and more pragmatic attitude when he wrote about the vortex theory of atoms. At the time Tait was writing the treatise of natural philosophy, he corresponded to Kelvin about his view on the ether, writing that "it is amusing to see how definitely you go into the ease of conception and treatment of the continuous uniform medium in which atoms (or at all events matter) are supposed to float. I am quite willing to adopt your views, but I should like you to send me as soon as you have leisure a little sketch of your proposed mathematical treatment of such fluid or solid".[68] For Tait, it first had to be shown on paper that a theory could be made to work and deliver some results before he would decide about whether the theory described part of reality.

[65]Kragh 2002, endnote 10.
[66]Tait to Andrews, Smith and Wise 1989, p. 354.
[67]Tait 1899, p. 22.
[68]Tait to Kelvin 1861, Smith & Wise 1989 p. 354.

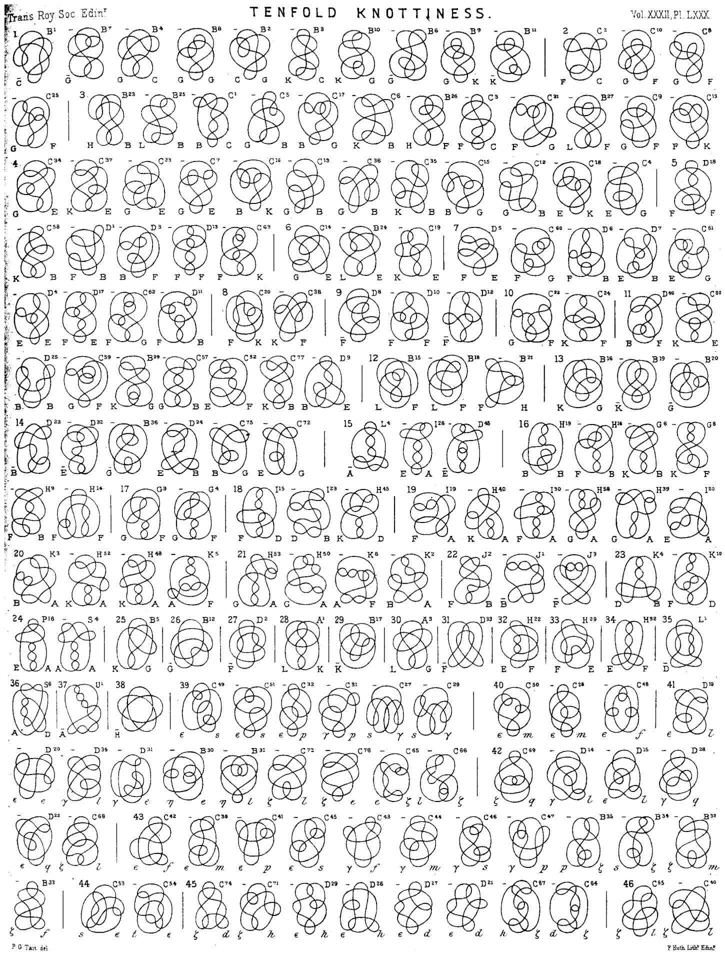

Figure 3.2: One of the characteristic tables of knots from Tait's work in which he listed all possible knots for a certain "knottiness". (Tait 1885, p. 507)

Maxwell

In the classification made earlier, Kelvin, Thomson, and Hicks formed the core group around the vortex theory of atoms. FitzGerald, Tait, and a couple of other scientists only published occasionally on the theory and stood therefore outside the group. Yet, most of the other physicists in England, who did not fit into those two groups, also followed the development of the vortex theory with a keen interest. This interest was partly because such eminent physicists as Kelvin and Thomson participated in the development of the theory, and partly because most physicists in nineteenth century England shared the interests and motivations of Kelvin, Thomson, and the other physicists, as described above.

James Clerk Maxwell was one of the "outsiders", who did not engage in developing the vortex atom theory itself but who did follow the progression of the theory from the sidelines and who mentioned the theory, in lectures and papers, in a favorable and sometimes even excited way. By including Maxwell, this chapter is completed with an account of one the outsider physicists. I then also have included one of the most important scientists of the nineteenth century, a scientist whose working method had great influence on the overall scientific culture of nineteenth century English physics. Furthermore, Maxwell's motivations largely coincide with the motivations of the already treated physicists, therefore a short account of Maxwell will suffice.

First of all, Maxwell depended in his thinking about electromagnetism heavily on analogies with hydrodynamics.[69] In his seminal work "On physical Lines of Force", Maxwell refers to Helmholtz' vortex paper, noting that it was Helmholtz who "has pointed out that the lines of fluid motion are arranged according to the same laws as the lines of magnetic force, the path of an electric current corresponding to a line of axes of those particles of the fluid which are in a state of rotation." This led Maxwell to remark that "this is an additional instance of a physical analogy, the investigation of which may illustrate both electro-magnetism and hydrodynamics."[70] Although the hydrodynamical analogies are no longer pointed out today to students who study electromagnetism, the four Maxwell equations still bear the operations "divergence" and "curl" on electric and magnetic fields. These operations, of which curl was in fact first suggested by Maxwell, were originally introduced in the context of the nineteenth century development of mathematical hydrodynamics.

Maxwell was also a religious man who, according to his scientific biography, mixed his beliefs "with a strain of mysticism".[71] These Christian beliefs committed Maxwell, as Paul Theerman explains in his paper "James Clerk Maxwell and religion", to a uniform picture of the universe.[72] The uniformity of the vortex theory of atoms was thus a characteristic that Maxwell praised: "the greatest recommendation of this theory", Maxwell wrote, "is that its success in explaining phenomena does not depend on the ingenuity with which its contrivers 'save appearances', by introducing first one hypothetical force and then another".[73]

Although Maxwell presented at official occasions such a positive attitude towards the vortex atom theory, from his private correspondence it is evident that he thought the theory to be no more than a curiosity at best. In a letter to Tait, for example, Maxwell teasingly remarked about Kelvin's efforts to construct a theory of vortex atoms, that "[Kelvin] set himself to spin the chains of destiny out of a fluid plenum."[74]

[69] Everitt 1974, p. 206.
[70] Maxwell 1861, p. 488.
[71] Everitt 1974, p. 198.
[72] Theerman 1986, p. 316.
[73] Maxwell 1875, p. 45.
[74] Kelvin to Tait 1867, Epple 1998, p. 324.

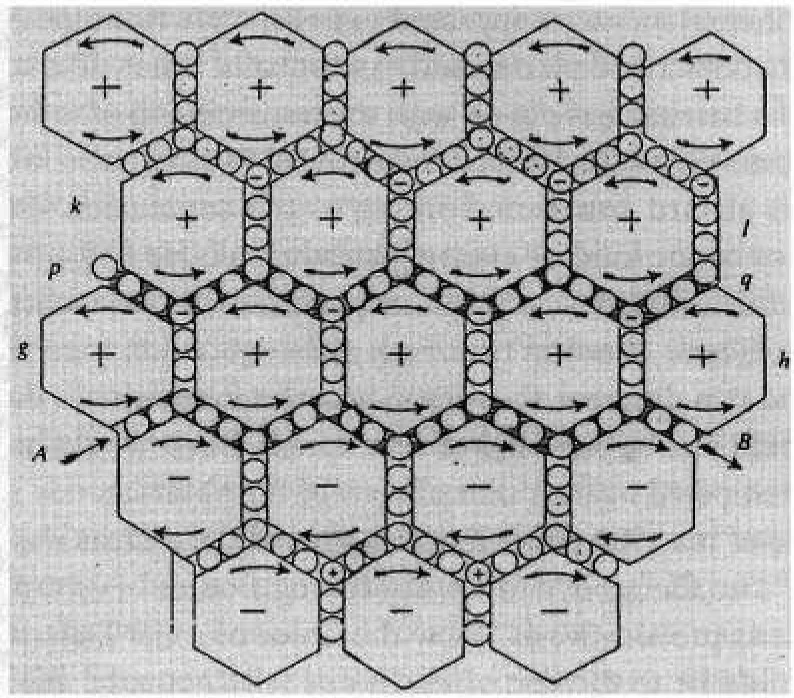

Figure 3.3: The famous model of Maxwell, which he designed to mechanically account for magnetism. The angular velocity of the (hexagonal) vortices corresponds to the magnetic field intensity. The spherical "idle-wheel particles" between the vortices would account for the electrical current, and, while flowing from one side of the conductor to the other, make the vortices rotate and induce a magnetic field. (Maxwell 1861, p. 282)

3.5 Conclusion

It is most often the case that the better known scientists, scientists that publish often and to which other scientists often refer to, have the most influence on a scientific culture. In this chapter the motivations and interests of Kelvin, Thomson, and Maxwell have been examined and these three physicists were undisputedly the most influential physicists of their time. Together with the accounts Hicks, FitzGerald, and Tait, a reasonable complete picture has been given of the general culture of late-nineteenth century English physics for the purpose of the vortex atom.

Kelvin was arguably the most influential physicist in England during the life span of the vortex atom theory. This influence was not confined to the academic community, in the public he was also a popular and well known figure thanks to his contribution to the transatlantic telegraph cable and the practical inventions he made. The authority of Kelvin was certainly a factor of importance for the popularity of the vortex atom. It has even been suggested by the historian George Fleck that Kelvin actively applied his authority to promote his vortex atoms: "the position of leadership held by [Kelvin] was significant, and the spreading of the gospel gained impetus when [Kelvin] was made a member of the threeman board of editors of the Philosophical Magazine in 1871". After Kelvin's appointment, so claims Fleck, "a constant stream of articles appeared in the journal questioning the classical atom theory."[75] However, after reading through all the volumes of the journal that were published in the relevant time frame, I found only one paper of a certain C. Wright, published in 1872, in which he attacked atoms for not being able to explain properties of matter.[76] Shortly thereafter, this paper received a reply from R. Atkinson, who defended the atomic theory,[77] and in the course of 1872 a discussion followed between Wright and Atkinson. A final verdict in favor of the atomists was given by the physicist A. Tribe, stating that for "the anti-atomists to attack to the object of their aversion [...] is productive waste of energy".[78] It is questionable whether it was due to Kelvin that these handful of papers were published. Certainly Kelvin was a driving force behind the anti-atomist' feeling, but he was not the only one. During the second half of the nineteenth century a general suspicion towards Dalton's atoms rose, because of the successes achieved in thermodynamics, which were independent of atomic hypotheses, and newly discovered phenomena like spectral lines, which forced new ad-hoc assumptions upon the atoms.[79]

That Kelvin and many of his colleagues were not satisfied with the Daltonian atom was a first prerequisite that motivated them to look for alternatives like the vortex theory of atoms. The vortex atom theory was considered as a theory worthy of investigation because its characteristics matched the four values that the here examined scientists thought to be important for such theories. Kelvin, Thomson, FitzGerald, and Maxwell had a habit to explain natural phenomena by means of visualizable models based on mechanical laws and the vortex theory of atoms promised a visualization of the the mechanical working of every natural phenomena. All scientists in general had a keen interest in hydrodynamics, a relatively new area of research that appealed to their mathematically inclined way of working. Furthermore, all the scientists, except for Tait, were eagerly looking to find a unified theory to explain all natural phenomena.

The first three values of reasoning by models, preference for hydrodynamics, and mathematical theory building, were certainly characteristics of late nineteenth century English physics

[75]Fleck 1963, p. 110.
[76]Wright 1872, p. 259.
[77]Atkinson 1872, p. 428.
[78]Tribe 1872, p. 121.
[79]Chalmers 2010.

and they explain in large part why the vortex atom theory could expect to get the attention it achieved. However, I argue that the enthusiasm with which the scientists worked on and spoke about the vortex atom theory is explained by the fourth value of the theory. English scientists were so appealed to vortex atoms because the theory of vortex atoms was a theory of everything. The reason why I draw this conclusion is because almost every time scientists wrote an appraisal for the vortex atom theory, they mentioned the theory's prospect of being a theory of everything. Many of the appraisals from the scientists working on the vortex theory have already been quoted in this work, but also for scientists who never had anything to do with the research after vortex atoms were often very much impressed by the fundamental character of Kelvin's idea. Albert Michelson, today a legend for his ether-drift experiment, called the vortex atom theory "most promising", a theory that, in the light of its ability to explain everything, "ought to be true even if it is not."[80] The unificatory prospect of the vortex atom theory even made it outside the scientific community: as Alkemade noted, George Eliot "alluded"[81] the vortex atom in her *Middelmarch* novel.

The vortex atom theory promised to explain every natural phenomenon with a couple of hydrodynamical explanations: it would be the completion of the natural sciences and this prospect was mostly enough to draw the attention of many scientists. Kelvin's theory could be successful in England because it was in line with the three values of hydrodynamical, mathematical, and model building of theories, the vortex atom theory was successful because it was such a grand idea.

[80]Michelson 1903, Kragh 2002, p. 80.
[81]Alkemade 1994, p. 30.

CHAPTER 4

The Vortex Theory of Atoms in Germany

Hypothesen, überall nur Hypothesen!

— Wilhelm Dilthey, German 19th century psychologist

This final chapter is about Kelvin's vortex theory in Germany. First, it will be argued that it is indeed a very curious historical fact that the theory was virtually ignored in Germany. The second part is about the theory of Wilhelm Weber, which was by some scientists elaborated into a German 'theory of everything', and it will also serve as an introduction to the third and major part of this chapter. This third part deals with the nineteenth century German scientific culture, which proves to be an explanation for the lack of interest for Kelvin's theory. Finally, several other explanations are examined and is shown why these are not as adequate as the explanation given in this work.

4.1 The surprising unpopularity of the vortex theory in Germany

It is a fact that the vortex theory of atoms was practically ignored in Germany. To give an explanation for this curious circumstance is the goal of the final part of this work. Kragh also remarked the curious lack of interest of German scientists but was not able to give an explanation for it. It is therefore clear that this explanation is not immediately obvious. In fact, it can be argued that various aspects of the German scientific culture in the second half of the nineteenth century were very favorable to theories like the vortex atom theory

The vortex theory and German theories

Some aspects of the vortex theory fitted nicely into several German-made theories. Spectral lines, as a first example, were very much a German research field, led by Bunsen and Kirchhoff. Naturally, these scientists wanted to have a good, preferable fundamental, explanation for this phenomenon. As already mentioned in the second chapter of this work, spectral lines were a natural result of the hypothesis of ring-shaped elastic atoms. The vortex atoms' feature of elasticity also supported the kinetic theory of gases. Although this theory was partly a child of Maxwell, it reached its maturity in the hands of the Austrian Ludwig Boltzmann.

Perhaps to the individual masterminds of these Boltzmann-equations and theories on spectral lines then vortex atoms could be an attractive idea (for Bunsen, Kirchhoff, and Boltzmann, though, it wasn't). Yet to get more than a handful of scientists excited for the vortex theory, it had to do more than be favorable to a couple of theories. It would also had to match the general values such as those held by the English physicists, or fit into a larger research program. Surprisingly, there was in fact such a research program Germany which had characteristics similar to the vortex theory of atoms.

The vortex theory and Energeticism

The program of 'Energeticism' had as its aim to describe every natural phenomena as the consequence of the interaction of various forms of energy.[1] Its followers, of which Wilhelm Ostwald was the most prominent, had a strict anti-materialistic, i.e. anti-atomic, approach to science. The idea of atoms as a manifestation of motion in a universal ether, as the vortex theory proposed, would not be strange as a theory in Energeticism. Yet, as Kragh remarked, "I have found almost no trace of the vortex atom theory in the German controversy over atomism versus Energeticism."[2] There is one reference from Ostwald to the vortex theory in his "Lehrbuch der Allgemeinen Chemie", where he critically comments on J.J. Thomson's attempt to explain properties of a gas in his Treatise.[3] About Kelvin's theory itself, though, Ostwald remained neutral. Why the Energeticists did not incorporate Kelvin's theory into their research program remains something of a mystery. Perhaps it was because when energetics was coming up, in the 1880s, the vortex theory was already on its way back.

Regardless whether the German scientific culture could be favorable to ideas like the vortex

[1] Wegener 2009, p. 181.
[2] Kragh 2002, p. 90.
[3] Ostwald 1887, p. 745.

atom theory, the fact remains that the theory was almost entirely ignored in Germany.

4.2 Theories of everything

With the vortex theory of atoms, Kelvin attempted to construct a theory which could account for every natural phenomenon: nowadays we say his aim was to construct a 'theory of everything'. In Kelvin's time, such an attempt was not unique. Ever since antiquity, the idea to construct such a theory was the ultimate goal for many natural philosophers and this aspiration experienced a high time at the end of the eighteenth century and the beginning of the nineteenth century. Around the turn of the century, Laplace introduced his demon for who, when knowing all the velocities and all positions of all particles at a given time, "nothing would be uncertain and the future just like past would be present before [his] eyes."[4] This urge for unification presented itself particular strong in Germany, which can be regarded as the epic-center of the Romantic period. More specifically, the exclusive German *Naturphilosophie* was largely characterized by the unification of all sciences, a historical fact that will prove to be important for my upcoming thesis.

Several German scientists in the mid-nineteenth century did have hopes for such a theory of everything in the work of Wilhelm Weber. Weber's theory was the German's best attempt at a theory of electromagnetism until it had to give way to Maxwell's theory. His "theory of electrons", guided by the German-preferred attributes of action-at-a-distance forces and point-like atoms, was built on the idea of electrically charged particles, both negative and positive. Limited to electromagnetic phenomena, the theory of Weber enjoyed great popularity in Germany and his laws were taught at most universities for several decades after their publication in 1864.[5]

Having said this, one notable exception who never was convinced of Weber's theories was Helmholtz. Apart from his (vague) objections to atoms and action-at-a-distance forces,[6] he could not accept the velocity dependent Coulomb force of the theory. As one of the key-architects of the law of energy conservation, Helmholtz thought that a force which depended on the velocity of charged particles would conflict with the conservation law he had derived in his "Über der Erhaltung der Kraft".[7]

Many other German physicists at the time, though, believed that Weber's laws describ-

[4] Laplace 1904, p. 4.
[5] Lunteren 2009, p. 77.
[6] Molella 1972, p. 205.
[7] Molella 1972, p. 202.

ing electromagnetism were fundamental to all natural phenomena: they were looking for an "electromagnetic theory of nature."[8] Using Weber's theory as a starting point, physicists like Johann Zöllner, Gustav Fechner, Carl Neumann, and Rudolf Clausius sought ways to extend it to include heat, light, and even matter and gravitation.[9]

Was it Weber's extended theory of electrons that stood in the way of Kelvin's vortex theory? Did German scientists not bother about an English, ether-based theory of everything because they had a German alternative? This could very well be the case for the above listed scientists who worked on such an electromagnetic theory of nature. Yet, I that think the scientists outside of this group had another reason to ignore the vortex theory of atoms. Actually, I will argue that the reason for the unpopularity of Kelvin's theory in Germany is the same reason for why the majority of German scientists did not bother about Weber's theory of everything — or anyone's theory of everything.

4.3 The German critical spirit

The reason why I think most German scientists were not interested in the vortex theory of atoms lies within the mainstream scientific culture in Germany at the time. This German scientific culture is largely characterized by a reaction to the preceding Naturphilosophie, a philosophy of science which was very popular in the first three decades of the nineteenth century. An understanding of Naturphilosophie is therefore essential to learn why the German scientific culture in the second half of the nineteenth century was such a poor soil to the vortex theory of Kelvin.

Naturphilosophie

As a sub-current in the German Romantic period, Naturphilosophie originated from the publication of Friedrich von Schelling's book "Ideen zur einer Philosophie der Natur" in 1797, and remained popular until the death of its most prominent representatives, Johann Wolfgang von Goethe and Georg Wilhelm Friedrich Hegel in 1832 and 1831. Naturphilosophie is characterized by an anti-mechanical world view and an interdisciplinary working method: "Naturphilosophie failed to acknowledge the boundaries between the sciences and instead saw only the unity of them all", so concludes historian of science Kathryn Olesko in her thesis.[10] Its followers urged

[8]Molella 1972, p. 108.
[9]Molella 1972, p. 3.
[10]Olesko 1980, p. 73.

that it was impossible to get a complete picture of the universe with only scientific formulas. A "melding" of science and metaphysics was needed in order to get an "intimate, all-embracing knowledge of the cosmos".[11] Another aspect of Naturphilosophie, which is important in this context, was its denial of atoms. Instead of a mechanical and atomistic worldview, scholars adhering to Schelling's and Hegel's ideas worked with a dynamical view of nature: natural phenomena were to be explained as the resultant of forces or powers.[12] This was indeed a very ambitious program which sailed away from the save havens of Newton's atomism and the, just attained, divisions between the different branches of science.

Anti-Naturphilosophie

Its ambitious aim is one of the reasons why the research program of Naturphilosophie yielded many speculations about the connections between different natural phenomena and remained without much practical result. It was with the death of its two best known advocates, Goethe and Hegel, that Naturphilosophie got into a rapid decline. Scientists rapidly turned away from Romantic philosophy, which, they thought, relied too much on speculation and its lack of empirical results was too big.[13] They did not just abandon Naturphilosophie, according to Molella, "The 1840s in Germany witnessed the beginnings of a well-known counter-reaction to the Naturphilosoph's visions of nature."[14] Within ten years of Hegel and Goethe's death, Naturphilosophie fell from being the mainstream philosophy of science to "one of the most frequent targets of criticism."[15] Indeed the reaction against it was remarkably severe. Justus von Liebig, founder of modern fertilizer, even compared Naturphilosophie to the Black Death, so disgusted was he with its methods.[16]

A consequence of this 'anti-Naturphilosophie' was that scientists distanced themselves from the main themes of Romantic philosophy: too little empirical application or too much speculation in a scientific work could expect to be criticized as speculative pseudoscience. As Ostwald concluded at the end of the 19th century: "[speculation] is regarded up to now as a curse word in the natural sciences."[17] This attitude is what John Merz, in his book "A history of European Thought in the Nineteenth Century", called "the critical spirit."[18] Additionally, he remarked

[11] Molella 1972, p. 17.
[12] Olesko 1980, p. 73.
[13] Molella 1972, p. 20.
[14] Molella 1972, p. 20.
[15] Molella 1972, p. 22.
[16] Prawer 1970, p. 5.
[17] Ostwald 1902, p. 2.
[18] Merz 1965b, p. 185.

that this critical attitude towards science in the nineteenth century was almost exclusively a German trait.[19]

German critical scientists

Can this critical, anti-speculative attitude be found in the work of scientists that are interesting in the context of this paper? One German physicist of who we would expect to appreciate Kelvin's theory the most, Helmholtz, was not only known to be an anglophile and a close friend of Kelvin, also his work on hydrodynamics sparked the idea of the vortex theory in the first place. Direct references of Helmholtz to the theory are scarce, as Alkemade remarked in his dissertation.[20] The lecture Helmholtz held at the funeral of the chemist Gustav Magnus was one of those rare occasions in which he made an (indirect) reference to the vortex theory:

> In the reference to atoms in theoretical physics, [Kelvin] says, with much weight, that their assumption can explain no property of the body which has not previously been attributed to the atoms. Whilst assenting to this opinion, I would in no way express myself against the existence of atoms but only against the endeavor to deduce the principles of theoretical physics from purely hypothetical assumptions as to the atomic structure of bodies. *We know now that many of these hypotheses, which found favor in their day, far overshot the mark.*[21]

Equally important for my argument here is that further on in his speech Helmholtz remarks that "One has to understand that mathematical physics is an empirical science as well; it has to follow the same principle as experimental science".[22] This is the 'critical spirit', about which Merz was talking, exhibited by Helmholtz. Merz is not the only one who noticed this. More recently, Gregor Schiemann wrote a book about Helmholtz containing a chapter titled "The Hypothetization of Helmholtz's Mechanism". The first part of this paper is dedicated to an apparent switch of Helmholtz's philosophy of science: from a reductionist to an empiricist. One of Schiemann's main conclusions is that Helmholtz was of the opinion that,"compared to what is observable, hypotheses appear to be an inevitable evil tolerated for the needs of scientific explanation."[23]

[19]Merz 1965b, p. 184.
[20]Alkemade 1994, p. 34.
[21]Helmholtz 1871, Schiemann 2009, p. 162, my italics.
[22]Helmholtz 1871, p. 47.
[23]Schiemann 2009, p. 164.

Looking at other physicists' work we can find the same dislike of speculation and preference for empirically based research. Another prominent example would be Kirchhoff. Schiemann notes that to Kirchhoff "the task of mechanics is not to discover the cause of the phenomena but to 'describe the movements that occur in nature [...] completely and in the simplest manner'."[24]

Kurd Laßwitz is a particular interesting case in this context. Born in 1848, he studied mathematics and physics in the German critical spirit described above. Next to his occupation as high-school physics teacher, Laßwitz became one of the first science fiction writers. He wrote speculative stories about how society would look like in the year 2371 and about fictitious encounters between humans and a Martian civilization. Yet despite his mental excursions into the far future and outer space, with all his speculative novel writing, he still thought vortex atoms to be "unvisualizable and of mathematical interest only",[25] as Kragh summarizes Laßwitz' opinion on the matter.

One of the most remarkable things about the vortex theory in Germany actually is the almost absolute silence from all physicists on the subject. The English physicist Samuel Preston complained in 1880 already that the Germans paid no attention to the theory.[26] Indeed, apart from the quotation of Laßwitz, the only other German scientists, that I could find, that criticized the vortex theory itself was Boltzmann, when he wrote that "every second-best [physicist] felt himself called upon to devise his own special combination of atoms and vortices, and fancied, having done so, that he pried out the ultimate secrets of the Creator."[27] The quotations of Helmholtz and Kirchhoff given above do not condemn the vortex theory in a direct way. What they say, however, is that they do not appreciate theory-building around atoms purely on a speculative basis. As Helmholtz said, whether atoms exist or not, one should not start out with hypothetical ideas about atoms, and derive from those entities the fundamental concepts of the physical world like inertia, gravity, the solidity of matter, and so on.

So, why was the vortex theory of atoms was ignored by German scientists? Naturphilosophie as a research program yielded such little empirical result that the German physicists who came after this Romantic philosophy inherited a critical attitude towards scientific theories. The vortex theory of atoms contained all the characteristics that German scientists apparently disliked: almost no applicable results, an interdisciplinary working method, and, above all, a highly speculative nature. Merz draws the same, general, conclusion about the German

[24]Schiemann 2009, p. 163.
[25]Kragh 2002, p. 88.
[26]Preston 1880, p. 85, Kragh 2002, p. 83.
[27]Boltzmann 1925, p. 218.

scientists:

> To [German scientists] it seemed necessary to discard as premature all attempts to solve by an omnipotent formula, after the manner of Hegel, the great fundamental problems which presented themselves."[28]

The Germans were fed up with highly speculative theories of everything, like the vortex theory. Scientific research, according to them, should respect its limits, it had to focus on particular problems or natural phenomena and had to deliver concrete results as a raison d'être.

4.4 Other possible factors

The explanation above is certainly not the only one thinkable. In fact, one could think of a variety of reasons of why the vortex theory of atoms was ignored in Germany. German nationalism would be a first possible example, we already saw that the extension of the theory of Weber provided a German substitute to the English vortex theory as a theory of everything. Also, whereas English physicists made frequent use of an ether, German physics was more built with conceptions like action-at-a-distance forces. Furthermore, Alkemade has suggested that a possible explanation for the unpopularity of Kelvin's theory in Germany lays in the philosophical current of Neo-Kantianism. To get a complete picture of the subject it is helpful to have a look at these other possible explanations. Also to see why they are not as plausible as the one that has been given above.

Nationalism, patriotism, and xenophobia

Judging from the literature, German scientists generally ignored Weber's theory of everything just as much as the vortex theory. Molella notes in his thesis that within the critical spirit that ran through German science, several of its members even became suspicious about 'Naturphilosophische' speculations of Weber.[29] Therefore, I disagree with Merz when he writes that Kelvin's theory is "one of the few remaining examples" which shows that there are "patriotic predilections" in science.[30] For the majority of German scientists it did not matter that the vortex theory was an English theory, the German theory of everything based on Weber's work faced the same lack of interest

[28] Merz 1965b, p. 177.
[29] Molella 1972, p. 215
[30] Merz 1965b, p. 66.

Certainly there were some exceptions to this, scientists that were guided by nationalistic and even xenophobic ideals. The most striking example of these exceptions was the astrophysicist Friedrich Zöllner. Zöllner's motivations to reject the theories of not only Kelvin but also Maxwell go much deeper than just nationalism, but it was certainly a large part of his "assault on British science."[31] An in-depth account of Zöllners motivations can be found in Molella's thesis, but I wanted to include Zöllner's case because he got in a quarrel with Helmholtz in which Helmholtz "blasted Zöllner for reawakening the spirit of Naturphilosophie" through his work on a Weberian theory of everything.[32]

To give an idea of how diffuse matters were at the time, Molella notes that "Helmholtz contrasts the *admirable empirical inductivism* of [Kelvin] and Tait to Zöllner's speculative a priori brand of physics."[33] The vortex theory of everything obviously slipped his mind when Helmholtz compared Kelvin's work to Zöllner's in 1875, because Kelvin's vortex atom theory, which was just experiencing its heyday, hardly fits into any form of empirical inductivism.

The ether

A first difference between German and English physics in the nineteenth century is the difference in conceptions about the ether. As already briefly mentioned, German physicists had less difficulties in adopting action-at-a-distance forces in their theories than their English colleagues. To give a reason for this difference is difficult and also not necessary for the purpose of this work. Yet an important factor in the endurance of action-at-a-distance forces in Germany was undoubtedly the authority of Weber's theory of electrodynamics.

Can the German lack of interest in the vortex atom theory be explained by the fact that in German physics scientists were more used to work in terms of action-at-a-distance forces than with the concept of the ether? That, for example, German physicists would not even consider the vortex theory because it required the existence of the ether, an hypothetical entity that Helmholtz and his colleagues were not willing to incorporate into their theories. Either because the English ether was not part of Weber's electrodynamic theory, or because the ether was too much of an hypothetical entity, too much for the German critical spirit.

This explanation, though, cannot be made to work for several reasons. First of all, German physicists were also convinced of the wave character of light and they rather accepted the existence of the luminiferous ether than to consider the light waves' undulation in vacuum. Also,

[31] Molella 1972, p. 199.
[32] Molella 1972, p. 202.
[33] Molella 1972, p. 201.

Weber was not hesitant to adopt the ether in his theory of electrodynamics. The first time Weber proposed his law of electrodynamics in 1846, so notes Molella, he held that electricity was a wave-like phenomena and that his law was "perhaps the resultant of effects transmitted through an invisible medium."[34] As already mentioned, Weber and his adherents entertained the idea that Weber's law might develop into a theory of everything. This all-encompassing theory, so concludes historian of science Norton Wise, was thought to be based on an "electrical ether."[35] Furthermore, Helmholtz made it his project to reconcile the action-at-distance forces of Weber's theory with the electromagnetic ether of Maxwell.[36] Finally, the German mathematician Bernhard Riemann, who laid the mathematical basis for Einstein's theory of general relativity, suggested a theory of everything based on motions in the ether "very similar [to the] ideas of W. Thomson, Maxwell, and other midcentury British physicists."[37]

Although English physicists had a much more outlined vision on the ether, German physicists were not afraid to speak of an ether in their theories, or to consider English ether theories. Only when there was speculation about the constitution of the ether itself they became reluctant to participate. As Helmholtz reviewed Maxwell's electromagnetic ether-model: "If such a molecular representation [Maxwell's ether model] of the all-pervading ether is resisted by our imagination as being too artificial, It still appears to me that Maxwell's hypothesis is of much importance".[38]

Neo-Kantianism

Nineteenth century German philosophy of science is indeed a complicated topic. The main reason for its complexity is that there were so many philosophical currents in Germany throughout the century. The Naturphilosophie of the first three decades was overtaken by a radical form of materialism which had a very short lifetime itself. The short materialistic uprising after Naturphilosophie was just as radical as the Romantic philosophy and its aims were just as ambitious. Yet whereas Naturphilosophie tried to combine science with metaphysics and spirituality to give a unified picture of the cosmos, materialists wanted an omnipotent formula based upon atoms and their equations of motions to describe, not only the physical, but also the mental world. As Merz notes, the materialistic movement fell into the pitfall of speculating

[34]Molella 1972, p. 129.
[35]Wise 1981, p. 277.
[36]Wise 1981, p. 299.
[37]Wise 1981, p. 291.
[38]Helmholtz 1882, p. 639, Darrigol 1993, p. 240.

outside, what were accepted as, the boundaries of science.[39] During the 1860s a compromise or "synthesis"[40] between Naturphilosophie and materialism was forged, which resulted in the Neo-Kantian movement, the philosophy of science that dominated German academic culture for the rest of the century.

Alkemade made the suggestion that "the rising popularity of the Neo-Kantian attitude may be an important explanation for the lack of enthusiasm, and interest, for Kelvin's theory in Germany."[41] Neo-Kantianism became a full-fledged Schulphilosophie during the 1860s, when the philosopher Otto Liebman cried out that "[we] have to return to Kant!"[42] Because Neo-Kantianism was the result of a merging between the idealistic Naturphilosophie and materialism, it was not a strict revival of Kant's philosophy, rather an acceptance of his general position and using this position as a starting point and guidance in conducting scientific research. Neo-Kantianism was far from a clear definable school of thought. Rather, as philosopher Frederick Copleston concludes, "Neo-Kantianism assumed pretty well as many shapes as it has representatives."[43] Adding to this diversity was the circumstance that its main representatives and initiators, which included Helmholtz, were guided by the above described 'critical spirit'. This group of "skeptische Programmatiker", as Köhnke calls them,[44] had a major influence on the forming of the Neo-Kantianist movement and through them it was that the 'anti-speculative' part of Kant's original ideas attained an even more prominent place in the revived Kantian movement of the late 19th century.

Is the rise of Neo-Kantianism an explanation for the unpopularity of the vortex theory of atoms? In a sense it is, because one of the school's prominent features was the critical spirit and the suspicion towards all too speculative ideas. These features, though, were contained in the scientific part of the philosophy mainly because the 'back to Kant' movement was to a certain extent instigated by these features.

So, to say the Germans ignored Kelvin's theory because they were part of the Neo-Kantianist school of thought is correct, but it is not a complete answer. The reason why German scientists did not bother with the vortex theory was because they were part of a critical spirit which was a reaction to four decades of Naturphilosophie and materialism which contained a lot of speculation about theories of everything but achieved little actual progress. This critical spirit evolved with time into a larger philosophical framework called Neo-Kantianism and, while

[39] Merz 1965b, p. 569.
[40] Köhnke 1986, p. 17.
[41] Alkemade 1994, p. 36.
[42] Liebman 1912, p. 109.
[43] Copleston 1963, p. 361.
[44] Köhnke 1986, p. 147.

residing in this framework, prevented the vortex theory of atoms from getting foot on German ground.

Conclusions and Reflections

The final part of my thesis consists out of two main sections. First, I give a general conclusion which also serves as a summary of my thesis. Second, I have made some reflections about how my research on the vortex atom theory fits into general historical research.

Conclusions

This thesis contains three main subjects: first, an investigations into the theory of vortex atoms; second, an account of English values in science to explain the popularity of the vortex atom theory in England; and third, an account of German scientific culture to explain the theory's lack of popularity in Germany.

The vortex theory of atoms was far from a coherent theory, almost every scientist had a different picture in his head of vortex atoms, vortex sponges, and vortex cells. Yet the basic idea in all those pictures was the same: the variety of matter and forces that we see in the macroscopic world could be reduced to rotations in a single, ethereal fluid. Kelvin's initial paper of 1867 was a very suggestive paper, limited to single atoms, and was mainly meant to spread this basic idea. Already in this first paper the difficulty of vortex dynamics became apparent. Kelvin had to acknowledge several times in this first paper that the hydrodynamical equations of motion for the behavior of single vortex rings were difficult to solve. The technical problems for single vortex atoms, though, were nothing compared to the difficulties that arose when molecules were considered, or in attempts to integrate the vortex atom into theories of electromagnetism, light, and gravity. The predictions of the vortex atom theory about the the constitution of the atom eventually turned out to be wrong, which was in part proven by Thomson when he discovered the subatomic electron in 1897. However, the prospects of Kelvin's theory did motivate many scientists to engage in the problems which emerged in vortex dynamics. In this light, the vortex theory of atoms can be seen as a catalyst that motivated the rapid developments of hydrodynamics which took place in the second half of the nineteenth century. The vortex atoms furthermore inspired Peter Tait to develop the theory of knots, which turned into a whole new branch of mathematics. Today, knot theory is formally called *topology* and is a very active field of research in mathematics. In fact, topology has been chosen as the 2012 topic for the Adam's prize, the same prize Thomson won 130 years ago for his Treatise. A third and final fruit of the vortex atom theory is that it inspired Thomson in his research after the electron. According to Kragh, vortex mechanics enabled Thomson to "form a conception of the electromagnetic field that included that non-Maxwellian concept of discrete electrical charges".[45] Even after Thomson's discovery that the electron was a discrete particle, parts of the vortex atom theory remained useful. To calculate stable configurations of multiple electrons was the same mathematical problem as to calculate the configuration of multiple vortex rings, a problem that Thomson already tackled in his Treatise. "In short", as Kragh concludes, "in the process that led to the discovery of the electron, the vortex atom played an indispensable role."[46]

The second subject of this thesis can be summarized as an investigation into the characteristics of the scientific works of Kelvin, Thomson, Hicks, FitzGerald, Tait, and Maxwell. The goal of this investigation was to explain why the vortex theory of atoms was developed in England. I listed four possible factors and tried to make it plausible that they were in part responsible for the emergence and popularity of the vortex atom theory. These four factors are: a preference for mathematical theory building; making use of mechanical models to visualize natural phenomena; a general interest in hydrodynamics; and many of the English physicists strove after a unified theory of everything. I identified these four factors as values which the above listed scientists held to be important for new theories in physics. I also maintained that although these four factors all contributed to the popularity of the vortex atom theory, the fourth value appears to have been the most important. The promised unifying powers of the vortex theory left many English scientists in such awe that they were willing to work on the theory for over twenty years although it never delivered verifiable results.

German scientists in the nineteenth century did not reject the vortex atom theory, they chose to ignore it. This makes it difficult to explain the unpopularity of the vortex atom in Germany because I cannot check any of the possible explanations for this unpopularity directly against the works of German scientists. In the case of the vortex theory in England, the works of Kelvin, Hicks, Thomson, and others directly told me what these scientists thought to be

[45] Kragh 2002, p. 70.
[46] Kragh 2002, p. 70.

the favorable aspects of the vortex atom. This is not possible in the German case because of the fact that there is almost no written account of what German scientists were thinking about the vortex atom. My alternative approach to still present a plausible explanation for the lack of interest was to check the characteristics of the vortex atom theory against the characteristics of the mainstream German scientific culture in the nineteenth century. This approach made me conclude that the vortex atom was too much of a hypothetical concept for German scientists to accept. After the reign of *Naturphilosophie*, which was characterized by an overload of speculations, most of German scientists felt the need to focus on concrete scientific problems by means of verifiable hypotheses only. The vortex theory of atoms made too much assumptions about the constitution of the ether and matter, assumptions that reminded too much of Naturphilosophie for German scientists to seriously consider the theory.

Reflections

This thesis is mostly a historical one. In the first chapter I outlined the history of an abandoned scientific theory, in the second chapter I created a more detailed picture of the development and aspects of that theory, and in the third and fourth chapters I investigated respectively the acceptance in England and the neglect in Germany of that theory. In the next section I shall describe how I engaged in the historical research and explain how I came to the conclusions that are spelled out in this thesis. After I have done this, I will discuss how the history of the vortex theory serves as an example for the philosophical problem of theory choice.

How did I do history of science?

The simple question of 'how do you do history of science?' has no definitive answer. Yet in the course of the twentieth century it became increasingly more accepted amongst historians of science that the history of science can be best understood by investigating a scientific culture. This cultural conception of science was enhanced in the sixties of the twentieth century by the publications of Kuhn's papers on scientific paradigms, a concept that is closely connected to the concept of scientific culture. To reconstruct the development of a scientific theory, like the vortex theory of atoms, one first has to reconstruct the scientific culture in which the theory was being developed. There is, however, no standard way to do this. This is partly because both 'science' and 'culture' are hard to define concepts themselves.

The reconstructing of my notion of scientific culture was done top-down. This means, in the case of the vortex theory, that I first considered the most general accepted assumptions in nineteenth century physics. Examples of these assumptions are the validity of Newton's laws, the Euclidean geometry of space, and the existence of an ether. Assumptions like these were so widely accepted that they can be used as reference points to reconstruct an image of all the significant scientific cultures that existed around the time of the vortex theory of atoms. Yet pinning down these reference points is mostly the easy part in doing history of science. In fact, I omitted to mention the reference points of the validity of Newton's laws and the Euclidean geometry of space because I thought them to be too trivial to mention. To move down from these general reference points by specifying a scientific culture like 'late-Victorian science' is the hard part and one has to be careful not to create something that never really existed. What existed was a group of individual scientists that were working on a general idea. What I thus did in chapter three was to investigate the works of the most important scientists in the vortex atom theory to find whether they had a common denominator in their approach to science. This was made easy by the paper of Kragh, since he already more or less spelled out the four shared values of which most of the treated scientists regarded as important for a scientific theory. What I did was to show that the four values were indeed genuinely shared by the protagonists of my study and that they, together with the generally accepted assumptions, thus explain the development of the vortex theory of atoms in England.

The unpopularity of the vortex atom theory in Germany, on the other hand, was not that easy to explain. In section 4.4 I listed several explanations that I considered and investigated during my research. The existence of these other explanations reveal an important problem in general history of science. For scientists like Helmholtz there is so much material available that it is perhaps possible to find evidence for an explanation that is not the right or best explanation. By carefully selecting quotes from German scientists it might be possible to make it plausible that German scientists ignored the vortex atom because they had a different conception of the ether, or they thought the Weberian theory of everything to be a better alternative. I found the best explanation while reading the passage of Merz which I quoted on page 54. The German desire for practical research, that did not contain excessive, *Naturphilosopisch* hypothesizing, was the one explanation that I could most convincingly find in the works of German scientists.

The problem of theory choice

The vortex atom theory offers an interesting case study of the problem of theory choice. As mentioned, the Daltonian atom fell in disgrace because of new discoveries. As a result of these discoveries, the existence of the Daltonian atom in England around 1870 was as uncertain as the reality of the vortex atom. To decide between two empirically equivalent theories is a central problem in philosophy of science. Thomas Kuhn famously argued that this decision, if it is made, is often based on weighing between the beneficial *values* of each theory. As an example, Kuhn listed five of these values: accuracy, consistency, scope, simplicity, and fruitfulness.[47] It is for this thesis not necessary to investigate if and how each of these five values were applicable to the vortex theory. The point is that we saw in chapter three and the above conclusion that scientists like Kelvin and Thomson were guided in their decision to develop the vortex atom indeed by four values that they attributed to the theory.

The four values that I listed were more or less shared values, which Kuhn denotes as being "objective". Next to objective values, Kuhn argues that scientists also employ subjective values in their theory choice. The religious background of Kelvin and the spiritual interests of Thomson, for example, were subjective values that motivated these scientists to strive after a unified theory. Undoubtedly, other subjective values played an important in the acceptance and development of the vortex theory of atoms. It is for instance likely that the tremendous authority of Kelvin played a crucial role in the young Thomson's decision to write his Treatise on vortices; it would certainly not harm his career. Kelvin, in turn, experienced in the 1850s a very difficult period in which he lost his father, brother, and daughter to diseases that were spread as a result of the Irish famine. Also, he married Margaret Crum who, almost immediately after the wedding, became seriously ill, never recovered and died "after prolonged sufferings and many set-backs" in 1870.[48] Smith and Wise note in their biography of Kelvin that during this difficult time there was a change in Kelvin's work: "1851 marks a great watershed in [Kelvin's] career", after which Kelvin's "theories became increasingly speculative and ill-founded."[49] It might very well be the case that this difficult time for Kelvin induced his religious convictions, which in turn induced his quest for a unified theory. Similar hypotheses can ben formulated for notable German scientists to explain why they individually ignored the vortex atom. In Boltzmann's case, for example, the idea of such a theory of everything made him feel depressed: "if we analyze the ultimate ground of everything, then everything falls into nothingness."[50] These are just speculations and serve as an example because my goal here is not to give a full biography of every scientist that is to reveal every subjective value that was taken in consideration in terms of the vortex atom theory. Yet what would we learn from such an account? Certainly it would reveal that every scientist had his own unique set of reasons to work on or ignore the vortex atom theory. Most probably, it would also explain why every one of the English scientists held

[47]Kuhn 1977, p. 321.
[48]Smith & Wise 1989, p. 146.
[49]Smith & Wise 1989, p. 396.
[50]Schneider & Sagain 2005, p. 323.

the four shared values, and perhaps such a deep investigation would even deliver a fifth shared value that played an important role in the vortex theory of atoms. I feel confident, though, that the final conclusion will not be very different from the one that I was able to draw. Although every scientist had his own considerations concerning the vortex atom, the most relevant and determinative reasons for English scientists to develop the vortex atom theory were the four given values. Similar, the aversion against *Naturphilosopische* speculations will turn out in such an account as the main reason German scientists shared to ignore the vortex theory of atoms.

Bibliography

[Alkemade, 1994] Alkemade, Alfons. 1994. *On Vortex Atoms and Vortons*. Ph.D. thesis, Technische Universiteit Delft.

[Atkinson, 1872] Atkinson, R. 1872. An Examination of the recent Attack upon the Atomic Theory. *Philosophical Magazine*, **43**, 428.

[Bjerknes, 1864-1880] Bjerknes, C.A. 1864-1880. *Hydrodynamische Fernkräfte. Fünf Abhandlungen über die Bewegung kugelförmiger Körper in einer inkompressiblen Flüssigkeit*. Leipzig: Engelmann.

[Boltzmann, 1895] Boltzmann, Ludwig. 1895. On Certain Questions of the Theory of Gases. *Nature*, **51**, 413–415.

[Chalmers, 2005] Chalmers, Alan. 2005. *Standford Encyclopedia of Philosophy*. `http://plato.stanford.edu/entries/atomism-modern/`.

[Copleston, 1963] Copleston, Frederick. 1963. *A History of Philosophy*. Vol. 7. London: Burns and Oates Limited.

[Darrigol, 1993] Darrigol, Oliver. 1993. The Electrodynamic Revolution in Germany as Documented by Early German Expositions of "Maxwell's Theory". *History of Exact Sciences*, **45**, 189–280.

[Epple, 1998] Epple, Moritz. 1998. Topology, Matter, and Space, I: Topological Notions in the 19th-Century Natural Philosophy. *Archive for History of Exact Sciences*, **52**, 297–392.

[Everitt, 1974] Everitt, C.W.F. 1974. *Dictionary of Scientific Biography*. Vol. 9. Charles Scribner's Sons: New York. Pages 198–230.

[FitzGerald, 1885] FitzGerald, George F. 1885. Sir W. Thomson and Maxwell's Electromagnetic Theory of Light. *Nature*, **32**, 4–5.

[FitzGerald, 1888] FitzGerald, George F. 1888. Presidential Address to the Section of Mathematical and Physical Science. *Report, British Association for the Advancement of Science*, 557–562.

[FitzGerald, 1889] FitzGerald, George F. 1889. On an Electromagnetic Interpretation of Turbulent Liquid Motion. *Nature*, **40**, 32–34.

[FitzGerald, 1899] FitzGerald, George F. 1899. *Lord Kelvin, Professor of Natural Philosophy in the University of Glasgow 1846-1899*. Glasgow: James MacLehose and Sons.

[FitzGerald, 1970] FitzGerald, George F. 1970. Electromagnetic Radiation. *The Royal Institution Library of Science: Physical Sciences*, **4**.

[Fleck, 1963] Fleck, Georg. 1963. Atomism in Late Nineteenth-Century Physical Chemistry. *Journal of the History of Ideas*, **24**(1), 106–114.

[Heilbron, 1974] Heilbron, J.L. 1974. *Dictionary of Scientific Biography.* Vol. 13. Charles Scribner's Sons: New York.

[Helmholtz, 1858] Helmholtz, Herman von. 1858. Ueber Integrale der hydrodynamischen Gleichungen, welche den Wirbelbewegungen entsprechen. *Journal für den reine und angewandte Mathematik*, **55**, 25–55.

[Helmholtz, 1867] Helmholtz, Herman von. 1867. On the Integrals of Hydrodynamical Equations, which Express Vortex Motions. *Philosophical Magazine*, **33**, 485–512.

[Helmholtz, 1871] Helmholtz, Herman von. 1871. *Züm Gedächtniss an Gustav Magnus*. English Translation in: On Thought in Medicine, 1884.

[Helmholtz, 1882] Helmholtz, Herman von. 1882. *Wissenschaftliche abhandlungen.* Vol. 1. Leipzig. J.A. Barth.

[Hicks, 1880a] Hicks, William M. 1880a. On the Problem of Two Pulsating Spheres in a Fluid I. *Proceedings of the Cambridge Philosophical Society*, 276–285.

[Hicks, 1880b] Hicks, William M. 1880b. On the Problem of Two Pulsating Spheres in a Fluid II. *Proceedings of the Cambridge Philosophical Society*, **4**, 29–35.

[Hicks, 1881] Hicks, William M. 1881. Report on Recent Progress in Hydrodynamics. *Report, British Association for the Advancement of Science*, 57–58.

[Hicks, 1885] Hicks, William M. 1885. On the Constitution of the Luminiferous Ether on the Vortex Atom. *Report, British Association for the Advancement of Science*, 930.

[Hicks, 1895] Hicks, William M. 1895. Presidential Address to the Section of Mathematical and Physical Science. *Report, British Association for the Advancement of Science*, 596–606.

[Hunt, 1984] Hunt, Bruce James. 1984. *The Maxwellians.* Ph.D. thesis, The John Hopkins University.

[Kelvin, 1851] Kelvin, William Thomson. 1851. On the Dynamical Theory of Heat. *Transactions of the Royal Society of Edinburgh.*

[Kelvin, 1862] Kelvin, William Thomson. 1862. On the Age of the Sun's Heat. *Macmillan's Magazine*, **5**, 388–393.

[Kelvin, 1867] Kelvin, William Thomson. 1867. On Vortex Atoms. *Philosophical Magazine*, **34**, 15–24.

[Kelvin, 1868] Kelvin, William Thomson. 1868. On Vortex Motion. *Transactions of the Royal Society of Edinburgh*, **25**, 217–260.

[Kelvin, 1871] Kelvin, William Thomson. 1871. Address. *British Association Report*, **41**.

[Kelvin, 1873] Kelvin, William Thomson. 1873. On the Ultramundane Corpuscles of Le Sage. *Philosophical Magazine*, **45**, 321–332.

[Kelvin, 1880a] Kelvin, William Thomson. 1880a. Vortex Statics. *Philosophical Magazine*, 97–108.

[Kelvin, 1880b] Kelvin, William Thomson. 1880b. On Maximum and Minimum Energy in Vortex Motion. *Report, British Association for the Advancement of Science*, 473–477.

[Kelvin, 1881] Kelvin, William Thomson. 1881. On the average Pressure due to impulse of Vortex-Rings on a Solid. *Nature*, **24**, 47.

[Kelvin, 1894] Kelvin, William Thomson. 1894. *Popular Lectures Addresses*. Vol. 2. London: Macmillan.

[Köhnke, 1986] Köhnke, Klaus Christian. 1986. *Enstehung und Aufstieg des Neukantianismus*. Suhrkamp.

[Kragh, 2002] Kragh, Helge. 2002. The Vortex Atom: A Victorian Theory of Everything. *Centaurus*, **44**, 32–114.

[Kragh, 2008] Kragh, Helge. 2008. *Higher Speculations*. Oxford University Press.

[Kuhn, 1977] Kuhn, Thomas S. 1977. *The Essential Tension: Selected Studies in Scientific Tradition and Change*. Chicago: University of Chicago Press.

[Laplace, 1902] Laplace, Pierr Simon. 1902. *A philosophical essay on probabilities*. New York: John Wiley & Sons.

[Liebmann, 1912] Liebmann, Otto. 1912. *Kant und die epigonen: Eine kritische abhandlung*. Berlin: Reuther & Reichard.

[Lodge, 1889] Lodge, Oliver J. 1889. *Modern Views of Electricity*. London: Macmillan.

[Lunteren, 1991] Lunteren, Frans van. 1991. *Framing hypotheses: Conceptions of gravity in the 18th and 19th centuries*. Ph.D. thesis, Universiteit Utrecht.

[Lunteren, 2009] Lunteren, Frans van. 2009. *Geschiedenis van de moderne natuurkunde*. Course reader.

[Maxwell, 1861] Maxwell, James Clerk. 1861. On Physical Lines of Force. *Philosophical Magazine*, **21**, 161–175;281–291;338–348.

[Maxwell, 1875] Maxwell, James Clerk. 1875. *Enyclopaedia Brittanica, Ninth Edition*. Pages 36–49.

[McCartney, 2002] McCartney, Mark. 2002. William Thomson: king of Victorian physics. *Physics World*, 25–29.

[Merz, 1965a] Merz, John T. 1965a. *A History of European Thought in the Nineteenth Century.* Vol. 2. Dover Publications, Inc.

[Merz, 1965b] Merz, John T. 1965b. *A History of European Thought in the Nineteenth Century.* Vol. 3. Dover Publications, Inc.

[Milner, 1935] Milner, S.R. 1935. William Mitchinson Hicks. 1850-1934. *Obituary Notices of Fellows of the Royal Society*, **1**(4), 393–399.

[Molella, 1972] Molella, Arthur Philip. 1972. *Philosophy and Nineteenth Century German Electrodynamics: the problem of action at a distance.* Ph.D. thesis, Cornell University.

[Navarro, 2005] Navarro, Jaune. 2005. J.J. Thomson on the Nature of Matter: Corpuscles and the Continuum. *Centaurus*, **47**, 259–282.

[Olesko, 1980] Olesko, Kathryn Mary. 1980. *The Emergence of Theoretical Physics in Germany: Franz Neumann & the Konigsberg school of physics, 1830-1980.* Ph.D. thesis, Cornell University.

[Oppenheim, 1986] Oppenheim, Janet. 1986. Physics and Psychic Research in Victorian and Edwardian England. *Physics Today*, **39**(62-70).

[Ostwald, 1887] Ostwald, Wilhelm. 1887. *Lehrbuch der allgemeinen chemie.* Leipzig: Engelmann.

[Ostwald, 1902] Ostwald, Wilhelm. 1902. *Vorlesungen über naturphilosophie, gehalten im sommer 1901 an der Universität Leipzig.* Leipzig: Veilt & comp.

[Pearson, 1892] Pearson, Karl. 1892. On a certain atomic hypothesis - ether squirts. *American Journal of Mathematics*, **13**, 310.

[Prawer, 1970] Prawer, Siegbert. 1970. *The Romantic Period in Germany.* New York: Schocken Books.

[Preston, 1877] Preston, Samual Tolver. 1877. On some Dynamical Conditions applicable to Le Sage's Theory of Gravitation. *Philosophical Magazine*, **4**, 206–212, 364–375.

[Schiemann, 2009] Schiemann, Gregor. 2009. *Herman von Helmholtz's Mechanism: The Loss of Certainty.* Springer. Tranlated by Cynthia Klohr.

[Schneider & Sagan, 2005] Schneider & Sagan, Eric D. Schneider & Dorion Sagan. 2005. *Into the Cool: Energy Flow, Thermodynamics and Life.*

[Sharlin, 1979] Sharlin, Harold Issadore. 1979. *Lord Kelvin, The Dynamic Victorian.* The Pennsylvania State University Press.

[Silliman, 1963] Silliman, Robert H. 1963. William Thomson: Smoke Rings and Nineteenth-Century Atomism. *Isis*, **54**(4), 461–474.

[Smith & Wise, 1989] Smith, Crosbie, & Wise, M. Norton. 1989. *Energy and Empire: A Biographical Study of Lord Kelvin*. Cambridge University Press.

[S.P. Thomson, 1910] S.P. Thomson, Silvanus Philips. 1910. *The life of William Thomson*. Vol. 2. London: Macmillan.

[Stewart & Tait, 1886] Stewart, Balfour, & Tait, Peter G. 1886. *The Unseen Universe Or Physical Speculations of a Future State*. The Macmillan And Company.

[Tait, 1877] Tait, Peter G. 1877. On Knots. *Transactions of the Royal Society of Edinburgh*, **28**, 145–190.

[Tait, 1879] Tait, Peter G. 1879. *Lectures on Some Recent Advances in Physical Science*. London: Macmillan.

[Tait, 1885] Tait, Peter G. 1885. On Knots Part III. *Transactions of the Royal Society of Edinburgh*.

[Tait, 1899] Tait, Peter G. 1899. *Properties of Matter*. 4 edn. London: Adam and Charles Black.

[The free dictionary, 2009] The free dictionary. 2009. `http://www.thefreedictionary.com/Zeitgeist`.

[Theerman, 1986] Theerman, Paul. 1986. James Clerk Maxwell and Religion. *American Journal of Physics*, **54**, 312–317.

[Thomson, 1883] Thomson, J.J. 1883. *A Treatise on the Motion of Vortex Rings*. Macmillan and Co.

[Thomson, 1888] Thomson, J.J. 1888. *Applications of dynamics to physics and chemistry*. London: Macmillan.

[Thomson, 1893] Thomson, J.J. 1893. *Notes on Recent Researches In Electricity And Magnetism*. Oxford, The Clarendon press.

[Thomson, 1895] Thomson, J.J. 1895. The Relation Between the Atom and the Charge of Electricity Carried by It. *Philosophical Magazine*, **40**, 511–527.

[Thomson, 1930] Thomson, J.J. 1930. *Recollections and Reflections*. London: G. Bell and Sons.

[Topper, 1971] Topper, David R. 1971. Commitment to Mechanism. J.J. Tomson, the Early Years. *Archive for History of Exact Sciences*, **7**(5), 393–410.

[Tribe, 1872] Tribe, A. 1872. Remarks on the Atomic Theory. *Philosophical Magazine*, **44**, 121.

[Warwick, 2003] Warwick, Andrew. 2003. *Masters of Theory*. University Of Chicago Press.

[Wegener, 2009] Wegener, Daan. 2009. *A True Proteus: A History of Energy Conservation in German Science and Culture*. Ph.D. thesis, Utrecht Universtity.

[Wise, 1981] Wise, M. Norton. 1981. *Conceptions of ether*. Cambridge University Press. Chap. German concepts of force, energy, and the electromagnetic ether: 1845-1880.

[Wright, 1872] Wright, C. 1872. On the Relation between the Atomic Hypothesis and Dissected (Structural) Formula. *Philosophical Magazine*, **43**, 259.