The Nobel Prize in Physics 1902
Hendrik A. Lorentz, Pieter Zeeman

Hendrik A. Lorentz - Nobel Lecture

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The Theory of Electrons and the Propagation of Light

When Professor Zeeman and I received the news of the great honour of the high distinction awarded to us, we immediately began to consider how we could best divide our roles with respect to our addresses. Professor Zeeman was first to have described the phenomenon discovered by him, given the explanation of it, and given an outline of his later experimental work. My task should have been to consider rather more deeply our present-day knowledge of electricity, in particular the so-called electron theory.

I am more sorry than I can say that Professor Zeeman has been prevented by illness from undertaking the journey to Stockholm, and that therefore you will now only be able to hear the second half of our programme. I hope you will excuse me if under these circumstances I say only a little about the main theme, Zeeman's fine discovery. A short description of it, however, might well precede my further thoughts.

As is well known to you, Faraday even in his day discovered that magnetic forces can have an effect on the propagation of light. He showed in fact that in suitable conditions the vibrations of a beam of polarized light can be made to rotate by such forces. Many years later Kerr found that such a beam of light also undergoes similar changes when it is simply reflected from the polished pole of a magnet. However, it remained for Zeeman's talent to show that a magnetic field affects not only the propagation and reflection of light but also the processes in which the beam of light originates, that is to say that the rays emitted by a light source assume different properties if this source is placed in the gap between a magnetic north and south pole. The difference is shown in the spectral resolution of the light, when one is working with the type of light source whose spectrum consists of single bright lines - that is, with a coloured flame, an electrical spark, or a Geissler tube. To have a specific case before your eyes, imagine that my hands are the two poles, only much closer together than I am holding them now, and that the light source is between these poles, that is to say in the space immediately in front of me. Now if the spectrum of the light which shines on a point directly opposite me is investigated, there can be observed, instead of a single spectral line such as can be seen under normal circumstances, a three-fold line, or triplet, whose components admittedly are separated from each other by a very small distance. Since each position in the spectrum corresponds to a specific frequency of light, we can also say that instead of light of one frequency the source is, under the influence of the magnetic field, emitting light of three different frequencies. If the spectrum consists of more than one line, then you can imagine that each line is resolved into a triplet. I must, however, add that the situation is not always as simple as this, and many spectral lines resolve into more than three components.

Before turning to the theory, I should like to remark that thanks to the speedy publication of research and the consequent lively exchange of views between scientists much progress must be considered as the result of a great deal of joint effort. Since it is expected of me, I am going to talk principally of my own ideas and the way in which I have come to them. I do beg

of you, however, not to lose sight of the fact that many other physicists, not all of whom I can name in this short space of time, have arrived at the same or very similar conclusions.

The theory of which I am going to give an account represents the physical world as consisting of three separate things, composed of three types of building material: first ordinary tangible or ponderable matter, second electrons, and third ether. I shall have very little to say about ponderable matter, but so much the more about ether and electrons. I hope it will not be too much for your patience.

As far as the ether - that bearer of light which fills the whole universe - is concerned, after Faraday's discovery which I have already mentioned and also independently of it, many attempts were made to exploit the ether in the theory of electricity also. Edlund went so far as to identify the electric fluid with the ether, ascribing to a positively charged body an excess of ether and to a negatively charged one a deficiency of ether. He considered this medium as a liquid, subject to the Archimedean principle, and in this way succeeded in imputing all electrostatic effects to the mutual repulsion of particles of ether.

There was also a place in his theory for the electrodynamic attraction and repulsion between two metallic wires with electrical current flowing in them. Indeed, he formed a most remarkable conception of these effects. He explained them by the condition that the mutual repulsion of two particles of ether needs a certain time to be propagated from the one to the other; it was in fact an axiom with him that everything which occurs in Nature takes a certain length of time, however short this may be. This idea, which has been fully developed in our present-day views, is found also in the work of other older physicists. I need only mention Gauss, of whom we know that he did not follow this up only because he lacked a clear picture of the propagation. Such a picture, he wrote to Wilhelm Weber, would be the virtual keystone of a theory of electrodynamics.

The way pioneered by Edlund, in which the distinction between ether and electricity was completely swept aside, was incapable of leading to a satisfactory synthesis of optical and electrical phenomena. Lorenz at Copenhagen came nearer the goal. You know, however, that the true founders of our present views on this subject were Clerk Maxwell and Hertz. In that Maxwell developed further and constructed a basis for the ideas put forward by Faraday, he was the creator of the electromagnetic theory of light, which is undoubtedly well known to you in its broad outline. He taught us that light vibrations are changes of state of the same nature as electric currents. We can also say that electrical forces which change direction extremely rapidly - many billions of times a second - are present in every beam of light. If you imagine a tiny particle in the path of a sunbeam, something like the familiar dust motes in the air, only considerably smaller, and if you also imagine that this particle is electrically charged, then you must also suppose that it is set into a rapid quivering movement by the light vibrations.

Immediately after Maxwell I named Hertz, that great German physicist, who, if he had not been snatched from us too soon, would certainly have been among the very first of those whom your Academy would have considered in fulfilling your annual task. Who does not know the brilliant experiments by which he confirmed the conclusions that Maxwell had drawn from his equations? Whoever has once seen these and learnt to understand and admire them can no longer be in any doubt that the features of the electromagnetic waves to be observed in them differ from light beams only in their greater wavelength.

The result of these and other investigations into the waves propagated in the ether culminate in the realization that there exists in Nature a whole range of electromagnetic waves, which, however different their wavelengths may be, are basically all of the same nature. Beginning with Hertz's "rays of electrical force", we next come to the shortest waves caused by electromagnetic apparatus and then, after jumping a gap, to the dark thermal rays. We traverse the spectrum far into the ultraviolet range, come across another gap, and may then put X-rays, as extremely short violent electromagnetic disturbances of the ether, at the end of the range. At the beginning of the range, even before the Hertzian waves, belong the waves used in wireless telegraphy, whose propagation was established last summer from the southwest tip of England to as far as the Gulf of Finland.

Although it was principally Hertz's experiments that turned the basic idea of Maxwell's theory into the common property of all scientists, it had been possible to start earlier with some optimism on the task of applying this theory to special problems in optics. We will begin with the simple phenomenon of the refraction of light. It has been known since the time of Huygens that this is connected with the unequal rate of propagation of the beams of light in different substances. How does it come about, however, that the speed of light in solid, liquid, and gaseous substances differs from its speed in the ether of empty space, so that it has its own value for each of these ponderable substances; and how can it be explained that these values, and hence also the refractive index, vary from one colour to another?

In dealing with these questions it appeared once more, as in many other cases, that much can be retained even from a theory which has had to be abandoned. In the older theory of undulation, which considered the ether as an elastic medium, there was already talk of tiny particles contained in ponderable substances which could be set in motion by light vibrations. The explanation of the chemical and heating action of light was sought in this transmission of motion, and a theory of colour dispersion had been based on the hypothesis that transparent substances, such as glass and water, also contained particles which were set into co-vibration under the influence of a beam of light. A successor to Maxwell now has merely to translate this conception of co-vibrating particles into the language of the electromagnetic theory of light.

Now what must these particles be like if they can be moved by the pulsating *electrical* forces of a beam of light? The simplest and most obvious answer was: they must be electrically charged. Then they will behave in exactly the same way as the tiny charged dust motes that we spoke of before, except that the particles in glass and water must be represented, not as floating freely, but as being bound to certain equilibrium positions, about which they can vibrate.

This idea of small charged particles was otherwise by no means new; as long as 25 years ago the phenomena of electrolysis were being explained by ascribing positive charges to the metallic atoms in a solution of a salt, and negative charges to the other components of the salt molecule. This laid the foundation of modern electrochemistry, which was to develop so rapidly once Prof. Arrhenius had expressed the bold idea of progressive dissociation of the electrolyte with increasing dilution.

We will return to the propagation of light in ponderable matter. The covibrating particles must, we concluded, be electrically charged; so we can conveniently call them "electrons", the name that was introduced later by Johnstone Stoney. The exact manner in which this co-vibration takes place, and what reaction it has on the processes in the ether, could be investigated with the aid of the well-known laws of electromagnetism. The result consisted of formulae for the velocity of propagation and the refractive indices, in their dependence on the one hand on the vibration period - i.e. on the colour of the light - and on the other hand on the nature and number of the electrons.

You will forgive me if I do not quote the rather complicated equations, and only give some account of their significance. In the first place, as regards the dependence of the refractive index on vibration period - that is, colour dispersion: in the prismatic spectrum and in rainbows we see a demonstration of the fact that the electrons in glass and water possess a certain mass; consequently they do not follow the vibrations of light of different colours with the same readiness.

Secondly, if attention is focussed on the influence of the greater or smaller number of particles in a certain space an equation can be found which puts us in a position to give the approximate change in the refractive index with increasing or decreasing density of the body - thus, for example, it is possible to calculate the refractive index of water vapour from that of water. This equation agrees fairly well with the results of experiments.

When I drew up these formulae I did not know that Lorenz at Copenhagen had already arrived at exactly the same result, even though he started from different viewpoints, independent of the electromagnetic theory of light. The equation has therefore often been referred to as the formula of Lorenz and Lorentz.

This formula is accompanied by another which makes it possible to deduce the refractive index of a chemical compound from its composition, admittedly only in rough approximation as was possible earlier with the aid of certain empirical formulae.

The fact that such a connection between the refraction of light and the chemical composition does exist at all is of great importance in the electromagnetic theory of light. It shows us that the power of refraction is not one of those properties of matter which are completely transformed by the action of chemical combination. The relative positions of, and type of bond between, the atoms are not of primary importance as concerns the speed of propagation in a compound. Only the number of atoms of carbon, hydrogen, etc. is of importance; each atom plays its part in the refraction of light, unaffected by the behaviour of the others. In the face of these results we find it hard to imagine that the forces which bind an electron to its equilibrium position and on the intensity of which depends the velocity of light are generated by a certain number of neighbouring atoms. We conclude rather that the electron, together with whatever it is bound to, has its place within a single atom; hence, electrons are smaller than atoms.

Permit me now to draw your attention to the ether. Since we learnt to consider this as the transmitter not only of optical but also of electromagnetic phenomena, the problem of its nature became more pressing than ever. Must we imagine the ether as an elastic medium of very low density, composed of atoms which are very small compared with ordinary ones? Is it perhaps an incompressible, frictionless fluid, which moves in accordance with the equations of hydrodynamics, and in which therefore there may be various turbulent motions? Or must we think of it as a kind of jelly, half liquid, half solid?

Clearly, we should be nearer the answers to these questions if it were possible to experiment on the ether in the same way as on liquid or gaseous matter. If we could enclose a certain quantity of this medium in a vessel and compress it by the action of a piston, or let it flow into another vessel, we should already have achieved a great deal. That would mean displacing the ether by means of a body set in motion. Unfortunately, all the experiments undertaken on these lines have been unsuccessful; the ether always slips through our fingers. Imagine an ordinary barometer, which we tilt so that the mercury rises to the top, filling the tube completely. The ether which was originally above the mercury must be somewhere; it must have either passed through the glass or been absorbed into the metal, and that without any force that we can measure having acted upon it. Experiments of this type show that bodies of normal dimensions, as far as we can tell, are completely permeable to the ether. Does this apply equally to much larger bodies, or could we hope to displace the ether by means of some sort of very-large, very-fast moving piston? Fortunately, Nature performs this experiment on a large scale. After all, in its annual journey round the sun the earth travels through space at a speed more than a thousand times greater than that of an express train. We might expect that in these circumstances there would be an end to the immobility of the ether; the earth would push it away in front of itself, and the ether would flow to the rear of the planet, either along its surface or at a certain distance from it, so as to occupy the space which the earth has just vacated. Astronomical observation of the positions of the heavenly bodies gives a sharp means of determining whether this is in fact the case; movements of the ether would assuredly influence the course of the beams of light in some way.

Once again we get a negative answer to our question whether the ether moves. The direction in which we observe a star certainly differs from the true direction as a result of the movement of the earth - this is the so-called aberration of light. However, by far the simplest explanation of this phenomenon is to assume that the whole earth is completely permeable to the ether and can move through it without dragging it at all. This hypothesis was first expressed by Fresnel and can hardly be contested at present.

If we wish to give an account of the significance of this result, we have one more thing to consider. Thanks to the investigations of Van der Waals and other physicists, we know fairly accurately how great a part of the space occupied by a body is in fact filled by its molecules. In fairly dense substances this fraction is so large that we have difficulty in imagining the earth to be of such loose molecular structure that the ether can flow almost completely freely through the spaces between the molecules. Rather are we constrained to take the view that each individual molecule is permeable. The simplest thing is to suggest further that the same is true of each atom, and this leads us to the idea that an atom is in the last resort some sort of local modification of the omnipresent ether, a modification which can shift from place to place without the medium itself altering its position. Having reached this point, we can consider the ether as a substance of a completely distinctive nature, completely different from all ponderable matter. With regard to its inner constitution, in the present state of our knowledge it is very difficult for us to give an adequate picture of it.

I hardly need to mention that, quite apart from this question of constitution, it will always be important to come to a closer understanding of the transmission of apparent distant actions through the ether by demonstrating how a liquid, for example, can produce similar effects. Here I am thinking in particular of the experiments of Prof. Bjerknes in Christiania[*] on transmitted hydrodynamic forces and of his imitation of electrical phenomena with pulsating spheres.

I come now to an important question which is very closely connected with the immobility of the ether. You know that in the determination of the velocity of sound in the open air, the effect of the wind makes itself felt. If this is blowing towards the observer, the required quantity will increase with the wind speed, and with the wind in the opposite direction the figure will be reduced by the same amount. If, then, a moving transparent body, such as flowing water, carries along with it in its entirety the ether it contains, then optical phenomena should behave in much the same way as the acoustical phenomena in these experiments. Consider for example the case in which water is flowing along a tube and a beam of light is propagated *within* this water in the direction of flow. If everything that is involved in the light vibrations is subject to the flowing movement, then the propagation of light in the flowing water will in relation to the latter behave in exactly the same way as in still water. The velocity of propagation relative to the wall of the tube can be found by adding the velocity of propagation *in* the water to the rate of flow of the water, just as, if a ball is rolling along the deck of a ship in the direction in which it is travelling, the ball moves relative to an observer on the shore at the sum of two speeds - the speed of the ship and the speed at which the ball is rolling on it. According to this hypothesis the water would drag the light waves at the full rate of its own flow.

We come to a quite different conclusion if we assume, as we now must, that the ether contained in the flowing water is itself stationary. As the light is partly propagated through this ether, it is easy to see that the propagation of the light beams, for example to the right, must take place more slowly than it would if the ether itself were moving to the right. The waves are certainly carried along by the water, but only at a certain fraction of its rate of flow. Fresnel has already demonstrated the size of this fraction; it depends on the refractive index of the substance - the value for water, for example, being 0.44. By accepting this figure it is possible to explain various phenomena connected with aberration. Moreover, Fresnel deduced it from a theoretical standpoint which, however ingenious it may be, we can now no longer accept as valid.

In 1851 Fizeau settled the question by his famous experiment in which he compared the propagation of light in water flowing in the direction of the beam of light with its propagation in water flowing in the opposite direction. The result of these experiments, afterwards repeated with the same result by Michelson and Morley, was in complete agreement with the values assumed by Fresnel for the drag coefficient.

There now arose the question of whether it is possible to deduce this value from the new theory of light. To this end it was necessary first of all to develop a theory of electromagnetic phenomena in moving substances, with the assumption that the ether does not partake of their motion. To find a starting-point for such a theory, I once again had recourse to electrons. I was of the opinion that these must be permeable to the ether and that each must be the centre of an electric and also, when in motion, of a magnetic field. For conditions in the ether I introduced the equations which have been generally accepted since the work of Hertz and Heaviside. Finally I added certain assumptions about the force acting on an electron, as follows: this force is always due to the ether in the immediate vicinity of the electron and is therefore affected *directly* by the state of this ether and *indirectly* by the charge and velocity of the other electrons which have brought about this state. Furthermore, the force depends on the charge and speed of the particle which is being acted upon; these values determine as it were the sensitivity of the electron to the action due to the ether. In working out these ideas I used methods deriving from Maxwell and partly also relied on the work of Hertz. Thus I arrived at the drag coefficient accepted by Fresnel, and was able to explain in a fairly simple way most of the optical phenomena in moving bodies.

At the same time, a start was made on a general theory which ascribed all electromagnetic processes taking place in ponderable substances to electrons. In this theory an electrical charge is conceived as being a surplus of positive or negative electrons, but a current in a metallic wire is considered to be a genuine progression of these particles, to which is ascribed a certain mobility in conductors, whereas in non-conductors they are bound to certain equilibrium positions, about which, as has already been said, they can vibrate. In a certain sense this theory represents a return to the earlier idea that we were dealing with two electrical substances, except that now, in accordance with Maxwell's ideas, we have to do with

actions which are transmitted through ether and are propagated from point to point at the velocity of light. Since the nature and manner of this transmission can be followed up in all its details, the demand that Gauss made for a theory of electrodynamics is fulfilled. I cannot spend any more time on these matters, but would like to mention that Wiechert at Göttingen and Larmor at Cambridge have produced very similar results, and that Prof. Poincaré has also contributed much to the development and evaluation of the theory.

I must also pass over many phenomena investigated in recent years, in which the concept of electrons has proved a useful guide, in order not to stray too far from the theory of the Zeeman effect.

When Prof. Zeeman made his discovery, the electron theory was complete in its main features and in a position to interpret the new phenomenon. A man who has peopled the whole world with electrons and made them covibrate with light will not scruple to assume that it is also electrons which vibrate within the particles of an incandescent substance and bring about the emission of light. An oscillating electron constitutes, as it were, a minute Hertzian vibrator; its effect on the surrounding ether is much the same as the effect we have when we take hold of the end of a stretched cord and set up the familiar motion waves in the rope by moving it to and fro. As for the force which causes a change in the vibrations in a magnetic field, this is basically the force, the manifestations of which were first observed by Oersted, when he discovered the effect of a current on a compass needle.

I will leave the explanation of triplets to Prof. Zeeman. I will confine myself to remarking that it is the negative electrons which oscillate, and that from the distance between the components into which the spectral line is resolved the ratio between the numerical value of the charge and the mass of these particles can be deduced. The results are in gratifying agreement with those which have been found in other contexts. The same or similar values for the ratio mentioned above have been found for the negative particles with which we are concerned in cathode rays.

A noteworthy aspect is the enormous size of the charge of these particles compared with their mass. A numerical example will give you some idea of this. Imagine that we had two iron spheres, each with a radius of one metre, situated ten metres apart, and that we gave each of them a surplus of our negative electrons of such a size that the mass of this surplus was the millionth part of a milligram. The spheres would then repel each other with a force equivalent to a weight of more than 80,000 kilograms and would therefore be able to reach a speed of many metres per second. I need hardly say that we are far from being able to make an experiment on this scale; we are not in a position to bring such a large number of electrons of one certain kind together on one body. If it were possible, we could carry out many interesting experiments which we can now only imagine. For instance, we could demonstrate the Zeeman effect on a simple pendulum. This can easily be made to swing in a circle, and if the bob is given an electrical charge the vertical component of the earth's magnetic field somewhat alters the period of rotation, which is increased in one direction and reduced in the other. With the charges which we have at our disposal this difference is completely imperceptible, and Prof. Zeeman himself would be unable to observe the Zeeman effect on a pendulum.

Let us now turn from the relative sizes of charge and mass to their absolute values. We can at least give an estimate of these. If we combine the results to which Zeeman's experiments lead with those which can be deduced from the colour dispersion of gases, on the hypothesis that it is the same type of electrons which is under consideration in both cases, we come to the conclusion that the charge of an electron is of the same order of size as the charge of an electrolytic ion. The mass, however, is much smaller - about one eight-hundredth part of that of a hydrogen atom. J.J. Thomson at Cambridge has confirmed this result by a completely different method. At present we are not concerned with the exact value; the principal thing is that, as we have remarked before, the electron is very small compared with the atom. The latter is a composite structure, which can contain many electrons, some mobile, some fixed; perhaps it bears electrical charges which are not concentrated at single points but distributed in some other way.

Of the other magneto-optical phenomena I will only describe one in any greater detail. Soon after Zeeman had published his discovery the Russian physicists Egorov and Georgievsky found that a sodium flame situated between the poles of an electromagnet emitted partially polarized light - i.e., in its beams vibrations in a certain direction were present with a greater intensity than vibrations in the direction perpendicular to this. To describe this phenomena to you more exactly and at the

same time to make clear how it is to be explained, I ask you to imagine once more that my hands are opposing magnetic poles and that the sodium flame is placed between them. Now if you were exactly opposite me, you would observe that the vertical electrical vibrations have a greater intensity than the horizontal ones.

This is connected with the fact that the flame has a certain thickness and that the beams emitted by the back half are partly swallowed up again as they pass through the front half. In accordance with a familiar rule, this absorption effect is strongest when all the incandescent particles in the flame are vibrating with the same period. It diminishes, and the flame therefore becomes brighter, as soon as this uniformity of the period of vibration is disturbed in any way. Now the magnetic field does this, in that instead of *one* common period of vibration it causes several to come into play. However, the increase in illuminating power brought about in this way is restricted to the vertical vibrations in the flame that we are imagining. The horizontal vibrations of the electrons, from right to left and back again, are - it follows from the principles of the theory - not at all influenced by the magnetic field.

The conclusion therefore is that of the vibrations emitted only the vertical ones and not the horizontal ones are reinforced, which is the cause of the phenomenon we have observed.

I may add that this phenomenon is one of those magneto-optical effects which are most easily observed. The explanation given can also be put to the proof by the use of two flames instead of one, and an investigation of the absorption to which the light of the rear one is subject in the front one which has been situated between the magnetic poles.

Now that I have come to absorption, I must also consider the masterly and important theoretical considerations to which Prof. Voigt at Göttingen has been led by Zeeman's discovery. His theory differs from mine in that he always has in mind, not the emission of light, but its absorption. He explains the so-called *inverse* Zeeman effect - that is, the phenomenon that, when a strong white light is transmitted through the flame situated between the poles, instead of an absorption stripe we get a triplet of dark lines. On the basis of the parallelism between absorption and emission, it is possible to work back from this inverse phenomenon to the direct one.

Voigt does not refer to vibrating electrons; he is content to add appropriately chosen new terms to the equations which represent propagation in an absorbent medium. This method throws into relief the connection between the Zeeman effect and the rotation of the direction of vibration which was discovered by Faraday, and has other advantages, namely when vapours of rather high density, with correspondingly wider spectral lines, are concerned. Professor Zeeman will be able to give you an example of the effects of Voigt's theory.

However, any one who sets himself the task of drawing conclusions about the nature of the vibrations of electrons from these observations will, I think, prefer to choose the emission from very rarefied gases as an object of study. Here the radiation from the single molecules or atoms, undimmed by their effects on each other, is mirrored by the sharp lines in the spectrum. I followed this course in my later research, but came across considerable difficulties due to the fact that although the simple triplet frequently appears, in many cases there is resolution into more than three lines. This is a stumblingblock in the way of the theory. At all events it is easy to draw some general rules about the state of polarization of the light beams corresponding to the different components - i.e., the shape and direction of their vibrations, but unfortunately I have hardly got any further.

As long as we have to deal only with resolution into three components, it is sufficient explanation to assume that each incandescent atom contains a single electron which can vibrate round its equilibrium position in all directions in the same way. This simple theory however leaves us high and dry as soon as the spectral lines split into more than three components in the magnetic field. It is obvious then that we must imagine atoms of more complicated structure, which are provided with electrical charges, and the parts of which are capable of making small vibrations, rather like the parts of an elastic resonant body. When I investigated the theory of such movements, which can be done without much difficulty, it became evident that such an arbitrary system would in general show no Zeeman effect at all.

However, no mathematical theory is necessary to perceive this and to find the condition necessary to bring about such an effect. Imagine a light source which shows a Zeeman triplet under the influence of a magnetic field. The three lines naturally cannot appear unless three types of vibration with slightly different periods are present in the particles of the light source. These periods however can only be different if the directions of movement or the shapes of the path in the three cases are not the same. We will say in short that we are dealing with three different *vibration patterns*, each with its own frequency, in the light source.

We will now gradually reduce the intensity of the magnetic field and finally let it disappear. As long as even a weak field is present, the three lines persist, only they draw nearer each other; the three vibration patterns thus always exist, but their frequencies approach a common limiting value, the frequency of the unresolved spectral line. In this way we come to suppose that even when we observe the latter, the three patterns of movement still exist, though without distinguishing themselves from each other by their frequency as is the case in a magnetic field. It can be expressed thus: the spectral line is already three-fold before the magnetic force comes into play, and this force has nothing else to do except, as it were, to push apart the three lines which originally coincided.

The same applies to a four-, five- or six-fold line, and you may rest assured that a spectral line will never resolve into six components unless, before the magnetic field is set up, each incandescent particle can vibrate in six different ways, that is, with exactly the same frequency.

Herein lies one necessary condition which is not quite so easy to fulfil. I could add a second condition for the appearance of clear-cut components of the spectral lines, but the one I have described should suffice to show that in the further development of the theory we cannot give free rein to our imagination. Instead, we are fairly limited in the choice of hypotheses. A suitable model of a vibrating atom would be an elastic spherical shell with a uniformly distributed electrical charge, whose surface is divided by nodal lines into a greater or lesser number of fields vibrating in different directions. However, I will not linger over the phenomena which appear in such models, for I fear I might wander too far from reality along these paths.

I have tried to delineate in broad outline how much - or it would be better to say, how little - the electron theory has achieved in the explanation of the new magneto-optical phenomena. If I were now to give an account of the experimental work, it would become clear that the experiments have made more considerable advances. The research workers have already made a start on comparing the different spectral lines of a chemical element with each other, with respect to their magnetic resolution, and on investigating the connection between this resolution and the regular relationships existing in spectra.

In this country, where the father of my worthy colleague Angstrom, and Prof. Thalén have worked, and where Prof. Hasselberg continued his observations and measurements with indefatigable diligence, I hardly need to say how wonderful and rich a world these investigations into spectra have opened up to us. A world whose laws we are beginning to understand. It has become apparent that many line spectra are constructed according to a definite type; the lines are arranged in certain series, and in such a way that each series consists of lines which are distributed over the spectrum in accordance with a fairly simple law, and moreover there are relationships between the one series and the next. These relationships, in the clarification of which Prof. Rydberg and the German physicists Kayser and Runge have been particularly prominent, suggest a connection between the magnetic resolution of lines belonging to the same series. Such a connection has now in fact been confirmed. Runge and Paschen have found, in their investigation of the Zeeman effect in mercury, that all the lines of one series are resolved in exactly the same way.

I am convinced that the theory will only make significant progress when it also turns its attention not simply to one single spectral line but to all the lines of a chemical element. When once we succeed in building a theoretical foundation for the structure of spectra, then and not before then will we be able to grasp successfully the more complicated forms of the Zeeman effect. It would be better to say: in the future, research into the regular relationships in the spectra and into the Zeeman effect must go hand in hand; thus they will be able to lead some day to a theory of light emission, the achievement of which is one of the greatest aims of present-day physics.

The electron theory also presents an enormous field of study outside the realm of magneto-optical phenomena. For one thing, the free-moving electrons, with which we are concerned in cathode rays and in some types of Becquerel rays, give rise to many interesting problems. I will single out only the important question of the so-called apparent mass of these particles. A definite magnetic field in the surrounding ether - and hence also a certain amount of energy in this medium - are inextricably connected with every movement of an electron; we can therefore never set an electron in motion without simultaneously imparting energy to the ether. To do this a great amount of work is necessary, and we must employ a greater force than if it were not necessary to set up this magnetic field. Calculation shows that the force required is the same as would be needed if the mass were somewhat greater than it is in reality. In other words, if we determine the mass in the usual way from the phenomena, we get the true mass increased by an amount which we can call the apparent, or electromagnetic, mass. The two together form the effective mass which determines the phenomena.

Now the investigations published by Kaufmann and Abraham in the past year have shown that the apparent mass is by no means to be discounted. It certainly forms a considerable part of the effective mass, and there is a possibility that in the end we shall have to ascribe apparent mass only and never true mass at all to electrons.

The peculiar thing about this apparent mass is, moreover, that it is not constant, but depends on the velocity; consequently the study of the motion of the electron differs in many ways from ordinary dynamics.

It is hard to say if it will ever be possible to examine further with any success the question of the nature of an electron, which the research I have mentioned has already touched on. Meanwhile, even without ascertaining this, we can continue to test the basic assumptions of the theory in practice, and to draw from the properties of ponderable matter conclusions about the electrons it contains. The conductivity of electricity and heat by metals, thermoelectricity, permanent and temporary magnets, heat radiation and absorption, the optical, electrical and magnetic properties of crystals - all these aspects promise us a rich harvest. And even farther fields are opening up to our view. If it is true, as had been concluded from optical experiments, that the dimensions of a ponderable body undergo a slight alteration as soon as it moves through the motionless ether, we must conclude that molecular forces are transmitted through the ether in a way similar to electrical effects, and that leads to the idea that these forces are basically of an electromagnetic nature and the material particles among which they exist are composed of electrons - or, at least, the electrical charges of these particles are not something accidental but something very significant, also where molecular forces are concerned.

Thus we hope that the electron hypothesis, as it is being taken up in widely different sectors of physics, will lead to a general theory embracing many aspects of physics and also of chemistry. Perhaps it will be itself completely transformed on the long journey; however, there can hardly be any doubt that our hypotheses about the connection of widely differing phenomena with electromagnetism will prove correct, and that hence, in so far as it relates to the nature of ponderable matter, that general theory will be an electrochemical one, as Berzelius already dimly foresaw and as he tried to demonstrate with the resources at his disposal.

This is admittedly a prospect of the distant future, and the individual scientist can scarcely hope to make any significant contribution to its achievement. As far as I am concerned, I would count myself fortunate if it fell to me, encouraged and spurred on as I am by the high distinction awarded to me by your Academy, to play a modest part in the solution of the problems which next present themselves to us.

I close with the warmest thanks for the attention with which you have listened to me.