Dialogue Concerning Magnetic Forces

Abstract

The question of how best to explain magnetic forces between uniformly moving charges has divided physicists. A fictitious dialogue styled on David Hume's *Dialogues Concerning Natural Religion* (1779) crystallises the various views expressed in the literature around three positions: a) special relativity can explain such forces as a relativistic aspect of electricity; b) special relativity cannot explain such forces and no explanation is required; c) special relativity cannot explain such forces and an alternative explanation is required. The arguments deployed suggest that it is possible to achieve a deeper understanding of the forces between moving charges than is commonly assumed.

1. Introduction

In the introduction to his *Dialogues Concerning Natural Religion*, David Hume observes that "any question of philosophy which is so *obscure* and *uncertain* that reason can reach no fixed determination with regard to it… seems to lead us naturally into the style of dialogue and conversation" (1779, 3). Here I will apply this style of inquiry to a question in the foundations of physics which has divided physicists but has attracted surprisingly little attention among philosophers of physics: the origin of magnetic forces between uniformly moving charges. In the physics literature, essentially three positions on this question can be discerned.

The first is what I will call the 'old orthodoxy'. In this view, magnetic forces between moving charges are the result of the laws of classical electromagnetism, which are regarded as fundamental laws of nature. More precisely, the old orthodoxy holds that any constellation of moving charges is associated with an electromagnetic field, comprising an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$, such that the force $\mathbf{F}$ on a charge q moving at the velocity $\mathbf{v}$ is given by the Lorentz force law $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$. The force $\mathbf{F}$ can thus be decomposed into an electric component $\mathbf{F}_{\mathrm{elec}} = q\mathbf{E}$ and a magnetic component $\mathbf{F}_{\mathrm{mag}} = q\mathbf{v} \times \mathbf{B}$. In this context, it does not matter whether the electric and magnetic fields are separately regarded as real or whether only the electromagnetic field as a whole, for example as defined by the electromagnetic field tensor, is regarded as real, or indeed whether none of these fields are regarded as real. The key point made by the old orthodoxy is that the magnetic component of the electromagnetic force exerted by one moving charge on another is a result of the laws of classical electromagnetism and that no deeper explanation is required. It is sometimes argued that accepting the laws of classical electromagnetism as fundamental can help to explain special relativity because, together with the principle of relativity, those laws imply the constancy of the speed of light c for every observer. In the dialogue below, the old orthodoxy will be defended by Demea.

Today many physicists feel that the old orthodoxy does not provide a satisfactory answer to the question of how the magnetic component in the Lorentz force law comes about. Why is there a component of the force on a moving charge that is perpendicular to its direction of motion? Why does that component depend linearly on the speed of the charge? And where does the factor c^{-2} in the magnetic constant $\mu_0 = 1/\varepsilon_0 c^2$ in magnetic field equations come from? Many of those who are intrigued by these questions believe that special relativity holds the answer. They argue that magnetic forces are not an effect *sui generis* but are the result of relativistic transformations applied to purely electric forces. In this sense, they do not regard magnetic fields or forces as real, but they do regard the resulting overall electromagnetic forces as real. Over the last few decades, this view has become so widely accepted that I will here call it the 'new orthodoxy'. As the dialogue will show, the old and the new orthodoxy exist side by side in the physics literature, often in one and the same text. In the dialogue, the new orthodoxy will be defended by Cleo.

The third view on magnetic forces in the physics literature is less mainstream but has been defended from time to time and in one form or another since the early days of electrodynamic theorising. According to this approach, which I will call the 'sceptical view', the whole concept of magnetic forces is misguided and no more than a historical accident. Proponents of this view do not regard electromagnetic fields or forces as real, and they do not think that special relativity can help to explain the forces between moving charges. Instead, they argue that there is a single 'electric' force between moving charges, for example as measured by co-moving spring balances. The question they seek to answer is thus not how magnetic forces come about but, more generally, how the forces between charges in any state of motion come about. One line of inquiry in this tradition is to accept Coulomb's law of electrostatics as fundamental and to explain how past acceleration gives rise to the forces between moving charges that we observe. It has been claimed that one advantage of this approach is that it can help to shed light on the foundations of special relativity, notably the cause of length contraction. In the dialogue, the sceptical view will be defended by Philia.

After setting out each of these three positions in more detail in the dialogue, I will discuss their relative merits in the Conclusion. The concept of explanation underlying that discussion and the article as a whole is deliberately broad: a set of physical laws *A* is deemed to be in need of an explanation if those laws are to some extent mysterious or surprising. Another set of laws *B* is said to explain *A*, and is thus deemed to be more fundamental than *A*, if *A* is a consequence of *B* and *B* is less mysterious or surprising than *A*. What makes one set of laws less mysterious or surprising than another is precisely what some of the arguments in the dialogue are about.

2. The dialogue: opening statements

Let me demonstrate to you, Cleo said to Demea, that magnetic forces between charges moving at constant velocities are nothing but a relativistic effect. Let two such charges q_1 and q_2 move at the velocities $\mathbf{u}$ and $\mathbf{v}$ in a first inertial frame of reference S, in other words a uniformly moving frame of reference in which clocks have been Einstein-adjusted (Einstein, 1905, 894). Traditionally, to calculate the force on q_2 in this situation, we calculate the electric and magnetic fields $\mathbf{E}_1$ and $\mathbf{B}_1$ surrounding q_1, and then we use the Lorentz force law $\mathbf{F} = q_2(\mathbf{E}_1 + \mathbf{v} \times \mathbf{B}_1)$ to calculate the force $\mathbf{F}$ on q_2. If we are interested in the force $\mathbf{F}'$ on q_2 as measured in the rest frame S' of q_2, for example by means of a co-moving spring balance, we can perform a relativistic force transformation. This is all well and good, but there is another way to calculate $\mathbf{F}$ and $\mathbf{F}'$ which does not involve the concepts of magnetic fields or magnetic forces at all. The key idea is to transform the whole situation into the rest frame S' of q_2. Here is how: we define our coordinate systems such that q_2 is at $(0, 0, 0, 0)$ in S and S', and $\mathbf{v}$ points in the direction of the x and x' axes in S and S'. We now Lorentz transform the time, space and velocity coordinates of q_1 from S into S'. Next, we determine the position of q_1 in S' at the time $t' = 0$ by calculating $\mathbf{x}' = \mathbf{x}_1' - \mathbf{u}_1' t_1'$. We can now determine the electric field $\mathbf{E}_1'$ surrounding q_1 in S' at the time $t' = 0$ and thus the force $\mathbf{F}' = q_2 \mathbf{E}_1'$ on q_2. If we are interested in the force $\mathbf{F}$ on q_2 in S, we can perform a relativistic force transformation. And that completes the demonstration. Of course, we can carry out the same procedure for any other moving charges in S to determine the overall force on q_2. What we call the 'electromagnetic forces' on a moving charge q_2 caused by other moving charges are thus nothing but electric forces that act on q_2 in the rest frame of q_2 and that manifest themselves as 'electromagnetic' forces in S as a result of relativistic transformations. The interpretation of magnetic forces between moving charges as a relativistic effect has by now become widely accepted in the literature. For example, Edward M. Purcell and David J. Morin have emphasised the need to "understand why there is a velocity-proportional force" in addition to the electrical force (2013, 239). They find that a detailed consideration of relativistic effects implies that there exists such a force that must be added to the electrical force, and they conclude that, from this viewpoint, magnetism is "a relativistic aspect of electricity" (237). Richard Feynman et al. have explained the appearance of the factor c^{-2} in magnetic field equations by saying that "magnetism is in reality a relativistic effect of electricity" (1964, 1-6). Similarly, William Geraint V. Rosser has described the magnetic forces between moving charges as a "second order relativistic effect" (1968, 20).

Thank you, Cleo, for this clear and concise explanation, Demea replied, but forgive me for suggesting that your youth and inexperience may have caused you to rush into judgment where a deeper analysis is required. I'm sure you would have seen this for yourself had you studied the learned writings of our elders more carefully. But let me come to the point. Let us be clear about what you have shown. You have shown that the forces between uniformly moving charges in a first frame S can be explained with reference to the physical situation in a second frame S'. But what about the physical situation in S? Which physical processes in S result in the forces between moving charges that we observe? The answer is: the action of the electromagnetic field that surrounds any moving charge on any other moving charge! Don't forget that, in the framework of special relativity, all inertial frames of reference have the same status. The explanations we give for any physical process may differ from frame to frame, but each explanation is equally valid. The explanation for the force on q_2 in S is the electromagnetic field surrounding q_1 plus the movement of q_2. The explanation for the force on q_2 in S' is the electric field surrounding q_1. These are two alternative explanations, of which neither is superior to the other. As Oleg D. Jefimenko (1996) has pointed out, in the case of a moving charge that is subjected to purely magnetic forces in the vicinity of electric currents, we could just as easily derive the existence of electric forces acting on that charge in its rest frame from those magnetic forces combined with the transformations of relativity. Don't forget, either, that electromagnetism is no less fundamental a theory than special relativity. Indeed, taking electromagnetism as our starting point comes with a big advantage. It follows from Maxwell's equations of electromagnetism together with the principle of relativity, i.e. the principle that the laws of physics have the same form in all inertial frames of reference, that the speed of light c is the same in every inertial frame of reference. This is nothing but the light speed principle of special relativity. Together with the principle of relativity, all of special relativity follows from this. Instead of saying that special relativity, combined with the concept of the electric field, explains magnetic forces, we could thus say that electromagnetism, together with the principle of relativity, explains special relativity. We are free to choose which of those two approaches to adopt. Edward M. Purcell and David J. Morin, whom you have quoted in support of your position, have made it clear that whether you want to explain the value of the relativistic speed limit c with reference to electromagnetism or magnetic forces with reference to special relativity is "a matter of opinion, based on the information you want to start with" (2013, 282). William Geraint V. Rosser, whom you also quote in your defence, points out that "if it is assumed that Maxwell's equations are correct and obey the principle of relativity, the principle of the constancy of the speed of light follows" (1968, 151). John David Jackson has made it clear that it was the development of electromagnetism that "forced special relativity on us" (1999, 514). Finally, with reference to attempts to derive electromagnetism from special relativity, I. S. Grant and W. R. Phillips have cautioned that "one ought not to attach too much importance to the philosophical game of choosing the neatest set of initial postulates as the basis of electromagnetism", a theory which is "extraordinarily successful" in its predictions (1990, 473). Enough of these quotes from the learned writings of our elders, I think my point is clear: instead of saying that magnetic forces are a relativistic effect, we might just as well say that special relativity is an electromagnetic effect!

Let me first of all congratulate you, Cleo, on trying to find an explanation for the magnetic forces between moving charges, said Philia, who had until then listened carefully to the other two. There can be no doubt that such an explanation is required if we are to make sense of the physical world. To see this, it suffices to take a look at the form of the equations for the electric and magnetic fields of moving charges and the Lorentz force law. They include the electric constant from Coulomb's law of electrostatics, the velocities $\mathbf{u}$ and $\mathbf{v}$ at which q_1 and q_2 move, and the speed c at which electric disturbances propagate in inertial frames of reference. This alone suggests to us that 'electromagnetic' forces between moving charges are the result of distortions in the electric properties surrounding moving charged particles resulting from their past accelerations. How does this happen? Classical electromagnetism doesn't tell us. In particular, in classical electromagnetism the appearance of the factor c^{-2} in magnetic field equations and the appearance of $\mathbf{v}$ in the Lorentz force law are completely unexplained empirical facts. There are thus compelling reasons to call for a deeper explanation of the forces between moving charges than that afforded by classical electromagnetism. Now to the next question: does special relativity provide such an explanation? Here I must say that I agree with Demea in saying that it does not, albeit for slightly different reasons. It is not just that the explanation you, Cleo, gave is incomplete because it just explains what happens in the frame S' and not S. The real problem with explaining magnetic forces as a relativistic effect is that special relativity itself is in need of an explanation. Writers such as Harvey R. Brown (2005) and Daniel Shanahan (2014) have recognised this by calling for an explanation of the physical processes behind the transformations of special relativity, and thus behind Einstein's light speed principle. Indeed, are we really to accept the surprising fact that the two-way speed of light is constant for every observer as a fundamental fact of nature that cannot be explained any further? Surely not! Light is an example of 'electromagnetic' radiation, which is itself an electric phenomenon that can be produced by the acceleration of charged particles. Therefore, what we really need is a new and fundamental explanation of both 'electromagnetic forces' and of the light speed principle, based on a new model of electricity. Only then can we say that we have explained either!

3. The dialogue: developing the argument

Demea and Philia, you have raised three concerns about my argument which I think I can easily dispel, said Cleo. The first is that special relativity does not fully explain magnetic forces because the explanation of such forces as a purely electric effect only works in one frame of reference, the rest frame of q_2, and not in any other, where we have to continue to resort to the concepts of magnetic fields and magnetic forces. You are of course right that the explanation only works in one frame of reference, Demea, but in fact it doesn't matter. Why? Because the rest frame of q_2 is, after all, a rather special frame. It is the one in which everything becomes very simple when we use Einstein-adjusted clocks. It's the one frame in which only electric forces act on q_2. We therefore assert that it is in this frame that we can see the true nature of the force on q_2, which is purely electric, and not 'magnetic'. The illusion of a different kind of 'magnetic' force only arises because of the complications created by trying to determine the forces on q_2 in a frame in which q_2 moves. The second concern you raised is that we can just as easily derive special relativity from Maxwell's theory of electromagnetism as electromagnetism from special relativity. This idea has indeed been expressed by several writers, but it does not bear closer scrutiny. Kevin Brown notes that "attempts to deduce the invariance of light speed from Maxwell's equations are fundamentally misguided" because "it's not clear a priori whether Maxwell's equations are valid in terms of relatively moving systems of coordinates" (2010, 68 and 52). Of course, we could simply assume that Maxwell's equations are valid in the inertial frames of reference that must exist according to the principle of relativity, but that is tantamount to accepting the validity of the light speed principle, so why not simply accept that principle in the first place?

Now to your concern, Philia. It is ironic that Demea should chide me for youthful rashness when it is you who is guilty of rushing headlong into conclusions which have long been rejected by our elders. How can you say that we need to find a new model of electricity which explains both electromagnetism and special relativity when those two theories are among the finest examples of fundamental theories human minds have devised? When for the last 100 years or so nobody has even come close to developing such a new and more fundamental model? What is more, there is no need for such a model because special relativity has all the properties that we could hope to find in a fundamental theory: it is supremely simple, and it is universal in its range of applicability. How much simpler than the principle of the constancy of the two-way speed of light for any observer can you get? Kevin Brown points out that all past attempts to deduce the constancy of the two-way speed of light from more fundamental premises have failed so that "most writers on the subject have concluded (reluctantly) that Einstein's light speed postulate, or something like it, is indispensable for deriving special relativity" (2010, 71). Helmut Günther (2007) has identified a minimal set of conditions that must be met for the light speed principle to be true. These are length contraction by the relativistic factor $(1 - v^2/c^2)^{1/2}$ in a single uniformly moving frame of reference in which clocks have been Einstein-adjusted, and time dilation by the relativistic factor in the same frame of reference. But he warns that it is impossible to push that explanation any further. "Asking 'why' there is length contraction or time dilation… seems doomed to failure from the start" for "what should be the substance of our explanation when basically all lengths we measure are subjected to this contraction?" (Günther 2007, 224). Whichever way you look at it, special relativity is fundamental, and it is only right and proper for us to derive the magnetic forces between moving charges from special relativity, and not the other way around.

Rest assured, Cleo, that I wholeheartedly agree with you on the simplicity and fundamental nature of special relativity, said Demea. My point is that it cannot serve to explain magnetic forces between moving charges in frames of reference in which such forces appear. You have played down this point by suggesting that what goes on in the rest frame of q_2 is somehow more fundamental than what goes on in any other frame. I'm afraid this argument can easily be turned against you by some malevolent minds, for there would appear to be another candidate for such special frames of reference: any frames in which the electric properties surrounding a charge at rest are isotropic, in other words, the same in every direction. Suppose we are in such a frame S in which the charges q_1 and q_2 are at rest. Now let q_1 briefly be accelerated to $\mathbf{u}$ and q_2 to $\mathbf{v}$, and let them continue to move at these velocities. We know that information on the acceleration of q_2 moves away from the point where q_2 was at rest in S at the speed c in all directions, provided we use Einstein-adjusted clocks. The movement of q_2 in one particular direction then inevitably creates asymmetric conditions in the electric properties surrounding q_2. Now here's the rub: Einstein's clock adjustment procedure only synchronises clocks if the conditions of signal transmission are the same in opposite directions. As Albert Einstein said, the "means of sending signals" in his clock adjustment procedure "must be such that we have no reason to believe that the phenomena of signal transmission in the direction AB differ in any way from the phenomena of signal transmission in the direction BA" (1910, 25). The asymmetry of electric properties surrounding the charge q_2 means that this condition is not fulfilled when we Einstein-adjust clocks in the new rest frame $S'$of q_2. Don't forget that in special relativity clocks are not adjusted so that equal time coordinates imply a relationship of simultaneity but so that, in Albert Einstein's words, we "arrive at a simple and consistent electrodynamics of moving bodies on the basis of Maxwell's theory for bodies at rest" (1905, 892), or, as Wolfgang Rindler puts it, "so that the mathematical expression of the physical laws reflects their inherent symmetries" (2001, 42). What you end up with, therefore, is a frame S' in which equal time coordinates do not imply a relationship of simultaneity. And this is what you want to regard as a more fundamental frame than S? I'm afraid these are the kinds of questions you open yourself up to if you abandon the time-honoured principle that all inertial frames of reference are equivalent and that there is no 'special' frame of any kind. Once the absence of any special frame is accepted, it is clear that special relativity cannot explain the magnetic forces between uniformly moving charges. Indeed, I would go further: there is no need to seek any deeper explanation for such forces, whether via relativity or any other route. After all, within its range of applicability, classical electromagnetism works. It enables us to calculate the forces between moving charges in any given situation, and that is all we can hope for.

I agree with Demea, said Philia, that there is a problem with explaining physical processes in S with reference to what happens in S', and yes, one of the reasons is that Einstein-adjusted clocks will not be synchronised in S' if they are synchronised in S. I continue to believe, however, that a bigger problem with your reasoning, Cleo, is that special relativity is just as much in need of an explanation as classical electromagnetism. The principle of the constancy of the two-way speed of light may look simple at first glance, but let us analyse it a bit. Speed is derived from measurements of time and space, so the principle tells us something about the behaviour of clocks and measuring rods. As you mentioned, Cleo, an equivalent statement to that of the light speed principle is that in any point in time and space there is a uniformly moving frame of reference S in which bodies moving at the velocity $\mathbf{v}$ are length contracted in the direction of movement by the relativistic factor if clocks have been Einstein-adjusted, and moving clocks go slow by the relativistic factor. We can see that the apparent simplicity of the light speed principle hides a rather complex set of more elementary phenomena which, on the face of it, are in need of an explanation. But we can push the analysis a little further. Length contraction plus the independence of the speed of light from the speed of the source implies time dilation in light clocks. A minimal set of conditions from which the light speed principle follows is thus this: a) the speed of light is independent of the speed of the source; b) in S, moving bodies are length-contracted by the relativistic factor; and c) acceleration in S to one and the same velocity $\mathbf{v}$ affects the rate at which any clocks tick in the same way. Let us push the analysis a little further still: b) requires that the forces between charges as measured by co-moving spring balances change upon acceleration in a manner that is consistent with length contraction. This is indeed the case: if two charges separated by the vector $\mathbf{r}$ that are initially at rest in S are accelerated at the same time to the same velocity $\mathbf{v}$, then the force between them as measured by co-moving spring balances continues to act along the line connecting them, but its magnitude is reduced by the factor $k = (1 - v^2/c^2)/(1 - v^2 \sin^2 \alpha/c^2)$, where α is the angle between $\mathbf{r}$ and $\mathbf{v}$. This means that a body K that is accelerated from rest to the velocity $\mathbf{v}$ in S must contract in the direction of movement by the relativistic factor if the internal electric forces in K are to remain unchanged. Any satisfactory theory of electrodynamics ought to be able to explain how the reduction in the forces between two charges by the factor k comes about. Classical electromagnetism is unable to do so, not only because on its own it cannot be used to determine the forces between moving charges as measured by co-moving spring balances, but also because it involves magnetic forces, which themselves cry out for an explanation. What we need, then, is a more fundamental theory of electrodynamics that explains both 'magnetic forces' and what could be called 'electric length contraction': the fact that the forces between charges that change their state of motion are transformed in a way that is consistent with length contraction. You may say this is impossible, Cleo. But over the years there have been repeated attempts to develop alternative theories of electrodynamics that make no use of the concept of the magnetic field or of special relativity. Historical overviews of such attempts have been given by Parry Moon and Domina Eberle Spencer (1954) and by André Koch Torres Assis (1994), who has also given a detailed account of one of those approaches, Weber's electrodynamics (1994). What these approaches have in common is that they start from Coulomb's law of electrostatics and try to generalise it to the case of moving charges in accordance with experimental results, without using the concept of the electromagnetic field. More recently, Georg Lentze (2018) has gone a step further by trying to explain how past acceleration results in the changes in the forces between moving charges that we observe. The model he proposes explains the forces between point charges in uniform motion as measured by co-moving spring balances without reference to magnetism or special relativity, and thus it explains electric length contraction. A central feature of this 'sphere model' is that, as its starting point, it assumes the existence of just one uniformly moving frame of reference, locally in any point in time and space, in which light propagates in isotropic conditions from bodies at rest and in which the two-way speed of light is c. The sphere model suggests that efforts to deepen our understanding of the forces between moving charges, and of the light speed principle, are far from doomed to failure.

4. The dialogue: closing statements

I've had a look at the sphere model of electricity, said Cleo, and I must say that I am not impressed. In the sphere model, the forces between moving charges are explained as the result of changes in the electric properties surrounding charged particles, and in the exchange of information between them, resulting from their past accelerations. Those changes are described by no fewer than three factors by which Coulomb's law of electrostatics must be modified. Each of these factors is the geometric mean of 'near-side' and 'far-side' factors. Do you call that clear and simple? I prefer the simplicity of the constancy of the two-way speed of light principle or, equivalently, the principle that spacetime is Minkowskian rather than Galilean. Start from that plus the concept of the electric field, and the formula for the forces between charges in uniform motion follows. I stand by my original assertion: the magnetic forces between charges in uniform motion are a relativistic effect!

I still do not understand, said Demea, why both of you see the need to 'explain' magnetic forces. They are what they are because of the laws of electromagnetism, end of story. I repeat that special relativity plus the concept of the electric field cannot explain what goes on in frames of reference in which two interacting charges both move. Only classical electromagnetism can do that. Perhaps the sphere model Philia mentioned can do it too, but in its current state of development it appears that it only works for charges in uniform motion, not in any state of motion. That is rather less than what classical electromagnetism can do, so I fail to see why anybody should devote much time and effort to understanding such a model. I conclude that the current situation is entirely satisfactory: classical electromagnetism and special relativity are both excellent theories that have stood the test of time and they don't require any 'deeper explanation'!

Habit of thought, said Philia, may indeed lead us to think that magnetic forces and the light speed principle are fundamental facts of nature that cannot be explained any further. After all, that's what we were all taught at school. If we shed those habits of thought for a moment and look at the phenomena with fresh eyes, I think it is difficult to avoid the conclusion that they do require deeper explanations. Why are there magnetic forces between moving charges at all? Why do they depend on the velocity $\mathbf{v}$ at which charges move in an inertial frame of reference S in the way they do? Why do they depend on the speed c at which electric disturbances move in S in the way they do? Classical electromagnetism has no answers to these questions. Special relativity cannot answer them, either, because the seemingly simple light speed principle raises a number of questions too. One of these is why the forces between charges initially at rest in S which are simultaneously accelerated to the velocity $\mathbf{v}$ are transformed in a way which is consistent with length contraction. It is true that, even if we were able to explain this, we would not have explained the full light speed principle, which turns out to encompass a rather complex set of phenomena. But the very fact that all forces of nature appear to be transformed in the same way upon acceleration suggests that there is a fundamental unity to those forces. The precise nature of that unity is waiting to be discovered. It seems that exciting times lie ahead in our continuing efforts to deepen our understanding of the physical world!

5. Conclusion

Perhaps all three participants in the dialogue might be able to agree that the old orthodoxy, the new orthodoxy and the sceptical view each have some merits at different levels of inquiry.

Physicists and philosophers of physics only interested in calculating the forces between uniformly moving charges without worrying too much about how those forces come about are probably best served by Maxwell's equations and the Lorentz force law. They do not need a deeper understanding of the origin of magnetic forces between moving charges, and they will not gain it from studying the laws of classical electromagnetism if those laws are regarded as fundamental. The inability of classical electromagnetism to explain the origin of magnetic forces is one of the reasons why that theory is a poor choice as a cornerstone of special relativity: it cannot serve to explain the speed of light principle since the magnetic component of electromagnetic forces is itself in need of an explanation.

What about the opposite approach then, according to which special relativity can serve to explain magnetic forces? This view can be expected to appeal to all those who accept special relativity as fundamental. Deriving the magnetic forces between uniformly moving charges from the concept of the electric field plus the transformations of special relativity is computationally laborious but it is possible. In that sense, the new orthodoxy succeeds in explaining the magnetic forces between uniformly moving charges. All explanation must stop somewhere, and most physicists and philosophers of physics seem to be happy to accept the principles of special relativity as fundamental. Still, some may feel that the explanation provided by the new orthodoxy is not very physical: it does not explain electromagnetic forces in a first frame S directly but regards them as the manifestation of purely electric forces, deemed to be more fundamental, in a frame S' with different time and space coordinates. Others may feel uneasy about accepting special relativity as fundamental because doing so leaves us with no answer to questions such as why the forces between moving charges are transformed upon acceleration in a manner that is consistent with length contraction.

Those who consider that a deeper explanation of the forces between moving charges is required, in other words one that explains such forces without relying on the equations of classical electromagnetism or the principles of special relativity, may want to look to the sceptical view. Since the explanations put forward in this tradition do not rely on the light speed principle, they can help to explain aspects of special relativity, such as the independence of the speed of light from the speed of the source and the length contraction of moving bodies. However, the work that has been done in this field is not as well developed as the old or new orthodoxy, and it can take some time and effort to get to grips with it. It is therefore likely that only physicists or philosophers of physics determined to achieve the deepest possible level of understanding of the forces between uniformly moving charges will engage with, or even strive to develop, the ideas that have been put forward by proponents of the sceptical view.

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