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The nature of fields

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Abstract
The concept of a 'field' is analysed, in connection with different physical situations, specifically, concerning the creation of radiation. The role of a field in relativistic physics shows that it is an independent physical entity that should be considered on the same grounds as matter particles.

1. Introduction

Recently, in two papers, Ghins [1] and van Frassen [2] have discussed the question of how much the existence of a field (electric, gravitational) can be proven by experimental measurements, in contrast to the crystalline sphere of ancient astronomy. The authors show how a criterion of existence can be applied to the field, and how observing 'observables' enables us to attribute an objective reality to the existence of a field.

However, the authors do not discuss the nature of a field. Actually, they discuss measurements of the force exerted on a unit charge (mass) at each electric (gravitational) field point, and thus they can map the force field over the entire space. But what is the field itself—is it just a convenient way to describe the distribution of force in space, or is it an independent physical entity that should be considered as such? Ghins and van Frassen do not discuss this question, and we want to discuss it here in some more detail.

The concept of field was used long ago, during the era of Newtonian mechanics. As long as an interaction between two particles was considered to take place at an infinite velocity, it could be considered that two distant objects mutually interact immediately, and the concept of field could be considered just as a convenient way to describe the distribution of force in space. When the theory of relativity was established, it became clear that an interaction between two particles takes place with a finite velocity, and the demand of conservation of energy and momentum dictates that the concept of a field becomes more realistic. We may quote here Landau and Lifshitz [3]: 'in the theory of relativity, because of the finite velocity of propagation of interactions, the situation is changed dramatically. . . . A change in the position of one of the particles influences other particles only after a lapse of a certain time interval. This means that the field itself acquires physical reality'.

The interaction between the particles is not between the particles at their present location, but according to their location at an earlier moment, where the time lapsed is proportional to their mutual distance. We have to consider the interaction of particle A with the field, and then the interaction of the field with particle B, at a time Δt later, where $\Delta t = l/c$, with l being the distance between the particles. The velocity of expansion of the interaction is c, and it can be different in a dispersive medium. When particle A interacts with the field it imparts to it energy and momentum. These changes in the field advance at a finite velocity until they reach the location of particle B, and then the field imparts to particle B the energy and momentum it acquired earlier.

Certainly, the paragraph given above does not present a new idea, and later we cite Einstein who phrased this idea very clearly. Recently, we have used this idea in analysing the creation of radiation by an accelerated charge, finding that the detachment of the Coulomb field from the charge that induced the field is crucial for the rational explanation of the process, in which the old problem of the 'energy balance paradox' finds a nice solution. However, when this solution was presented in meetings and conferences, not a few physicists objected to it, arguing that the idea that a Coulomb field is detached from its source is incorrect. Hence we find it important to re-present this vital idea. In section 3 we present in short the solution for the creation of electromagnetic radiation, showing how it depends on the detachment of the Coulomb field from its source.

2. The electric field of charges in motion

We consider here specifically the behaviour of electric fields. When a charge resides at rest in a free space, its electric field is distributed isotropically, as it is usually drawn in a high school course on electricity. The field strength is $E = e\hat{r}/r^2$, where $\hat{r}$ is a unit vector from the source to the field point. Since the situation is static, we are not interested in temporal evolution of the field. We can look at it as if it exists forever, and any test charge located in that field will interact with it as if it interacts immediately with the field source.

The situation is different for a charge in a motion. It induces its field on space, the field expands with a finite velocity, and each point in space feels the field induced at an earlier time, when the moving source was located at a former point along its trajectory, depending on the distance of the field point from the source trajectory. This statement also concerns the Coulomb fields, and not only the radiation fields, as is sometimes stated in the literature. This is why the field of a charge in motion is calculated by the method of retarded potentials (Lienard–Wiechert potentials). It should be mentioned here that mathematically, both retarded and advanced potentials are possible, but causality dictates that (in classical physics) only retarded potentials are physical. Thus the field at a field point x, t, is produced by the source when it was located at a point x', at time t', given by $t - t' = l/c$, where l is the distance from the field point x, t, to the source point x', t'. The coordinates x', t' are called the retarded coordinates of the source. For a charge moving in a uniform motion (a constant velocity), the field strength is given by

$$E = \frac{e\hat{r}(1-\beta^2)}{r^2(1-\beta^2\sin^2\phi)^{3/2}} \tag{1}$$

where β is the charge velocity, and $\hat{r}$ is the unit vector from the present location of the source to the field point. The angle ϕ is the angle between $\hat{r}$ and the direction of motion of the source. The field lines for this case are drawn in figure 1.

Although it seems as if the field lines flow from the source, the extra terms in this expression that include β show that the field at a certain field point is induced by the source from its retarded location. This also becomes clear from the way expression (1) is calculated, as shown in any textbook [4, 5].

It comes out that, in this case, the field lines are also straight lines, but they are not distributed isotropically. The field is more intense towards the plane perpendicular to the velocity of the source. The field lines are straight lines because there is a constant ratio between the expansion velocity of the field and the uniform velocity of the field source, and the field is symmetric with respect to the plane perpendicular to the direction of motion,

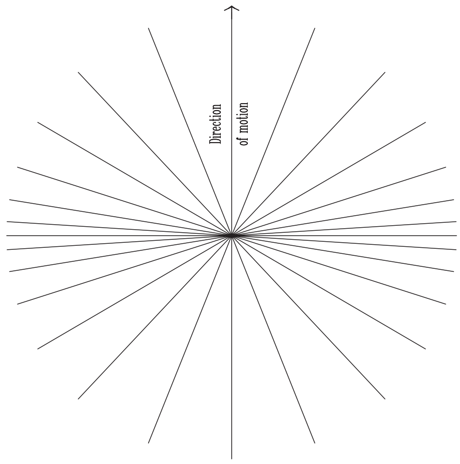

Figure 1. The field lines of a uniformly moving charge.

passing through the charge location. This is also the reason why the field lines seem as if they emerge from the present source location.

Things change dramatically when we consider accelerated motions of the field source. The ratio between the expansion velocity of the field and the velocity of the field source is not constant, and the field lines become curved. The strength of the curvature (the magnitude of the inverse of the radius of curvature) depends on the rate of change of the ratio between the velocity of the field expansion and the velocity of the field source; namely, on the magnitude of the acceleration of the field source. Let us look at the most simple case of an accelerated motion—a charge moving with a constant acceleration a in its own system of reference. Such a motion is called 'a hyperbolic motion' [6]. The field equations for this case were calculated by Gupta and Padmanabhan [7] by using transformations for the field expressions from the system of reference of the accelerated charge to the system of reference of free space. Their expressions are similar to those calculated by Fulton and Rohrlich [8], who calculated them directly by the retarded potentials method. They are given in cylindrical coordinates (ρ, z, ϕ):

$$E_\rho = \frac{8e\alpha^2\rho z}{\xi^3} \tag{2}$$

$$E_z = \frac{-4e\alpha^2}{\xi^3}[\alpha^2 + (ct)^2 + \rho^2 - z^2] \tag{3}$$

$$B_\phi = \frac{8e\alpha^2\rho ct}{\xi^3} \tag{4}$$

where

$$\xi^2 = [\alpha^2 + (ct)^2 - \rho^2 - z^2]^2 + (2\alpha\rho)^2 \tag{5}$$

and all other field components vanish. $\alpha = c^2/a$ is the location of the charge at time $t = 0$, and it is also the characteristic radius of curvature of the electric field. The equation for the field lines was calculated by Singal [9], and they are drawn in figure 2.

As can be expected, the field lines are curved and the radius of curvature, R_c, is inversely proportional to the acceleration and is given by

$$R_c = \frac{c^2}{a\sin\theta} \tag{6}$$

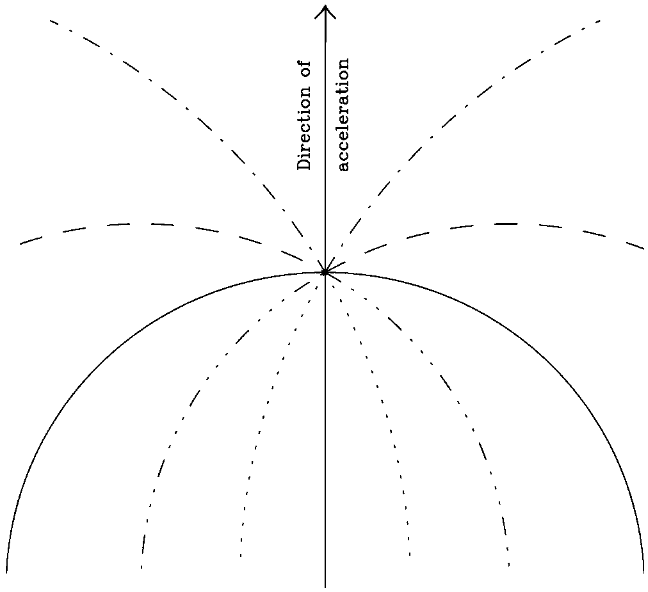

Figure 2. The field lines of a charge moving with a constant acceleration.

where θ is the angle between the direction of motion and the initial direction of the field line. Again, the curved field lines seem as if they emerge from the source. However, they originate from the retarded locations of the source and, after being transformed to the local flat system of reference, they have acquired this form.

Calculating the field of a point source by the retarded potentials method guarantees that the field at a certain field point does not depend on the field source at its present location, but on the field source at its retarded location. This means that once the field is induced by the source on space, it is no longer connected to the source. It is an independent physical entity that expands in free space with a constant velocity c. It possesses energy and momentum, it has inertia and it falls in a free fall in a gravitational field. It is detached from the source that induced it and, when the source is accelerated by an external (non-gravitational) force, the field is not accelerated with the source. Actually, when one considers the field given in equations (2)–(5) (and in figure 2), one observes that the form of the field lines is such, exactly because the field is not accelerated with the source.

3. The role of fields

The relation between electric (gravitational) field and a charge (mass) is not a new question. It bothered Einstein, who wrote in 1938 [10]: 'we have two realities: matter and field. There is no doubt that we cannot at present imagine the whole of physics built upon the concept of matter as the physicist of the early nineteenth century did. For the moment we accept both the concepts. . . . The theory of relativity stresses the importance of the field concept in physics. But we have not yet succeeded in formulating a pure field physics. For the moment we must still assume the existence of both: field and matter'. Einstein expected that a unified theory would be able to describe matter (charge) points as concentrated fields, but he did not succeed in reaching this goal. In a recent paper [11], Wilczek argues that this goal is supposed to be achieved in electro-weak interactions theory.

However, when one considers classical (relativistic, non-quantum) physics, one should consider fields and charge points as two independent entities, and treat them on an equal level.

In this regard, the approach of physicists that cannot accept the idea that a field is an independent entity limits the ability to understand correctly physical phenomena. Physicists intuitively accept the idea that radiation fields (the part that falls with the distance such as $1/\text{distance}$) are independent entities that lost their dependence on the source, once they were induced on space. They are *uneasy* about accepting that this is also correct for the Coulomb fields. An example is the statement of Rohrlich [12, p 111] that velocity (Coulomb) fields are permanently 'attached' to the charge and are carried along with it.

Consider the creation of radiation by an accelerated charge. The most simple case to be considered is a charge accelerated by a constant acceleration in its own system of reference, the example mentioned in section 2 as the hyperbolic motion. One may expect that this simple case can be explained in a simple manner. However, it comes out that, in this simple case, large controversies arise. One is the 'energy balance paradox' [13], in which the nonexistence of a radiation reaction force raises the question what is the source of the energy carried by the radiation [14]. Another controversy concerns the question 'who can observe the radiation', where the idea that radiation is observed when a relative acceleration exists between the source and the observer [8, 15] leads to the conjecture that radiation is a phenomenon that can be transformed away by a coordinate transformation. However, it is clear that emission or absorption of radiation is a physical event that cannot be transformed away by a coordinate transformation (see [16]). Only when one accepts the principle that a field is detached from the source that induced it, and that a relative acceleration exists between the source and its field, are these controversies solved satisfactorily [14, 17, 18].

A more sophisticated approach may consider the expansion of a field as the propagation of information, where here 'information' possesses a physical meaning. Certainly, once information leaves its origin, it has an independent reality, and it no longer depends on its origin. This point of view may connect the approach presented in the present paper with quantum theory. However, this topic is not included in the scope of the this paper.

4. Conclusions

The concept of 'field' is not an artificial concept used to conventionally describe the distribution of force in space around a source. Both radiation fields as well as Coulomb fields have a physical reality; they are detached from the source that induced them, and they should be treated as independent physical entities. In classical (relativistic, non-quantum) physics, fields and sources should be treated as equally important entities. The concept that an electric field expands with a finite velocity in space is well established in the retarded potentials method, where the electric field at a field point is induced by the source from its location at an earlier (retarded) time. The field of an accelerated charge becomes curved, and this curvature creates a stress force, which acts as a reaction force, that creates the energy carried by the radiation.

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