Relativistic Electrodynamics

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Introduction

Electrostatics is the study of charges that remain stationary; electrodynamics is the study of charges and fields that are continuously moving as well as changing; the laws of electrodynamics can be described completely by Maxwell's equations. In this paper, we will be interested in how these equations can be represented from relativistic frames, but before we can discuss this, we must understand some of the concepts/ideas that led up to these representations/derivations. Therefore, this paper will have the following layout:

- A brief overview of Maxwell's equations as they are.
- A brief history surrounding Relativistic Electrodynamics
- Derivations used to find the transformation laws used for Maxwell's equations
- How these transformation laws can be represented in Tensor notation

Electrodynamics can generally be described by Maxwell's equations (Griffiths, David J Ch.7):

$$\begin{aligned} \nabla \cdot \boldsymbol{E} &= \frac{1}{\epsilon_0}\rho && \text{(Gauss's Law)} \\ \nabla \times \boldsymbol{E} &= -\frac{\partial \boldsymbol{B}}{\partial t} && \text{(Faraday's law)} \\ \nabla \cdot \boldsymbol{B} &= 0 && \text{(No name)} \\ \nabla \times \boldsymbol{B} &= \mu_0 \boldsymbol{J} + \mu_0 \epsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} && \text{(Ampere's law with Maxwell's correction)} \end{aligned} \tag{1}$$

Where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field, μ_0 is the permeability of free space, ϵ_0 is the permittivity constant, ρ represents charge density, and $\boldsymbol{J}$ represents current density. Vectors throughout this paper will be represented by being bold.

Maxwell's equations agree with the two postulates of Special Relativity:

1.**The Principle of Relativity:** all the laws of physics have the same form in all inertial reference frames.

2.**The Constancy of the Speed of Light:** The speed of light in a vacuum has the same value: c= $3 \times 10^8 m/s$ (Serway, Raymond A., et al. pp.10-13).

Which were discovered by Einstein when he noticed that Newton's laws of physics did not invariantly transform with the Galilean transformations the way they should have. While

Maxwell's equations did not remain the same with the Galilean transformations, they did remain the same with the Lorentz transformations, which was discovered by H.A. Lorentz when he made the substitutions into the Maxwell equations himself (Phillips Feynman et al., I, pp 15-1 -15-3). The Lorentz transformations are the following (Griffiths):

$$\begin{aligned} \overline{x} &= \gamma(x - vt) \\ \overline{y} &= y \\ \overline{z} &= z \\ \overline{t} &= \gamma(t - \frac{v}{c^2}x) \end{aligned} \tag{2}$$

Where $\overline{x}$, $\overline{y}$, $\overline{z}$, $\overline{t}$, represent the spatial and time coordinates of an inertial system, $\overline{S}$; these space and time components are unknown. However, If the spatial and time coordinates of $\overline{S}$ are known in a different inertial system, S, then the spatial and time components in $\overline{S}$ can be found using this dictionary of equations (Griffiths, p.519-521). The t represents the time of the event that is happening in the system whose coordinates are known, system S . The v represents the velocity of the event, and γ is used to represent the Lorentz factor, which is generally shown as:

$$\gamma \equiv \frac{1}{1 - v^2/c^2} \tag{3}$$

Where c of course represents the speed of light ($3 \times 10^8 m/s$) (Griffiths, p. 515).

Applying these transformations to Maxwell's equations (classical electrodynamics), showed that Maxwell's equations and the Lorentz force law are consistent with special relativity. Einstein pieced this information together himself and realized that it wasn't Maxwell's equations that needed to be modified, it was Newton's (Feynman, et al., Vol I. p.15-1 – 15-8). He then modified Newton's laws to make them consistent with the Lorentz transformations. It turned out that this only required altering the mass in Newton's equations, i.e., mass is not a constant variable and thus does not remain the same in every reference frame. Once this relationship was altered, electrodynamics would also have to be altered to fit with these new laws of motion (Feynman, et al., Vol I. p.15-1 – 15-8).

Now that we know the fundamentals about relativistic electrodynamics, we can develop a much deeper understanding of the relativistic relationship found between electricity and magnetism. In this paper, the derivations that lead to the laws that define relativistic electrodynamics will be explained using examples found from the listed sources. Once the laws are defined, the way to represent these laws in tensor nation will be explained as well.

Electrodynamics in a relativistic frame: for a current carrying wire

Now that we know the fundamentals about relativity, we can develop a deeper understanding of the relativistic relationship found between electricity and magnetism, to do so, we should consider a situation where there is a charge q a distance s away from a current carrying wire from the perspective of two different reference frames.

The configuration we should use for the first reference is shown in figure 1, part (a). In this frame there is going to be a string of positive charges moving to the right at a speed v. These charges are assumed to be close enough together that we can consider them to be acting as one continuous line charge λ . There will also be a string of negative charges superimposed on the positive string, these will be moving to the left at the same speed, v, and below this string, there will be a charge q that is moving to the right at a speed of $u < v$. The net current would then be to the right at a magnitude of:

$$I = 2\lambda v \tag{4}$$

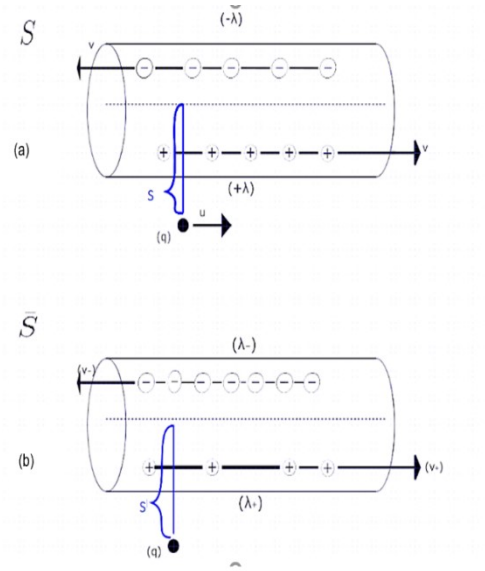


Figure 1: The relationship between a current-carrying wire and a particle q as seen in two frames. In S, the charge is moving with respect to the wire at a speed of $u < v$. In $\overline{S}$ the charge is at rest with respect to the wire

Examining the situation from S, we see no electrical force on q, this is because the two-line charges cancel, and they cancel in this reference frame because the charge per unit area is the same for both line charges. Now we can examine this situation from the second reference frame, $\overline{S}$, which is shown in Figure 1. Part (b). In this reference frame, the charge is at rest, and the system is moving to the right at a speed of v (Griffiths, p.550). To figure out what charge the wire carries, we must first apply the Einstein velocity addition rule, which is the following (Griffiths, p.523):

$$V_{AC} = \frac{V_{AB} + V_{BC}}{1 + (V_{AB}V_{BC}/c^2)} \tag{5}$$

Where A is the velocity of the charge, B represents the system S, and C represents the $\overline{S}$ system. Since we have two velocities moving in the $\overline{S}$ system, we will get two different velocities from Einstein's velocity addition rule, we will get a velocity for the charges moving to the right, v_+ and we will get a velocity for the charges moving to the left, v_-. The velocity for the charges moving to the left v_-, will be additive, this is because the velocity the charges moving to the left with respect to the system S, will be positive. However, the velocity of the charges moving to the right are not found to be additive, and this is mainly due to the fact that the charge q in system S is moving in the same direction as v_+. Therefore the velocity of the charges moving to the left v_- are greater than the velocity of the charges moving to the right (Griffiths, p.550):

$$v_\pm = \frac{v \mp u}{1 \mp \frac{vu}{c^2}} \tag{6}$$

The Lorentz factor we use for the negative charges will be greater than the Lorentz factor we use for the positive charges, and this is due to the negative charges having a greater velocity than the positive charges:

$$\gamma_{\pm} = \frac{1}{\sqrt{1 - \frac{v_{\pm}^2}{c^2}}} \tag{7}$$

We can represent that magnitude of the line charges as the following:

$$\lambda_{\pm} = \pm(\gamma\pm)\lambda_0 \tag{8}$$

Where λ_0 is the charge density of the positive line in any system to which it is at rest in. This means that we can solve for charge density, doing so leads us to the conclusion that the positive charges have a smaller charge density, or a smaller amount of charge per unit area, meaning that the charge density of the negative charges is greater due to the length contraction. Equation (8) shows us that the negative charges will have a greater magnitude due to a larger Lorentz factor. With that being said, it is also important to note that λ_0 is different from λ, which is the charge density in S, "where the positive line is already moving at speed v" (Griffiths, p.551). We end up getting

$$\lambda = \gamma\lambda_0 \tag{9}$$

&

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \tag{10}$$

Eventually we get the electric force on q in $\overline{S}$ to be (Griffiths, p.552):

$$\overline{F} = qE = -\frac{\lambda v}{\pi\epsilon_0 c^2 s}\frac{qu}{\sqrt{1 - \frac{u^2}{c^2}}} \tag{11}$$

Where s is the distance from the charge to the wire. We can also find the force in S "[s]ince q is at rest in $\overline{S}$, and $\overline{F}$ is perpendicular to u[1]" (Griffiths, p.552):[2]

$$F = \sqrt{1 - u^2/c^2}\vec{F} = -\frac{\lambda v}{\pi\epsilon_0 c^2}\frac{qu}{s} \tag{12}$$

We can use the equation $\frac{1}{c^2} = \epsilon_0\mu_0$ to substitute our current, I, in for λv, and we will get the following (Griffiths, p.552 & p.505):

$$F = -qu(\frac{\mu_0 I}{2\pi s}) \tag{13}$$

[1] $\overline{F}_{\perp} = \frac{1}{\gamma}\overline{F}_{\perp}$, $\overline{F}_{\parallel} = F_{\parallel}$ is the equation used to find the force (Griffiths, p. 544)

[2] This is rule comes from the Minkowski force, which is a relativistic form of the Lorentz force (Griffiths, p. 545)

To understand the significance of this derivation we should recall a couple equations. The first one being the equation that represents the magnitude of the electric field of a long straight wire whose charge density is λ ("Chapter 8 Relativistic Electromagnetism"; Griffiths p.552):

$$E = \frac{\lambda}{2\pi_0 r} \tag{14}$$

Where r in this case is represents the distance. We should also recall the magnetic field of a long straight wire; whose current density is I:

$$B = \frac{\mu_0 I}{2\pi r} \tag{15}$$

This is the same force that we would have gotten had we used the Lorentz Force law in system S (Griffiths). The significance of this is that in a moving reference frame, the force felt by a charge in that reference frame is simply an electrical force, and the force felt by the stationary charge is a magnetic force; they are both the same force, but they are both viewed as different (Veritasium; Griffiths, p. 552).

General Transformation rules for electric and magnetic fields:

For the general transformation rules,we will want to start with a rule that works not just in systems that have no magnetic field, but we will want one that will work in systems that have "both electric and magnetic fields"(Griffiths, p. 556).

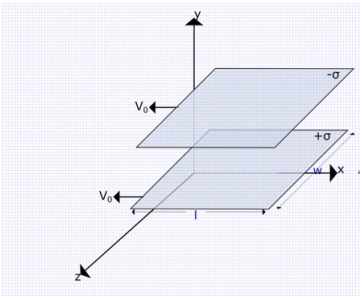


Figure 2: S fram for the parallel plate capacitors

Where σ is the charge per unit area, and ϵ_0 is the permittivity constant, we can use this configuration to see how these general rules are derived (Griffiths, p. 556). There is also a surface current present:

$$K_{\pm} = \mp \sigma v_0 \hat{x} \tag{16}$$

We can use this to find the magnetic field, and from the Biot-Savart law, we know that we can use the right-hand-rule to find the direction this field will point, which will be in the negative z-direction. The magnitude, however, can be found by using Ampere's law (Griffiths, p. 556):

$$B_z = -\mu_0 \sigma v_0 \tag{17}$$

We can add in a third system that is traveling to the right at speed v relative to S, which we will call $\overline{S}$ (Griffiths, p. 556), this configuration can be seen in Figure 3. The corresponding fields for $\overline{S}$ will be:

$$\overline{E} = \frac{\overline{\sigma}}{\epsilon_0}, \quad \overline{B}_z = -\mu_0 \overline{\sigma} \overline{v} \tag{18}$$

Where $\overline{v}$ is the velocity of $\overline{S}$ relative to our frame at rest, S_0 . Thus, applying the Lorentz transformation laws brings us to the following relationships (Griffiths, p. 556):

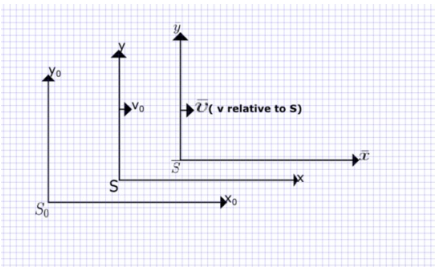


Figure 3

$$\overline{v} = \frac{v + v_0}{1 + v v_0 / c^2} \quad , \quad \overline{\gamma} = \frac{1}{\sqrt{1 - \overline{v}/c^2}} \tag{19}$$

Due to the length contraction, the surface charge will also need a relativistic correction (Griffiths, p. 556):

$$\overline{\sigma} = \overline{\gamma} \sigma_0 \tag{20}$$

We will also need to include a relativistic correction for the S frame:

$$\sigma = \gamma_0 \sigma_0 \tag{21}$$

Where $\overline{\sigma}$ represents the surface charge of the capacitor in the $\overline{S}$ frame, and σ_0 represents the surface charge that is found on the capacitor in the frame that is at rest, S_0. The only thing left for this frame is to take the electric, $\overline{E}$ and magnetic, $\overline{B}$, fields that are in the $\overline{S}$ system (Eq. 18), and to express them in terms of the electric, E and magnetic, B fields found in the S system (Eqs. 13 and 15).

We can use Equation's 20 and 21 to obtain the following (Griffiths p.557):

$$\overline{E}_y = (\frac{\overline{\gamma}}{\gamma_0})\frac{\sigma}{\epsilon_0},\ \overline{B}_z = -(\frac{\overline{\gamma}}{\gamma_0})\mu_0\sigma\overline{v}, \tag{22}$$

The $\overline{\gamma}$ and γ_0 taken as a ratio[3] can give us an equation that allows us to relate the three systems (Griffiths p.557):

$$\frac{\overline{\gamma}}{\gamma_0} = \gamma(1 + \frac{vv_0}{c^2}) \tag{23}$$

We can now substitute Eq.(23) in for the $\overline{\gamma}/\gamma_0$ term that is in Eq. (22).With the equation now being correct with respect to relativity, we can now write $\overline{E}_y$ in terms of the E and B components found in S (Griffiths p.557):

$$\overline{E}_y = \gamma(1 + \frac{vv_0}{c^2})\frac{\sigma}{\epsilon_0} = \gamma(E_y - \frac{v}{c^2\epsilon_0\mu_0}B_z) \tag{24}$$

Where we can get

$$\overline{B}_z = -\gamma(1 + \frac{vv_0}{c^2})\mu_0\sigma\frac{v + v_0}{1 + vv_0/c^2} = \gamma(B_z - \mu_0\epsilon_0 vE_y) \tag{25}$$

And since we know that, $\mu_0\epsilon_0 = 1/c^2$, we can make the substitution and get the following:

$$\left.\begin{aligned}\overline{E}_y &= \gamma(E_y - vB_z)\\ \overline{B}_z &= \gamma(B_z - \frac{v}{c^2}E_y)\end{aligned}\right\} \tag{26}$$

Similarly, we can get the transformations for E_z and B_y, for this we have to setup the capacitor to be parallel to the xy plane instead of the xz plane (as is shown in Figure 4), doing so will give us the following electric and magnetic fields (Griffiths p.558):

$$E_z = \frac{\sigma}{\epsilon_0},\ B_y = \mu_0\sigma v_0 \tag{27}$$

According to Griffiths, the rest of the transformation for E_z and B_y are identical for the ones we found for E_y and B_z, the only difference is that the E_y's would be replaced with E_z's, and the B_z's would be replaced with the B_y's (which includes the signs that come with them), giving us the following (Griffiths p.558):

$$\left.\begin{aligned}\overline{E}_z &= \gamma(E_z + vB_y)\\ \overline{B}_y &= \gamma(B_y + \frac{v}{c^2}E_z)\end{aligned}\right\} \tag{28}$$

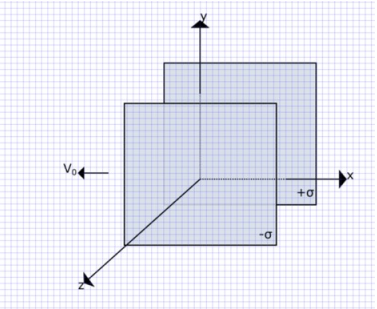


Figure 4

[3]The ratio can be found on p.537 of Griffiths Introduction to Electrodynamics, Fourth ed.

If we orient the capacitor parallel to the xz plane, we can get the transformation for x-components to be the following (Griffiths p.558):

$$\overline{E}_x = E_x \tag{29}$$

Griffiths makes a similar argument for the x direction of the magnetic field, but instead of a plate capacitor, the book uses a "long solenoid aligned parallel to the x-axis" to find the transformation for the x-components of a magnetic field (Griffiths, p.559):

$$\overline{B}_x = B_x \tag{30}$$

This end's up finishing the transformation rules for Maxwell's equations, giving us the following (Griffiths, p.559):

$$\boxed{\begin{array}{lll} \overline{E}_x = E_x & \overline{E}_y = \gamma(E_y - vB_z) & \overline{E}_z = \gamma(E_z + vB_y) \\ \overline{B}_x = B_x & \overline{B}_y = \gamma(B_y + \dfrac{v}{c^2}E_z) & \overline{B}_z = \gamma(B_z - \dfrac{v}{c^2}E_y) \end{array}} \tag{31}$$

Where there are two cases that should be known (Griffiths, p.559):

1. If $\boldsymbol{B} = 0$ in S, then,

$$\overline{\boldsymbol{B}} = \gamma\frac{v}{c^2}(E_z\hat{\boldsymbol{y}} - E_y\hat{\boldsymbol{z}}) = \frac{v}{c^2}(\,\overline{E}_z\hat{\boldsymbol{y}} - \overline{E}_y\hat{\boldsymbol{z}})$$

or since $\boldsymbol{v} = v\hat{\boldsymbol{x}}$

$$\overline{\boldsymbol{B}} = -\frac{1}{c^2}(\boldsymbol{v} \times \boldsymbol{E}) \tag{32}$$

2. If $\boldsymbol{E} = 0$ in S,

$$\overline{\boldsymbol{E}} = \boldsymbol{v} \times \overline{\boldsymbol{B}} \tag{33}$$

These cases are meant to be used to relate two different systems fields at certain a certain point where E or B is zero, i.e., if E or B is zero at such a point than the two points can be related using equations 32 and 33.

Electrodynamics in Tensor Notation:

Maxwell's equations are most useful through relativistic means when expressed using tensors, where a tensor is just a type of notation that is used to represent mathematical relationships between sets of numbers or functions, and that share common transformational properties. An example of something that can be represented in tensor notation is a four vector, so we must develop a basic understanding of what a four-vector is. A four-vector is similar to a three vector in that a three vector is any set of three components that transform under rotations the same way (x, y, z) does, and a four vector is a vector that is made up of any 4 components that transform the same way $(\overline{x}, \overline{y}, \overline{z}, \overline{t})$ does under the Lorentz transformations (Griffiths pp. 525-526; Feynman). A four vector can be represented by the notation,a_μ, where the μ takes on the four values seen in the Lorentz transformation, $(\overline{x}, \overline{y}, \overline{z}, \overline{t})$,this vector can also be represented as a vector that has three space components, and one time component: $a_\mu = (a_t, a)$, where a is the three-vector that represents the three space components ("Electrodynamics in Relativistic Notation"). The main idea is that we want to transform a system of equations to behave in the same manner they would in the Lorentz equations ("Electrodynamics in Relativistic Notation").

To understand how to write electrodynamics in tensor notation we will need a few mathematical relationships. The first of which makes use of the four vector that contains charge density and current density, i.e., the current density 4-vector (Griffiths p. 563- 567):

$$J^\mu = \rho_0 \eta^0 \tag{34}$$

Where the components can be written as:

$$J^\mu = (c\rho, J_x, J_y, J_z) \tag{35}$$

We will also need the continuity equation,

$$\nabla \cdot \boldsymbol{J} = -\frac{\partial \rho}{\partial t} \tag{36}$$

If we express the local conservation of charge (the left-hand side), with respect to the current density 4-vector, we will get the following (Griffiths p. 566):

$$\nabla \cdot \mathbf{J} = \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z} = \sum_{i=1}^{3} \frac{\partial \mathbf{J}^i}{\partial x^i} \tag{37}$$

Where,

$$\frac{\partial \rho}{\partial t} = \frac{1}{c}\frac{\partial \mathbf{J}^0}{\partial t} = \frac{\partial \mathbf{J}^0}{\partial x^0} \tag{38}$$

If we take the $\partial\rho/\partial t$ of the left side as well, we get the following relationship (Griffiths p. 563- 567):

$$\frac{\partial J^\mu}{\partial x^\mu} = 0 \tag{39}$$

We will also need the two following tensors (Griffiths p. 563- 567):

$$F^{\mu v} = \begin{bmatrix} 0 & E_x/c & E_y/c & E_z/c \\ -E_x/c & 0 & B_z & -B_y \\ -E_y/c & -B_z & 0 & B_x \\ -E_z/c & B_y & -B_x & 0 \end{bmatrix} \tag{40}$$

Which is the field tensor, this tensor combines the laws of electric and magnetic fields into one system, $F^{\mu v}$. The second tensor we need is the dual tensor (Griffiths p. 563- 567):

$$G^{\mu v} = \begin{bmatrix} 0 & B_x & B_y & B_z \\ -B_x & 0 & -E_z/c & E_z/c \\ -B_y & E_z/c & 0 & -E_x/c \\ -B_z & -E_y/c & E_x/c & 0 \end{bmatrix} \tag{41}$$

Both the field and dual tensor invariantly transform under the Lorentz transformations. The way these tensor indices work can be described by the following matrix (Griffiths p. 563 - 567):

$$t = \begin{bmatrix} t^{00} & t^{01} & t^{02} & t^{03} \\ t^{10} & t^{11} & t^{12} & t^{13} \\ t^{20} & t^{21} & t^{22} & t^{23} \\ t^{30} & t^{31} & t^{32} & t^{33} \end{bmatrix} \tag{42}$$

Finally, we can see what Maxwell's equations look like in Tensor notation:

$$\boxed{\frac{\partial \mathbf{F}^{\mu v}}{\partial x^v} = \mu_0 \mathbf{J}^{\mu} \ , \ \frac{\partial \mathbf{G}^{\mu v}}{\partial x^v} = 0} \tag{43}$$

Where a summation over v is implied, and "each of these stands for 4 equations," i.e., there is one equation for every value of μ.

If $\mu = 0$, then

$$\begin{aligned} \frac{\partial F^{0v}}{\partial x^v} &= \frac{\partial F^{00}}{\partial x^0} + \frac{\partial F^{01}}{\partial x^1} + \frac{\partial F^{02}}{\partial x^2} + \frac{\partial F^{03}}{\partial x^3} \\ &= \frac{1}{c}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right) = \frac{1}{c}(\nabla \cdot \boldsymbol{E}) \\ &= \mu_0 \boldsymbol{J}^0 = \mu_0 c \rho \\ &= \nabla \cdot \boldsymbol{E} = \frac{1}{\epsilon_0}\rho \qquad \text{(Gauss's Law)} \end{aligned}$$

If we set $\mu = 1$,

$$\frac{\partial F^{1v}}{\partial x^v} = \frac{\partial F^{10}}{\partial x^0} + \frac{\partial F^{11}}{\partial x^1} + \frac{\partial F^{12}}{\partial x^2} + \frac{\partial F^{13}}{\partial x^3}$$

$$= -\frac{1}{c^2}\frac{\partial E_x}{\partial t} + 0 + \frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} = (-\frac{1}{c^2}\frac{\partial \mathbf{E}_x}{\partial t} + \nabla \times \mathbf{B})_x$$

$$= \mu_0 J^1 = \mu_0 J_x$$

Combining $\mu = 2$ and $\mu = 3$,gives:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \epsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \text{ (Ampere's law with Maxwell's correction)}$$

We can use similar summation rules for the second equation in Eq. 43, and if we start with $\mu = 0$,we can get the following (Griffiths p. 567):

$$\frac{\partial G^{0v}}{\partial x^{0v}} = \frac{\partial G^{00}}{\partial x^0} + \frac{\partial G^{01}}{\partial x^1} + \frac{\partial G^{02}}{\partial x^2} + \frac{\partial G^{03}}{\partial x^3}$$

$$= \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z}$$

$$= \nabla \cdot \boldsymbol{B} = 0 \quad \text{(Maxwell's Third Equation)}$$

Setting $\mu = 1$ gives us,

$$\frac{\partial G^{1v}}{\partial x^v} = \frac{\partial G^{10}}{\partial x^0} + \frac{\partial G^{11}}{\partial x^1} + \frac{\partial G^{12}}{\partial x^2} + \frac{\partial G^{13}}{\partial x^3}$$

$$= -\frac{1}{c}\frac{\partial B_x}{\partial t} - \frac{1}{c}\frac{\partial E_z}{\partial y} + \frac{1}{c}\frac{\partial E_y}{\partial z} = -\frac{1}{c}(\frac{\partial \mathbf{B}}{t} + \nabla \times \mathbf{E}) = 0$$

If we combine this with the results from setting $\mu = 2$ and $\mu = 3$, we get the following (Griffiths p. 563- 567):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \text{ (Faraday's law)}$$

Conclusion:

In conclusion, relativistic electrodynamics is a much more complete description of electrodynamics, and from the examples discussed in this paper it is easy to see that this phenomenon transforms easily within the Lorentz transformations. In fact, from the transformations, relativity would appear to be an intrinsic characteristic of electrodynamics. Electrodynamics is also widely applicable, anything that can be done in a frame that is at rest can also be applied to a frame that is moving, and if you know the electric or magnetic field in one frame, you can easily transform it using the relativistic laws to find it in the other. Furthermore, once these laws are known, being able to write and understand them in tensor notation can be a powerful tool, as this notation allows you to write out these equations with a much greater sense of brevity

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