B2: The Electric Field - Description and Effect

An electric field is an invisible entity which exists in the region around a charged particle. It is caused to exist by the charged particle. The effect of an electric field is to exert a force on any charged particle (other than the charged particle causing the electric field to exist) that finds itself at a point in space at which the electric field exists. The electric field at an empty point in space is the force-per-charge-of-would-be-victim at that empty point in space. The charged particle that is causing the electric field to exist is called a source charge. The electric field exists in the region around the source charge whether or not there is a victim charged particle for the electric field to exert a force upon. At every point in space where the electric field exists, it has both magnitude and direction. Hence, the electric field is a vector at each point in space at which it exists. We call the force-per-charge-of-would-be-victim vector at a particular point in space the "electric field" at that point. We also call the infinite set of all such vectors, in the region around the source charge, the electric field of the source charge. We use the symbol $\vec{E}$ to represent the electric field. I am using the word "victim" for any particle upon which an electric field is exerting a force. The electric field will only exert a force on a particle if that particle has charge. So all "victims" of an electric field have charge. If there does happen to be a charged particle in an electric field, then that charged particle (the victim) will experience a force

$$\vec{F} = q\vec{E} \tag{B2.1}$$

where q is the charge of the victim and $\vec{E}$ is the electric field vector at the location of the victim. We can think of the electric field as a characteristic of space. The force experienced by the victim charged particle is the product of a characteristic of the victim (its charge) and a characteristic of the point in space (the electric field) at which the victim happens to be.

The electric field is not matter. It is not "stuff." It is not charge. It has no charge. It neither attracts nor repels charged particles. It cannot do that because its "victims", the charged particles upon which the electric field exerts force, are within it. To say that the electric field attracts or repels a charged particle would be analogous to saying that the water in the ocean attracts or repels a submarine that is submerged in the ocean. Yes, the ocean water exerts an upward buoyant force on the submarine. But, it neither attracts nor repels the submarine. In like manner, the electric field never attracts nor repels any charged particles. It is nonsense to say that it does.

If you have two source charge particles, e.g. one at point A and another at point B, each creating its own electric field vector at one and the same point P, the actual electric field vector at point P is the vector sum of the two electric field vectors. If you have a multitude of charged particles contributing to the electric field at point P, the electric field at point P is the vector sum of all the electric field vectors at P. Thus, by means of a variety of source charge distributions, one can create a wide variety of electric field vector sets in some chosen region of space. In the next chapter, we discuss the relation between the source charges that cause an electric field to exist, and the electric field itself. In this chapter, we focus our attention on the relation between an existing electric field (with no concern for how it came to exist) and the effect of that electric field on any charged particle in the electric field. To do so, it is important for you to be able to accept a given electric field as specified, without worrying about how the electric field is caused to exist in a region of space. (The latter is an important topic which we deal with at length in the next chapter.)

Suppose for instance that at a particular point in an empty region in space, let's call it point P, there is an eastward-directed electric field of magnitude $0.32 N/C$. Remember, initially, we are talking about the electric field at an empty point in space. Now, let's imagine that we put a particle that has $+2.0$ coulombs of charge at point P. The electric field at point P will exert a force on our $2.0C$ victim:

$$\vec{F} = q\vec{E}$$

$$\vec{F} = 2.0C(0.32\frac{N}{C}\text{ eastward})$$

Note that we are dealing with vectors so we did include both magnitude and direction when we substituted for $\vec{E}$. Calculating the product on the right side of the equation, and including the direction in our final answer yields:

$$\vec{F} = 0.64N\text{ eastward}$$

We see that the force is in the same direction as the electric field. Indeed, the point I want to make here is about the direction of the electric field: The electric field at any location is defined to be in the direction of the force that the electric field would exert on a positively charged victim if there was a positively charged victim at that location.

Told that there is an electric field in a given empty region in space and asked to determine its direction at the various points in space at which the electric exists, what you should do is to put a single positively-charged particle at each of the various points in the region in turn, and find out which way the force that the particle experiences at each location is directed. Such a positivelycharged particle is called a positive test charge. At each location you place it, the direction of the force experienced by the positive test charge is the direction of the electric field at that location.

Having defined the electric field to be in the direction of the force that it would exert on a positive test charge, what does this mean for the case of a negative test charge? Suppose that, in the example of the empty point in space at which there was a $0.32N/C$ eastward electric field, we place a particle with charge -2.0 coulombs (instead of $+2.0$ coulombs as we did before). This particle would experience a force:

$$\vec{F} = q\vec{E} \tag{B2.2}$$

$$= -2.0C\,(0.32\frac{N}{C}\text{ eastward}) \tag{B2.3}$$

$$= -0.64N\text{ eastward} \tag{B2.4}$$

A negative eastward force is a positive westward force of the same magnitude:

$$\vec{F} = 0.64N\text{ westward}$$

In fact, any time the victim particle has negative charge, the effect of the minus sign in the value of the charge q in Equation B2.1 is to make the force vector have the direction opposite that of the electric field vector. So the force exerted by an electric field on a negatively charged particle that is at any location in that field, is always in the exact opposite direction to the direction of the electric field itself at that location.

Let's investigate this direction business for cases in which the direction is specified in terms of unit vectors. Suppose that a Cartesian reference frame has been established in an empty region of space in which there is an electric field. Further assume that the electric field at a particular point, call it point P, is:

$$\vec{E} = 5.0\frac{kN}{C}\hat{k}$$

Now suppose that a proton ($q = 1.60 \times 10^{-19}C$) is placed at point P. What force would the electric field exert on the proton?

$$\vec{F} = q\vec{E} \tag{B2.5}$$

$$= (1.60 \times 10^{-19}C)5.0 \times 10^{3}\frac{N}{C}\hat{k} \tag{B2.6}$$

$$= 8.0 \times 10^{-16}N\hat{k} \tag{B2.7}$$

The force on the proton is in the same direction as that of the electric field at the location at which the proton was placed (the electric field is in the +z direction and so is the force on the proton), as it must be for the case of a positive victim.

If, in the preceding example, instead of a proton, an electron ($q = -1.60 \times 10^{-19}C$) is placed at point P, recalling that in the example $\vec{E} = 5.0\frac{kN}{C}\hat{k}$, we have

$$\vec{F} = q\vec{E} \tag{B2.8}$$

$$= (-1.60 \times 10^{-19}C)5.0 \times 10^{3}\frac{N}{C}\hat{k} \tag{B2.9}$$

$$= -8.0 \times 10^{-16}N\hat{k} \tag{B2.10}$$

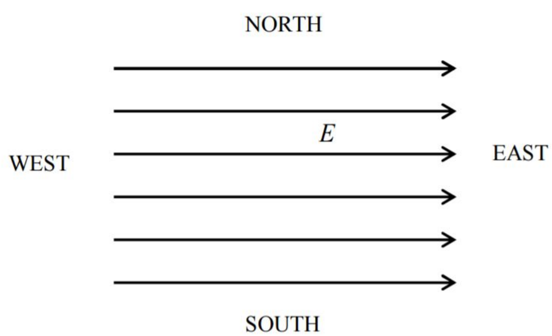
The negative sign is to be associated with the unit vector. This means that the force has a magnitude of $8.0 \times 10^{-16}N$ and a direction of $-\hat{k}$. The latter means that the force is in the –z direction which is the opposite direction to that of the electric field. Again, this is as expected.

The force exerted on a negatively charged particle by the electric field is always in the direction opposite that of the electric field itself.

In the context of the electric field as the set of all electric field vectors in a region of space, the simplest kind of an electric field is a uniform electric field. A uniform electric field is one in which every electric field vector has one and the same magnitude and one and the same direction. So, we have an infinite set of electric field vectors, one at every point in the region of space where the uniform electric field is said to exist, and every one of them has the same magnitude and direction as every other one. A charged particle victim that is either released from rest within such an electric field, or launched with some initial velocity within such a field, will have one and the same force exerted upon it, no matter where it is in the electric field. By Newton's 2^{nd} Law, this means that the particle will experience a constant acceleration. If the particle is released from rest, or, if the initial velocity of the particle is in the same direction as, or the exact opposite direction to, the electric field, the particle will experience constant acceleration motion in one dimension. If the initial velocity of the particle is in a direction that is not collinear with the electric field, then the particle will experience constant acceleration motion in two dimensions. The reader should review these topics from Calculus-Based Physics I.

Electric Field Diagrams

Consider a region in space in which there is a uniform, eastward-directed field. Suppose we want to depict this situation, as viewed from above, in a diagram. At every point in the region of space where the electric field exists, there is an electric field vector. Because the electric field is uniform, all the vectors are of the same magnitude and hence, we would draw all the arrows representing the electric field vectors, the same length. Since the field is uniform and eastward, we would draw all the arrows so that they would be pointing eastward. The problem is that it is not humanly possible to draw an arrow at every point on the region of a page used to depict a region of space in which there is an electric field. Another difficulty is that in using the convention that the length of a vector is representative of its magnitude, the arrows tend to run into each other and overlap.



Physicists have adopted a set of conventions for depicting electric fields. The result of the application of the conventions is known as an *electric field diagram*. According to the convention, the drawer creates a set of curves or lines, with arrowheads, such that, at every point on each curve, the electric field is, at every point on the curve, directed tangent to the curve, in the direction agreeing with that depicted by the arrowhead on that curve. Furthermore, the spacing of the lines in one region of the diagram as compared to other regions in the diagram is representative of the magnitude of the electric field relative to the magnitude at other locations in the same diagram. The closer the lines are, the stronger the electric field they represent. In the case of the uniform electric field in question, because the magnitude of the electric field is the same everywhere (which is what we mean by "uniform"), the line spacing must be the same everywhere. Furthermore, because the electric field in this example has a single direction, namely eastward, the electric field lines will be straight lines, with arrowheads.