Electric Fields: Crash Course Physics #26

Crash Course: Physics
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Shini: Last time, we talked about how charged particles exert electrostatic forces on one another. We calculated these forces using the charge of each particle: which can be either positive or negative, and the distance between them, and we did it with the help of Coulomb's Law: the equation that tells us the force generated by two charged particles on one another.

But what if we want to talk about more that two charges, or if we're dealing with charged objects of various shapes and sizes? Coulomb's Law is great for finding the force between small objects, like particles, but in physics we deal with all sorts of shapes and sizes.

Electric forces are used to bring power to your home, charge your computer, and light up the screen that you're using to watch this video. These everyday electric phenomena require physical components that manipulate charged particles in amazing ways. We make electrical components that excite millions of electrons in each pixel on this screen. But how to we design then to transmit just the right amount of electric force?

We've got some equations and concepts under our belt already, but we'll need a few more to understand how to control charged particles and expand the possibilities of electricity.

[Theme Music]

So we want to describe complex situations involving charged particles using more than just Coulomb's Law. If we have an object with a known amount of net charge, can we predict how other electric charges will react when they pass nearby? Well, British scientist Michael Faraday came up with a way to do just that. He hypothesized that every charged object generates an electric field that permeates space and exerts a force on all charged particles it encounters.

And he was right: an electric field is a measurable effect generated by any charged object. A field carries energy and passes it on to other charged materials by exerting electric forces. And we can get to know how electric fields work in a couple of different ways.

First there's good old math. Let's consider a positive point charge which we'll call capital Q. To study the effect that big Q has on other charges, we'll bring in a small positive test charge, small q, and measure the force that's acting on it.

Now, when we express it as an equation, the electric field created by a charged object is the electric force between the objects and the test charge divided by the magnitude of that test charge. To find F, you just have to use Coulomb's Law. And you only need to know the value for big Q, the point charge.

In fact, you can plug the equation for Coulomb's Law into this equation, in place of capital F. And if you do, you'll see that the magnitude of the test charge cancels out and we're left with an expression that relies solely on big Q. Now we've got an equation to calculate the electric field generated by any point charge.

But let's make this field even easier to picture. Another way of understanding what's going on between these charges is to diagram it with vectors using what we've learned about Coulomb's Law and force vectors. Again, let's start with our positive point charge, capital Q located at Point A and our small positive test charge, small q.

While both big Q and small q generate electric fields, we're going to assume that big Q has a much larger magnitude than small q. Now let's plot a series of vectors that result from placing small q at various points around big Q. These vectors are called electric field lines and their purpose is to show the magnitude and direction of the force exerted on any nearby positive test charge.

The density of these field lines signifies the magnitude of the electric force on small q and the closer small q is to big Q, the greater the force. And the same logic applies to how we represent negative charges although we do implement it in a slightly different way. The electric field line diagram for a fixed Q that's negatively charged would look like that of a positive Q, but with arrows pointing inward to signify that positive test charges would be attracted to Q.

Now let's see what an electric field looks like for a more complicated situation. Say we have one positively charged particle and one negatively charged particle that are some distance apart with an equal and opposite magnitude of charge. This pair of particle is known as an electric dipole. Since we have two particles that each generate their own electric field, we can add the fields together to create a total electric field. This is the principle known as superposition.

Now let's examine the electric field created by this electric dipole because along the way, that's going to show us four important properties of electric field lines. First: the field lines must be tangent to the direction of the field at any point. This means if we place a positive test charge anywhere the field lines will point in the direction of the force exerted on a positive test charge. This also means that a negative test charge would feel a force in the exact opposite direction

Next: the greater the line density, the greater the magnitude of the field. As a test charge moves closer to one of the fixed charges, the forces on it will be larger, thus the greater number of lines in that area. All of this together means that the number of lines leaving a charged object is proportional to the magnitude of its charge. If the magnitude of the positive charge in our electric dipole is doubled, then twice as many lines leave the positive point charge.

The third property of electric field lines is that the lines always start from positively charged objects and end on negatively charged objects. And if there are no negatively charged objects around, then the lines just keep going on forever into infinity, seeking out negatively charged objects wherever they can find them. So in our electric dipole the lines start at the positively charged particle and move toward the negatively charged one. And the same number of lines come out of each particle because the magnitude of their charges is equal and opposite.

Finally, the fourth property of electric field lines: the lines must never cross. Criss-crossing lines means the field acts in different directions for charges in the same location which is impossible.

Now that we know these properties, we can create field lines for any set of charged objects. So lets look at a scenario with one negatively charged particle with charge -Q and a positively charged particle with charge +2Q. If a positive test charge were placed directly between the particles the force exerted on it would be in the same direction that the electric field points toward the negative particle. If we zoom out: looking at this pair of particles from far away, you can see that it looks like the field lines for a single positive point charge. Keep in mind, groups of charged particles can look totally different when viewed from far away.

Alright, you're probably wondering why we're still talking about particles when I spent all that time earlier talking about configurations of things that we see in real life. Now that we know how to build electric field lines based on a set up of charged objects let's try to do the reverse and set up charged objects to achieve a certain purpose. Let's say we want to create an electric field where all positive test charges move uniformly in a single direction. We

can model this as a field created by two infinitely large conductive plates one positive, and one negative.

All positive test charges between the plates would move from the positive plate to the negative plate So we construct the electric field as a series of lines moving from the positive plate to the negative one. This pair of plates is known as a capacitor, and it's an integral part of almost every electronic system partly because it can use its electronic field to store an electric charge.

But so far we've only talked about electrical fields between charged objects like particles and plates. So can an electric field exist in a conductor, where electrons can move around freely in the material? To figure this out, let's imagine we have a conductive sphere with a net negative charge meaning it has too many free electrons.

These extra free electrons want to move as far away from one another as possible. This means they redistribute themselves on the surface of the sphere. When they do, they've reached electrostatic equilibrium. In this state, the excess charges have moved as far apart as possible to reduce their forces on one another. Once these free charges are at equilibrium, their acceleration is zero, which means that there are no longer any net forces acting on them. And since the electric field represents electric forces acting on nearby charges, when the net forces are zero, the electric field must also be zero.

So what do these observations tell us? Well for one thing, it shows that the electric field inside conductors is always zero when the system is in electrostatic equilibrium and it also shows that the net charge is distributed on the surface. These conditions hold true for all conducive materials. While the electric field inside the material is zero, an electric field exists outside the surface of the conductor.

Let's look again at the capacitor and see what I mean. You can see that all excess charge is on the surface of the plates and while no electric field exists inside the plates themselves, a field is generated between the two. Now, what if we take a neutral conductive sphere, hollow out the inside, and stick a positively charged particle in the centre?

The positive charge inside the sphere attracts the negative charges inside the shell while it's pushing the positive charges to the surface of the sphere. Once the system is at electrostatic equilibrium, the observations we made before still hold true. The charges stop moving, so no electric field exists inside the shell.

Now the inside of the shell has a net negative charge due to the attraction of the central positive particle leaving the outer shell with a net positive charge. So an electric field is generated from the outside of the shell, because of the net positive charge. And while no field exists inside the shell, there is an electric field between that particle in the centre and the inside surface. Any positive test charges in the region would follow the field lines and be pushed toward the negative interior of the shell.

So we've managed to use our knowledge of electric charges and Coulomb's Law to figure out a way to describe the effect of any charged object on the entire universe surrounding it. Later we'll learn about how electric forces and fields are just half of the story in our pursuit of understanding the larger concept of electromagnetism.

Today we learned how all objects with net charge generate electric fields that affect all other charged materials. We learned how to construct electric field lines and how to calculate the magnitude and direction of the electric field for a charged particle. Finally, we learned how electric fields interact in capacitors and conductors.

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