IX. Electricity and Magnetism

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CONFLICTING CONTENTIONS

1. Electric Force and Neutral Objects

The Situation

Mr. Nicholls had brought a water jug to class with a spigot on the side that one usually takes along to a Summer picnic. He placed it on the edge of the table and also set a bucket on the floor underneath it.

“You already know that two like charges repel each other and that opposite charges attract each other. You also know that all matter is composed of massive, positively-charged nuclei surrounds by very light, negatively-charged electrons. If an object is neutral, then matter contains equal numbers of positive and negative charges; if it is charged, then there is an excess of one or the other types of charges.

“So what do you think will happen if I bring a positively charged glass rod near a stream of water falling from the spigot into the bucket? Will the water be attracted to the rod and curve toward it, will it be repelled by it and curve away, or will it be unaffected by the charged rod and just fall straight down?”

“Well let’s start at the beginning,” Alonzo said. “If the water is neutral, then its net charge is zero. So most people would say — and I’m not claiming to be one of them — that the stream of water shouldn’t be affected by the charged rod at all, and it should just fall straight down into the bucket.”

“Yes,” the instructor agreed, “That is the simplest answer, and a logical one. And sometimes simple and obvious is a good thing. But the Universe also does a number of interesting, amazing, and unexpected things that are worth exploring. And we probably never would have realized it if someone, probably a scientist, hadn’t decided to observe what does happen instead of deciding in advance what is supposed to happen.”

“And if you decided to show us a new demonstration, then it probably falls into one of those ‘interesting, amazing, or unexpected’ categories,” Beth added.

“Yes,” he agreed, “So I can tell you right now that the water will curve either toward the positively-charged rod or away from it. What I need from you is a prediction and a reason.”

Here is your chance. Put on your nicest, fanciest, most expensive ‘thinking cap’ and give it a shot before you hear from the rest of your classmates.

The Predictions

“Okay! I’ve got it!” Frank perked up. “A glass rod gets charged up because you rub it, right? And the same thing with a rubber rod. So friction is needed to charge something up. Well, what about the water falling through the spout-thingy? Doesn't the water rub against the plastic hole? So I bet some of the electrons in the water get rubbed off, making the water positively charged. I predict the stream of water is repelled by the glass rod because it is positively charged, and the water curves away!"

"Wait a minute," Cathy interjected. "Why do you think the electrons are rubbed off? Maybe the falling water picks up electron hitchhikers and is attracted to the glass rod."

"Frank! I am duly impressed," said an admiring instructor, "I didn't think that anyone would imagine a charged stream of water. But, yes, the stream of water can become slightly charged as it falls through the spigot. In fact, there is another demonstration called the Kelvin Water Dropper that uses the action to build up enough charge to light a small light bulb. And Cathy is also right: the water can be either positively or negatively charged, depending on fate and circumstance.

"But, I'm sorry to say, that isn't what's happening here. The size of the net charge is much too small to see a noticeable effect. Also, I could have chosen to use small bits of paper or Styrofoam instead of a stream of water to check the effect of a charged object on a neutral one. I just thought the water was more fun to observe. The stream of water remains effectively neutral, with an equal number of positive and negative charges."

"Then it has to be in the charges themselves," John concluded. "So what do we know about them, I ask myself. Electrons are small and light, and the protons are stuck in the heavy nucleus. So I'm guessing that the electrons rush toward the glass rod, pulling the stream of water with them."

"Okay, I can see that," Beth agreed, "But wouldn't that mean that the stream would curve away? Because the positive nuclei have most of the mass, the light electrons won't have much momentum to pull the stream toward the rod. Wouldn't the effect of the repulsive force will be greater?"

"So then, one of you says the electrons pull the stream of water because they are light; and the other says the positive nuclei push the stream away from the rod because they are more massive. Any other suggestions?" Mr. Nicholls looked around the room and only saw bewildered faces.

"Would you at least agree then, based on your explanations, that whatever the stream does with the positive rod, the opposite effect should happen with a negatively-charged rubber rod?" Mr. Nicholls saw a roomful of nods. "Then let's see what does happen."

The instructor turned the spigot and a stream of water began falling into the bucket on the floor. He charged up a glass rod with a silk cloth and held it near the stream. About half the class had looks of satisfaction on their faces when the stream clearly curved toward the glass rod. However, all the faces in the room showed startled faces or furrowed eyebrows when Mr. Nicholls charged up a rubber rod with a piece of fur, and the stream of water . curved toward the charged rod!

"Okay. I'm stumped," Daniel announced.

“That’s okay,” the teacher assured him. “This is a tough one. First, let me say that you were right about at least one thing: the electrons move in the stream of water and the nuclei don’t. Or, at least, the heavier nuclei only shift their positions slightly. But it isn’t about momentum or mass.

“The key to our observations is in Coulomb’s law of electric force. Remember, the size of the force is proportional to the magnitude of the charge on the charged rod, and also to the net negative (or positive) charge that has been shifted in the stream of water. But it is also inversely proportional to the square of the separation distance between the rod and the new average center of positive or negative charge.”

“Now can you explain why a neutral object, whether a stream of water or a block of wood, is attracted to a charged object, whether the object is positively-charged or negatively-charged?”

Coulomb’s law: $$F_E = \frac{q_1 q_2}{r^2}$$

The Solution

In any neutral object, only the electrons will shift position significantly. Suppose an object with a net positive charge is brought near a neutral object. The electrons will be drawn closer to the positive charge, causing a charge separation in the neutral object, which is called a *dipole* in scientific terminology. The magnitude of the ‘net’ positive and negative separated charges must be the same since the object is still neutral. Therefore, the numerator of Coulomb’s law will be the same for both the positive and negative net charges. However, the negative charges, on average, are closer to the positive object than the positive charges, so the denominator for the negative force is smaller than that of the positive force, and therefore the negative force is stronger.

If an object with a net negative charge is brought near a neutral object, the electrons are repelled to a farther distance compared to the positive charges and the negative electric force is less than the positive force. Therefore, the neutral object with a dipole is still attracted to the charged object.

2. Electrical Resistance in a Wire

“I’m afraid I have to make an apology to all of you,” Mr. Nicholls announced one day.

“You mean you really are an alien from outer space sent to Earth only to torment us?” Daniel asked.

“No,” he said, “But that is a good guess. I think I may sometimes give the impression in these demonstrations that the answers are always easy and obvious, and that if you only understood the physics then you should get the right answer on the first try.”

“ ‘Sometimes’? “ Cathy questioned.

“Anyway,” he continued, “I just wanted all you to know that these concept questions are not easy, and they aren’t supposed to be. If they were easy and obvious, then there would be no reason to ask them, since you couldn’t learning anything from them about physics.

“I also want you to know that these brain teasers aren’t any easier for people who love physics, like myself. When I get together with my friends and colleagues at meetings, we often share new demonstrations with each other. Where did you think I got all these demos, anyway? And the first time around, we do just as badly as you do trying to figure out what’s going on.

“That’s even when we know what the right answer is supposed to be! Even I can misuse Newton’s laws of motion now and again. It’s only because I teach them to a new crop of students, year after year, that I get this stuff right. I’ve just indoctrinated my memory with the correct explanation, and I pull it out of the right mental file drawer at the appropriate time.

“But it isn’t about being right on the first try; it’s about understanding the fundamental physics principles that govern the universe and how they can be correctly applied in important situations.

“So, having said that, I’m now going to show you a demo where two opposite predictions could *both* be right. By that I mean, appropriate physics principles and correct logic could be used to predict both effects. The only way we know which principle and explanation is more important for the situation is to actually do the experiment.

“So here is the set up. I have a battery connected to a light bulb in a circuit that includes this iron rod. You can see how brightly the lightbulb is glowing. I also have a gas burner that I can light underneath the rod. When I heat the rod, it *will* affect the resistance of the rod. If the rod decreases in resistance, then the bulb will glow brighter. If the rod increases in resistance, then the bulb will dim.

“We have already learned that the resistance of a conducting wire, or rod like this one, depends on its length, the area of a perpendicular cut through the wire or rod, and the type of material. Now we want to explore the effect of temperature on resistance.

“Here is your task. I want you to develop a reasonable argument based on correct physics which would support the prediction that the resistance of the iron will *decrease* with an *increase* in temperature. I then want you to present an equally correct and reasonable argument to suggest that the resistance of the iron should increase as the temperature rises.”

“So are you saying that physics is just a set of mental word games?” Mary asked. “Guess at this, guess at that, and whatever happens, happens?”

“No”, the teacher countered, “What I’m saying is that understanding how the Universe works is like falling in love with the person that you eventually marry. At first, it’s all new and exciting as you get to know them. But there also comes a stage in the relationship when you *think* you know what your partner will say or how they will react, but then they do the exact opposite. And even after twenty years, you still won’t be able to say that you know exactly how your partner thinks or feels all the time, even though their habits and personality are very familiar to you. That’s the part of a relationship that keeps it from getting boring. It’s also the part that takes work to keep a marriage alive.

"So, like in this situation, if I understand why the resistance might increase, or why it might decrease, and then I find out which way it actually changes, it may help me solve other physics problems because I come to understand which types of changes in matter are probably most significant in most situations. But even then, at times the Universe may surprise me."

"I suggest," Mr. Nicholls continued, "that you think about the structure of matter in the iron rod — massive nuclei in fixed positions with some freely moving electrons on the outside of the atoms. You should also consider what is happening inside the metal, in particular to the electrons, when current is flowing through the metal."

Will you accept Mr. Nicholls' challenge? Can you develop two reasonable and logical arguments that lead to opposite predictions concerning the effect of temperature on resistance?

[By the way, when Mr. Nicholls heated the rod, the lightbulb dimmed: An increase in temperature increases the resistance of a material.]

3. Magnets and Charges

"What would happen if I placed a positive charge near the north pole of a permanent magnet?" Mr. Nicholl's asked.

Beth: "Wouldn't the two repel each other? Aren't positive charges like north poles and negative charges like south poles?"

Mary: "I thought the charges had to be moving. If you push the positive charge straight toward the north pole, it will repel; if you push it away, it will attract."

Cathy: "I think that's right, but don't both have to be moving? If either one is at rest, the force is zero. If they both move toward each other, then they repel. And they attract if they both move away from each other."

Daniel: "There's something wrong with heading straight toward the pole, though. If you did that, then they would crash into each other, and I don't think that's allowed. You have to send it past the magnet, but parallel to the bar. Then it will be pulled toward the magnet or pushed away."

Alonzo: "The direction's wrong. You send the positive charge perpendicular to the magnet. Send it past the magnet in one direction — up, let's say – and it's pulled toward the north pole. Reverse the direction of the positive charge, or make the charge negative but traveling in the same direction as before, and it's pushed away.

John: "No, not toward or away from the north pole, Alonzo. The moving charges must get pushed sideways."

Frank: "I say this is another trick question. The magnet and charge won't interact at all, whether they are moving or at rest. That stuff only works if you have currents moving through wires, and a single charge isn't a current."

Only one of your classmates is right. Who is it? And what is wrong with each of the other six predictions?

QUALITATIVE REASONING

1. Charged Objects

Three Styrofoam pieces are hanging from strings. When the first and second are brought near each other, they repel. The same happens when the second and third are brought near each other.

a) Can any definite statement be made about the relative charges on the three Styrofoam bits? Do they all have the same charge? Can two of the pieces have a charge that is opposite the third? Could any of the three be uncharged?

Suppose, instead, that the first and second bits are attracted to each other when they are brought near each other, and the same is true when the second and third are placed in close proximity.

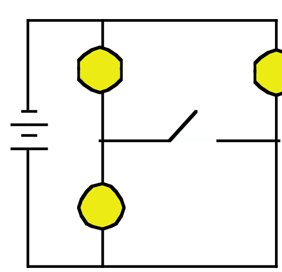
b) Can any definite statement be made about the relative charges on the three Styrofoam bits? Do they all have the same charge? Can two of the pieces have a charge opposite the third? Could any of the three be uncharged?

2. Closing a Switch

The figure below shows three light bulbs of identical resistance (the three circles) in a simple circuit. Bulbs 1 and 2 are in series in one branch of the circuit; bulb 3 is in parallel with the first branch. Recall the rules of voltage, current and equivalent resistance for resistors in series and in parallel. Also recall that the power output of a resistor is the product of voltage and current (P = IV) and that a larger power output will result in a brighter bulb.

a) How will the relative brightness of the three bulbs compare when the circuit is activated?

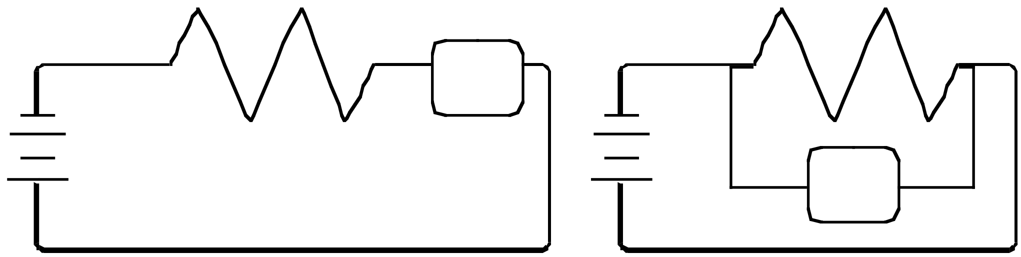
b) Suppose the switch shown in the drawing is closed while the bulbs are lit. How would the relative brightness of the three bulbs change as a result?



3. Ammeters and Voltmeters

An ammeter measures current; a voltmeter measures voltage. Consider a simple circuit consisting of a voltage source and a single resistor. Our goal is to measure the current in the circuit and the voltage discharged by the resistor. One of the two diagrams shows the correct placement of the meter (the box) to measure current; the other to measure voltage: one meter is placed in series with the resistor; the other is placed in parallel with the resistor. But which is which? The following questions will help you to deduce the correct placement of an ammeter and voltmeter in a circuit.

You will also see why choosing the wrong setup can cause one of the meters to be destroyed (and, perhaps, result in a significant cost to your physics instructor to replace it).



a) In one type of circuit — parallel or series — the current is the same in the resistor and the meter; in the other type of circuit, the voltage drop of the meter and the resistor will be the same. Which is which?

b) The current through the ammeter must be the same as the current through the resistor in order to make a correct measurement. Based on your answer to the last question, which type of placement of an ammeter, in series or in parallel with the resistor, will insure that the currents are the same?

c) The other type of placement should then insure that the voltage drop across the voltmeter is the same as the voltage drop across the resistor. Can you verify this for that type of circuit?

Both the ammeter and voltmeter follow Ohm's law (V = IR) and become part of the circuit in which the measurements are being made. In other words, the ammeter is using some of the current it is supposed to be measuring and the voltmeter is draining some of the voltage it is supposed to measure.

We also know that multiple resistors in circuits can be added together in such a way to calculate an equivalent resistance for the full circuit. Obviously, the voltage and current through an 'equivalent resistor' circuit will not be the same as the current and resistance through the original circuit we are testing.

Finally, recall that:

Series: $R_{eq} = R_1 + R_2 + ...$

Parallel: $1/ R_{eq} = 1/ R_1 + 1/ R_2 + ...$

d) In order to minimize the 'equivalent resistance' effect causes by the ammeter in the circuit (given your choice of either series or parallel placement in the circuit), should the ammeter's resistance be very large or very small?

e) In order to minimize the ‘equivalent resistance’ effect causes by the voltmeter in the circuit (given your choice of either series or parallel placement in the circuit), should the voltmeter’s resistance be very large or very small?

f) Suppose you chose the wrong placement of the ammeter in the circuit: series instead of parallel or parallel instead of series. Given the size of the internal resistance of the meter (very large or very small), how would the wrong placement affect the meter, the circuit, or the meter’s reading?

g) Suppose you chose the wrong placement of the voltmeter in the circuit: series instead of parallel or parallel instead of series. Given the size of the internal resistance of the meter (very large or very small), how would the wrong placement affect the meter, the circuit, or the meter’s reading?

4. Electromagnets

A current-carrying wire wrapped around an iron nail will act as a magnet. For the following questions, be sure to give a reasonable explanation based on physics principles along with your prediction.

a) What, if anything, would happen to the behavior of the electromagnet if the current in the wire is increased?

b) What, if anything, would happen to the behavior of the electromagnet if the current in the wire is reversed?

c) What, if anything, would happen to the behavior of the electromagnet if the wire is wrapped around the wire a greater number of times?

d) What would happen to the behavior of the electromagnet if the iron nail was replaced by an aluminum nail?

5. Straightening an electron beam

Here is a practical and important application of electric and magnetic forces. A standard cathode ray tube (CRT), which is also called the picture tube of a television or computer monitor, sends a beam of electrons from the top of the screen to the bottom while at the same time making the beam sweep from left to right, row upon row, exciting the phosphors of the pixels in the CRT. How do engineers do that, anyway?

There are two ways to deflect an electron beam: by applying a net electric force on the moving charged particle, or by applying a net magnetic force on the moving charged particle.

In order to understand how it is possible to control the path of a speeding electron, let’s first just try to keep the particle moving in a straight line.

Figure [A] shows an electron moving through a region of space at a constant speed and surrounded by two charged plates above and below it. Figure [B] shows the two balanced forces we want to be acting on the electron so that it will move in a straight line through space. Figure [C] shows the possible orientations in space for the north and south poles of a magnet: above and below, like the charged plates [1]; front and back, in the direction of the electron's motion [2]; or closer and farther from the observer [3].

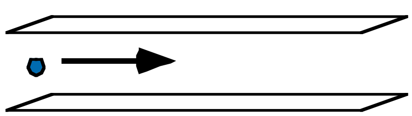
Be sure to give complete explanations based on physics principles for all of your answers.

a) The electron is negatively charged. In order to create the direction of the electric force shown in Figure [B], must the top plate be positively charged and the bottom one negatively charged, or vice versa?
b) In order to create the direction of the magnetic force shown in Figure [B], what should be the orientation of the north and south poles of the magnet: oriented in the X direction, the Y direction, or the Z direction as shown in Figure [C]?

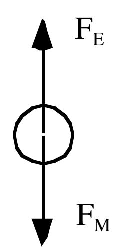
c) Using the right hand rule, and noting that the direction of the current is opposite the direction of motion of the electron, what should be the placement of the north and south poles of the magnet around the electron for your answer to (b)?

d) Now that we know the placement of the charged plates and magnets, it is possible to adjust the strengths of both so that the electric and magnetic forces are balanced. But now suppose a second electron enters this region of space moving faster than the first electron. Would it also travel in a straight line? In other words, does the speed of the electron have an effect on the strengths of either the electric or magnetic forces acting on it?

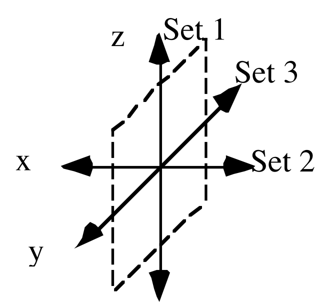
e) And finally, suppose a positively charged proton was launched into this region of space with the same constant speed as the original electron. Would it follow a straight-line path? How would the electric and magnetic forces on the proton be different form those acting on the electron, if at all?



[A]



[B]



[C]

6. Mass Spectrometer

The mass spectrometer is a device that can very accurately determine the mass of an atom, molecule, or fragment of a molecule. The atom or molecule is stripped of one or more electrons (creating an ion) and then accelerated through an electric field to a known speed. It is injected into a region of space with a constant magnetic field, traveling perpendicular to the field. The charged particle then travels in a circular path (CYET # 5 asks you to explain why) until it strikes a detector. The masses of the charged particles will be related to the radii of their paths, assuming the other conditions of the apparatus, such as their speeds and the strength of the magnetic field, are held constant.

a) Suppose two ions with different masses are injected into the mass spectrometer. Which ion, the heavier one or the lighter one, will have the larger radius of its circular path?

b) Suppose two ions are exactly the same, except one lost two electrons instead of one. How would that affect the path of the doubly-ionized particle compared to the singly-ionized one, if at all?

CAN YOU EXPLAIN THIS?

1. Electrostatic Ping Pong Ball

A ping pong ball is dropped between two metal plates, one positively charged and the other negatively charged. The ping pong ball bounces rapidly between the two plates.

Can you explain why?

HINT: The ping pong ball is able to acquire a charge, and also to become uncharged.

2. The Electroscope

You can probably find this explanation in your textbook, but we instructors are very good at recognizing direct quotes without any real understanding behind the words. So, *without re-reading any references*, can you explain in your own words how an electroscope works?

Just in case you didn't read about them yet, an electroscope consists of two freely-moving metal foils or plates attached to each other and a metal ball. The plates are usually hanging in a glass flask or jar to minimize discharging and the effect of air currents.

Conduction:

a) When a charged rod is touched to the metal ball, the plates swing apart. Why?

Induction:

b) When a charged rod is brought near the electroscope, the plates begin to swing apart. A person then touches the metal ball while the charged rod is near and the plates drop. The person then removes his hand. Finally, the charged rod is removed, never having touched the metal ball. As it is removed, the plates swing apart. Can you explain what happened: (1) when the charged rod was brought near; (2) when the person touched the ball; (3) when the rod was removed?

3. The Faraday Cage

A Faraday cage is able to protect a person from large voltages and electrostatic forces. The 'cage' is simply a wire mesh box. A person or object inside the cage will not be shocked by charges or large electric fields that exist outside the cage; the electric field inside the cage is zero. Any ideas on how the Faraday cage might work?

4. Eddy Currents

Try this yourself. Get two bar magnets, and a copper pipe and a plastic pipe of the same diameter and length. Drop the bar magnets through each pipe simultaneously and the magnet falling through the copper pipe has a noticeable 'lag time', even though neither magnet experienced friction against the sides of the pipes.

a) Can you explain why this occurs? HINT: Electromagnetic induction

b) Can you explain why the magnet falling through the copper pipe must slow down and not speed up compared to the one falling through the plastic pipe? HINT: Conservation of energy

c) Is the plastic pipe necessary for this demonstration?

d) Suppose the magnets are reversed, so that the south pole takes the lead through the pipe instead of the north pole (or vice versa). Would the magnet then speed up through the pipe? [HINT: review your answer to part (b)] If not, then can you describe what must be happening to the electrons in the copper pipe while the magnet is falling south-end first, compared to north-end first?

5. Particle Path

A charged particle entering a region of space with a constant magnetic field will travel in a circular orbit with a constant speed if the direction of the velocity vector is perpendicular to the direction of the magnetic field vectors. Can you explain why?

HINT: Recall the properties and behavior of centripetal forces.

6. Generators and Motors

Explain (or argue with) this statement: a generator is a motor run in reverse, and vice versa.