RELATIVITY REQUIRES MAGNETISM

So magnetism is an interaction between moving charges and moving charges. But how can that be? Relativity tells us that motion is a matter of opinion. Consider figure k. In this figure and in figure l, the dark and light coloring of the particles represents the fact that one particle has one type of charge and the other particle has the other type.

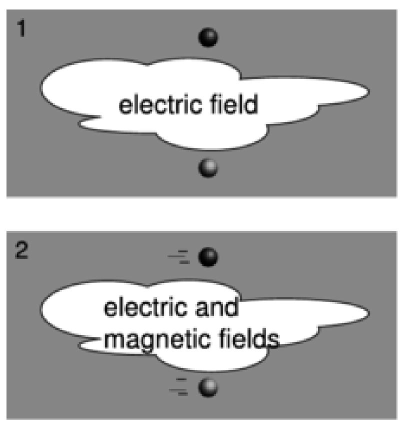


Figure k./ One observer sees an electric field, while the other sees both an electric field and a magnetic one.

Observer k/2 sees the two particles as flying through space side by side, so they would interact both electrically (simply because they're charged) and magnetically (because they're charges in motion). But an observer moving along with them, k/1, would say they were both at rest, and would expect only an electrical interaction.

This seems like a paradox. Magnetism, however, comes not to destroy relativity but to fulfill it. Magnetic interactions *must* exist according to the theory of relativity. To understand how this can be, consider how time and space behave in relativity. Observers in different frames of reference disagree about the lengths of measuring sticks and the speeds of clocks, but the laws of physics are valid and self-consistent in either frame of reference. Similarly, observers in different frames of reference disagree about what electric and magnetic fields there are, but they agree about concrete physical events. An observer in frame of reference k/1 says there are electric fields around the particles, and predicts that as time goes on, the particles will begin to accelerate towards one another, eventually colliding. She explains the collision as being due to the electrical attraction between the particles. A different observer, k/2, says the particles are moving. This observer also predicts that the particles will collide, but explains their motion in terms of both an electric field and a magnetic field. As we'll see shortly, the magnetic field is *required* in order to maintain consistency between the predictions made in the two frames of reference.

To see how this really works out, we need to find a nice simple example. An example like figure k is *not* easy to handle, because in the second frame of reference, the moving charges create fields that change over time at any given location, like when the V-shaped wake of a speedboat washes over a buoy.

Examples like figure j are easier, because there is a steady flow of charges, and all the fields stay the same over time. Figure l/1 shows a simplified and idealized model of figure j. The charge by itself is like one of the charged particles in the vacuum tube beam of figure j, and instead of the wire, we have two long lines of charges moving in opposite directions. Note that, as discussed in discussion question C on page 106, the currents of the two lines of charges do not cancel out. The dark balls represent particles with one type of charge, and the light balls have the other type. Because of this, the total current in the “wire” is double what it would be if we took away one line.

As a model of figure j, figure l/1 is partly realistic and partly unrealistic. In a real piece of copper wire, there are indeed charged particles of both types, but it turns out that the particles of one type (the protons) are locked in place, while only some of the other type (the electrons) are free to move. The model also shows the particles moving in a simple and orderly way, like cars on a two-lane road, whereas in reality most of the particles are organized into copper atoms, and there is also a great deal of random thermal motion. The model's unrealistic features aren't a problem, because the point of this exercise is only to find one particular situation that shows magnetic effects must exist based on relativity.

What electrical force does the lone particle in figure l/1 feel? Since the density of “traffic” on the two sides of the “road” is equal, there is zero overall electrical force on the lone particle. Each “car” that attracts the lone particle is paired with a partner on the other side of the road that repels it. If we didn't know about magnetism, we'd think this was the whole story: the lone particle feels no force at all from the wire.

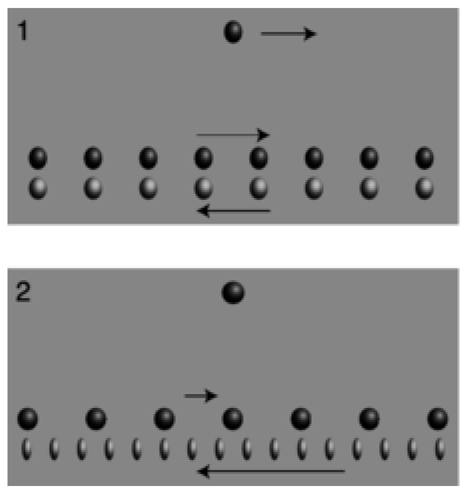


Figure l: A model of a charged particle and a current-carrying wire, seen in two different frames of reference. The relativistic length contraction is highly exaggerated. The force on the lone particle is purely magnetic in 1, and purely electric in 2.

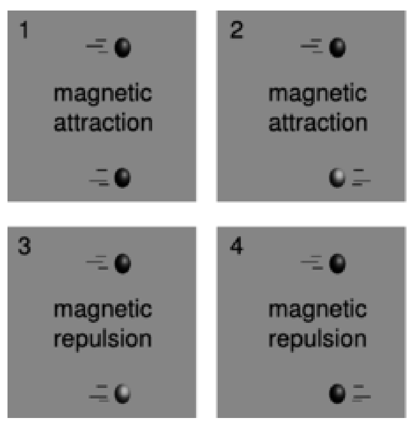
Figure l/2 shows what we'd see if we were observing all this from a frame of reference moving along with the lone charge. Here's where the relativity comes in. Relativity tells us that moving objects appear contracted to an observer who is not moving along with them.

Both lines of charge are in motion in both frames of reference, but in frame 1 they were moving at equal speeds, so their contractions were equal. In frame 2, however, their speeds are unequal. The dark charges are moving more slowly than in frame 1, so in frame 2 they are less contracted. The light-colored charges are moving more quickly, so their contraction is greater now. The “cars” on the two sides of the “road” are no longer paired off, so the electrical forces on the lone particle no longer cancel out as they did in l/1. The lone particle is attracted to the wire, because the particles attracting it are more dense than the ones repelling it. Furthermore, the attraction felt by the lone charge must be purely electrical, since the lone charge is at rest in this frame of reference, and magnetic effects occur only between moving charges and other moving charges.

Now observers in frames 1 and 2 disagree about many things, but they do agree on concrete events. Observer 2 is going to see the lone particle drift toward the wire due to the wire's electrical attraction, gradually speeding up, and eventually hit the wire. If 2 sees this collision, then 1 must as well. But 1 knows that the total electrical force on the lone particle is exactly zero. There must be some new type of force. She invents a name for this new type of force: magnetism. This was a particularly simple example, because the force was purely magnetic in one frame of reference, and purely electrical in another.

In general, an observer in a certain frame of reference will measure a mixture of electric and magnetic fields, while an observer in another frame, in motion with respect to the first, says that the same volume of space contains a different mixture.

We therefore arrive at the conclusion that electric and magnetic phenomena aren't separate. They're different sides of the same coin. We refer to electric and magnetic interactions collectively as electromagnetic interactions. Our list of the fundamental interactions of nature now has two items on it instead of three: gravity and electromagnetism.



FigureFgm: Magnetic interactions involving only two particles at a time. In these figures, unlike figure l/1, there are electrical forces as well as magnetic ones. The electrical forces are not shown here. Don't memorize these rules!

The basic rules for magnetic attractions and repulsions, shown in figure m, ar enot quite as simple as the ones for gravity and electricity. Rules m/1 and m/2 follow directly from our previous analysis of figure l. Rules 3 and 4 are obtained by flipping the type of charge that the bottom particle has.

For instance, rule 3 is like rule 1, except that the bottom charge is now the opposite type. This turns the attraction into a repulsion. (We know that flipping the charge reverses the interaction, because that's the way it works for electric forces, and magnetic forces are just electric forces viewed in a different frame of reference.)

Example 1: A magnetic weathervane placed near a current

Figure n shows a magnetic weathervane, consisting of two charges that spin in circles around the axis of the arrow. (The magnetic field doesn't cause them to spin; a motor is needed to get them to spin in the first place.)

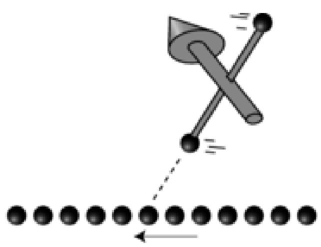


Figure n: Example 1

Just like the magnetic compass in figure h, the weathervane's arrow tends to align itself in the direction perpendicular to the wire. This is its preferred orientation because the charge close to the wire is attracted to the wire, while the charge far from the wire is repelled by it.

Source:
http://physwiki.ucdavis.edu/Electricity_and_Magnetism/Fields/Electromagnetism