INDUCTION

Introduction

We've already seen that the electric and magnetic fields are closely related, since what one observer sees as one type of field, another observer in a different frame of reference sees as a mixture of both. The relationship goes even deeper than that, however. Figure t shows an example that doesn't even involve two different frames of reference. This phenomenon of induced electric fields --- fields that are not due to charges --- was a purely experimental accomplishment by Michael Faraday (1791-1867), the son of a blacksmith who had to struggle against the rigid class structure of 19th century England. Faraday, working in 1831, had only a vague and general idea that electricity and magnetism were related to each other, based on Oersted's demonstration, a decade before, that magnetic fields were caused by electric currents.

Faraday on a British banknote.

Figure t is a simplified drawing of the experiment, as described in Faraday's original paper: “Two hundred and three feet of copper wire ... were passed round a large block of wood; [another] two hundred and three feet of similar wire were interposed as a spiral between the turns of the first, and metallic contact everywhere prevented by twine [insulation]. One of these [coils] was connected with a galvanometer [voltmeter], and the other with a battery... When the contact was made, there was a sudden and very slight effect at the galvanometer, and there was also a similar slight effect when the contact with the battery was broken. But whilst the ... current was continuing to pass through the one [coil], no ... effect ... upon the other [coil] could be perceived, although the active power of the battery was proved to be great, by its heating the whole of its own coil [through ordinary resistive heating] ...”

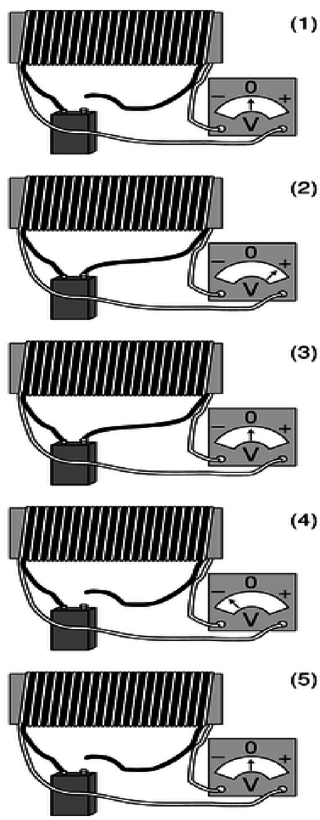

Figure t: Faraday's experiment, simplified and shown with modern equipment.

From Faraday's notes and publications, it appears that the situation in figure t/3 was a surprise to him, and he probably thought it would be a surprise to his readers, as well. That's why he offered evidence that the current was still flowing: to show that the battery hadn't just died. The induction effect occurred during the short time it took for the black coil's magnetic field to be established, t/2. Even more counter intuitively, we get an effect, equally strong but in the opposite direction, when the circuit is *broken*, t/4. The effect occurs only when the magnetic field is changing: either ramping up or ramping down.

What are we really measuring here with the voltmeter? A voltmeter is nothing more than a resistor with an attachment for measuring the current through it. A current will not flow through a resistor unless there is some electric field pushing the electrons, so we conclude that the changing *magnetic field* has produced an *electric field* in the surrounding space. Since the white wire is not a perfect conductor, there must be electric fields in it as well. The remarkable thing about the circuit formed by the white wire is that as the electrons travel around and around, they are always being pushed forward by electric fields. That is, the electric field seems to form a curly pattern, like a whirlpool.

What Faraday observed was an example of the **principle of induction:**

- Any magnetic field that changes over time will create an electric field. The induced electric field is perpendicular to the magnetic field, and forms a curly pattern around it.
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The first part was the one Faraday had seen in his experiment. The geometrical relationships are illustrated in figure u. In Faraday's setup, the magnetic field was pointing along the axis of the coil of wire, so the induced electric field made a curly pattern that circled around the circumference of the block.

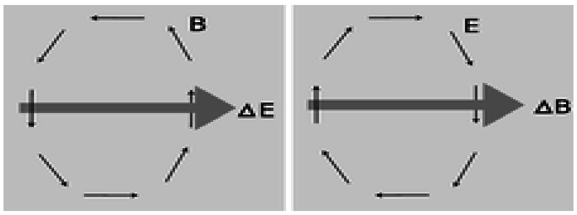

Figure u: The geometry of induced fields. The induced field tends to form a whirlpool pattern around the change in the field producing it. The notation Δ (Greek letter delta) stands for "change in." Note how the induced fields circulate in opposite directions.

Fun with sparks

Unplug a lamp while it's turned on, and watch the area around the wall outlet. You should see a blue spark in the air at the moment when the prongs of the plug lose contact with the electrical contacts inside the socket.

This is evidence that fields contain energy. Somewhere on your street is a transformer, one side of which is connected to the lamp's circuit. When the lamp is plugged in and turned on, there's a complete circuit, and current flows. as current flows through the coils in the transformer, a magnetic field is formed --- remember, any time there's moving charge, there will be magnetic fields. Because there is a large number turns in the coils, these fields are fairly strong, and store quite a bit of energy.

When you pull the plug, the circuit is no longer complete, and the current stops. Once the current has disappeared, there's no more magnetic field, which means that some energy has disappeared. Conservation of energy tells us that if a certain amount of energy disappears, an equal amount must reappear somewhere else. That energy goes into making the spark. (Once the spark is gone, its energy remains in the form of heat in the air.)

We now have two connections between electric and magnetic fields. One is the principle of induction, and the other is the idea that according to relativity, observers in different frames of reference must perceive different mixtures of magnetic and electric fields.

At the time Faraday was working, relativity was still 70 years in the future, so the relativistic concepts weren't available --- to him, his observations were just surprising empirical facts. But in fact, the relativistic idea about frames of reference has a logical connection to the idea of induction.

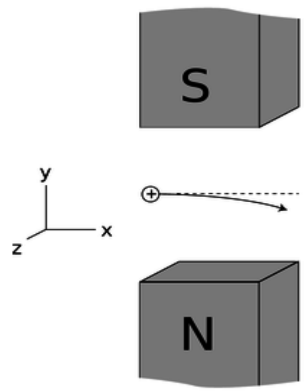

Figure x: Observer A sees a positively charged particle moves through a region of upward magnetic field, which we assume to be uniform, between the poles of two magnets. The resulting force along the *z* axis causes the particle's path to curve toward us.

Figure x is a nice example that can be interpreted either way. Observer A is at rest with respect to the bar magnets, and sees the particle swerving off in the *z* direction, as it should according to the right-hand rule. Suppose observer B, on the other hand, is moving to the right along the *x* axis, initially at the same speed as the particle. B sees the bar magnets moving to the left and the particle initially at rest but then accelerating along the *z* axis in a straight line. It is not possible for a magnetic field to start a particle moving if it is initially at rest, since magnetism is an interaction of moving charges with moving charges.

B is thus led to the inescapable conclusion that there is an electric field in this region of space, which points along the *z* axis. In other words, what A perceives as a pure magnetic field, B sees as a mixture of electric and magnetic fields. This is what we expect based on the relativistic arguments, but it's also what's required by the principle of induction. In B's frame of reference, there's initially no magnetic field, but then a couple of bar magnets come barging in and create one. This is a change in the magnetic field, so the principle of induction predicts that there must be an electric field as well.

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