In a hydroelectric plant, water coming from the reservoir is used to turn wheels, and these push wires through magnetic fields, etc., etc.

Once your automobile has started, it no longer needs a battery. From then on, all the electricity it needs (for spark plugs, and to light the headlights) is made from the gasoline engine, which turns an axle called a crankshaft, which turns a wheel that moves wires through a magnetic field.

Dynamos

To work well, a generator needs a strong magnetic field. For small generators, the field can be made out of permanent magnets. But for big generators, the magnets must be electromagnets. Guess where they get the electricity to run the electromagnets.

That's right. They get the electricity from the generator! When this is done, the generator is called a dynamo.

This sounds paradoxical, but it really works. Most large generators are dynamos. It sounds like you are getting something for nothing, but that isn't true. It takes energy to push the wire through the magnetic field,[10] and all the electric energy that emerges (in the current of the wire, and in the magnetic field) comes from the energy that you put in.

The North Pole is a South Pole

As we discussed earlier, the Earth is a great magnet. That's why compasses point towards the poles. But the Earth's magnetism is not perfectly aligned with the axis of the Earth's spin, so the direction that the compass points is not true north but a different location. The magnetic pole is located at a latitude of about 75 degrees, in northern Canada near Baffin Island. Maps often have a little symbol on them that shows the difference between magnetic north and true north.

The situation is much worse on some of the other planets. On Uranus and Neptune, the magnetic poles are 60 degrees away from the poles of the rotation axis.

You should be aware of a semantic problem in our terminology. The north pole of a compass needle points towards the Earth's magnetic pole. But the north pole of a magnet is attracted to a "south pole" of another magnet. Thus, magnetically speaking, the magnetic pole that is up in Canada is really a south magnetic pole!

Einstein's mystery

When William Gilbert deduced that the Earth was a magnet, he naturally assumed that it was a permanent magnet, perhaps from large deposits of lodestones. But we now know that rocks below the Earth are hot, from the Earth's radioactivity. At a depth of about 30 km, the temperature is higher than the Curie temperature, so all magnetism must disappear. These paradoxes led Albert Einstein to list the origin of the Earth's magnetism to be one of the greatest unsolved problems of physics.

We now believe we know the answer: the Earth is a dynamo. We don't know in detail how this works, but we understand the general picture. The early Earth (4.5 billion years ago) was very hot, and most of the iron melted

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[10] The current that flows in the wire interacts with the magnetism, and produces a force that resists the motion. That's why you have to do work to move the wire.

and sank to the center. It is still there; if you go about halfway to the center of the Earth, the material changes from rock to molten iron. Moreover, this iron is in constant flow from heat that is being released from a small solid iron core deep within. This flowing iron behaves like a dynamo. When liquid iron moves in a magnetic field, electric currents flow (just as in a moving wire). The arrangement of flow in the core is such that these electric currents circle around to create the magnetic field, just as they do in a commercial dynamo generator.

This picture is verified by computer and mathematical models, but it is hard to be sure, since the center of the Earth is far harder to reach than the surface of the Moon.

The Earth flips -- its magnet

As ocean animals die and drift to the bottom of the sea, they eventually form new layers of rock. These rocks become slightly magnetized by the Earth's magnetic field, and then they hold that magnetism for millions of years. If we study the layers of rock, and measure their ages (from potassium-argon dating, as discussed in Chapter 4), we can read the history of the Earth's magnetism.

From these records we have learned that the strength of the magnetic field changes slowly with time. But much more startling is the discovery that from time to time the magnetism of the Earth flips! That means that if you took a present-day magnetic compass back into the past, that the north-pointing needle would point south instead of north.

The last flip was almost a million years ago, and such flips (at least in recent times) seem to occur, on average, once or twice every million years. The flip takes several thousand years to happen, but in the geologic record that seems very fast.

We don't know why the magnetism flips, but several theories have been proposed. It turns out that the actual flow of liquid iron that drives the dynamo doesn't have to change. Instead only the electric current has to reverse. When that happens, the magnetism will flip too. There are some theories that attribute the change to the chaotic behavior seen in some dynamo models.

My favorite theory (also unproven) is that the flip magnetism consists of two steps: a destruction of the dynamo flow (perhaps triggered by avalanches of rock at the liquid/rock boundary), followed by a rebuilding of the dynamo in the opposite direction.[11]

Now you can understand the following paradoxical thought: "The Earth's North Pole is a south pole. However, about a million years ago, it was a north pole." Try it on your friends.

Flipping magnetism and geology

The fact that the Earth's magnetism flips every million years or so has been enormously useful in geology and related fields such as climate study. It is valuable because we often cannot measure the age of a rock from its radioactivity. For example, rocks often don't contain enough potassium for the potassium-argon method to be used. However, most rocks formed under

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[11] This theory is my favorite, in part, because it is my theory. It was published in the journal Geophysics Research Letters, and is available online at
http://muller.lbl.gov/papers/Avalanches_at_the_CMB.pdf.

the sea preserve a record of the Earth's magnetism. We can see a pattern in the layers, almost like a fingerprint, with some flips coming close to each other in time, and others with wide spacing. Once this pattern is known, then we can correlate the patterns at different locations around the Earth. We don't know how old a layer is, but at least we know it is the same age as another rock somewhere else on Earth.

But we can do even better. If we search long enough, we'll probably find a rock that was formed near a volcano. Volcanic ash contains lots of potassium. If we can use potassium-argon dating to obtain the age of this one rock, then we immediately know the age of rocks all around the world that are at the same position in the geomagnetic pattern.

This is also important because these other rocks often contain unique records of their own. Some of them record the patterns of previous climate. If you put all this together, you can figure out when the last ice age occurred on Earth, how long it lasted, and how quickly it ended. In this way, much of our knowledge of the past has used the Earth's magnetic field flips.

Earth's magnetism and cosmic radiation

Just as electrons flowing in a wire feel a force from a magnetic field, cosmic rays coming from space feel a force and are deflected by the Earth's magnetic field. This prevents a large number of these particles from hitting the top of the Earth's atmosphere. Some people have speculated that when the Earth's field collapses (as during a magnetic reversal) that life on Earth will be exposed to this deadly radiation. This idea has been widely spread by science fiction movies such as *The Core* (2003).

If the field collapses, then it is true that the cosmic rays will hit the Earth's upper atmosphere. But the atmosphere is the true shield, and even without the field, the radiation that reaches the Earth's surface will increase by only a few percent.[12] Thus, the field collapse will not significantly affect life.

In fact, the current north magnetic pole of the Earth, in northern Canada, currently has no magnetic field production whatsoever, because all the field lines point inward (and therefore they don't deflect cosmic rays). Yet the cosmic radiation at that location is only a tiny bit higher than at the equator. That's because the atmosphere stops most of the radiation.

Beware – even many good scientists have fallen into the trap of thinking that it is the Earth's magnetic field that protects us from cosmic rays. There was a recent NOVA program that assumed this, and talked about the possible impending disaster if the Earth's magnetic field is in the process of reversing. But it ain't so.

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[12] At the geomagnetic pole, the Earth's field presently gives no shielding whatsoever. This results in a much stronger cosmic radiation at the top of the atmosphere, and yet the radiation at the bottom of the atmosphere is only slightly greater than elsewhere on Earth.

Transformers

An electric generator works by moving a wire past a magnetic field. It would work equally well if the magnet were moved past the wire.[13] In fact, the magnets don't actually have to move; it works equally well if their magnetic field is just changing, and that can be done by changing the current in an electromagnet.

If all the ideas in the previous paragraph are put together, we get one of the great inventions of all time: the electric transformer. In a transformer, there is a coil of wire called the primary. Changing electric currents in this primary create a changing magnetic field. The changing magnetic field passes through a second coil of wire called the secondary, and it causes current to flow in the secondary.

One remarkable fact about a transformer is that it can pass energy from the primary coil to the secondary coil very efficiently, with almost none being lost. The primary and the secondary don't touch each other. The energy is all passed through in the form of magnetism!

What makes the transformer so valuable is the fact that the number of loops of wire in the primary and secondary can be different, and the result is that the voltage and current in the two coils will be different. A transformer transforms high voltage electricity to low voltage electricity, or the other way around. It is transformers that take the high voltage from power lines and reduce the voltage to make it safe for our homes. And they all work using magnetism.

If there is any iron near the transformer, then that iron may vibrate as the magnetic field changes. You can often hear a "hum" from a transformer that is doing this. Of course, that hum means that some energy is being lost from electricity to sound, so high quality transformers are built so this doesn't happen.

The Tesla coil

Nikola Tesla, a scientist who worked with Thomas Edison, invented a very high voltage transformer we now call a Tesla coil. One of his tricks was to make the current change very rapidly, and that generated very high voltages in the secondary. A Tesla coil can be used for a dramatic demonstration in the classroom, with continuous sparks over a foot long. At the same time, the sparks are not particularly dangerous. When the transformer raises the voltage of electricity, it must also lower the current--since the power is current times voltage, and the power doesn't change. So a Tesla coil can create extremely high voltage sparks, but they release relatively low power.

A description of the demonstrations used in the Berkeley Physics Department can be seen at these web pages:

http://www.mip.berkeley.edu/physics/D+75+04.html
http://www.mip.berkeley.edu/physics/D+75+08.html

[13] This is true, but it isn't really obvious. The discovery that it was true was led to Einstein's postulate that the laws of physics are identical regardless of the way you are moving, and that lead him to the theory of relativity.

Magnetic levitation

Ordinary iron, when exposed to a magnet, becomes a magnet itself, and is attracted to the original magnet. But some materials behave differently. When exposed to magnetism, they become magnets themselves, but in the opposite sense. The part which is exposed to the north pole of the magnet becomes a north pole itself, and instead of being attracted, it is repelled.

Such materials are not common, and that is why our experience is that magnets "attract" things. Liquid oxygen is one of the uncommon materials that is repelled by ordinary magnets. But superconductors are also repelled. When exposed to magnets, currents start flowing inside superconductors in just such a way as to create a repulsive force. If you place a small superconductor on top of a magnet, the force can make the superconductor "levitate" above the magnet, with the repulsive force countering gravity.

If you have a changing magnetic field, created by an electromagnet with alternating current, then levitation can be done with ordinary metals. The changing magnetism will cause currents to flow in the metal, and these currents will create magnetism that repels the original magnet. This approach can be used to levitate large objects.[14]

Levitation can also be done with moving magnets. If a strong magnet (samarium cobalt, or a strong electromagnet) is moved over a conductor, then electrical currents will be induced in the conductor. Those create a magnetic field that repels the original magnet. This approach is used commercially in magnetically levitated trains in Japan. At slow velocities, there is no levitation (since the induced magnetism requires a rapidly changing, or moving electrons). As the trains moves faster, the magnet moving over the rails induces stronger and stronger currents, until finally the magnetic repulsion lifts the wheels off the tracks. The advantage of magnetic levitation is that it avoids all the friction of contact. However, the currents flowing in the rails do lose some energy to electrical resistance, and that can be a serious limitation. Superconducting rails would avoid this problem, but they have to be kept cold. With all these problems, magnetic levitation has not proven to be as successful as some futurists have predicted. That could change if we ever develop room temperature superconductors.

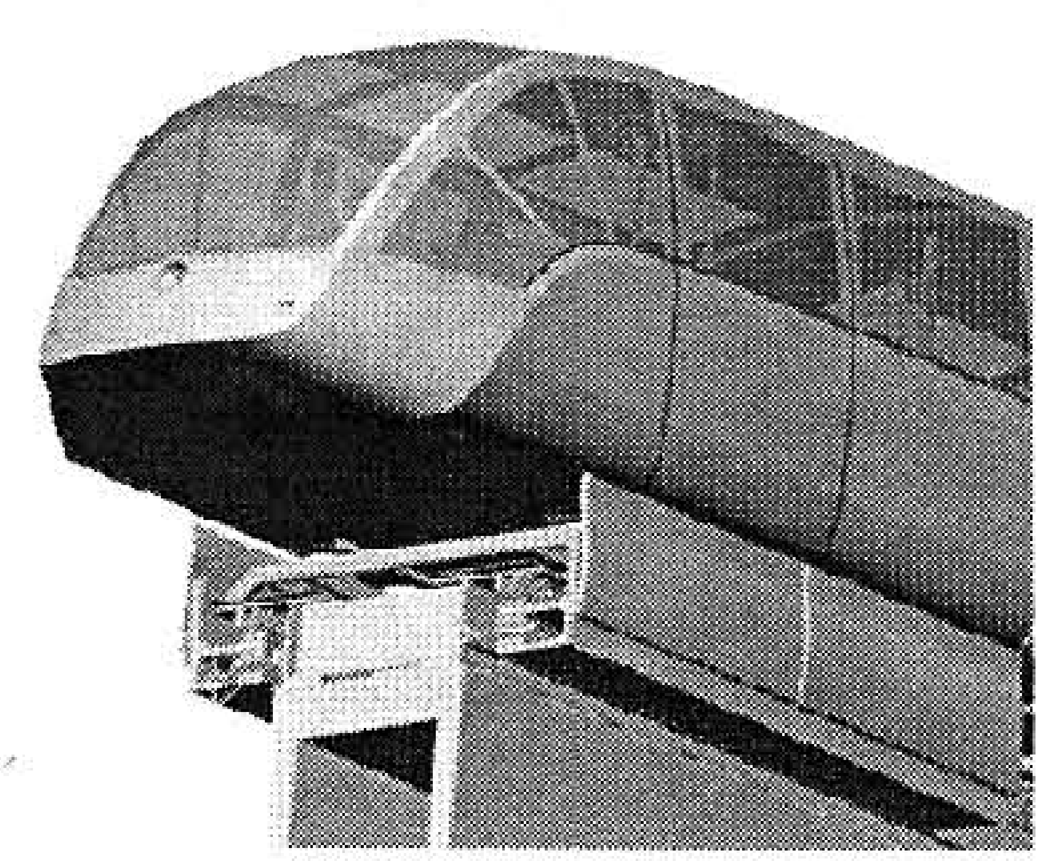

Fig. 6.6 Magnetic levitation concept based on rare-earth magnets

Rail guns

In Chapter 3 "Force and Gravity" we discussed the limitations of launching objects into space using chemical fuels. The problem was the exhaust velocity of such fuels was only 1 or 2 km/s, so it was hard to use them to push objects that had to go 11 km/s. But using magnetism, we can overcome that limit. The device that does this is called a rail gun.

The simplest version of a rail gun consists of two long parallel metal rails, just like those used for railroads. A high voltage is placed across the ends of the rails, and a piece of metal (called a sabot) is placed across or in between the two rails. High current flows from the end of one rail, down the

[14] A description of the demonstration we do in class can be found at www.mip.berkeley.edu/physics/D+15+24.html.

rail, across the metal, to the second rail, and back. The high current in the rails creates a strong magnetic field, and this puts a force on the current flowing through the metal sabot. As a result, the sabot is pushed down the rails. Theoretically, rail guns can launch a sabot at extremely high velocities.

Rail guns are under development by the U.S. Navy as a way of shooting down missiles attacking a ship, and they may one day be used to launch materials from the moon.

AC vs. DC

Most of our homes use alternating current electricity, abbreviated AC. In AC, the current is constantly changing, cycling its flow from positive to negative and then back again, 60 times every second. That's what we mean when we say that house current is 60 cycles-- that is short for 60 "cycles per second." There are 60 minutes in an hour, 60 seconds in a minute, and 60 cycles in a second.

A new terminology is to use the name Hertz to mean "cycles per second." Hertz is abbreviated Hz. In the U.S. we use 60 Hz electricity. In Europe, they use 50 Hz.

Batteries give DC, or "direct current." So why do we use AC in our homes? The answer is because AC works naturally with transformers. High voltage (and low current) is used in high-tension power lines to bring electricity to our homes. But before it enters the home, a transformer changes it to a relatively low voltage of 110 V and relatively high current of up to about 15 amps.

It was not always obvious that our electrical system would be based on AC. In the late 1800s, Thomas Edison believed the future would be DC. His rival, Nikola Tesla, was a believer in AC. I'll give the gruesome details (including the execution of an elephant) in the next section.

In the end, Tesla won. We use AC, not DC, and our power plants are located far away, not on every street corner. Our wall-plugs deliver 110 volts at 60 Hz. Many of our homes have a separate set of wires for 220 V, used on devices that take much more power, such as air conditioners. The higher voltage allows less current to be used for the same power, and that reduces losses from resistance. In Europe, virtually all appliances use 220 V (at 50 Hz). This higher voltage is more dangerous, but it does reduce resistive loss that turns power into heat.

The Edison-Tesla conflict

Here's the story of how we adopted AC power instead of DC.

In the late 1800s, Thomas A. Edison had invented the light bulb. This had such a great impact on the world, that even today cartoonists use an image of a light bulb suddenly appearing above someone's head as an indication that the person had a great idea.

The man who most disliked Edison's invention was a John D. Rockefeller, who had made a fortune selling oil. At that time, oil was used almost exclusively for heating and lighting. Electricity (which could be made by burning coal--which boiled water, which ran a turbine, which ran a generator), could conceivably make his oil virtually worthless. Fortunately for him, right about that time improvements in oil-driven engine technology (in particular, the internal combustion engine) made possible a new invention: the auto-carriage, also known as the automobile. So Rockefeller's fortune was preserved.

Edison wanted to "electrify" New York City. His vision was to put metal wires on poles above the city streets to carry current to every house. Because some energy is lost in those wires (from resistance), the energy could not be transported very far. But he saw that as creating no real problem: he would place an electric power generator in every neighborhood, so the wires would never be more than a few blocks long.

Edison had hired a very talented engineer named Nikola Tesla. But Tesla quit in a huff. Tesla claimed that Edison had patented all of Tesla's ideas in the name Edison, and had not given Tesla the monetary rewards that he had promised.

Thomas Edison

Nikola Tesla

Tesla had become enamored with the idea of "alternating current," AC for short. In AC the voltage and the current oscillated, positive and then negative and then positive again, 60 times every second. If one used AC instead of Edison's DC (for "direct current") then you could make use of a wonderful invention called the transformer. (The transformer was invented in 1860 by Antonio Pacinotti. Recall that transformers used to generate extremely high voltages are often called "Tesla coils".) A transformer used the fact that a wire with current in it creates a magnetic field. If the current varies, then the magnetic field varies. A changing magnetic field will create a current in a second wire. The amazing part of all this is that the voltage in the second wire could be very different from the voltage in the first wire. What the transformer transforms is the voltage.

Start with low voltage AC, put it through a transformer, and what comes out is high voltage AC. The advantage of high voltage AC is that it carries power with very little electric current. That means that there is very little power loss in the wires, so the power can be sent for long distances using long wires. There would be no need to have electric generating plants in every neighborhood. When the electricity got close to a home, it could be transformed again, to convert the electricity to low voltage, which is less dangerous to use. A small transformer could be placed on the top of the pole that supported the wires. (Most neighborhoods today have just these transformers on the pole tops. When they burn out or otherwise fail, the neighborhood is left without electricity, and the transformer must be replaced or repaired. The local electric company, such as PG&E, usually does this within a few hours.)

AC turned out to have such an advantage (no neighborhood power plants) that it completely won out over Edison's DC. Tesla got the support of George Westinghouse, and their system turned into the one we use today. The voltage in our homes is only 110 volts AC. (Actually 110 is an average voltage; the voltage varies between about -170 volts and +170 volts.) The voltage changes from positive to negative and then back to positive 60 times per second, i.e. 60 Hertz, abbreviated 60 Hz. In Europe, they use the slower frequency of 50 Hz, which is why their lights and their televisions flicker. (Our eyes don't notice flickering if it is faster than about 55 Hz. I think the Europeans made a dumb mistake, all for the purpose of trying to be a little more metric than the US. For a while, they also tried 50 seconds to the minute, and 50 minutes to the hour, but they gave up--people couldn't get used to it. But the 50 cycles per second remained.) Our peripheral vision is significantly faster than our central (foveal) vision, so some people see flicker, even for 60 Hz, out of the corner of their eye. That can really annoy you if you are in a house with old flickering fluorescent lights.

Electrocuting elephants and murderers

But Edison did not give up without a fight. He tried to convince the public that high voltage was too dangerous to use in cities. He did this with a series of demonstrations of the danger, in which he invited the public to watch as he used the Westinghouse/Tesla high voltage system to electrocute puppies and other small animals. Eventually he put on a demonstration using high voltage to kill a horse. Edison had also invented a motion picture camera, and so he was able to make a movie of the electrocution of an elephant. I find the movie horrifying. The name of the elephant executed was Topsy and she was a "bad" elephant who had been condemned to die for having killed three men (including one who fed her a lit cigarette). Apparently the Society for Prevention of Cruelty to Animals approved of the execution, since they thought it would be inhumane to hang Topsy. See the Topsy page:

www.lhup.edu/~dsimanek/scenario/analogy.htm

for the details. In an unrelated quote, Edison said, "Non-violence leads to the highest ethics, which is the goal of all evolution. Until we stop harming all other living beings, we are still savages." I found a copy of the movie, but I don't recommend that you view it. If you can't resist, it is at available http://muller.lbl.gov/movies/Topsy.html. The Topsy story was part of the inspiration that led to the Walt Disney movie *Dumbo*.

The ultimate horror, of course, was to show that high voltage electricity could kill humans. To do this, Edison convinced the State of New York to switch from hanging its condemned inmates, to electrocuting them. He also argued that this method of execution was more humane -- a conclusion that most modern observers think is exactly backwards. But New York adopted the method, and then so did several other states. Despite the publicity created by all these things, the advantages of AC won the day, and that is what we use now.

Chapter Review

Electricity is the flow of electrons, or other similar particles that carry "electric charge." By convention, the electric charge on the electron is -1.6×10^{-19} Coulombs. The proton has an equal and opposite charge. This is a basic quantum of charge; all observed charges are multiples of this, with the exception of the quark (hidden inside the nucleus) which has 1/3 or 2/3 of this value. Atoms usually have zero net charge, since the electrons and protons balance. (If they don't, the object is called an "ion".) The flowing of charges (usually electrons) is called electric current, and is measured in amperes. One ampere is a Coulomb of charge every second. Current usually flows in loops, otherwise charge builds up and the resulting force slows the flow.

Current can flow in gases, in vacuum, and in metal. When electrons do this, they usually lose some energy, and that is called electric resistance. The power lost is determined by the current flow. Insulators are materials that are poor conductors (high resistance). Superconductors, which require very low temperatures, have resistance = 0. "High temperature superconductors" require temperatures of 150K, equal to −189 F.

Voltage measures the energy of the electrons. Power is voltage x current. High voltage is not particularly dangerous unless the current is large enough to give high power.

Batteries are rated by amp hours. That is actually the total charge they can deliver. Multiply the amp hours by voltage and you get the total energy available in watt hours.

In our homes we use AC (rather than DC) because the voltage can be changed easily using transformers. High voltage (low current) is used to bring the electricity to our homes, but the voltage is lowered to make it safer before it comes in.

The equations for electric force look similar to those of gravity. There are two laws, one for charge and one for current. The force drops with the square of the distance, so things 10x further away have 100x less force. But there are differences. Two charges with the same sign repel, and with opposite signs attract. For electrons, the electric force is much greater than gravity. When the force is between currents, we call it magnetism. Permanent magnets arise when the flow of electric charge within a large number of atoms is all in the same direction. Permanent magnets are used in magnetic compasses. No magnetic monopoles have ever been found, but the search continues. Electromagnets are made by making currents flow, typically in loops. They are used in automobile door locks, speakers, and earphones. When done in a rotary design, it is called an electric motor. Strong permanent magnets like samarium cobalt have made small earphones and motors possible. Iron, when placed in a magnetic field, strengthens the field, unless the iron is warmer than its Curie temperature. Some materials remain magnetized after being exposed to magnetic fields, and these are used for magnetic recording.

When a wire passes through a magnetic field, currents flow in the wire, and this is used for electric generators. If the current is used to make the magnetic field stronger, the generator is called a dynamo. Dynamos are used for the generation of commercial electric power. The core of the Earth has a natural dynamo, and that makes the Earth into a magnet. The magnetism of the Earth flips, on average, several times every million years. That discovery is very useful in geology for determining the age of rocks.

Transformers change voltage and current, while wasting very little power. A Tesla coil is a transformer that produces very high voltages.

Magnetic levitation uses repelling magnetic fields. These fields are sometimes generated by moving metal or by AC current. Rail guns can accelerate metal to high velocities more efficiently (with less wasted energy) than can rockets.

Discussion and Internet Research Questions

1. Read the following passage, taken from *Popular Science* in 1892, and see what sense you can make of it, given the modern understanding of electricity.

> We know little as yet concerning the mighty agency of electricity. Substantialists tell us it is a kind of matter. Others view it not as matter, but as a form of energy. Others, again, reject both these views. One professor considers it "a form, or rather a mode of manifestation, of ether." Another professor demurs to the view of his colleague, but thinks that "nothing stands in the way of our calling electricity ether associated with matter, or bound ether." Higher authorities cannot even yet agree whether we have one electricity or two opposite electricities. The only way to tackle the difficulty is to persevere in experiment and observation. If we never learn what electricity is, if, like life or like matter, it should remain an unknown quantity, we shall assuredly discover more about its attributes and its functions.
>
> The light which the study of electricity throws on a variety of chemical phenomenon cannot be overlooked. The old electrochemical theory of Berzelius is superseded by a new and wider theory. The facts of electrolysis are by no means either completely detected or coordinated. They point to the great probability that electricity is atomic, that an electrical atom is as definite a quantity as a chemical atom. The electrical attraction between two chemical atoms being a trillion times greater than gravitational attraction is probably the force with which chemistry is most deeply concerned.
>
> --*Popular Science*, February 1892
> (Quoted in the Feb 1992 edition)

2. Where is magnetic levitation being used around the world? What other places are considering adopting it? Can you find web pages that say it is not as good an idea as others think? What kind of magnets do they use?

3. Some people regard Tesla as one of the greatest geniuses of all time. In his later years, he claimed to have invented ways of transmitting electric power without wires. See what you can find out about this. Why don't we use these ideas today?

4. How long are the longest power transmission lines? Are people considering making them even longer? Why? Why not just put the source of power near where it is most needed, for example, near cities?