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A HANDBOOK FOR WIRELESS/RF, EMC, AND
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A HANDBOOK FOR WIRELESS/RF, EMC, AND
HIGH-SPEED ELECTRONICS

Ron Schmitt



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2 FUNDAMENTALS OF ELECTRIC FIELDS

THE ELECTRIC FORCE FIELD

To understand high-frequency and RF electronics, you must first have a good grasp of the fundamentals of electromagnetic fields. This chapter discusses the electric field and is the starting place for understanding electromagnetics. Electric fields are created by charges; that is, charges are the source of electric fields. Charges come in two types, positive (+) and negative (-). Like charges repel each other and opposites attract. In other words, charges produce a force that either pushes or pulls other charges away. Neutral objects are not affected. The force between two charges is proportional to the product of the two charges, and is called Coulomb's law. Notice that the charges produce a force on each other without actually being in physical contact. It is a force that acts at a distance. To represent this "force at distance" that is created by charges, the concept of a *force field* is used. Figure 2.1 shows the electrical force fields that surround positive and negative charges.

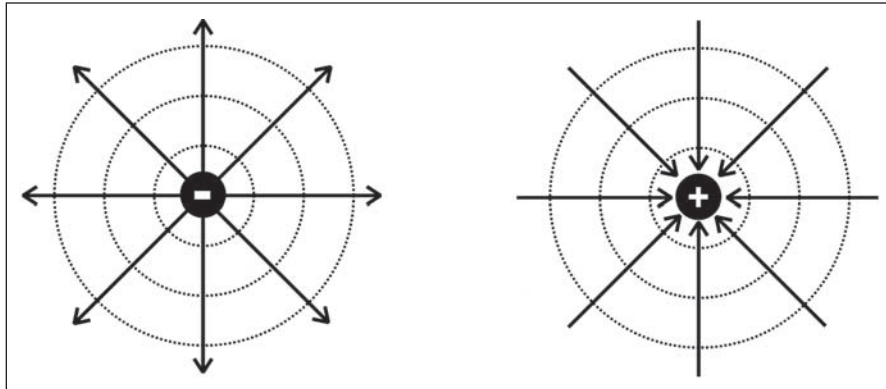
By convention, the electric field is always drawn from positive to negative. It follows that the force lines emanate from a positive charge and converge to a negative charge. Furthermore, the electric field is a normalized force, a force per charge. The normalization allows the field values to be specified independent of a second charge. In other words, the value of an electric field at any point in space specifies the force that would be felt if a unit of charge were to be placed there. (A unit charge has a value of 1 in the chosen system of units.)

Electric field = Force field as "felt" by a unit charge

To calculate the force felt by a charge with value, q , we just multiply the electric field by the charge,

$$\vec{F} = q \cdot \vec{E}$$

Figure 2.1 Field lines surrounding a negative and a positive charge. Dotted lines show lines of equal voltage.



The magnitude of the electric field decreases as you move away from a charge, and increases as you get closer. To be specific, the magnitude of the electric field (and magnitude of the force) is proportional to the inverse of the distance squared. The electric field drops off rather quickly as the distance is increased. Mathematically this relation is expressed as

$$E = \frac{q}{r^2}$$

where r is the distance from the source and q is the value of the source charge. Putting our two equations together gives us Coulomb's law,

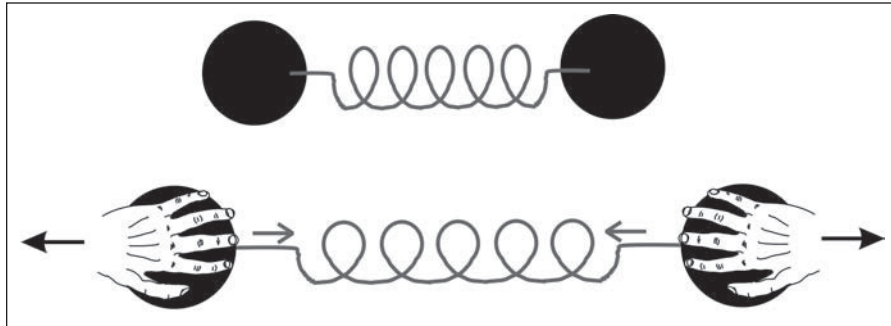
$$F = \frac{q_1 \cdot q_2}{r^2}$$

where q_1 and q_2 are the charge values and r is the distance that separates them. Electric fields are only one example of fields.

OTHER TYPES OF FIELDS

Gravity is another field. The gravitational force is proportional to the product of the masses of the two objects involved and is always attractive. (There is no such thing as negative mass.) The gravitational field is much weaker than the electric field, so the gravitational force is only felt when the mass of one or both of the objects is very large. Therefore,

Figure 2.2 Two balls attached by a spring. The spring exerts an attractive force when the balls are pulled apart.



our attraction to the earth is big, while our attraction to other objects like furniture is exceedingly small.

Another example of a field is the stress field that occurs when elastic objects are stretched or compressed. For an example, refer to Figure 2.2. Two balls are connected by a spring. When the spring is stretched, it will exert an attractive force on the balls and try to pull them together. When the spring is compressed, it will exert a repulsive force on the balls and try to push them apart. Now imagine that you stretch the spring and then quickly release the two balls. An oscillating motion occurs. The balls move close together, then far apart and continue back and forth. The motion does not continue forever though, because of friction. Through each cycle of oscillation, the balls lose some energy until they eventually stop moving completely. The causes of friction are the air surrounding the balls and the internal friction of the spring. The energy lost to friction becomes heat in the air and spring. Before Einstein and his theory of relativity, most scientists thought that the electric field operated in a similar manner. During the 1800s, scientists postulated that there was a substance, called *aether*, which filled all of space. This aether served the purpose of the spring in the previous example. Electric fields were thought to be stresses in the aether. This theory seemed reasonable because it predicted the propagation of electromagnetic waves. The waves were just stress waves in the aether, similar to mechanical waves in springs. But Einstein showed that there was no aether. Empty space is just that—empty.* Without any aether,

*This statement is not really true in quantum physics, which states that even the vacuum contains fluctuations of virtual particles. Refer to Chapter 6 for more information.

there is no way to measure absolute velocity. All movement is therefore relative.

VOLTAGE AND POTENTIAL ENERGY

A quantity that goes hand in hand with the electric field is *voltage*. Voltage is also called potential, which is an accurate description since voltage quantifies potential energy. Voltage, like the electric field, is normalized per unit charge.

$$\text{Voltage} = \text{Potential energy of a unit charge}$$

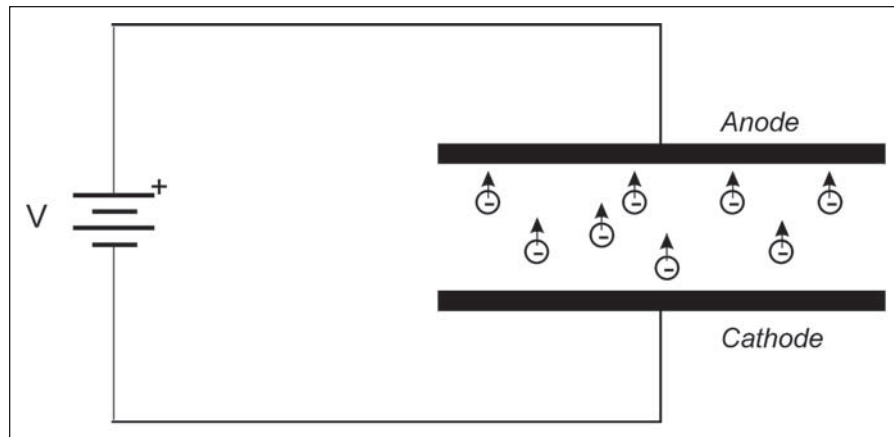
In other words, multiplying voltage by charge gives the potential energy of that charge, just as multiplying the electric field by charge gives the force felt by the charge. Mathematically we represent this by

$$U = q \cdot V$$

Potential energy is always a relative term; therefore voltage is always relative. Gravity provides a great visual analogy for potential. Let's define ground level as zero potential. A ball on the ground has zero potential, but a ball 6 feet in the air has a positive potential energy. If the ball were to be dropped from 6 feet, all of its potential energy will have been converted to kinetic energy (i.e., motion) just before it reaches the ground. Gravity provides a good analogy, but the electric field is more complicated because there are both positive and negative charges, whereas gravity has only positive mass. Furthermore, some particles and objects are electrically neutral, whereas all objects are affected by gravity. For instance, an unconnected wire is electrically neutral, therefore, it will not be subject to movement when placed in an electrical potential. (However, there are the secondary effects of electrostatic induction, which are described later in the chapter.)

Consider another example, a vacuum tube diode, as shown in Figure 2.3. Two metal plates are placed in an evacuated glass tube, and a potential (10V) is placed across them. The negative electrode is heated. The extra electrons in the negative electrode that constitute the negative charge are attracted to the positive charge in the positive electrode. The force of the electric field pulls electrons from the negative electrode to the positive electrode. (The heating of the electrode serves to "boil off" electrons into the immediate vicinity of the metal.) Once free, the elec-

Figure 2.3 A vacuum tube diode, showing electrons leaving the negatively biased cathode to combine with positive charge at the anode.



trons accelerate and then collide with the positive electrode where they are absorbed. Just before each electron collides, it is traveling very fast because of the energy gained from the electric field. Its kinetic energy can be easily calculated, in terms of electron-Volts (eV) and in terms of Joules (J):

$$\begin{aligned} U &= q \cdot V = e \cdot (10 \text{ volts}) = 10 \text{ eV} \\ &= 10 \cdot (1.6 \times 10^{-19} \text{ C}) \cdot V = 1.6 \times 10^{-18} \text{ J} \end{aligned}$$

From this example, you can see how natural the unit of electron-Volts (eV) is for describing the energy of an electron.

The most important thing for you to remember is that voltage is a relative term. On a 9 volt battery, the (+) contact has a voltage of 9 volts relative to the (–) contact. Furthermore, the battery has a net charge of zero, although the charge is separated into negative and positive regions. The charge on the positive side is drawn to the charge on the negative side. Connecting a wire between the terminals allows the charges to recombine. The same result is true for a charged capacitor. What would happen if you brought a neutral unconnected wire close to one of the battery's terminals? Nothing, the wire is neutral. It has no net charge. We'll revisit the details of this situation a little later in the chapter.

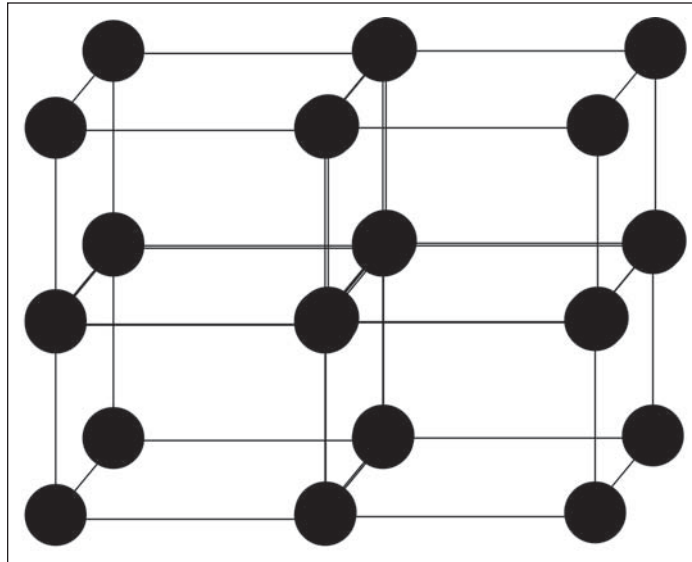
CHARGES IN METALS

In electronics you will only encounter two types of charged particles, electrons and ions. To understand each, let's review the basic building blocks of matter. Matter consists of tiny particles called atoms. In each atom is a core or nucleus that contains protons and neutrons. The nucleus is very compact. Surrounding the nucleus are electrons. For a neutral atom, there are equal numbers of electrons and protons. The protons possess positive charge, and the electrons possess an equal but opposite charge. The neutrons in the nucleus are neutral. The electrons orbit the nucleus in a special way. You might imagine the electron as a small ball orbiting the nucleus in the same way that planets orbit the sun. However, this analogy is not quite correct. Each electron is smeared out in a three-dimensional cloud called an *orbital*. Atoms can lend out or borrow electrons, which leaves the atom with a net charge. Such atoms are called *ions* and they can be positively charged (missing electrons) or negatively charged (extra electrons). Ions of opposite charge can attract one another and form ionic bonds. These bonded ions are called *molecules*. Table salt, NaCl, is a good example of molecules. Each salt molecule consists of a positive ion (Na^+) and a negative ion (Cl^-). There also exist other types of molecular bonds. For instance, covalent bonds are established when two atoms share an electron.

Metal materials have special properties that make them good conductors of electricity. First of all, metals are crystals; that is, metals have an orderly construction of atoms. Most people who have not studied solid-state or semiconductor physics find it very surprising that metals are crystals, because we tend to associate crystals with transparent materials like quartz. As with all crystals, the structure of a metal is a three-dimensional lattice like that shown in Figure 2.4. Metals have a rather interesting bonding structure. The positive ions of the metal are held together by a sea of electrons that is shared by the entire crystal. Each atom of the metal typically contributes one or two electrons to this sea. You can picture a metal as closely packed balls (the ions) in a gas of small particles (the electrons). Because the "sea" electrons are free to roam throughout the metal, they serve to conduct electricity quite well. It then makes sense to call them conduction electrons to differentiate them from the electrons that are bound to the ions.

At the microscopic level, a metal has a lot going on, even without any applied electric field. Thermal vibrations cause the lattice of ions to vibrate and cause the conduction electrons to move around. With higher temperatures, the vibrations in the metal get larger. This effect stems

Figure 2.4 Example of atoms arranged in a crystal lattice structure (simple cubic).



from the microscopic relationship of temperature. Temperature is proportional to the average kinetic energy of the particles,

$$T = \frac{m}{3k} v_{rms}^2$$

where k is Boltzman's constant, m is the atomic mass, and v_{rms}^2 is the root-mean-square particle velocity. (This formula applies directly to ideal gases, but it gives a decent approximation for the temperature of metals.) These thermal vibrations result in the random agitation of electrons and are sources of thermal noise in electronics. Every wire and resistor in a circuit injects white noise (i.e., with the same power level at all frequencies) from its internal thermal vibrations. Now if we place a voltage across a metal wire (or resistor), an electric field is developed through the wire. The electric field causes the conduction electrons to move more toward the positive (+) end of the wire. In other words, a current is produced. This current is a direct current (DC) so it has a constant value.

Current is defined as the amount of charge through a cross section of wire, per second. This definition implies that the charges are moving

at a steady, constant value. However, this assumption is incorrect. Only the statistical average of the charge movement is a constant value. Each individual charge's movement is very random. The electrons are constantly colliding with the vibrating lattice ions and the other electrons. On average an electron in copper at room temperature only spends about 25 fsec between collisions (1 fsec equals 1/1,000,000,000,000,000 sec.). The electrons have a very large velocity between collisions, about 100,000 m/sec. However most (99.999999%) of the velocity is in a random direction. Statistically, the random components of the velocity cancel each other out, leaving a much smaller average velocity. Therefore, while the root-mean-square (RMS) velocity is very high, the average velocity is much lower. The average velocity of the electrons, which is in the direction of the applied field, is very small. This average velocity is called the drift velocity, and it accounts for the observed current. For a 1 meter long copper wire with 1/10 volt across it, the drift velocity is about 0.5 mm/sec or 5 feet per hour! It will therefore take an electron about 38 minutes to travel from one side of the wire to the other. Assuming this copper wire is 20 gauge wire, its resistance is 33 mΩ, and the current from 0.1 volts is 3 amps. Even though the electrons travel very slowly, their effect adds up to large currents because there are so many of them. In a 1 meter long 20 gauge copper wire, there are about 4.4×10^{22} conduction electrons. Now that is strength in numbers!

THE DEFINITION OF RESISTANCE

Besides the flow of DC current, something else happens when you apply a voltage across a conductor: it heats up. The temperature of the conductor rises because DC flow causes the electrons to have higher-energy collisions (on average) than they would if the voltage were not present. Since it requires energy to heat something up, energy must be provided by the voltage supply. The energy per second lost to heat is exactly equal to the power calculated from the power law of electric circuits:

$$I^2 \cdot R = \frac{V^2}{R}$$

In a rather roundabout way, we have arrived at the definition of *resistance*. Resistance quantifies the power that is lost to heating when a voltage or current is applied to the conductor.

ELECTRONS AND HOLES

Imagine that you have a solid metal ball or sphere and you place a charge on it. For a negative charge, this process equates to adding an excess of electrons to the sphere. For a positive charge, this equates to removing some electrons, leaving an excess of positive ions or *holes*, as they are called in semiconductor parlance. Holes can be thought of as virtual positive particles, which can move around in a material like a bubble moving in water. Whereas negative charges (electrons) move freely about the material, holes must move by means of charge theft. Let's say there is an atom that is missing one electron. This atom is therefore a positive ion (+), or equivalently, this atom is carrying a hole. This ion can "steal" a bound electron from a neighbor. (Remember that not all atoms are ionized at all times.) By stealing an electron from its neighbor, it has in effect given the hole to the neighbor. This way holes can move through the material, and can be thought of as positive particles in their own right.

In semiconductors like silicon, the holes and electrons can move with approximately equal ease. In other words, the hole and electron mobilities are approximately equal in silicon. In most metals, however, the electrons are very mobile, and the holes have negligible mobility. The holes are virtually stationary and only the negatively charged electrons can move. Negative charge in metals is created when electrons move away from a region, leaving positively charged holes behind. Positive charge in metals should be thought of as a lack of free electrons. Most often, when we are not so formal, we do talk about positive charges moving about in a metal; just keep in mind that in most metals, it is always the negatively charged electrons that do the moving.

Back to the problem of the metal ball. When charge is placed onto the ball, the individual charges will immediately spread apart as far as possible because like charges repel each other. The upshot is that all the charge becomes concentrated at the surface. It's like a bunch of people in a large room. If each person tries to avoid the rest, they will migrate to the walls of the room, like a "wallflower" at a high school dance. How quickly charges distribute themselves to the surface is proportional to the *relaxation time* of the material. In the present context, the relaxation time can be approximated as the dielectric constant (discussed later in the chapter) of the material divided by the conductivity of the material. The relaxation time specifies how freely charge can move in a material. For copper, the relaxation constant is

$$\tau = \frac{\epsilon}{\sigma} = \frac{8.85 \times 10^{-12} \frac{F}{m}}{5.8 \times 10^7 \frac{1}{\Omega \cdot m}} = 1.5 \times 10^{-19} \text{ sec}$$

Therefore, charge placed on a copper object will very quickly redistribute so that it all resides on the surface. The charge half-life of a material is about 0.7 times the relaxation time. An example will help illustrate this concept. If charge is somehow placed at the center of a metal ball, the charge will immediately start to migrate toward the surface. After a half-life in time (0.7τ), half of the charge will have migrated away from the center.

ELECTROSTATIC INDUCTION AND CAPACITANCE

To understand capacitance, you need to first understand the process of *electrostatic induction*. For example, consider that you have a metal ball that is positively charged, near which you bring a neutral metal ball. Even though the second ball has overall neutrality, it still contains many charges. Neutrality arises because the positive and negative charges exist in equal quantities. When placed next to the first ball, the second ball is affected by the electric field of the charged ball. The charges of the second ball separate. Negative charges are attracted, and positive charges are repelled, leaving the second ball polarized, as shown in Figure 2.5. This polarization of charge is called electrostatic induction.

A direct consequence of electrostatic induction is that the electric field inside an unconnected conductor is always zero at steady state. When a conductor is first placed in a field, the field permeates the conductor. The charges then separate as described in the preceding paragraph. The separation of charge tends to neutralize the electric field. Charge movement continues until the electric field reaches zero. Another way of stating this is that the voltage inside a conductor is constant at steady state. Placed in an ambient electric field, the conductor quickly adjusts its charge configuration until it has reached the voltage potential of its environment.

Now let's connect a metal object to the second ball using a wire. As shown in Figure 2.6, the charge polarizes even further, with the negative charge of the neutral objects moving as far away as possible. Figure 2.7 takes this one step further by connecting the earth to the second ball. (An earth connection can be achieved by connecting the ball to the third prong of a wall outlet, which typically is "earthed" on the

Figure 2.5 A) A negatively charged metal sphere. B) A neutral sphere (right) is brought close to the negative sphere (left).

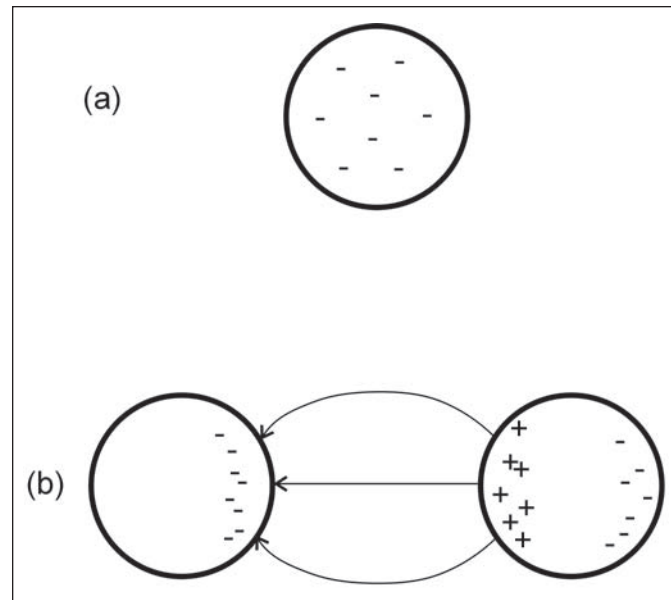
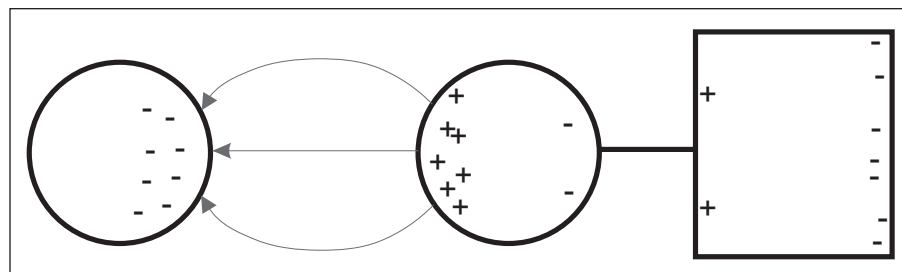


Figure 2.6 A second neutral object is connected by a wire.



outside of each building using 8 foot or longer copper stakes.) Here the negative charge will move down the wire, into the earth, and go very far away.

Instead of placing a constant charge on the first metal ball, you could connect an oscillating charge, as in Figure 2.8. For example, assume that the AC voltage is at a frequency of 60Hz; the polarization induced

Figure 2.7 The neutral sphere is connected to ground with a wire.

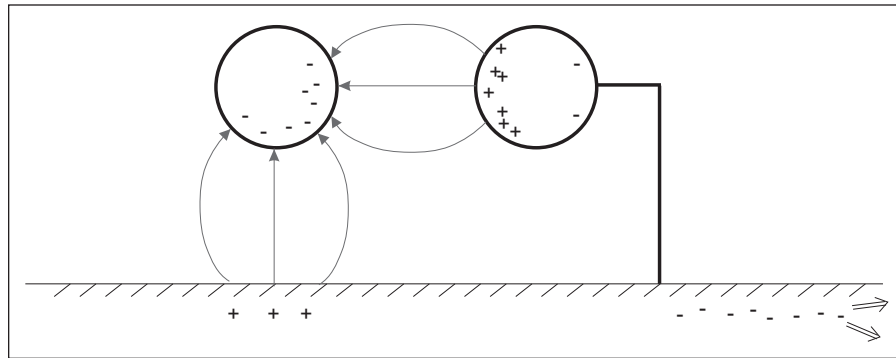
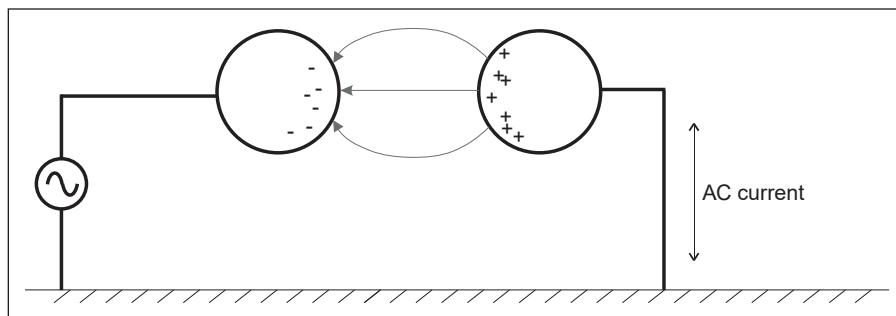
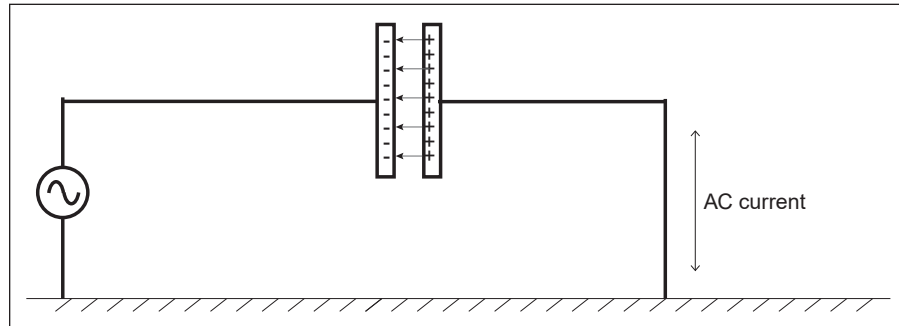
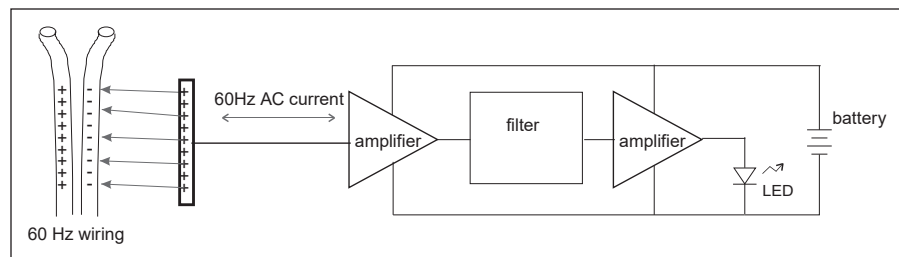


Figure 2.8 An AC source is connected to the first sphere.



in the second ball will alternate at a frequency of 60Hz. The alternating polarization will also cause current to flow in the wire that connects the second ball to the ground. What you have created is simply a *capacitor*! Any metal conductors that are separated by an insulator form a capacitor. In Figure 2.9, the two balls have been replaced with metal plates, forming a more familiar and efficient capacitor. Notice that no current actually traverses the gap between the plates, but equal current flows on both sides, as charge rushes to and from the plates of the capacitor. The virtual current that passes between the plates is called *displacement current*. It is really just a changing electric field, but we call it a current.

You can get a good feel for electrostatic induction by learning how some simple, but ingenious, inventions work. If you have ever worked

Figure 2.9 Spheres are replaced by metal plates.**Figure 2.10 Block diagram for a non-contact field detector.**

on the electric *mains* wiring that runs in the walls of your house and provides the 120V power to your electric outlets and lamps, you have probably purchased what is called a *non-contact field detector*. (Incidentally, the term “mains” refers to the fact that your power is provided by your electric utility company. The same term is also used for the water that enters your house from the water utility.) A non-contact field detector is a device that is about the size and shape of a magic marker. It allows you to determine if a wire is live (is connected to voltage) or not without actually making metallic contact. This nifty invention can be waved near insulated wires, or it can be inserted into an electric outlet. It detects live wires and live outlets using the phenomenon of electrostatic induction that you just learned about. A simple schematic of such a device is shown in Figure 2.10. A metal lead or plate is attached to the input of a high-impedance amplifier. This plate serves one side of a capacitor. When the plate is brought close to an object that has an electric field, charge is induced on the plate. Some of the charge has to pass through the amplifier. Because the amplifier has high input impedance,

a reasonable voltage will be created at its output. If the object being tested has a varying electric field, like a wall outlet, an AC current will be induced in the device. The rest of the circuitry serves to light an LED when the induced current varies continuously at around 60Hz.

A variation of this circuit uses a human as the capacitive plate of the device. Glow tube meters and zero-pressure “touch” buttons work in this manner. A glow tube meter is a device for testing electrical outlets. It looks like a screwdriver, except the handle is made of clear plastic and contains a small glow tube inside. The glow tube is a glass tube filled with neon gas and contains two separated electrodes. One electrode is connected to the screwdriver blade and makes contact inside the electric outlet. The other electrode is connected to a piece of metal at the end of the screwdriver handle. By touching your finger to the handle end, you become part of a circuit. Being a decent conductor, your body serves the function of being one half of a capacitor. A small amount of the 60Hz displacement current ($\sim 10\mu\text{A}$) is able to capacitively couple from your body to the ground wires in the wall. This small current causes a voltage drop across you and across the glow tube. The gas inside the glow tube ionizes and conducts electricity. In the process, it gives off a faint orange glow, telling you that the outlet is working. You certainly should use care with such a device, and be sure not to touch the screwdriver shaft directly.

Touch buttons are found in some elevators. These buttons are metal, and if you encounter one, you will notice that the button does not physically depress when you touch it. This button is connected to a high-impedance amplifier. When you touch the button, you again form a capacitor plate. In this application, your body couples 60Hz energy from the wires in the elevator and the fluorescent lights on the ceiling to the metal touch pad. A high-impedance amplifier amplifies the current and determines that you have, for instance, touched the button for the third floor.

It may be tempting to think of these applications as antennas picking up 60Hz radiation, but this idea is incorrect. Being electrically small wires, virtually no energy is radiated. In addition, you are standing well within the near field of the source. These topics are discussed in detail in Chapter 5.

INSULATORS (DIELECTRICS)

To make an electronic circuit work, you not only need conductors, you also need insulators. Otherwise, every part of the circuit would be

shorted together! A perfect insulator is a material that has no free charge. Therefore, if a voltage is placed across an insulator, no current will flow. Even though no current flows, that does not mean that the dielectric does not react to electric fields. Most insulators, also known as dielectrics, become internally polarized when placed in an electric field. The internal polarization occurs from rotation of molecules (in liquids and gases) or from distortion of the electron cloud around the atoms (in solids).

A simple example is the polarization of H₂O molecules in liquid water. An H₂O molecule is shown in Figure 2.11. Due to the structure of the molecule, the charge is not exactly symmetric. Without an external electric field applied, the molecules have random orientations (polarizations) due to thermal motion. When a field is applied, the molecules tend to line up so that their negative sides are facing the positive voltage. The molecules therefore set up a secondary electric field that opposes the direction of the applied field. The result is that inside the dielectric material, the net electric field is reduced in value. The ratio of the applied field to the reduced field is called the (relative) dielectric constant, ϵ_r . This value is relative to the permittivity of a vacuum, $\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$. The dielectric constant of a material has a direct effect on capacitance. For example, a capacitor made from two parallel plates has a capacitance,

$$C = \frac{\epsilon_r \epsilon_0 A}{d}$$

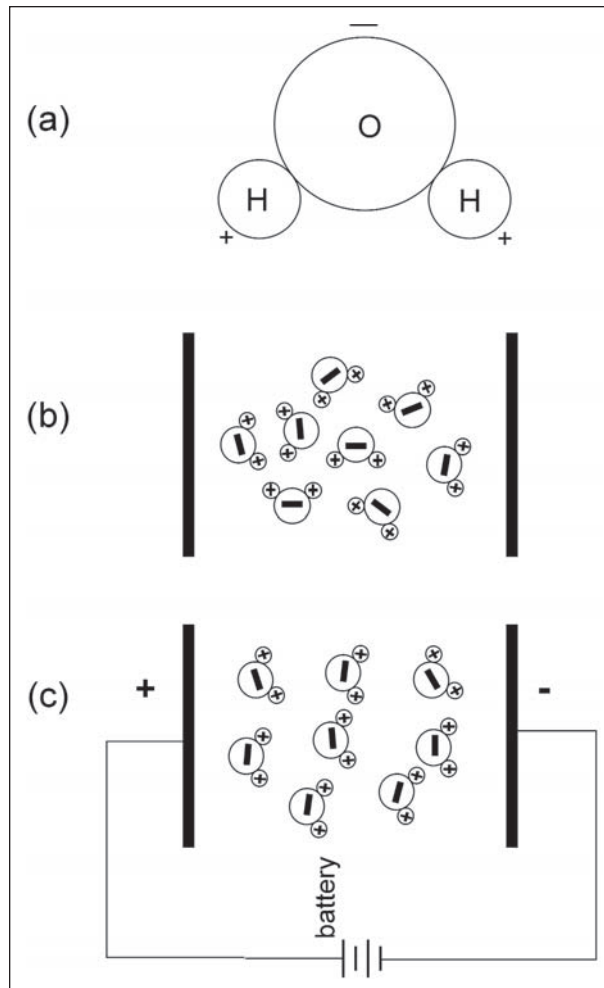
where A is the area of each plate, d is the distance between the plates, and ϵ_r is the dielectric constant of the material sandwiched between the plates. As you can see from this formula, increasing the dielectric constant causes an increase in capacitance. Therefore, if you want to make a capacitor that is physically small but has a large capacitance, use a high dielectric constant material between the plates. It follows that a higher dielectric constant corresponds to higher energy storage.

Although a perfect dielectric has no free charge, even the best insulators in the real world will have some free charge. Even air conducts electricity, albeit poorly.

STATIC ELECTRICITY AND LIGHTNING

Let's go back to the charged sphere of Figure 2.5. If the second metal ball is placed closer to the charged ball so that they actually touch, the

Figure 2.11 A) Water molecule. B) Water molecules in random orientation with no field applied. C) Water molecules line up when an electric field is applied.

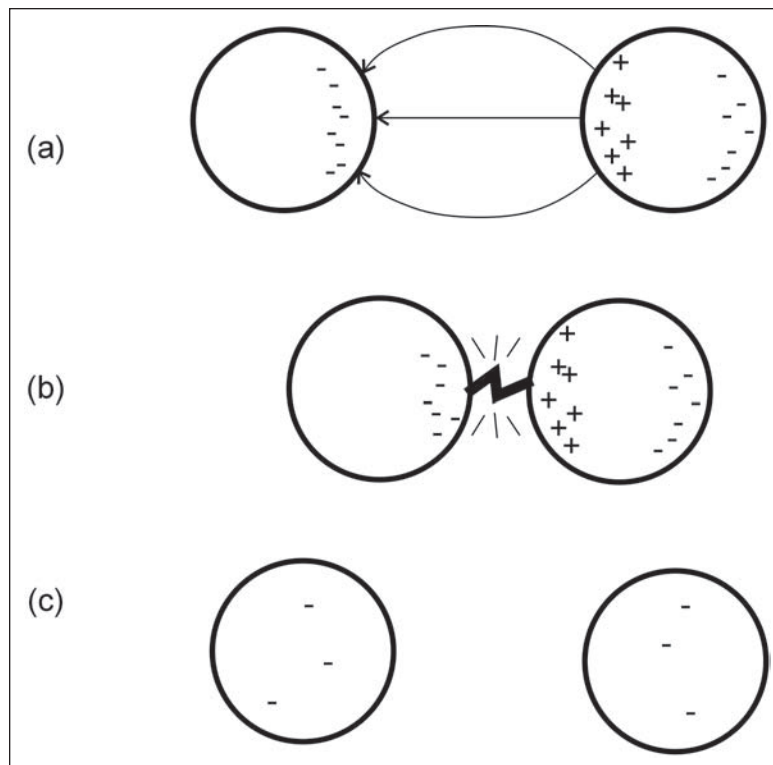


negative charge will now redistribute itself evenly over the two balls. If the balls are moved apart again, each will now have half of the original negative charge. If balls of unequal size were used, then more charge would end up on the larger ball, because it has a larger surface area. If the charge is large enough, very high voltages will be produced as the balls are brought close together. When the electric field exceeds the breakdown strength of air (typically about 5000 volts per centimeter),

a spark will occur between the two balls, allowing charge to transfer without physical contact. In this phenomenon, air molecules become ionized, forming a jagged conducting path between the two conductors. In the process, some of the original charge is lost to the air ions. What you have just learned is the process of *static discharge* (illustrated in Figure 2.12). The same effect occurs when you walk across the carpet and then get shocked by a doorknob. Your body becomes charged while walking across the carpet. Called the *triboelectric* effect, it consists of charge separation when certain materials are placed and/or rubbed together and then pulled apart. The outcome is that your body takes up a charge and the carpet stores an equal but opposite charge. Typical static discharges you encounter will be in the range of 5kV to 15kV and will produce a peak current of about 1 amp! Quite a large jolt.

You may wonder why such high voltage and current hurts but is not dangerous. There are several reasons for this. First of all, the entire discharge only lasts about 1 μ sec. For this same reason, shocks from spark plugs *usually* cause no harm. Second, the current is mostly concentrated near the discharge (i.e., your finger) and then quickly spreads and dissipates. Negligible current will traverse your heart, which is the danger zone for current in the human body. Typically, a person can sense currents of 1mA or more, with currents over 40mA being possibly lethal as they pass through the heart. Therefore, it is how much current flows through the body and where it flows that is of concern. When a person becomes part of a circuit, there are four parameters that determine the current: 1) source voltage, 2) source resistance, 3) contact resistance, and 4) internal body resistance for the current path. The second two parameters are a function of body physiology. The contact resistance is mainly caused by the dead skin layer where contact is made. Contact resistance is typically on the order of 100ohms for sweaty skin to 100 kohms for very dry skin. Beware that if the skin is cut, the contact resistance becomes negligible. The internal body resistance is fairly low due to the fact that nerves and blood vessels make good conductors. Any limb-to-limb internal resistance can be approximated as about 500ohms. The effects of electricity are felt differently, depending on frequency. The most dangerous frequency range is from about 5Hz to about 500Hz and peaks in danger right about 60Hz, the frequency of power lines. The frequency sensitivity has to do with the physiology of the human nervous system, which typically communicates via pulse trains in this range of frequencies. A 60Hz current has approximately two to three times the danger as the same current at DC. As opposed to DC signals, these AC signals can cause muscles to lock up, leaving a person unable to let go of the voltage source.

Figure 2.12 A) A neutral sphere (right) is brought close to the negative sphere (left). B) The spheres become very close and a path of ionized molecules forms in the air, causing a spark. C) After the spark has dissipated, some of the charge has been carried away by the ions in the air. The remaining charge is split equally between the spheres.



Lightning is static electricity on a grand scale. In the large circulating winds of a thunderstorm, raindrops and ice crystals collide, causing charge separation. The process of charge separation is not fully understood, but it is known that positive charge collects at the top of the cloud and negative charge collects at the bottom of the cloud. The negative charge at the bottom of the cloud induces an equal but opposite region of charge on the ground below. You can think of it as a localized charge shadow. When the charge builds up to a high enough voltage (typically 10MV to 100MV), the air starts to ionize in the form of a jagged “leader” which migrates from the cloud to the ground in discrete jumps of (typically) a few hundred feet. When the ionized leader gets one jump away

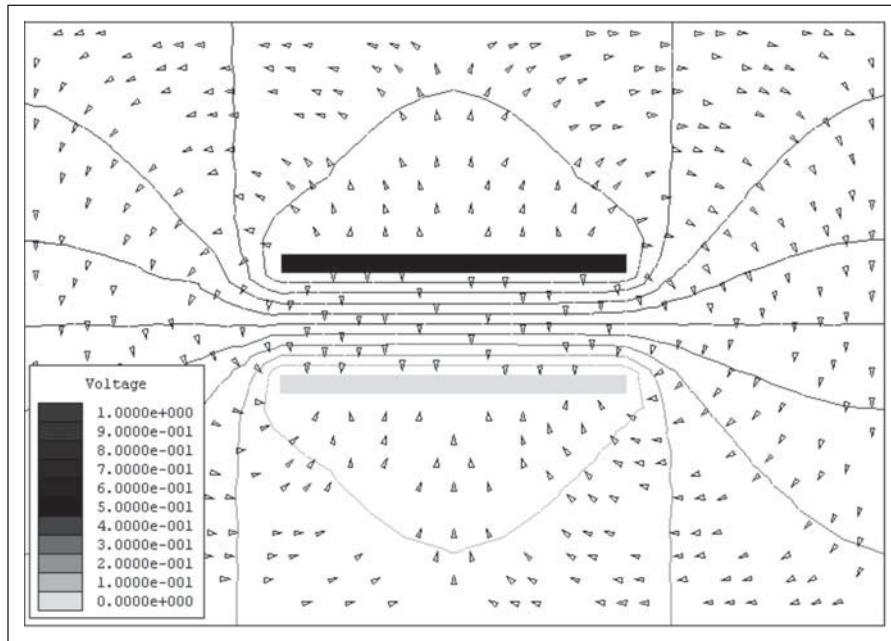
from the ground, its path is affected by the objects within the immediate vicinity, often connecting to the highest projecting object. Upon contact, a conducting path then connects the cloud with the ground, allowing the cloud to discharge. Peak currents can range from a few kAmps to 150kAmps, and the event typically lasts about several hundred microseconds. With such high currents, lightning is always dangerous to people.

So what happens to all this negative charge that accumulates on the ground? It gradually migrates back to the atmosphere through the small concentration of ions always present in air. During fair weather, the upper atmosphere has a positive charge and the earth has a negative charge, forming a giant capacitor (about 5000 Farad) that is discharging an average of 1800amps at any given time. This "fair weather current" is needed to balance out the currents from thunderstorms. We are standing in the middle of it! Consequently, the air of a typical day has a DC electric field in it of about 100 volts/meter. Even though we are in the middle of this high field, we don't experience much of a problem because, being very good conductors when compared to air, we locally short out the field. Approximating head-to-toe human body internal resistance as 700ohms and the air resistance of a 6 foot long, 3 foot by 3 foot columnar region as about 10^{14} ohms, an equivalent circuit can be constructed. We end up being a very small resistance in series with a very large resistance (the miles of air between a person and upper atmosphere). Using these assumptions, the voltage across the body is approximated as $3\mu\text{V}$.

Large electric fields can cause other interesting effects. As mentioned earlier, large electric fields can cause gases to ionize; that is, electrons are freed from the gas atoms, leaving charged ions behind. Ionized gases conduct electricity and produce visible light in the process. Electrical *corona* is the term used to describe the glowing region of ionized gas that can occur around conductors. The glow is visible radiation produced when an atom gives up or accepts an electron. Coronas are created near conductors that have high electric fields emanating from them. High-voltage power lines must be placed far enough apart to avoid creating coronas since a corona consumes energy. Fluorescent light bulbs work via the same phenomena. A high voltage causes the gas inside the bulb to ionize. In fact, an unconnected fluorescent light bulb will glow if held in air near high-voltage wires! The large electric field causes the gas inside the bulb to ionize, which in turn causes the visible light.*

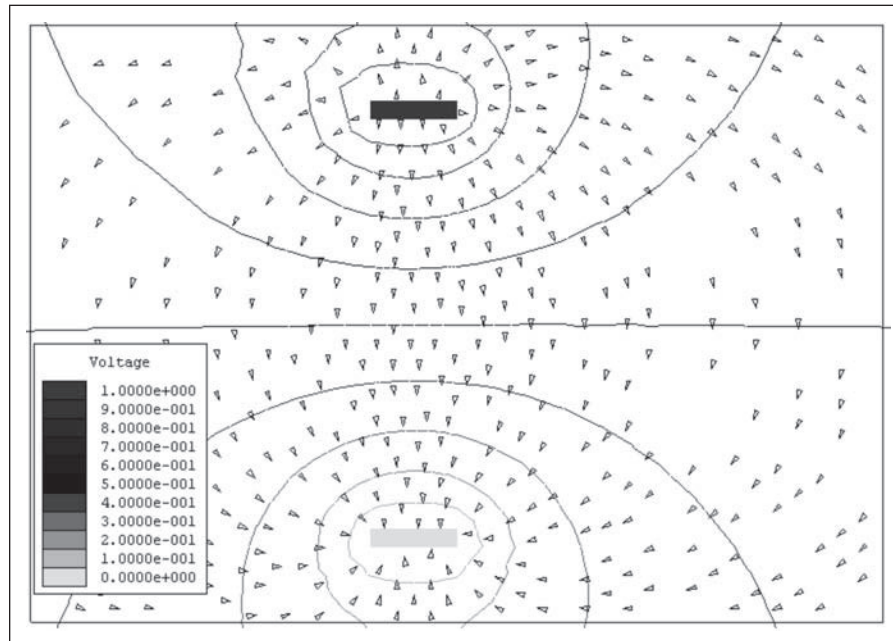
*To be exact, the gas emits UV radiation, which is absorbed and then reradiated by the fluorescent powder on the inside surface of the bulb. The reradiated light is in the visible region of the spectrum.

Figure 2.13 Electric field surrounding a capacitor with DC voltage applied. This figure was created using Ansoft Corporation's Maxwell 2D field solver software (<http://www.ansoft.com>).



Pointed objects such as flagpoles and ship masts tend to concentrate electric charge and can produce a corona during a strong thunderstorm. Before this effect was understood, sailors thought that it was the sign of a ghost or spirit and called it *St. Elmo's fire*. If you see a corona during a storm, this is a bad sign, since whatever object is producing the corona is acting as a lightning rod and will attract a lightning bolt if one approaches the area. A *lightning rod* is a metal rod that is connected to earth and protects a house or structure by attracting nearby lightning strikes. The lightning rod conducts the lightning current safely into the earth, preventing it from finding alternative paths to ground (like through your roof). It is a common myth believed by many engineers and scientists that a lightning rod prevents lightning by slowly discharging the cloud immediately above. Let me emphasize that this myth has been proven false many times over by lightning researchers. In fact, it would take over 800 hours for a lightning rod to discharge the typical

Figure 2.14 Electric field surrounding another capacitor with DC voltage applied. This figure was created using Ansoft Corporation's Maxwell 2D field solver software (<http://www.ansoft.com>).



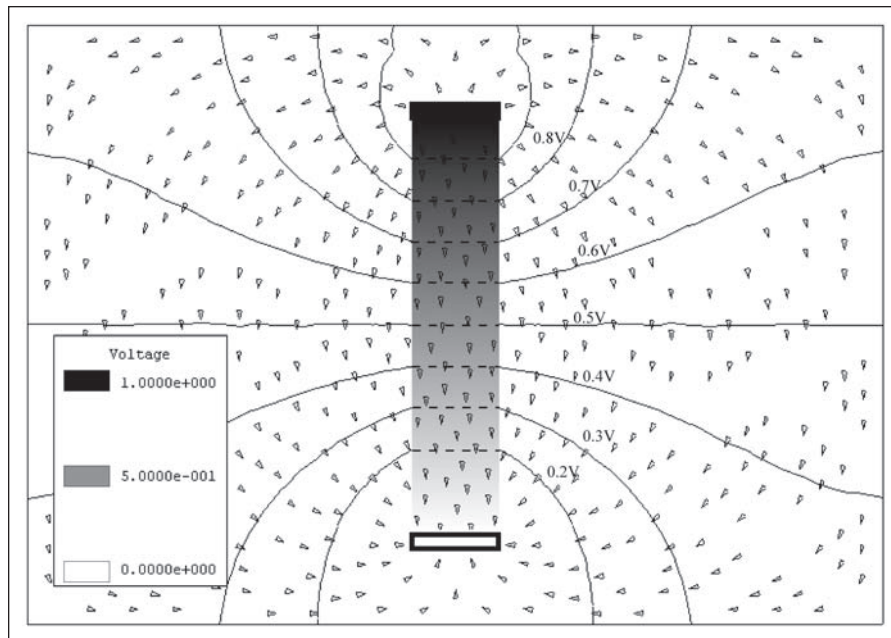
cloud, and most of the ions the lightning rod releases get dispersed by the high storm winds.

The triboelectric effect can cause other, less dramatic problems. Moving cables can cause noise via the triboelectric effect. The movement of the cable causes friction between the insulation and the metal, rubbing charge from the insulation. A similar effect can happen with outdoor cables or antennas that are blown by the wind, especially if the weather is stormy and the air is well ionized.

THE BATTERY REVISITED

Earlier in this chapter, during the introduction of voltage, I mentioned that a neutral conductor like a wire or metal plate that is brought close to a battery will not be affected by the battery. Even if the battery or

Figure 2.15 Electric field of DC voltage across a conducting wire. Arrowheads show the direction of the electric field. Voltage is shown by shade inside the conductor and as contours outside the conductor. This figure was created using Ansoft Corporation's Maxwell 2D field solver software (<http://www.ansoft.com>).



capacitor has a very high voltage, you will not see a spark (static discharge) develop to a third conductor. Why not?

To avoid discussing the details of the electrochemistry inside a battery, let's assume that we have a capacitor charged to a large voltage. One plate has many positive charges and the other plate has many negative charges. The net charge of the capacitor is neutral. Now bring a neutral, isolated metal ball near to the negative terminal. A slight charge is induced in the wire, but not much because most of the negative charge has a greater attraction to the other plate of the capacitor. Furthermore, we will not see a spark because the capacitor as a whole has a neutral charge. Suppose that charge did start to leave the capacitor to jump to the neutral sphere. The capacitor would then have a charge imbalance and the charge would be attracted right back.

Table 2.1 Low-Frequency (DC) Conductivity and Permittivity of Various Materials

<i>Material</i>	<i>Conductivity, 1/[Ωm]</i>	<i>Permittivity (Dielectric Constant $\times \epsilon_0$)</i>
Copper	5.7×10^7	$1 \times \epsilon_0$
Stainless steel	10^6	$1 \times \epsilon_0$
Salt water	~ 4	$80 \times \epsilon_0$
Fresh water	$\sim 10^{-2}$	$80 \times \epsilon_0$
Distilled water	$\sim 10^{-4}$	$80 \times \epsilon_0$
Animal muscle	0.35	[no data]
Animal fat	4×10^{-2}	[no data]
Typical ground (soil)	$\sim 10^{-2}$ to 10^{-4}	$3 \times \epsilon_0$ to $14 \times \epsilon_0$
Glass	$\sim 10^{-12}$	$\sim 5 \times \epsilon_0$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$$

Table 2.1 data adapted from Krauss and Fleisch, *Electromagnetics with Applications*, 5th Edition, Boston: McGraw-Hill, 1999, and from Paul and Nasar, *Introduction to Electromagnetic Fields*, 2nd Edition, New York: McGraw-Hill, 1987.

ELECTRIC FIELD EXAMPLES

Figures 2.13 through 2.15 show examples of the electric fields surrounding various circuit configurations. Figure 2.13 shows the electric field surrounding a simple plate capacitor. Figure 2.14 shows the electric field of a plate capacitor whose plates are less wide and farther apart. Figure 2.15 shows the same structure, with a conductor inserted between the plates. This figure shows how the electric field looks inside a current-carrying wire.

CONDUCTIVITY AND PERMITTIVITY OF COMMON MATERIALS

To conclude this chapter on electric fields, I have listed the conductivity and dielectric constants of several common materials in Table 2.1. Note that salt water and body tissue are much more conductive than distilled water. The conductivity is caused by dissolved chemicals like salt, which dissolves into Na^+ and Cl^- when placed in water. These ions act to conduct electricity. Also notice that the typical ground is not a very good conductor.

Keep in mind that these values are for DC and low frequency. All materials, conductors and insulators, change characteristics at different

frequencies. Most materials used in electronics have constant properties into the microwave region, and some materials such as metals, glass, and teflon don't change until the infrared. Materials such as water and soil change dramatically in the radio wave frequencies. You'll learn more about the frequency dependence of materials in Chapter 15.

BIBLIOGRAPHY: ELECTRIC FIELDS AND CONDUCTION

- Cogdell, J. R., *Foundations of Electrical Engineering*, 2nd Edition, Englewood Cliffs, NJ: Prentice-Hall, 1995.
- Eisberg, R., and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*, 2nd Edition, New York: John Wiley & Sons, 1985.
- Epstein, L. C., *Thinking Physics—Is Gedanken Physics; Practical Lessons in Critical Thinking*, 2nd Edition, San Francisco: Insight Press, 1989.
- Feynman, R. P., R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics Vol I: Mainly Mechanics, Radiation, and Heat*, Reading, Mass.: Addison-Wesley Publishing, 1963.
- Feynman, R. P., R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics Vol II: Mainly Electromagnetism and Matter*, Reading, Mass.: Addison-Wesley Publishing, 1964.
- Glover, J. D., and M. Sarma, *Power System Analysis and Design with Personal Computer Applications*, Boston: PWS Publishers, 1987.
- Griffiths, D. J., *Introduction to Electrodynamics*, 3rd Edition, Upper Saddle River, NJ: Prentice Hall, 1999.
- Halliday, D., R. Resnick, and J. Walker, *Fundamentals of Physics*, 6th Edition, New York: John Wiley & Sons, 2000.
- Heald, M., and J. Marion, *Classical Electromagnetic Radiation*, 3rd Edition, Fort Worth, Texas: Saunders College Publishing, 1980.
- Jackson, J. D., *Classical Electrodynamics*, 2nd Edition, New York: John Wiley & Sons, 1975.
- Kraus, J. D., and D. A. Fleisch, *Electromagnetics with Applications*, 5th Edition, Boston: McGraw-Hill, 1999.
- Pierret, R. F., *Semiconductor Device Fundamentals*, Reading, Mass.: Addison-Wesley, 1996.
- Ramo, S., J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics*, 2nd Edition, New York: John Wiley, 1989.
- Shadowitz, A., *The Electromagnetic Field*, New York: Dover Publications, 1975.
- Ulaby, F. T., *Fundamentals of Applied Electromagnetics*, Englewood Cliffs, NJ: Prentice-Hall, 1999.
- Vanderlinde, J., *Classical Electromagnetic Theory*, New York: John Wiley & Sons, 1993.

BIBLIOGRAPHY: STATIC ELECTRICITY AND LIGHTNING

- Adams, J. M., *Electrical Safety a Guide to the Causes and Prevention of Electrical Hazards*, London: The Institution of Electrical Engineers, 1994.
- Anderson, K., *Frequently Asked Questions (FAQ) About Lighting*, www.nofc.forestry.ca Edmonton: Canadian Forest Service.
- Carlson, S., "Detecting the Earth's Electricity," *Scientific American*, July 1999.
- Carlson, S., "Counting Atmospheric Ions," *Scientific American*, September 1999.
- Carpenter, R. B., Jr., *Lightning Protection Requirements for Communications Facilities*, Lightning Eliminators & Consultants, Inc., Report No. T9408, August 1994.
- Carpenter, R. B., Jr., and Y. Tu, *The Secondary Effects of Lightning Activity*, Lightning Eliminators & Consultants, Inc., January 1997.
- Chalmers, J. A., *Atmospheric Electricity*, Oxford: Pergamon Press, 1967.
- Diels, J.-C., R. Bernstien, K. E. Stahlkopf, and X. M. Zhao, "Lightning Control with Lasers," *Scientific American*, August 1997.
- Encyclopedia Britannica Inc., "Electricity," *Encyclopedia Britannica*, Chicago: Encyclopedia Britannica Inc., 1999.
- Feynman, R. P., R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics Vol II: Mainly Electromagnetism and Matter*, Reading, Mass.: Addison-Wesley Publishing, 1964.
- Frydenlund, M. M., *Lightning Protection for People and Property*, New York: Van Nostrand Reinhold, 1993.
- Golde, R. H., *Lightning Protection*, New York: Chemical Publishing, 1973.
- Jonassen, N., *Electrostatics*, New York: Chapman and Hall, 1998.
- Kithil, R., *Lightning Rod Behavior: A Brief History*, National Lightning Safety Institute Facilities Protection, September 18, 2000.
- Kraus, J. D., and D. A. Fleisch, *Electromagnetics with Applications*, 5th Edition, Boston: McGraw-Hill, 1999.
- Moore, C. B., "Measurements of Lightning Rod Responses to Nearby Strikes," *Geophysical Research Letters*, Vol. 27, No. 10, May 15, 2000.
- Sorwar, M. G., and I. G. Gosling, "Lightning Radiated Electric Fields and Their Contribution to Induced Voltages," *IEEE*, 1999.
- Uman, M. A., *The Lightning Discharge*, Orlando, Florida: Academic Press, 1987.
- Uman, M. A., and E. P. Krider, "Natural and Artificially Initiated Lightning," *Science*, Vol. 246, October 27, 1989.
- Williams, E. R., "The Electrification of Thunderstorms," *Scientific American*, November 1988.

Web Resources

Animations of how fields interact with water molecules can be found at <http://www.Colorado.EDU/physics/2000/microwaves/index.html>

EMF and Human Health
<http://www.dnai.com/~emf/>

7 THE HIDDEN SCHEMATIC

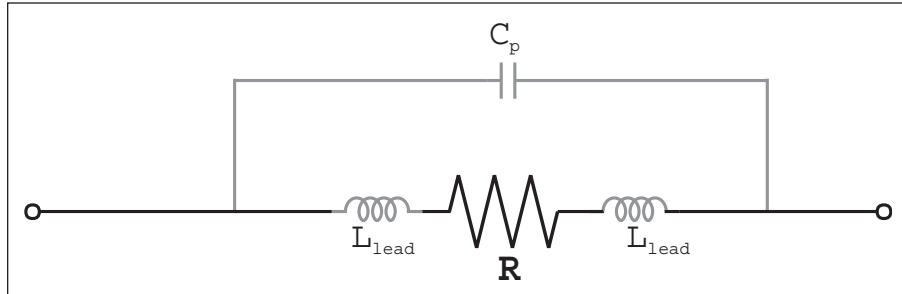
Typically, schematic diagrams show resistors, capacitors, inductors, and wires as ideal components. In many cases, components can be considered as ideal. However, at high frequencies such approximations are often no longer valid. The frequency-dependent departures from ideality are mainly due to parasitic capacitances and parasitic inductances. Electromagnetic theory dictates that any two conductors will have a capacitance between them and that any conductor used for carrying current will have inductance. Parasitic capacitance and inductance create reactive impedance that varies with frequency. For a capacitor, the impedance is $Z_c = -j/2\pi fC$. At DC, capacitive impedance is infinite—an open circuit. Capacitive impedance decreases with frequency. For an inductor, impedance is $Z_L = j2\pi fL$. At DC, inductive impedance is zero—a short circuit. Inductive impedance increases with frequency. These parasitic impedances cause real components to behave differently at high frequencies. The parasitic impedances of components are present in every real component but are typically not shown in their schematic symbols, hence the phrase *hidden schematic*.

In addition to the frequency-dependent parasitic elements, there exist other non-ideal characteristics of components. All conductors, including wires and component leads, have a non-zero resistance. At times this resistance must be accounted for in the design process. The characteristics of all components also vary with temperature. Components made from different materials will often display varying degrees of sensitivity to temperature. Temperature dependence must be accounted for in any real-world design. Finally, individual components will vary from the nominal value. The amount by which a component can be expected to vary from the nominal value is called *tolerance*.

THE NON-IDEAL RESISTOR

There are three common types of resistors: carbon resistors, wire-wound resistors, and metal film resistors. Carbon resistors are inexpensive

Figure 7.1 The hidden schematic of a real-world resistor includes lead inductance (L_{lead}) and parasitic capacitance (C_p). Most often (except in the case of very low resistance values) it is the parasitic capacitance that limits the high-frequency performance.

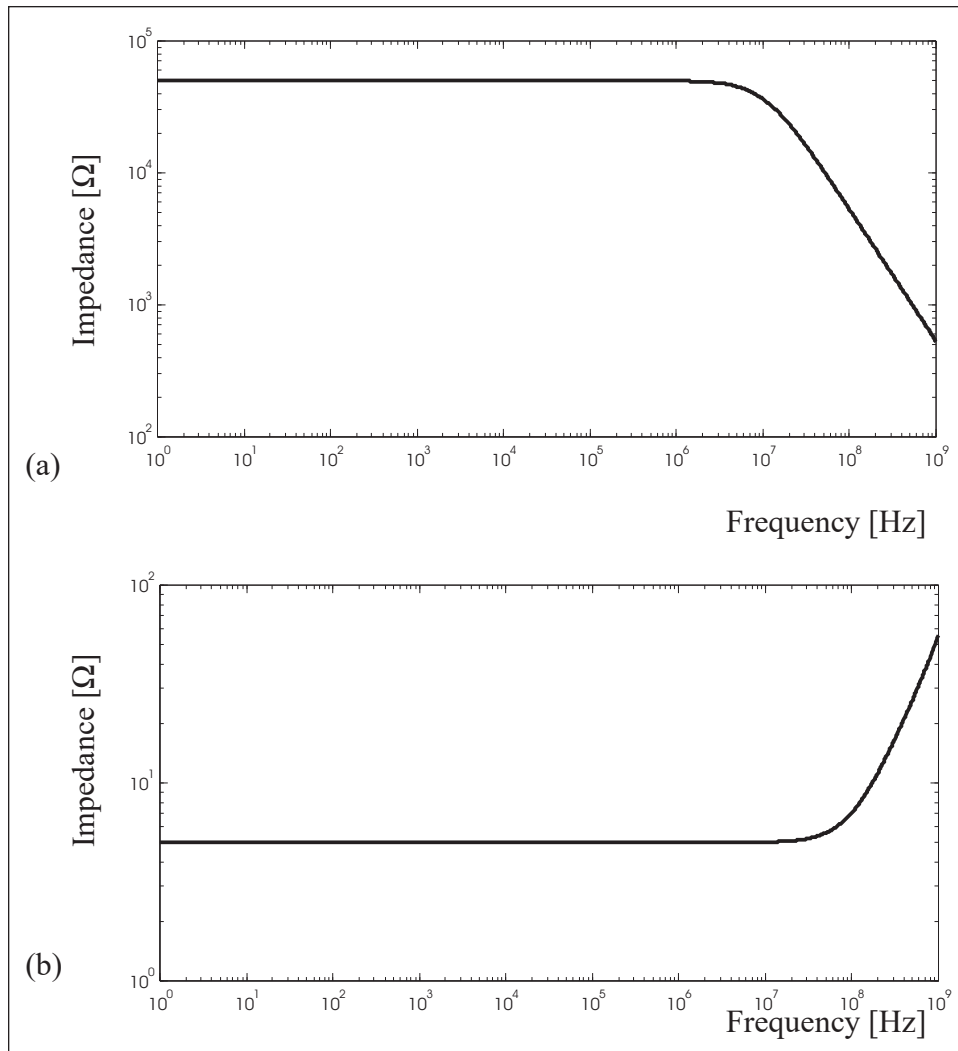


components that can use the low conductivity of carbon to create resistance. Wire-wound resistors are simply a very long wire, wound into a tight form. Metal film resistors are thin films that create resistance due to their small cross-sectional area. Wire-wound and metal film resistors are available in tighter tolerances and lower temperature coefficients than are carbon resistors. Low price is typically the only benefit of carbon resistors. Another consideration for resistors is their power-handling capability. If too much current is forced through a resistor, it will become too hot and will burn up or experience other permanent damage. Resistors are therefore given power ratings.

Real resistors also have frequency limitations. An equivalent circuit is shown in Figure 7.1. The leads of a resistor create a capacitance that is in parallel to the resistance. The leads of the resistor, and the resistive material itself create a series inductance. Both parasitic effects limit the frequency range of the resistor. For large resistances, the capacitance dominates the high-frequency response, shunting out the resistance and reducing the effective impedance of the resistor. Figure 7.2 shows the frequency response of two resistors.

The resistance remains constant until a corner frequency, defined by $f = 1/(RC)$. The frequency performance of a resistor, therefore, is worse for large resistances and for large parasitic capacitances. For this reason, high-resistance resistors are not used at high frequencies. To improve performance, the leads of a resistor can be shortened, reducing the parasitic capacitance. Surface-mount chip resistors, which are rectangular

Figure 7.2 Simulated frequency-dependent behavior of typical axial (through-hole mount) resistors: A) $R = 50\text{ kohm}$, $L_{\text{lead}} = 8\text{ nH}$, $C_p = 0.3\text{ pF}$; B) $R = 5\text{ ohm}$, $L_{\text{lead}} = 8\text{ nH}$, $C_p = 0.3\text{ pF}$.



blocks of resistive material with metal ends, reduce capacitance greatly because they do not have extended leads.

For small-valued resistors, the parasitic inductance dominates the high-frequency response, increasing the effective impedance. Wire-wound resistors have notoriously high inductance, and cannot be used

at high frequencies. Therefore, at high frequencies the very high- and very low-valued resistors will change the most. It turns out that 50 ohms, the most common characteristic impedance for use at high frequencies, serves as a good gauge for determining whether or not a resistor is very high or very low. A general, but somewhat arbitrary, guideline to use for selecting chip resistors is

$$\frac{f}{3 \times 10^{10} \text{ Hz}} \leq \frac{R}{50 \Omega} \leq \frac{3 \times 10^{10} \text{ Hz}}{f}$$

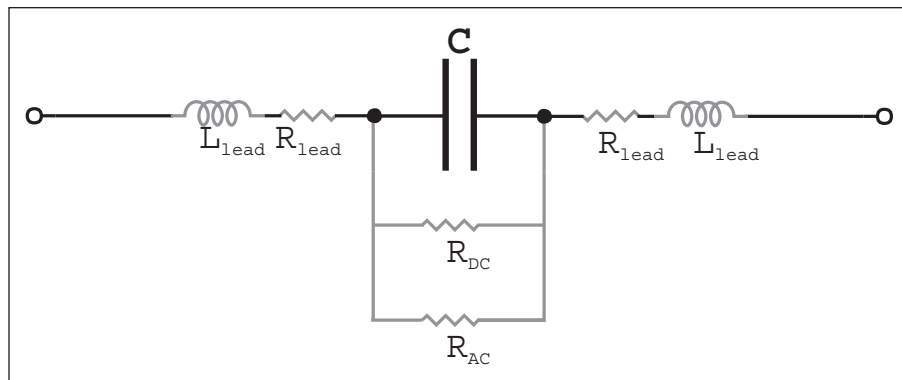
where f is the frequency of operation in Hz and R is resistance in ohms. Of course this is a rule of thumb and is not a substitute for measurements or simulation.

THE NON-IDEAL CAPACITOR

An ideal capacitor has a reactive impedance of $Z_c = -j/(2\pi fC)$. All real capacitors have several parasitic elements, as shown in Figure 7.3.

The leads of the capacitor have inductance and resistance. In addition, the dielectric material between the plates does not have infinite

Figure 7.3 The hidden schematic of a real-world capacitor includes lead inductance (L_{lead}), lead resistance (R_{lead}), dielectric leakage (R_{DC}), and dielectric “frictional” loss (R_{AC}). The resistances are often combined and called Equivalent Series Resistance (ESR). Dielectric losses (and hence ESR) are typically frequency dependent.



resistance, although the actual DC or leakage resistance is typically quite large. In addition to the DC resistance there is an AC loss, which can be represented as a resistance. The AC loss corresponds to microscopic frictional loss, which arises from polarization of charge as the voltage changes. This loss translates to heat and is very important to consider when using capacitors for high-current applications such as power supplies. If too much AC current passes through the capacitor, it will heat up, limiting its useful lifetime. Manufacturers often specify this resistance as ESR (Equivalent Series Resistance), which lumps all the resistances together. Ceramic capacitors typically have low ESRs, but they require too large a volume to be practical for large capacitance values. Aluminum electrolytic and tantalum electrolytic capacitors are available in large capacitance values but have higher ESRs. Of the two types, tantalum electrolytic capacitors have lower ESRs. Figure 7.4 shows the frequency response of several capacitors.

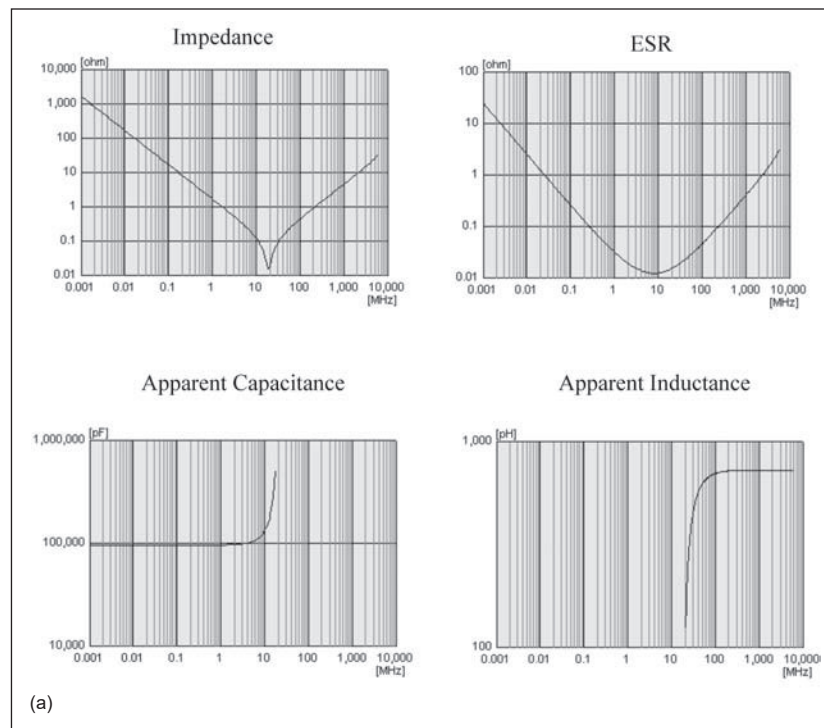
For high-frequency design, the parasitic series inductance poses the largest problem. The inductance creates a resonant frequency at $f_o = 1/\sqrt{LC}$. Above this frequency, the impedance of the capacitor increases with frequency; in other words, the component acts like an inductor above the resonant point. There are two options to increase the resonant frequency: 1) reduce the parasitic inductance or 2) use a smaller value of capacitance. From the second statement, you can assume that large values of capacitance are not useful at high frequencies.

Different dielectric materials also have different temperature dependences. Ceramic materials have less temperature dependence than do electrolytic capacitors. The last parameter to consider in choosing capacitors is the working voltage. Above the working voltage the dielectric will be damaged. At high enough voltages the dielectric will break down and short circuits will form between the plates.

THE NON-IDEAL INDUCTOR

In general, inductors are more problematic than capacitors. The circuit model for a real inductor is shown in Figure 7.5. The parasitic elements are: 1) resistance within the leads and the wire of the inductor, 2) the capacitance between the leads and between the loops of wire, and 3) the equivalent resistance corresponding to core losses (if the inductor uses a ferromagnetic core). The parasitic capacitance forms a resonant circuit with the inductance, with a resonant frequency at $f_o = 1/\sqrt{LC}$. Above this frequency, the impedance of the inductor decreases with frequency; in other words, the component acts like a

Figure 7.4 A) Frequency response of a $0.1\ \mu\text{F}$ surface-mount, size 0805 ($0.08'' \times 0.05''$) capacitor ($L_{\text{lead}} = 0.73\ \text{nH}$). B) Frequency response of a $0.015\ \mu\text{F}$ surface-mount, size 0805 ($0.08'' \times 0.05''$) capacitor ($L_{\text{lead}} = 0.88\ \text{nH}$). Above the self-resonant frequency (SRF) of $\sim 40\ \text{MHz}$, the device acts like a $0.88\ \text{nH}$ inductor. C) Frequency response of a $0.001\ \mu\text{F}$ surface-mount, size 0805 ($0.08'' \times 0.05''$) capacitor ($L_{\text{lead}} = 0.77\ \text{nH}$). Above the self-resonant frequency (SRF) of $\sim 200\ \text{MHz}$, the device acts like a $0.77\ \text{nH}$ inductor. Plots were created with muRata's MCSIL software (<http://www.murata.com/>).



capacitor above the resonant point. Again, there are two options to increase the resonant frequency: 1) reduce the parasitic capacitance or 2) use a smaller value of inductance. Large values of inductance, thus, are not practical at high frequencies.

If the inductor contains a ferromagnetic core, the core losses will also limit frequency response. The core losses arise from hysteresis losses and from eddy currents within the core. The situation is compli-

Figure 7.4 Continued.

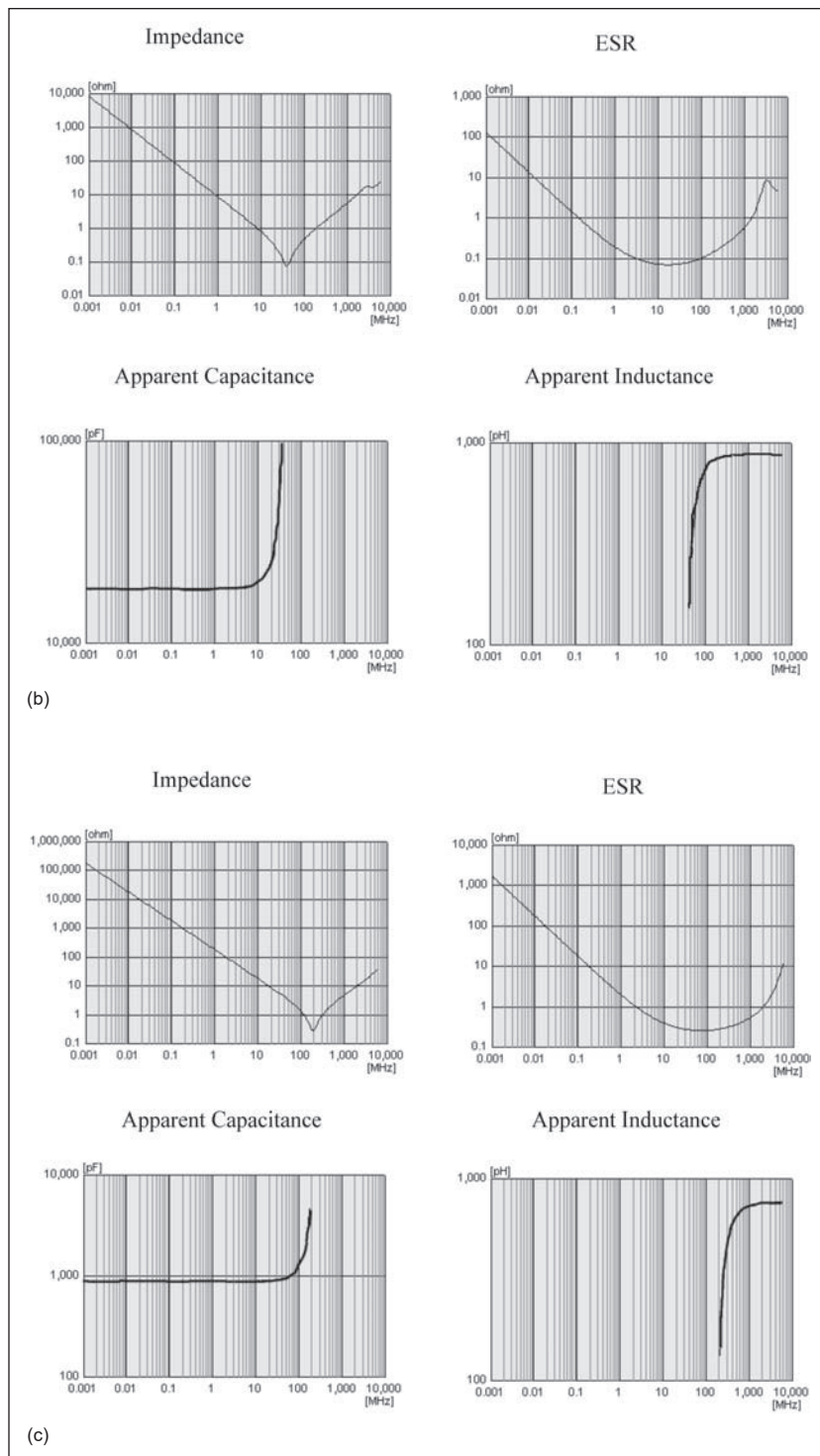
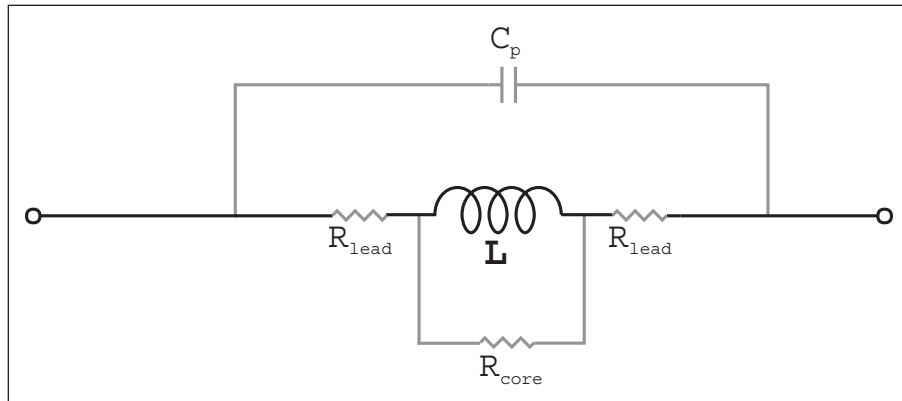


Figure 7.5 Hidden schematic of a real-world inductor includes lead resistance (R_{lead}), core loss (R_{core}), and parasitic capacitance (C_p) resulting from the leads and windings. Core losses are typically frequency dependent.



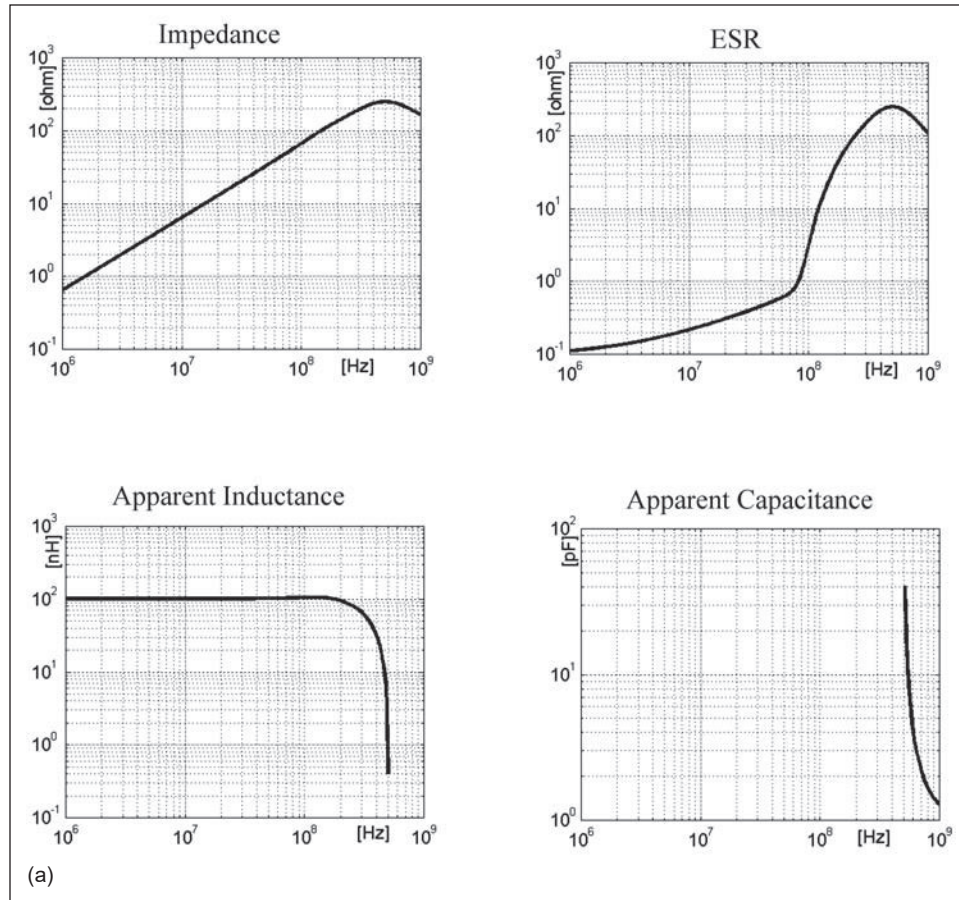
cated by the fact that hysteresis losses are nonlinear and that eddy current losses increase with frequency. Figure 7.6 plots the frequency response of two non-ideal inductors.

All real inductors are limited as to how much current they can carry. This limitation stems from the resistance of the conductors that make up the inductor and its leads. Inductors with ferromagnetic cores are further limited in that the current must be kept below the saturation level for the device to operate properly.

NON-IDEAL WIRES AND TRANSMISSION LINES

In circuit analysis, wires are usually considered to be ideal short circuits. All wires have resistance, which can be a problem at any frequency if the wire gauge (or trace width in the case of printed circuit traces) is not chosen properly. In addition, all wires have inductance. At low frequencies, the inductance can usually be ignored. At high frequencies, the inductance greatly affects how the wires carry signals. Furthermore, all circuits use at least two wires to deliver the signal from source to load. Typically one wire is designated for the source current and the other is designated for the return current and is often grounded.

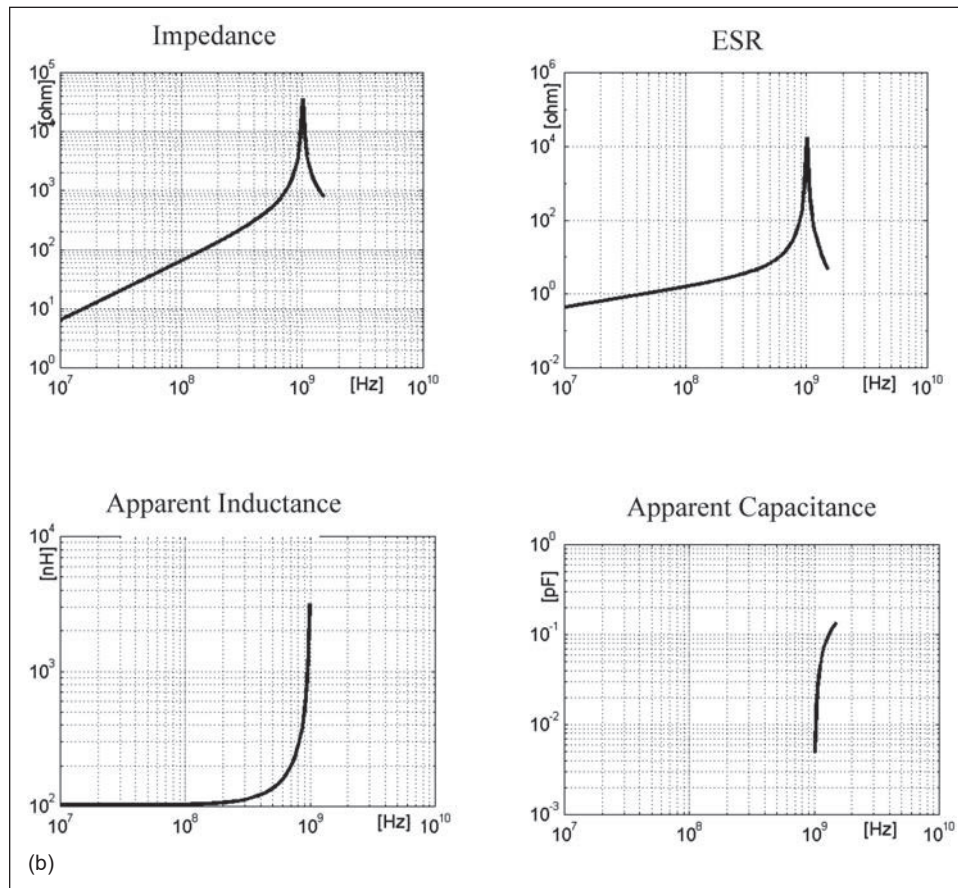
Figure 7.6 A) Frequency response of a ferrite-core, 100 nH surface-mount inductor ($C_p = 1$ pF; $R_{DC} = 0.26$ ohm). Above about 80 MHz, the ESR increases dramatically due to ferrite losses in the core. The self-resonant frequency occurs at about 500 MHz. Above the self-resonant frequency, the device acts like a ~ 1 pF capacitor.



Like any two conductors, these two wires have a capacitance between them. A simple circuit is shown in Figure 7.7, showing the parasitic elements of the wires.

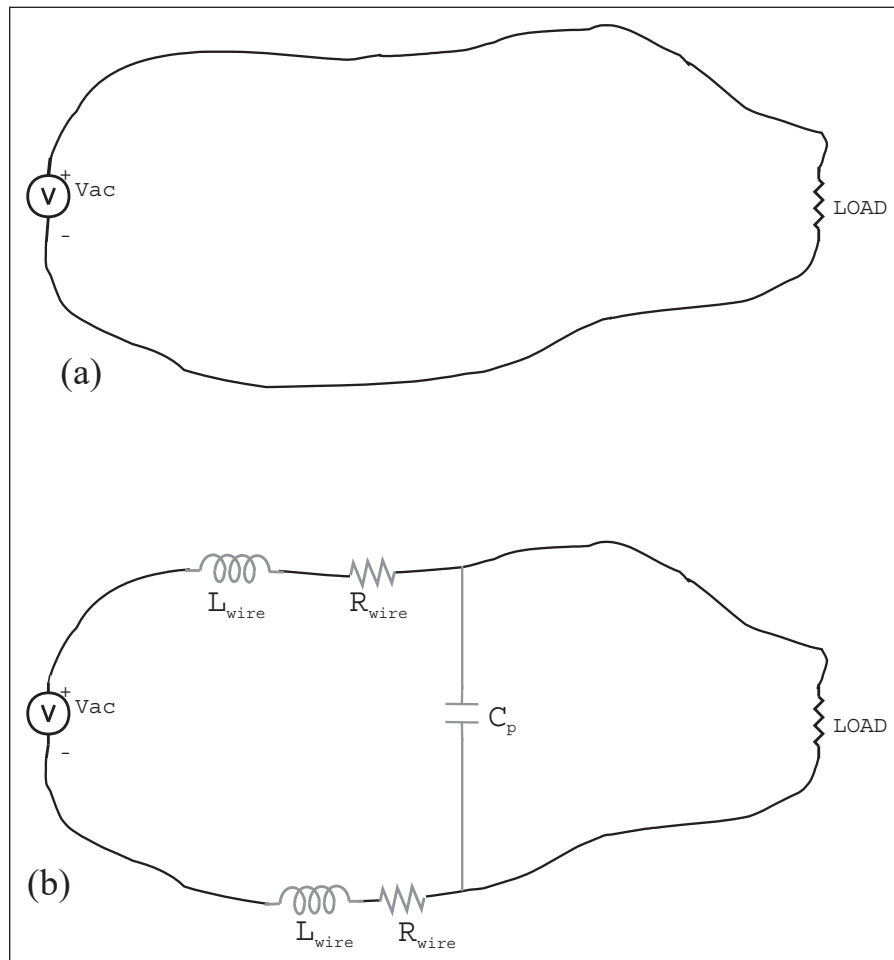
To make the problem of parasitic inductance and capacitance manageable at high frequencies, transmission lines are used. A transmission

Figure 7.6 B) Frequency response of an air-core, 100 nH surface-mount inductor ($C_p = 0.25$ pF; $R_{DC} = 0.38$ ohm). The self-resonant frequency occurs at about 1 GHz. Above the self-resonant frequency, the device approaches the behavior of a ~ 0.25 pF capacitor.



line is a set of conductors with uniform spacing. Some examples are coaxial cable (used for cable TV and lab instruments), twisted pair cable (used for telephone lines and computer network cables), ribbon cables (used to connect circuit boards inside computers), twin lead cables (used for TV antennas), microstrip and stripline (used on printed circuit boards). Transmission lines serve to guide the electromagnetic signals predictably and to reduce radiation.

Figure 7.7 A) A simple circuit consisting of a voltage source connected to a load resistor. B) The hidden schematic for the wires includes resistance (R_{wire}), inductance (L_{wire}), and parasitic capacitance (C_p).



OTHER COMPONENTS

Resistors, capacitors, and inductors are not the only components that change behavior at high frequency. All components have parasitic behavior. Transformers are basically coupled inductors, and are the most complicated of the passive components. Semiconductor parts such as diodes, transistors, and amplifiers also have parasitic capacitance and

inductance. In addition, the electronic behavior of the semiconductor material itself plays a role in high-speed applications.

MAKING HIGH-FREQUENCY MEASUREMENTS OF COMPONENTS

Accurately measuring the high-frequency response of components is not an easy task. It requires the use of a vector network analyzer (VNA) and a test fixture (a device in which to place the components during testing). The difficulty arises in isolating the component response from the cables, connectors, and test fixture used to connect the component to the network analyzer. Very accurate calibration is therefore needed. If the standard SOLT (Short Open Load Thru) calibration technique is used, then an accurate calibration kit (set of short, open, load, and thru standards) must be constructed for the test fixture. Furthermore, the calibration kit parameters for your test fixture must be entered manually into the network analyzer before the actual calibration of the instrument is performed. Determining the calibration kit parameters is a task that involves making an accurate high-frequency model of your test fixture and connectors. Another option is to use the TRL (Transmission Reflection Load) calibration technique. Calibration kit parameters are not needed for this technique. The most accurate and easiest route to take is to purchase component test fixtures from a company such as Agilent Technologies (formerly the test and measurement division of Hewlett-Packard). To make measurements on an IC wafer, microwave probe stations such as those manufactured by Cascade Microtech can be used.

RF COUPLING AND RF CHOKES

RF amplifiers typically require that you AC couple to the input and output. In other words, you must use a capacitor in series with the input and output, otherwise you will disrupt the DC bias point of the amplifier. For these applications, I typically select the capacitor such that the magnitude of its impedance is about 1 ohm at the signal frequency, $C = 1/2\pi f$. Setting the capacitor to this value balances the two design considerations involved. First, the capacitor should be large enough that it presents a very low-ohm connection for the signal to travel through. Second, the capacitor should be small enough that its self-resonant frequency is above the frequency range of the signal. The value of 1 ohm is a good compromise for these two requirements.

RF amplifiers also often require that you place an inductor in series with the power input to prevent the signal from leaking onto the power supply. Such an application of an inductor is often called an RF choke. Ideally, you would like the impedance of the RF choke to be as large as possible at the frequency of interest. You also need to be sure that the signal frequency is below the self-resonant frequency of the inductor. Finally, you must be sure the inductor can handle the DC current without saturating or being damaged. Typically, you should aim for an impedance of 500ohms or greater at the signal frequency to achieve good results.

COMPONENT SELECTION GUIDE

Parasitic capacitance and inductance limit the frequency response of all components including wires. The frequency response of the materials themselves can also play a role; examples are dielectric materials in

Table 7.1 Selection Considerations for Real-World Components

<i>Component</i>	<i>Considerations</i>
Resistors	Tolerance Power rating Temperature coefficient Parallel capacitance Series inductance
Capacitors	Tolerance Voltage rating Temperature coefficient Series inductance (or resonant frequency) Equivalent series resistance (ESR)
Inductors	Tolerance (Thermal) Current rating Parasitic capacitance (or resonant frequency) Series resistance Saturation current rating (if ferromagnetic core) Cores loss frequency response (if ferromagnetic core)

capacitors, core materials in inductors, and semiconductor materials in active elements. In general, components with smaller physical size will have smaller parasitics and therefore better high-frequency performance. Keeping resistance, capacitance, and inductance values small also helps at high frequency. SMD (Surface Mount Device) components allow for lumped element design on printed circuit boards (PCBs) up to several GHz. Integrated circuits, which allow very small components to be created, are needed at higher frequencies. Another option for high-frequency electronics is the use of distributed elements as described in Chapter 10. Table 7.1 gives some general selection rules for common passive components.

BIBLIOGRAPHY

- Agilent Technologies, *Understanding the Fundamental Principles of Vector Network Analysis*, Agilent Technologies, AN 1287-1.
- Agilent Technologies, *Accessories Selection Guide for Impedance Measurements*, Agilent Technologies, April 2000.
- Bowick, C., *RF Circuit Design*, Carmel, Indiana: SAMS Publishing, 1995.
- Breed, G. A., "Inductor Behavior at Radio Frequencies," *RF Design*, February 1996.
- Hamilton, N., "A Cheaper Alternative to Measuring Complex Impedance," *RF Design*, January 1999.
- Paul, C. R., *Introduction to Electromagnetic Compatibility*, New York: John Wiley & Sons, 1992.
- Pease, R. A., *Troubleshooting Analog Circuits*, Newton, Mass.: Butterworth-Heinemann, 1991.
- Ramo, S., J. R. Whinnery, T. Van Duzer, *Fields and Waves in Communication Electronics*, 2nd Edition, New York: John Wiley, 1989.
- Rhea, R. W., "A Multimode High-Frequency Inductor Model," *Applied Microwave & Wireless*, November 1997.
- Shrader, R. L., *Electronic Communication*, 5th Edition, New York: McGraw-Hill, 1985.
- Williams, T., *The Circuit Designer's Companion*, Newton, Mass.: Butterworth-Heinemann, 1991.