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Electromagnetics Around Us: Some Basic Concepts

1.1 Introduction

Electromagnetics is a brief name for the subject that deals with the theory and applications of electric and magnetic fields. Its implications are of fundamental importance in almost all segments of electrical engineering. Limitations on the speed of modern computers, the range of validity of electrical circuit theory, and the principles of signal transmission by means of optical fibers are just a few examples of topics for which knowledge of electromagnetics is indispensable. Electricity and magnetism also affect practically all aspects of our lives. Probably the most spectacular natural manifestation of electricity is lightning, but without tiny electrical signals buzzing through our nervous system we would not be what we are, and without light (an electromagnetic wave) life on our planet would not be possible.

The purpose of this chapter is to give you a glimpse of what you will learn in this course and how powerful this knowledge is. You will find that you are familiar with some of the information. However, you may also find that some concepts or equations mentioned in this chapter are not easy to understand. Don’t let this problem bother you, because we will explain everything in detail later. What is expected at this point is that you refresh some of your knowledge, note some relationships,
get a rough understanding of the unity of electricity and magnetism, and above all, understand how important this subject is in most of electrical engineering.

Electromagnetic devices are almost everywhere: in TV receivers, car ignition systems, elevators, and mobile phones, for instance. Although it may sometimes be hard to see the fundamental electromagnetic concepts on which their operation is based, you certainly cannot design these devices and understand how they work if you do not know basic electromagnetic principles.

In this chapter we first look at a few examples that show how the knowledge you will gain through this course can help you understand, analyze, and design different electrical devices. We will start with a typical office, which is likely to have a computer and a printer or a copier. We will list the different components and mechanisms inside the computer, relating them to chapters we will study later in the course. You may not yet understand what all the words mean, but that should not alarm you. During the course we will come back to these examples, each time with more understanding.

Questions and problems: Q1.1 to Q1.3

1.2 Electromagnetics in Your Office

Let us consider a personal desktop computer connected to a printing device and list the different components and mechanisms that involve knowledge of electricity or magnetism (Fig. 1.1).

1. The computer needs energy. It has to be plugged into a wall socket—that is, to an ac voltage generator. An ac voltage generator converts some form of energy into electrical energy. For example, hydroelectric power plants have large
generators in which the turbines, powered by water, produce rotating magnetic fields. We will study in Chapter 14 how such a generator can be built. These generators are made of copper conductors and iron or other magnetic materials, the properties of which we will study in Chapter 13.

2. Most desktop computers use a cathode-ray tube (CRT) monitor. In Chapter 17, we will explain how a CRT works. It involves understanding charge motion in electric and magnetic fields. Basically, a stream of electrons (negatively charged particles) is accelerated by an electric field and then deflected by a magnetic field, to trace a point on the front surface of the monitor and, point by point, a full image. The CRT runs off very high voltages, so the 110-V (or 220-V) socket voltage needs to be transformed into a voltage of a few kilovolts, which accelerates the electron beam. This is done using a magnetic circuit, or transformer, which we will study in Chapters 13 and 17.

3. The computer cabinet, or system unit, contains numerous printed-circuit boards. They contain conductive traces (Chapter 6) on dielectric substrates (Chapter 7); chips with many transistors, which are essentially charge-control devices (Chapter 7); and elements such as capacitors, resistors, and inductors (Chapters 8, 10, and 15). Signals flowing through the board traces couple to each other by electric (capacitive) and magnetic (inductive) coupling, which we will study in Chapters 8 and 15.

4. Many disks are read by magnetic heads from ferromagnetic traces. This is the topic of Chapters 14 and 17.

5. Computer memory used to be magnetic, built of small ferromagnetic toruses (Chapter 17). Now it is made of transistors, which serve as charge storage devices. We describe this mechanism in Chapter 8.

6. Inside the computer a motor operates the cooling fan. A motor converts electric energy to mechanical energy.

7. The semiconductor chips in the computer need typically 5 V or 3 V dc, instead of the 60-Hz 110 V (or 50-Hz 220 V) available from the socket. The power supply inside the computer performs the conversion. It uses components such as inductors, capacitors, and transformers, which we have already listed above.

8. The computer is connected to the printer by a multi-wire bus. The different lines of the bus can couple to each other capacitively (Chapter 8) and inductively (Chapter 15), and the bus can have an electromagnetic wave traveling along it, which we will discuss in Chapters 18, 23, and 25.

9. The printer will probably be a laser printer or an ink-jet printer. The laser printer operates essentially the same way as a copier machine, which is based on recording an electrostatic charge image and then transferring it to paper. The ink-jet printer is also an electrostatic device, and we will describe operations of both types of printers in Chapter 11.

10. The computer parts are shielded from outside interference by their metal casings. We are all bathing constantly in electromagnetic fields of different frequencies and intensities, which have different penetration properties into different materials (Chapter 20). However, some of the computer parts sometimes act
as receiving antennas (Chapter 24), which couple the interference onto signal lines, causing errors. This is called electromagnetic interference (EMI). The regulations that are imposed on frequency band allocations, allowed power levels, and shielding properties are generally referred to as electromagnetic compatibility (EMC) regulations.

11. The computer also radiates a small amount of energy—that is, it acts as a transmitting antenna at some frequencies. We will study basic antenna principles in Chapter 24.

12. Finally, when we use the computer we are (we hope) thinking, which makes tiny voltage impulses in our neurons. Since our cells are mostly salty water, which is a liquid conductor, the current in the neurons will roughly have the same properties as the one through wire conductors.

1.3 Electromagnetics in Your Home

Now let us look at some uses of electromagnetics in your home. We know that most household appliances need ac voltage for their operation and that most of them (for example, blenders, washers, dryers, fans) contain some kind of electric motor. Both motors and generators operate according to principles that are covered in the third part of this book. An electric oven, as well as any other electric heating element (such as the one in a hair dryer or curling iron), operates according to Joule’s law, which is covered in Chapter 10. Your washer, dryer, and car have been painted using electrostatic coating techniques, which we will briefly describe in Chapter 11.

Your TV receiver contains a cathode-ray tube, which, as we mentioned earlier, is described in Chapter 17. It is connected to the cable distribution box with a coaxial cable, a transmission line we will study throughout this book (Chapter 18). A transmission line supports an electromagnetic wave (Chapters 21 and 22). A similar wave traveling in free space is captured by an antenna, which you might also own. It could be a simple “rabbit ears” wire antenna or a highly directional reflector (dish) antenna. Basic antenna principles are covered in Chapter 24. Your cordless phone also contains an antenna, as well as high-frequency (rf) circuitry. All these applied electromagnetics topics are discussed in higher level courses in this field. Some of these applications are briefly described in Chapter 25 in the context of communications engineering.

A microwave oven is essentially a resonant cavity (Chapter 23), in which electromagnetic fields of a very high frequency are contained. The energy of these fields (Chapter 19) is used to heat up water (Chapter 25), whose molecule has a rotational resonance in a broad range around the designated heating frequency of 2.45 GHz. Thus the energy of the electromagnetic wave is transformed into kinetic energy of the water molecules, which on average determines the temperature of water. Because a large percentage of most foods is water, this in turn determines the food temperature.

Many other examples of electromagnetic phenomena occur in everyday life—light, which enables you to read these pages, is an electromagnetic wave. White light covers a relatively narrow range of frequencies, and our eyes are frequency-dependent sensors of electromagnetic radiation (that is, antennas for the visible part of the electromagnetic spectrum).
1.4 A Brief Historical Introduction

A tour through the historical development of the knowledge of electricity and magnetism reveals that this seemingly theoretical subject is entirely based on experimentally discovered laws of nature.

1.4.1 THE BEGINNING

When and where were the phenomena of electricity and magnetism first noticed? Around 600 B.C., the Greek philosopher and mathematician Thales of Miletus found that when amber was rubbed with a woolen cloth, it attracted light objects, such as feathers. He could not explain the result but thought the experiment was worth writing down. Miletus was at the time an important Greek port and cultural center. Ruins of Miletus still exist in today’s Turkey, shown on the map in Fig. 1.2. Some 20 km from Miletus is an archaeological site called Magnesia, where the ancient Greeks first found magnetite, a magnetic ore. They noticed that lumps of this ore attracted one another and also attracted small iron objects. The word magnet comes from the name of the place where this ore was found.

![Map of the Mediterranean coast. Until Roman times, most coast colonies were Greek. Miletus was an important port and cultural center, connected by a 16-km marble road, lined with statues, to the largest Greek temple ever built (but never finished), at Didime.](image-url)
Thus the first manifestations of both electricity and magnetism were noticed by the ancient Greeks at about the same time and at almost the same place. This coincidence was in a way an omen: we now know that electricity and magnetism are two facets of the same physical phenomenon.

1.4.2 CHRISTENING OF ELECTRICITY 22 CENTURIES LATER

There is no evidence that people thought about what Thales had observed for the next 2200 years. Around the year 1600 a physician to Queen Elizabeth I, William Gilbert, repeated Thales’s experiments in a systematic way. He christened “electricity” from the Greek word for amber, electron, in honor of Thales’s experiments. He rubbed different materials with woolen or silk cloth and concluded that some repel each other, and others are attracted after they are rubbed. We now know that when a piece of amber is rubbed with wool, some electrons (negative charges) from the wool molecules hop over to the amber molecules and therefore the amber has extra electrons. We say that the amber is negatively charged. The wool has fewer electrons, which makes it also different from neutral, and we say it is positively charged.

1.4.3 POSITIVE AND NEGATIVE CHARGES

The terms positive and negative electric charges were introduced by Benjamin Franklin (around 1750) for no particular reason; he could also have called them red and blue. It turned out, however, that for mathematically describing electrical phenomena, associating “+” and “−” signs with the two kinds of electricity was extremely convenient. For example, electrically neutral bodies are known to contain very large but equal amounts of positive and negative electric charges; the “+” and “−” convention allows us to describe them as having zero total charge.

Why were electrical phenomena not noticed earlier? The gravitational force has been known and used ever since the ancient man poured, for example, water in his primitive container. This time lag can be easily understood if we compare the magnitudes of electrical forces and some other forces acting around us.

1.4.4 COULOMB’S LAW

Electrical forces were first investigated systematically by Charles de Coulomb in 1784. By that time it was well established that like charges repel and opposite charges attract each other, but it was not known how this force could be calculated. Using a modified, extremely sensitive torsion balance (with a fine silk thread replacing the torsion spring), Coulomb found experimentally that the intensity of the force between two “point” charges (charged bodies that are small compared to the distance between them) is proportional to the product of their charges (\(Q_1\) and \(Q_2\) in Fig. 1.3), and inversely proportional to the square of the distance \(r\) between them:

\[ F_e = k_e \frac{Q_1 Q_2}{r^2}. \]  (1.1)
This is Coulomb’s law. The unit for charge we use is called a coulomb (C). With the distance \( r \) in meters and force \( F \) in newtons (N), the constant \( k_e \) is found to be very nearly \( 9 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \). This force is attractive for different charges (one positive and the other negative), and repulsive for like charges (both negative or both positive). The charge of an electron turns out to be approximately \(-1.6 \times 10^{-19} \text{ C}\).

How large is this force? Let us first look at the formula. If we replace the constant \( k_e \) with the gravitational constant \( \gamma = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2 \), and the charges by the masses, \( m_1 \) and \( m_2 \), of the two particles (in kg), the formula becomes that for the gravitational force between the two particles due to their masses:

\[
F_g = \gamma \frac{m_1 m_2}{r^2}.
\]

Let us calculate how the electric force in a hydrogen atom (which has one electron and one proton) compares to the gravitational force. Using the preceding formulas and the data for the masses of an electron and a proton given in Appendix 3, we find that the ratio of the electric to gravitational forces between the electron and the proton of a hydrogen atom is astonishing:

\[
\frac{F_e}{F_g} \approx 10^{39}.
\]

We know that atoms of matter are composed of elemental charges that include protons and electrons. If this is the ratio of electric to gravitational force acting between one proton and one electron, we should also expect enormous electric forces acting around us. Yet we can hardly notice them. They include such minor effects as our hair rising after we pull off a sweater. There are simply no appreciably larger electric forces in everyday life. How is this possible? To understand it, let us do a simple calculation.

Assume two students are sitting 1 m apart and their heads are charged. Let us find the force between the two heads, assuming they are point charges (for most students, of course, this is not at all true, but we are doing only an approximate calculation). Our bodies consist mostly of water, and each water molecule has 10 electrons and the same number of protons in one oxygen atom and two hydrogen atoms. Thus we are nothing but a vast ensemble of electric charges. In normal circumstances, the amount of positive and negative charges in the body is practically balanced, i.e., the net charge of which our body is composed is very nearly zero.
1.4.5 PERCENTAGE OF EXCESS CHARGE ON CHARGED BODIES

Let us assume, however, that a small percentage of the total electron charge, say 0.1%, exists in excess of the total positive charge. If each head has a volume of roughly $10^{-3}$ m$^3$, and solids and liquids have about $10^{28}$ atoms/m$^3$, each head has on the order of $10^{25}$ atoms. Assume an average of 10 electrons per atom (human tissue consists of various atoms). One tenth of a percent of this is roughly $10^{23}$ electrons/head. Since every electron has a charge of $-1.6 \times 10^{-19}$ C, this is an extra charge of about $-1.6 \times 10^4$ C. When we substitute this value into Coulomb’s law, we find that the force between the two students’ heads 1 m apart is on the order of $2 \times 10^{20}$ newtons (N).

How large is this force? The “weight” of the earth, if such a thing could be defined, would be on the order of $10^{20}$ N, that is, of same order of magnitude as the previously estimated force between the two students. How is it then possible that we do not notice the electric force? Where did our calculation go wrong? The answer is obvious: we assumed too high a percentage (0.1%) of excess electrons. Since we do not notice electric forces in common life, this tells us that the charges in our world are extremely well balanced, i.e., that only a very small percentage of protons or electrons in a body is in excess over the other.

1.4.6 CAPACITORS AND ELECTRIC CURRENT

We know that extra charge can be produced by rubbing one material against another. This charge can stay on the material for some time, but it is very difficult to collect from there and put somewhere else. It is of extreme practical importance to have a device analogous to a water container in which it is possible to store charge. Devices that are able to act as charge containers are called capacitors. They consist of two conducting pieces known as capacitor electrodes that are charged with charges of equal magnitude but opposite signs. An example is in Fig. 1.4a.

If the medium between the two electrodes is air, and if many small charged particles are placed there, the electric forces due to both electrodes will move the charges systematically toward the electrode of the opposite sign. Such an ordered motion of a large number of electric charges is called the electric current because it resembles

![Figure 1.4](image)

Figure 1.4 (a) A simple capacitor consists of two oppositely charged bodies. (b) If the two capacitor electrodes are connected by a wire, a short flow of charges occurs until the capacitor is discharged.
the current of a fluid. We can get the same effect more easily if we connect the two electrodes by a metallic (conducting) wire. A short flow of electrons in the metal wire will result, until the capacitor is discharged (Fig. 1.4b), i.e., until all of the negative charges neutralize the positive ones. Thus a charged capacitor cannot sustain a permanent electric current.

1.4.7 ELECTRIC GENERATORS

This flow of charges, more precisely an effect of this flow, was first noticed around 1790 by Luigi Galvani when he placed metal tweezers on a frog's leg and noticed that the leg twitched. Soon after that, between 1800 and 1810, Alessandro Volta made the first battery—a device that was able to maintain a continuous charge flow for a reasonable time.

A sketch of Volta's battery is shown in Fig. 1.5. The battery consisted of zinc and copper disks separated by leather soaked in vinegar. The chemical reactions between the vinegar and the two types of metal result in opposite charges on copper and zinc disks. These charges exert a force on freely movable electrons in a wire connecting them, resulting in electric current in the wire. Obviously, the larger these charges, the stronger the force on electrons in the wire. A quantity that is directly proportional to the charge on one of the disks is known as voltage. The unit of voltage is the volt (V), in honor of Volta. Volta “measured” the voltage by placing two pieces of wire on his tongue (the voltage is about 1 V per cell).

The chemical reaction that governs the process in a zinc-copper battery that uses a solution of sulfuric acid (H₂SO₄) is given by the following equation, assuming

![Diagram of Volta's battery](image-url)
the end copper (Cu) and zinc (Zn) plates to be connected with a conducting wire:

\[
\text{Cu} + \text{Zn} + 3\text{H}_2\text{SO}_4 = \text{Zn}^{++} + 2\text{SO}_4^{--} + \text{Cu}^{++} + \text{SO}_2 + \text{H}_2 + 2\text{H}_2\text{O}. \quad (1.3)
\]

Hydrogen gas molecules (H₂) are given off at the copper plate, which loses electrons to the solution and becomes positively charged. Zinc dissolves from the zinc plate, leaving electrons behind. The electrons move through the wire from the zinc to the copper plate, making an electric current. The process stops when the zinc plate is eaten away, or when no more acid is left.

Volta’s battery is just one type of electric generator. Other chemical generators operate like Volta’s battery but with different substances. However, generators can separate positive and negative electric charges, that is, can produce a voltage between their terminals, in many different ways: by a wire moving in a magnetic field; by light charging two electrodes of a specific semiconductor device; by heating one connection of two wires made of different materials; and even by moving charges mechanically (which, however, is extremely inefficient). All electric generators have one common property: they use some other kind of energy (chemical, mechanical, thermal, solar) to separate electric charges and to obtain two charged electrodes.

## 1.4.8 Joule’s Losses

When there is an electric current in a substance, the electric force accelerates charged particles that can move inside the substance (e.g., electrons in metals). After a very short trip, however, these particles collide with atoms within the substance and lose some energy they acquired by acceleration. This lost energy is transformed into heat—more vigorous vibrations of atoms inside the substance. This heat is known as Joule’s heat or Joule’s losses.

## 1.4.9 Magnetism

As mentioned, the phenomenon of magnetism was first noticed at about the same time as that of electricity. The magnetic needle (a small magnet suspended to rotate freely about a vertical axis) was observed by the Chinese about 120 B.C. The magnetic force was even more mysterious than the electric force. Every magnet always has two "poles" that cannot be separated by cutting a magnet in half. In addition, one pole of the magnetic needle, known as its north pole, always turns itself toward the north.

People could not understand why this happened. An “explanation” that lasted for many centuries (until about A.D. 1600) was that the north pole of the needle was attracted by the North Star. This does not show, of course, that our ancestors were illogical, for without the knowledge we have today we would probably accept the same explanation. Instead it shows at least two things typical of the development of human knowledge: we like simple explanations, and we tend to take explanations for granted. Whereas the desire to find a simpler explanation presents a great positive challenge, the tendency to take explanations for granted presents a great danger.

The magnetic forces were also studied experimentally by Coulomb. Using long magnets and his torsion balance, he concluded that the magnetic poles exert forces on each other and that these forces are of the same form as those between two point
charges. This is known as the Coulomb force for magnetic poles, and it represents another approach we frequently use in trying to understand things: the use of analogies. We will see shortly that magnetic poles actually do not exist. This example, therefore, demonstrates that we should be careful about analogies and be critical of them.

1.4.10 ELECTROMAGNETISM AND ORIGIN OF MAGNETISM IN PERMANENT MAGNETS

Because of Coulomb’s law for magnetic poles, magnetism was for some time considered to be separate from electricity but to have very similar laws. Around 1820, however, the Danish physicist Hans Christian Oersted noticed that a magnetic needle is deflected from its normal orientation (north-south) if placed close to a wire with electric current. Knowing that two magnets act on each other, he concluded that a wire with electric current is a kind of magnet, i.e., that magnetism is due to moving electric charges. This “magnet” is, of course, different from a piece of magnetic ore (a permanent magnet) because it can be turned on and off and its value can be controlled. It is called an electromagnet and has many uses, for example cranes and starter motors.

Soon after Oersted’s discovery, the French physicist André Marie Ampère offered an explanation of the origin of magnetism in permanent magnets. He argued that inside a permanent magnet there must be a large number of tiny loops of electric current. He also proposed a mathematical expression describing the force between two short segments of wire with current in them. We will see in a later chapter that this expression is more complicated than Coulomb’s law. However, for the particular case of two parallel short wire segments \( l_1 \) and \( l_2 \) with currents \( l_1 \) and \( l_2 \), shown in Fig. 1.6, and only in that case, this expression is simple:

\[
F_m = k_m \frac{(I_1l_1)(I_2l_2)}{r^2},
\]

(1.4)

where \( k_m \) is a constant. The direction of the force in the case in Fig. 1.6 (parallel elements with current in the same direction) is attractive. It is repulsive if the currents in the elements are in opposite directions. Note that an analogy with electric forces might tempt us to anticipate (erroneously) different force directions than the actual ones.

![Figure 1.6 Magnetic force between two parallel current elements](image)
1.4.11 ELECTROMAGNETIC INDUCTION

The final important physical fact of electricity and magnetism we mention was discovered in 1831 by the British physicist Michael Faraday. He performed experiments to check whether Oersted's experiment was reciprocal, i.e., whether current will be produced in a wire loop placed near a magnet. He did not find that, but he realized that a current in the loop was obtained while the magnet was being moved toward or away from it. The law that enables this current to be calculated is known as Faraday's law of electromagnetic induction.

As an example, consider a simple generator based on electromagnetic induction. It consists of a wire frame rotating in a time-constant magnetic field, as in Fig. 1.7, with the ends of the frame connected to the "outer world" by means of sliding contacts. Let the sliding contacts be connected by a separate and stationary wire, so that a closed conducting loop is obtained. When the wire frame turns, its position with respect to the magnet varies periodically in time, which induces a varying current in the frame and the wire that completes the closed conducting loop.

Questions and problems: Q1.4 to Q1.16, P1.1 to P1.4, P1.10

1.5 The Concept of Electric and Magnetic Field

Let us now assume that we know the position of the charge \( Q_1 \) in Coulomb's law, but that there are several charges close to charge \( Q_1 \), of unknown magnitudes and signs and at unknown locations (Fig. 1.8). We cannot then calculate the force on \( Q_1 \) using Coulomb's law, but from Coulomb's law, and knowing that mechanical forces add as vectors, we anticipate that there will be a force on \( Q_1 \) proportional to \( Q_1 \) itself:

\[
F_e = Q_1 E. \quad (1.5)
\]
Figure 1.8 The electric field vector, \( \mathbf{E} \), is defined by the force acting on a charged particle.

(It is customary in printed text to use boldface fonts for vectors, e.g., \( \mathbf{r} \). In handwriting, vectors are denoted by an arrow above the letter, e.g., \( \vec{r} \). A brief survey of vectors is given in Appendix 1.)

This is the definition of the electric field strength, \( \mathbf{E} \). It is a vector, equal to the force on a small charged body at a point in space, divided by the charge of the body. Note that \( \mathbf{E} \) generally differs from one point to another, and that it frequently varies in time (for example, if we move the charges producing \( \mathbf{E} \)). The domain of space where there is a force on a charged body is called the electric field. Thus, we can describe the electric field by \( \mathbf{E} \), a vector function of space coordinates (and possibly of time). For example, in a Cartesian coordinate system we would write: \( \mathbf{E}(x, y, z, t) = E_x(x, y, z, t) \mathbf{i} + E_y(x, y, z, t) \mathbf{j} + E_z(x, y, z, t) \mathbf{k} \). Obviously, sources of the electric field are electric charges and currents. If sources producing the field are not moving, the field can be calculated from Coulomb's law. This kind of field is termed the electrostatic field, meaning "the field produced by electric charges that are not moving."

Consider now Eq. (1.4) for the magnetic force between two current elements and assume that several current elements of unknown intensities, directions, and positions are close to current element \( I_1 l_1 \). The resulting magnetic force will be proportional to \( I_1 l_1 \). We know that current elements are nothing but small domains with moving charges. Let the velocity of charges in the current element \( I_1 l_1 \) be \( \mathbf{v} \), and the charge of individual charge carriers in the current element be \( Q \). The force on the current element is the result of forces on individual moving charge carriers, so that the force on a single charge carrier should be expected to be proportional to \( Q \mathbf{v} \). Experimentally, the expression for this force is found to be of the form

\[
\mathbf{F}_m = Q \mathbf{v} \times \mathbf{B},
\]

where the sign "\( \times \)" implies the vector, or cross, product of two vectors (Appendix 1). The vector \( \mathbf{B} \) is known as the magnetic induction vector or the magnetic flux density vector. If in a region of space a force of the form in Eq. (1.6) exists on a moving charge, we say that in that region there is a magnetic field.

Questions and problems: Q1.17 to Q1.20, P1.5 to P1.9

1.6 The Electromagnetic Field

Faraday's law shows that a time-varying magnetic field produces a time-varying electric field. Is the converse also true? About 1860 the British physicist James Clerk Maxwell stated that this must be so, and he formulated general differential equations
of the electric and magnetic fields that take this assumption into account. Because the electric and magnetic fields in these equations are interrelated in such a manner that if they are variable in time one cannot exist without the other, this resulting field is known as the electromagnetic field. These famous equations, known as Maxwell's equations, have proven to be exact in all cases of electromagnetic fields considered since his time. In particular, Maxwell theoretically showed from his equations that an electromagnetic field can detach itself from its sources and propagate through space as a field package, known as an electromagnetic wave. He also found theoretically that the speed of this wave in air is the same as the speed of light measured earlier by several scientists (for example, Roemer in 1675 estimated it to be about $2.2 \times 10^8$ m/s, and Fizeau in 1849 and Foucault in 1850 determined it to be about $3 \times 10^8$ m/s). This led him to the conclusion that light must be an electromagnetic wave and he formulated his famous electromagnetic theory of light. Maxwell's equations break down, however, at the atomic level because the field quantities used in the equations are averaged over many atoms. Such quantities are called macroscopic. (The science that deals with electromagnetic phenomena at the atomic and subatomic levels is called quantum physics.)

The first person who experimentally verified Maxwell's theory was the German physicist Heinrich Hertz. Between 1887 and 1891 he performed a large number of ingenious experiments at frequencies between 50 MHz and 5 GHz. At that time, these were incredibly high frequencies. One of his experiments proved the existence of electromagnetic waves. A device that launches or captures electromagnetic waves is called an antenna. Hertz used a high voltage spark (intense current in air of short duration, and therefore rich in high frequencies) to excite an antenna at about 60 MHz (Fig. 1.9). This was his transmitter. The receiver was an adjustable loop of wire with another spark gap. When he adjusted the resonance of the receiving antenna to that of the transmitting one, he was able to notice a weak spark in the gap of the receiving antenna. Hertz thus demonstrated for the first time that Maxwell's predictions about

![Diagram of Hertz's experiment](image-url)

*Figure 1.9 Hertz's first demonstration of an electromagnetic wave*
the existence of electromagnetic waves were correct. Hertz also introduced the first reflector antennas, predicted the finite velocity of waves in coaxial transmission lines and the existence of standing electromagnetic waves, as well as a number of radio techniques used today. He was, in fact, the first radio engineer.

Electric, magnetic, or electromagnetic fields are present in any device we use in electrical engineering. Therefore, Maxwell's equations should strictly be used for the analysis and design of all such devices. This would be quite a complicated process, however. Fortunately, in many cases approximations that simplify the analysis process are possible. For example, circuit theory is essentially a very powerful and simple approximation of the exact field theory. In the next chapter we look at the interconnection between fields and circuits, and explore briefly the electromagnetic foundations of circuit theory and its limitations.

Questions and problems: Q1.21, Q1.22

1.7 Chapter Summary

1. The principal developments in the history of the science of electricity and magnetism began with the ancient Greeks. Key concepts, however, have been described only in the past 400 years.

2. The objects in the world around us are composed of very nearly equal numbers of elemental positive and negative electric charges. The excess charge of one kind over the other can be only an extremely small fraction of the total charge of that kind.

3. Between stationary bodies with excess charges, which we term charged bodies, there is a force known as the electric force.

4. If there is a force on a charge Q in a region of space of the form \( F_e = QE \), we say that an electric field exists in that region. The vector \( E \) is known as the electric field vector.

5. If charges are moving, there is an additional force acting between them. It is called the magnetic force.

6. If there is a force on an electric charge Q moving with a velocity \( v \) in a region of space, of the form \( F_m = Qv \times B \), we say that a magnetic field exists in that region. The vector \( B \) is known as the magnetic induction vector or magnetic flux density vector.

7. An electric field that varies in time is always accompanied by a magnetic field that varies in time, and vice versa. This combined field is known as the electromagnetic field.

8. The equations that mathematically describe any electric, magnetic, and electromagnetic field are known as Maxwell's equations. They are mostly based on experimentally obtained physical laws.
QUESTIONS

Q1.1. What is electromagnetics?
Q1.2. Think of a few examples of animals that use electricity or electromagnetic waves. What about a bat?
Q1.3. The basis of plant life is photosynthesis, i.e., synthesis (production) of life-sustaining substances by means of light. Is an electromagnetic phenomenon included?
Q1.4. What is the origin of the word electricity?
Q1.5. What is the origin of the word magnetism?
Q1.6. When did Thales of Miletus and William Gilbert make their discoveries?
Q1.7. Why is it convenient to associate plus and minus signs with the two kinds of electric charges?
Q1.8. When did Coulomb perform his experiments with electric forces?
Q1.9. What is the definition of a capacitor?
Q1.10. What is electric current?
Q1.11. What are electric generators?
Q1.12. What common property do all electric generators have?
Q1.13. Describe in your own words the origin of Joule’s losses.
Q1.14. What is the fundamental cause of magnetism?
Q1.15. What is an electromagnet?
Q1.16. What did Faraday notice in 1831 when he moved a magnet around a closed wire loop? What did he expect to see?
Q1.17. Explain the concept of the electric field.
Q1.18. Define the electric field strength vector.
Q1.19. Explain the concept of the magnetic field.
Q1.20. Define the magnetic induction (magnetic flux density) vector.
Q1.21. What is an electromagnetic wave?
Q1.22. What are macroscopic quantities?

PROBLEMS

P1.1. How many electrons are needed to obtain one coulomb (1 C) of negative charge? Compare this number with the number of people on earth (about \(5 \times 10^9\)).

P1.2. Calculate approximately the gravitational force between two glasses of water a distance \(d = 1 \text{ m}\) apart, containing 2 dl (0.2 liter) of water each.

P1.3. Estimate the amount of equal negative electric charge (in coulombs) in the two glasses of water in problem P1.2 that would cancel the gravitational force.

P1.4. Two small equally charged bodies of masses \(m = 1 \text{ g}\) are placed one above the other at a distance \(d = 10 \text{ cm}\). How much negative charge would the bodies need to have so that the electric force on the upper body is equal to the gravitational force on it (i.e., so the upper body levitates)? Do you think this charge can be realized?
P1.5. Calculate the electric field strength necessary to make a droplet of water of radius \( a = 10 \mu m \), with an excess charge of 1000 electrons, levitate in the gravitational field of the earth.

P1.6. How large does the electric field intensity need to be in order to levitate a body 1 kg in mass and charged with \(-10^{-8} \text{ C}\)? Is the answer of practical value, and why?

P1.7. A drop of oil, \( r = 2.25 \mu m \) in radius, is negatively charged and is floating above a very large, also negatively charged body. The electric field intensity of the large body happens to be \( E = 7.83 \times 10^4 \text{ V/m} \) at the point where the oil drop is situated. The density of oil is \( \rho_m = 0.851 \text{ g/cm}^3 \). (1) What is the charge of the drop equal to? (2) How large is this charge compared to the charge of an electron? Note: the values given in this problem can realistically be achieved in the lab. Millikan used such an experiment at the beginning of the 20th century to show that charge is quantized.

P1.8. Find the force between the two parallel wire segments in Fig. P1.8 if they are 1 mm long and 10 cm apart, and if they are parts of current loops that carry 1 A of current each. The constant \( k_m \) is equal to \( 10^{-7} \) in SI units (N/A²).

![Figure P1.8 Two parallel wire segments](image)

P1.9. A small body charged with \( Q = -10^{-10} \text{ C} \) finds itself in a uniform electric and magnetic field as shown in Fig. P1.9. The electric field vector and the magnetic flux density vector are \( \mathbf{E} \) and \( \mathbf{B} \), respectively, everywhere around the body. If the magnitude of the electric field is \( E = 100 \text{ N/C} \), and the magnetic flux density magnitude is \( B = 10^{-4} \text{ N} \cdot \text{s/C} \cdot \text{m} \), find the force on the body if it is moving with a velocity \( v \) as shown in the figure, where \( v = 10 \text{ m/s} \) (the speed of a slow car on a mountain road). How fast would the body need to move to maintain its direction of motion?

![Figure P1.9 Point charge in an electric and magnetic field](image)
P1.10. Volta used a chemical reaction to make the first battery that could produce continuous electric current. Use the library, or any other means, to find out if electric current can be used to make chemical reactions possible. Write one page on the history and implications of these processes.