CHAPTER 12

Electromagnetic Waves

12.1 FARADAY'S SUGGESTION

On April 11, 1846, the distinguished physicist Charles Wheatstone was scheduled to give a lecture at the Royal Institution in London. Michael Faraday was to introduce Wheatstone to the audience. At the last minute, just as Faraday and Wheatstone were about to enter the lecture hall, Wheatstone got stage fright, turned around, and ran out into the street. Faraday had to improvise and give a lecture himself. Normally, Faraday discussed in public only his actual experiments. But on this occasion he revealed certain speculations which, as he later admitted, he would never have made public had he not suddenly been forced to speak for an hour—although these speculations soon changed physics.

Faraday's speculations dealt with the nature of light. Faraday, like Oersted before him, believed that all the forces of nature are somehow connected. Electricity and magnetism, for example, could not be separate forces that just happen to exist in the same universe. Rather, they must be different forms of one basic phenomenon. This belief paralleled that of Immanuel Kant, Friedrich Wilhelm Joseph von Schelling, and other German nature philosophers at the beginning of the nineteenth century. It had inspired Oersted to search in the laboratory for a connection between electricity and magnetism. Eventually he found such a connection in his discovery

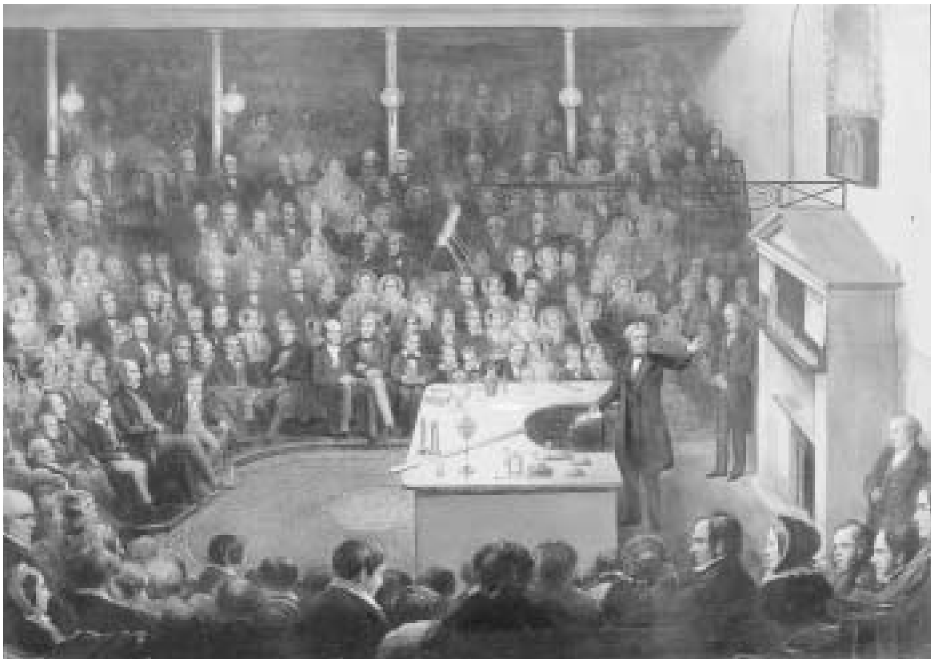

FIGURE 12.1 Faraday's Christmas Lecture at the Royal Institution, London (painting by Blaikley).

that an electric current in a conductor can turn a nearby magnet (see Chapter 10).

Faraday, too, had been guided by a belief in the unity of natural forces. Could *light* be another form of this basic "force"? Or rather, to use more modern terms, is light a form of *energy*? If so, scientists should be able to demonstrate experimentally its connection with other forms of energy such as electricity and magnetism. Faraday did succeed in doing just this. In 1845, he showed that light traveling through heavy glass had its plane of polarization rotated by a magnetic field applied to the glass.

Having shown a definite connection between light and magnetism, Faraday could not resist going one step further in his unrehearsed lecture the following year, revealing thoughts he had held privately. Perhaps, he suggested, light itself is a vibration of magnetic lines of force. Suppose, for example, that two magnetized or charged objects are connected by a magnetic or electric line of force. If one of them moved, Faraday reasoned, a disturbance would be transmitted along the line of force. Furthermore, if light waves were vibrations of lines of force, then a hypothetical elastic substance such as "ether" would not be needed in order to explain the propagation of light. The concept of the ether could be replaced if it could be shown that lines of force themselves have the elastic properties needed for wave transmission.

Faraday could not make his idea more precise. He lacked the mathematical skill needed to prove that waves could propagate along lines of electric or magnetic force. Other physicists in Britain and Europe might have been able to develop a mathematical theory of electromagnetic waves. But at the time these scientists either did not understand Faraday's concept of lines of force or did not consider them a good basis for a mathematical theory. Ten years passed before James Clerk Maxwell, a Scottish mathematical physicist, saw the value of the idea of lines of force and started using mathematics to express Faraday's concepts.

12.2 MAXWELL'S PRINCIPLES OF ELECTROMAGNETISM

The work of Oersted, Ampère, Henry, and Faraday had established two basic principles of electromagnetism:

1. *An electric current in a conductor produces magnetic lines of force that circle the conductor.*
2. *When a conductor moves across externally set-up magnetic lines of force, a current is induced in the conductor.*

In the 1860s, James Clerk Maxwell developed a mathematical theory of electromagnetism. In it, he added to and generalized these principles so that they applied to electric and magnetic fields in conductors, in insulators, and even in space free of matter. In 1855, less than 2 years after completing his undergraduate studies at Cambridge University, Maxwell had already presented to the Cambridge Philosophical Society a long paper titled "On Faraday's Lines of Force." It described how these lines are constructed:

> . . . if we commence at any point and draw a line so that, as we go along it, its direction at any point shall always coincide with that of the resultant force at that point, this curve will indicate the direction of that force for every point through which it passes, and might be called on that account a *line of force*. We might in the same way draw other lines of force, till we had filled all space with curves indicating by their direction that of the force at any assigned point.

JAMES CLERK MAXWELL

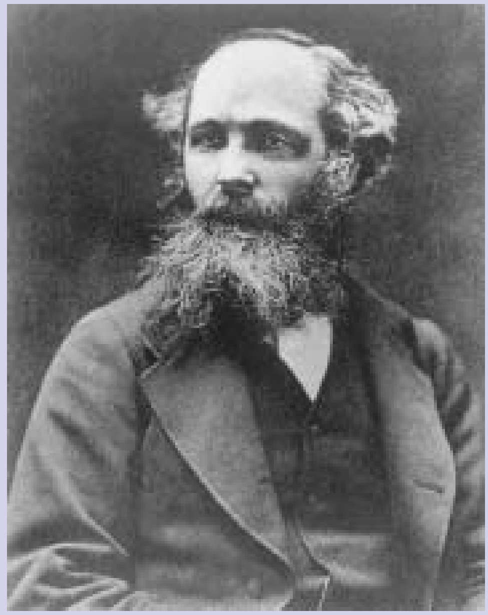

FIGURE 12.2

James Clerk Maxwell (1831–1879) was born in Edinburgh, Scotland, in the same year Faraday discovered electromagnetic induction. Unlike Faraday, Maxwell came from a well-off family. He was educated at the Edinburgh Academy and the University of Edinburgh. He showed a lively interest in how things happened when he was scarcely three years old. As a child, he constantly asked, "What's the go of that?" He studied mechanisms, from a toy top to a commercial steam engine, until he had satisfied his curiosity about how they worked. His formal studies, begun at the Academy in Edinburgh and continued through his work as an undergraduate at Cambridge, gave Maxwell experience in using mathematics to develop useful parallels among apparently unrelated occurrences. His first publication appeared in the proceedings of the Royal Society of Edinburgh when he was only 14 years old. In the 1870's, Maxwell organized the Cavendish Laboratory at Cambridge University, which soon became a world center for physics research. Maxwell was one of the main contributors to the kinetic theory of gases, to statistical mechanics and thermodynamics, and also the theory of color vision. His greatest achievement was his electromagnetic theory. Maxwell is generally regarded as the most profound and productive physicist between the time of Newton and Einstein.

Maxwell stated that his paper was designed to

> show how, by a strict application of the ideas and methods of Faraday, the connection of the very different orders of phenomena which he has discovered may be clearly placed before the mathematical mind.

During the next 10 years, Maxwell created his own models of electric and magnetic induction. In developing his theory, he first proposed a mechanical model for the electrical and magnetic quantities observed experimentally by Faraday and others. Maxwell then expressed the operation of the model in a group of equations that gave the relations between the electric and magnetic fields. He soon found these equations to be the most useful way to represent the theory. Their power allowed him eventually to discard the mechanical model altogether. Maxwell's mathematical view is still considered by physicists to be the proper approach to the theory of electromagnetic phenomena. If you go on to take another physics course after this introductory one, you will find the development of Maxwell's mathematical model (Maxwell's equation, using vector calculus) to be one of the high points of the course.

Maxwell's work contained an entirely new idea of far-reaching consequences: *An electric field that is changing with time must be accompanied by a magnetic field*. Not only do steady electric currents passing through conductors (a "conduction current") produce magnetic fields around the conductors, but changing electric fields in insulators such as glass, air, or even empty space also produce magnetic fields.

It is one thing to accept this newly stated connection between electric and magnetic fields. But it is harder, and more interesting, to *understand* the physical necessity for such a connection. The remainder of this section is intended to make it clearer.

An uncharged insulator (such as glass, wood, paper, or rubber) contains equal amounts of negative and positive charges. In the normal state, these charges are distributed evenly. Thus, the *net* charge is zero in every region of the material. But when the insulator is placed in an electric field, these charges are subjected to electrical forces. The positive charges are pushed in one direction, the negative in the opposite direction. Unlike the charges in a conductor, the charges in an insulating material are *not* free to move far through the material. The charges can be displaced only a small distance before restoring forces in the insulator balance the force of the electric field. If the strength of the field is increased, the charges will be displaced further. But the changing displacement of charges that accompanies a changing electric field in an insulator briefly forms a *current*. Maxwell called this current a *displacement current*. He assumed that this momentary displacement current in an insulator surrounds itself with a magnetic field just as a conduction current of the same magnitude does.

In an insulator, the displacement current is defined as *the rate at which the charge displacement changes.* This rate is directly proportional to the rate at which the electric field is changing in time. Thus, the magnetic field that circles the displacement current can be considered a consequence of the time-varying electric field. Maxwell assumed that this model, developed for matter, also applies to space free of matter (though at first glance this may seem absurd). Therefore, under all circumstances, as noted above, an electric field that is changing with time surrounds itself with a magnetic field. Previously, it was thought that the only current that produced a magnetic field was the current in a conductor. Now Maxwell predicted that a magnetic field would also arise from a changing electric field, even in empty space. Unfortunately, this field was very small in comparison to the magnetic field produced by the current in the conductors of the apparatus. So it was not at that time possible to measure it directly. But as you will see, Maxwell predicted consequences that soon could be tested.

According to Maxwell's theory, then, the two basic principles of electromagnetism should be expanded by adding a third principle:

3. *A changing electric field in space produces a magnetic field.*

The induced magnetic field vector **B** is in a plane perpendicular to the changing electric field vector **E**. The magnitude of **B** depends on the rate at which **E** is changing—not on **E** itself, but on $\Delta\mathbf{E}/\Delta t$. Therefore, the higher the rate of alteration of **E**, the greater the field **B** so induced.

For instance, consider a pair of conducting plates connected to a source of current. Charges are moved onto or away from plates through the conductors connecting them to the source. Thus, the strength of the electric field **E** in the space between the plates changes with time. This changing electric field produces a magnetic field **B** as shown. (Of course, only a few of the infinitely many lines for **E** and **B** are shown.)

An additional principle, known before Maxwell, assumed new significance in Maxwell's work because it is so symmetrical to Statement 3 above:

4. *A changing magnetic field in space produces an electric field.*

The induced electric field vector **E** is in a plane perpendicular to the changing magnetic field vector **B**. Similarly to Principle 3, the magnitude of **E** depends on the rate at which **B** is changing—not on **B** itself, but on $\Delta\mathbf{B}/\Delta t$. For instance, consider the changing magnetic field produced by temporarily increasing the current in an electromagnet. This changing magnetic field

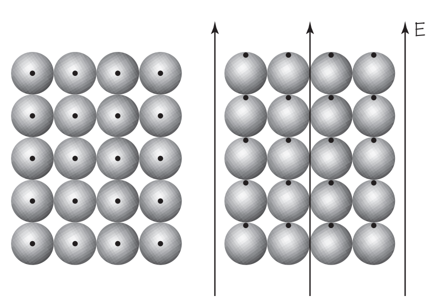

FIGURE 12.3 When an electric field is set up in an insulating material (as in the diagram here), the positive and negative charges, which are bound to one another by attraction, are displaced. This displacement forms a current (the positive charges are represented by dots, and the negative charges by shaded circles).

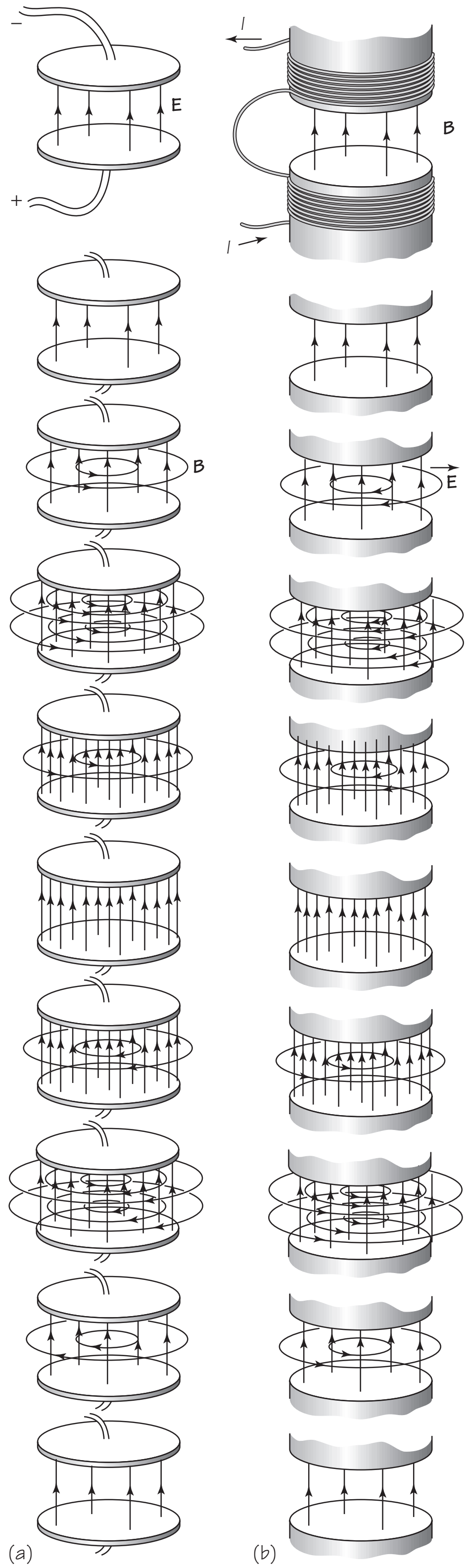

FIGURE 12.4 (a) A changing electric field produces a magnetic field: When the electric field **E** between a pair of charged plates starts to increase in intensity, a magnetic field **B** is induced. The faster **E** changes, the more intense **B** is. When **E** momentarily has reached its maximum value, **B** has decreased to zero momentarily. When **E** diminishes, a **B** field is again induced, in the opposite direction, falling to zero as **E** returns to its original strength. (b) A changing magnetic field produces an electric field. When the magnetic field **B** between the poles of an electromagnet starts to increase, an electric field **E** is induced. The faster **B** changes, the more intense **E** is. When **B** momentarily has reached its maximum value, **E** has decreased to zero momentarily. When **B** diminishes, an **E** field is again induced, in the opposite direction, falling to zero as **B** returns to its original strength.

induces an electric field in the region around the magnet. If a conductor happens to be lined up in the direction of the induced electric field, the free charges in the conductor will move under the field's influence. Thus, a current in the direction of the induced field will arise in the conductor. This electromagnetic induction had been discovered experimentally by Faraday (Section 11.3).

Maxwell's theory, involving the total set of relations between electric and magnetic fields in space, was not at once directly testable. When the test finally came, it concerned his prediction of the existence of waves traveling as interrelating electric and magnetic fields, that is, as *electromagnetic waves*.

12.3 THE PROPAGATION OF ELECTROMAGNETIC WAVES

Suppose in a certain region of space, an electric field is created that changes with time. According to Maxwell's theory, an electric field **E** that varies in time simultaneously induces a magnetic field **B** that also varies with time. (The strength of the magnetic field also varies with the distance from the region where the changing electric field was created.) Similarly, a magnetic field that is changing with time simultaneously induces an electric field that changes with time. (Here, too, the strength of the electric field also changes with distance from the region where the changing magnetic field was created.) The electric and magnetic field changes occur together, much like the "action" and "reaction" of Newton's third law.

As Maxwell realized and correctly predicted, the mutual induction of varying electric and magnetic fields should set up an unending sequence of events. First, a time-varying electric field in one region produces a time-

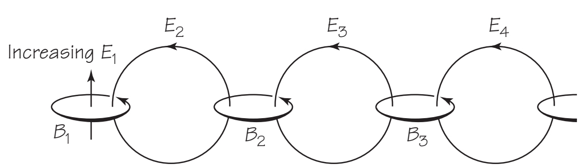

FIGURE 12.5 Electric and magnetic fields linked by induction. An increasing electric field at the left (or current) surrounds itself with a magnetic field. As the current changes, it induces an interlinking electric field. The chain-like process continues with finite velocity. This is only a symbolic picture of the process, which propagates itself in all directions in space.

and space-varying magnetic field at points near this region. But this *magnetic* field produces a time- and space-varying *electric* field in the space surrounding it. And this electric field produces time- and space-varying magnetic fields in its neighborhood, and so on. Thus, suppose that an electromagnetic disturbance is started at one location, say by vibrating charges in a hot gas or in the transmitter wire of a radio or television station. This disturbance can travel to distant points through the mutual generation of the electric and magnetic fields. The fluctuating, interlocked electric, and magnetic fields *propagate* through space as a *wave*. This wave is an *electromagnetic wave*, a disturbance in the electric and magnetic field intensities in space.

Maxwell had shown that in an electromagnetic disturbance **E** and **B** should be perpendicular to each other and to the direction of propagation of the wave. Therefore, in the language of Chapter 8, electromagnetic waves are *transverse*. And as was noted in Chapter 8, it was long known that light waves are transverse.

In Part One, Chapter 8, we showed that waves occur when a disturbance created in one region produces at a later time a disturbance in adjacent regions. Snapping one end of a rope produces, through the action of one part of the rope on the other, a displacement at points farther along the rope and at a later time. Dropping a pebble into a pond produces a disturbance that moves away from the source as one part of the water acts on neighboring parts. Analogously, time-varying electric and magnetic fields produce a disturbance that moves away from the source as the varying fields in one region create varying fields in neighboring regions.

The Speed of Electromagnetic Waves

What determines the speed with which electromagnetic waves travel? For mechanical waves the speed of propagation is determined by the stiffness and density of the medium (see Section 8.3). Speed increases with increasing stiffness, but decreases with increasing density. It is given by the expression

$$\text{speed} \propto \frac{\text{stiffness}}{\text{density}}.$$

This relationship between wave speed, stiffness, and density holds for mechanical wave motions and for many other types of waves. Only the barest outline of how Maxwell proceeded beyond this point is given here. First, he assumed that a similar “stiffness and density” relation would hold for electromagnetic waves. Then he computed what he thought to be the “stiffness” and “density” of electric and magnetic fields propagating through the hypothetical ether. In finding values for these two properties of the elec-

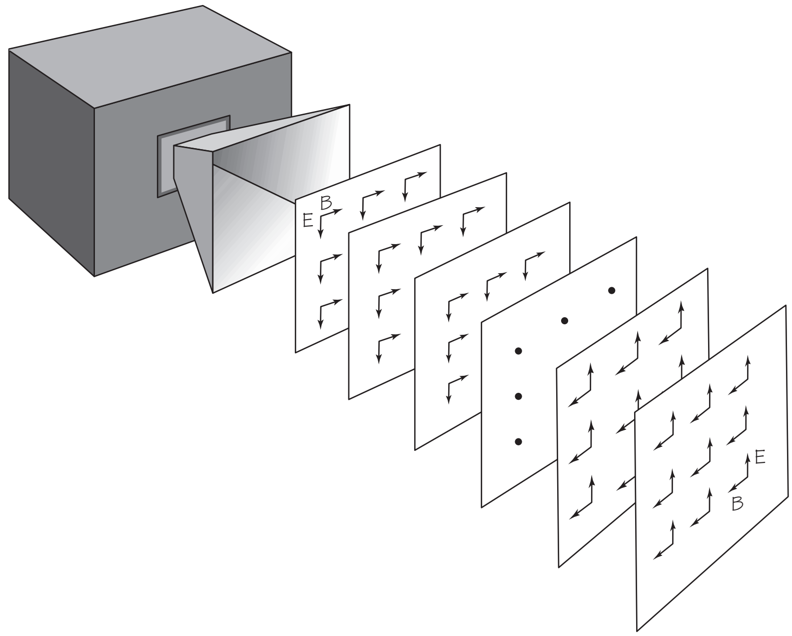

FIGURE 12.6 In a microwave oscillator, which you may see in your laboratory work, electric oscillations in a circuit are led onto a rod in a metal "horn." In the horn, they generate a variation in electric and magnetic fields that radiates away into space. This drawing represents an instantaneous "snapshot" of almost plane wave fronts directly in front of such a horn.

tric and magnetic fields, Maxwell was guided by his mechanical model representing the ether. In this model, stiffness was related to the electric field, and density to the magnetic field. Next, he proved mathematically that the ratio of these two factors, which should determine the wave speed, is the same for all strengths of the fields. Finally, Maxwell demonstrated that the speed of the waves (if they exist!) is a definite quantity that can be deduced from measurements in the laboratory.

The necessary measurements of the factors involved actually had been made 5 years earlier by the German scientists Weber and Kohlrausch. Using their published values, Maxwell calculated that the speed of the supposed electromagnetic waves (in metric units) should be about 311,000,000 m/s. He was immediately struck by the fact that this large number was very close to a measured speed already well known in physics. In 1849, Armand Fizeau had measured the speed of *light* and had obtained a value of about 315,000,000 m/s. (Today, the measured speed of light in vacuum is known to be 299,792,458 m/s.) The close similarity could have been a chance occurrence. But Maxwell believed that there must be a deep underlying reason for these two numbers being so nearly the same. The significance for physics seemed obvious to him. Making an enormous leap of the imagination, he wrote:

> The velocity of the transverse undulations in our hypothetical medium, calculated from the electromagnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena*.

It was already long known that light waves are transverse. When Maxwell found that in an electromagnetic disturbance **E** and **B** should be perpendicular to each other and to the direction of propagation of the wave, he concluded that electromagnetic waves are also transverse.

Here, then, in Maxwell's statement, was *an explanation of light waves and at the same time a joining of the previously separate sciences of electricity and magnetism with optics—a new synthesis.* Maxwell realized the importance of his discovery. Now he set to work making the theory mathematically sound and freeing it from his admittedly artificial model based on the ether hypothesis.

Classical Physics

Maxwell summarized his synthesis of electromagnetism and optics in his monumental *Treatise on Electricity and Magnetism*, published in 1873. After the experimental confirmation of his work (see Section 12.14), Maxwell's synthesis was seen as a great event in physics. In fact, physics had known no greater time since the 1680s, when Newton was writing his monumental work on mechanics. Of course, Maxwell's electromagnetic theory had arisen in Maxwell's mind in a Newtonian, mechanical framework. But it had grown out of that framework, becoming another great general physical theory, independent of its mechanical origins.

Like Newtonian mechanics, Maxwell's electromagnetic field theory succeeded spectacularly. You will see something of that success in the next few sections. The success occurred on two different levels: the practical and the theoretical. Practically, it led to a host of modern developments, such as radio and television. On the theoretical level, it led to a whole new way of viewing phenomena. The Universe was not only a Newtonian machine of whirling and colliding parts; it included fields and energies that no machine could duplicate. Maxwell's work formed a basis of the special theory of relativity. Other physical theories were nourished by it also. In a sense, the work of Maxwell and Newton, as well as that of Carnot and other founders of thermodynamics, enabled a fairly complete understanding of events in the physical world that surrounds us, from the motions of space satellites, cars, and atoms in gases to the behavior of light and other electromagnetic waves. The physics of the everyday, visible world, based upon the work of Newton and Maxwell, has remained to this day and is often known as *classical physics*. It is based on three steps of verification: Galileo's and Newton's verification of terrestrial and celestial phenomena; Oested's fusion of electric and magnetic phenomena; and Maxwell's addition of light to Oested's verification

Eventually, however, as research pushed into unfamiliar realms of nature at the scale of the very small (inside atoms), the very fast (approaching the speed of light), and the very large (the size of the Universe), results accumulated that could not be explained using classical physics. Something more was needed. Starting about 1925, after a quarter century of discovery, the development of quantum mechanics led to a larger synthesis, which included Maxwell's electromagnetism (see Chapter 15).

12.4 HERTZ'S EXPERIMENTAL CONFIRMATION

Did Maxwell himself establish without doubt that light actually does consist of electromagnetic waves, or even that electromagnetic waves exist at all? No. Most physicists remained skeptical for several years. The fact that the ratio of two quantities determined by electrical experiments came out nearly equal to the speed of light certainly suggested *some* connection between electricity and light. No one would seriously argue that this was only a coincidence. But stronger evidence was needed before the rest of Maxwell's theory, with its notion of the displacement current, could be accepted.

What further evidence was needed to persuade physicists that Maxwell's theory was correct? Maxwell showed that his theory could explain all the known facts about electricity, magnetism, and light. But so could other theories, although with less sweeping connections between their separate parts. To a modern physicist, the other theories proposed in the nineteenth century seem much more complicated and artificial than Maxwell's. But at the time, Maxwell's theory seemed strange to physicists who were not accustomed to thinking in terms of fields. It could be accepted over other theories only if it could be used to predict best some newly discovered property of electromagnetism or light.

Maxwell himself made two such predictions from his theory. He did not live to see them verified experimentally in 1888, for he had died in 1879, at the age of 48. Maxwell's most important prediction was that electromagnetic waves of many different frequencies could exist. All such waves would propagate through space at the speed of light. Visible light itself would correspond to waves of only a small range of high frequencies (from 4×10^{14} Hz to 7×10^{14} Hz), the range of frequencies detectable by the human eye. (Recall that the unit "cycles per second" is called the hertz, symbol Hz, after Heinrich Hertz.)

To test Maxwell's predictions required inventing apparatus that could both produce and detect electromagnetic waves, preferably of frequencies other than light frequencies. This was first done by the German physicist Heinrich Hertz, whose contribution was triggered by a chance observation. In 1886, Hertz noticed a peculiar effect produced during the sparking of an induction coil. As was well known, sparks sometimes jump the air gap between the terminals of an induction coil (see drawing). You will recall (Chapter 11) that an induction coil can be used to produce high voltages if there are many more turns of wire on one side than on the other. Ordinarily, air does not conduct electricity. But when there is a very large potential difference between two wires a short distance apart, a conducting pathway may form briefly as air molecules are ionized. A short burst of electricity then may pass through, attended by a visible spark. Each visible spark produced is actually a series of many small sparks, jumping rapidly back and forth (oscillating) between the terminals. Hertz found that he could control the spark's frequency of oscillation by changing the size and shape of metal plates attached to the spark gap of the induction coil.

Hertz then took a simple piece of wire and bent it so that there was a short gap between its two ends. When it was held near an induction coil, a *spark jumped across the air gap in the wire just when a spark jumped across the terminals of the induction coil*. This was a surprising phenomenon. To explain it, Hertz reasoned that as the spark jumps back and forth across the gap of the induction coil, it must set up rapidly changing electric and magnetic

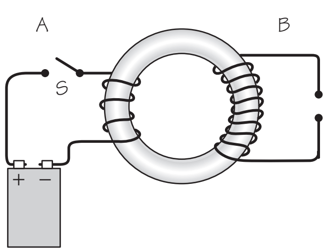

FIGURE 12.7 Operation of the induction coil: Starting and stopping the current in coil *A* with a vibrating switch *S* produces a rapidly changing magnetic field in the iron core. This rapidly changing field induces high-voltage peaks in the many-turn coil *B* and can cause a spark to jump across the air gap. Spark coils for use in car engines operate this way.

FIGURE 12.8 Heinrich Hertz (1857–1894) was born in Hamburg, Germany. During his youth, Hertz was mainly interested in languages and the humanities, but he was attracted to science after his grandfather gave him some experimental apparatus. Hertz did simple experiments in a small laboratory which he had fitted out in his home. After completing secondary school (and a year of military service) he undertook the serious study of mathematics and physics at the University of Berlin in 1878. In 1882, Hertz devoted himself to the study of electromagnetism, including the recent and still generally unappreciated work of Maxwell. Two years later he began his famous series of experiments with electromagnetic waves. During the course of this work, Hertz discovered the photoelectric effect, which has had a profound influence on modern physics. His early death is thought to have been caused by poisoning of vapor from mercury, then much used in laboratories without precautions.

fields. According to Maxwell's theory, these changes propagate through space as electromagnetic waves. (The frequency of the waves is the same as the frequency of oscillations of the sparks.) When the electromagnetic waves pass over the bent wire, which acted as a detector, they set up rapidly changing electric and magnetic fields there, too. A strong electric field around the detector produces a spark in its air gap, just as the transmitter field did between the terminals of the induction coil. Since the field is rapidly changing, sparks can jump back and forth between the two ends of the wire. Hertz's observation of the induced spark in the detector was the first solid clue that electromagnetic waves exist.

Hertz showed that the electromagnetic radiation coming from his induction coil has all the usual properties of light waves. It can be reflected at the surface of solid bodies, including metallic conductors. In addition, the angle of reflection is equal to the angle of incidence. The electromagnetic radiation can be focused by concave metallic mirrors. It shows diffraction when it passes through an opening in a screen. It displays all interference phenomena, including standing waves. Also, electromagnetic waves are refracted by prisms made of glass, wood, plastic, and other nonconducting material. By setting up a standing-wave pattern by using a large metal reflector, Hertz was also able to determine the distance between consecutive nodes and thus measure the wavelength. He determined the frequency of the oscillating electric current through an analysis of his circuits. Thus, he was able to determine the speed of his waves and found it to be the same value that Maxwell had predicted: the speed of light!

Hertz's experiments dramatically confirmed Maxwell's electromagnetic theory, by showing that electromagnetic waves actually exist, that they do travel with the speed of light, and that they have the familiar characteristics of light. Now physicists rapidly accepted Maxwell's theory and applied it with great success to the detailed analysis of a wide range of phenomena.

Thus, at the end of the nineteenth century, Maxwell's electromagnetic theory stood with Newton's laws of mechanics as an established part of the foundations of physics.

12.5 THE ELECTROMAGNETIC SPECTRUM

Hertz's induction coil produced electromagnetic radiation with a wavelength of about 1 m. This is about one million times the wavelength of visible light. Later experiments showed that a very wide and continuous range of electromagnetic wavelengths (and frequencies) is possible. The entire possible range is called the *electromagnetic spectrum*. The electromagnetic spectrum should not be confused with the *visible spectrum*, which includes only the frequencies of visible light. In principle, the electromagnetic spectrum ranges from close to 0 Hz to infinite Hz, but in practice the range of frequencies from about 1 Hz to 10^{26} Hz, corresponding to wavelengths in the range from 10^8 m to 10^{-18} m, has been studied. Many of these frequency regions have been put to practical use.

As shown in the illustration, light, heat, radio waves, and X rays are names given to radiations in certain regions of the electromagnetic spectrum. In each of these regions radiation is produced or observed in a particular way. For example, visible light may of course be perceived directly through its effect on the retina of the eye. But to detect radio waves requires electronic equipment. The named regions overlap. For example, some radiation is called "ultraviolet" or "X ray," depending on where it lies on the total spectrum or how it is produced.

All waves in the electromagnetic spectrum, although produced and detected in various ways, behave as predicted by Maxwell's theory. All electromagnetic waves travel through empty space at the same speed—the speed of light, 3×10^8 m/s. They all carry energy; when they are absorbed, the absorber is heated, as, for example, is food in a microwave oven. Electro-

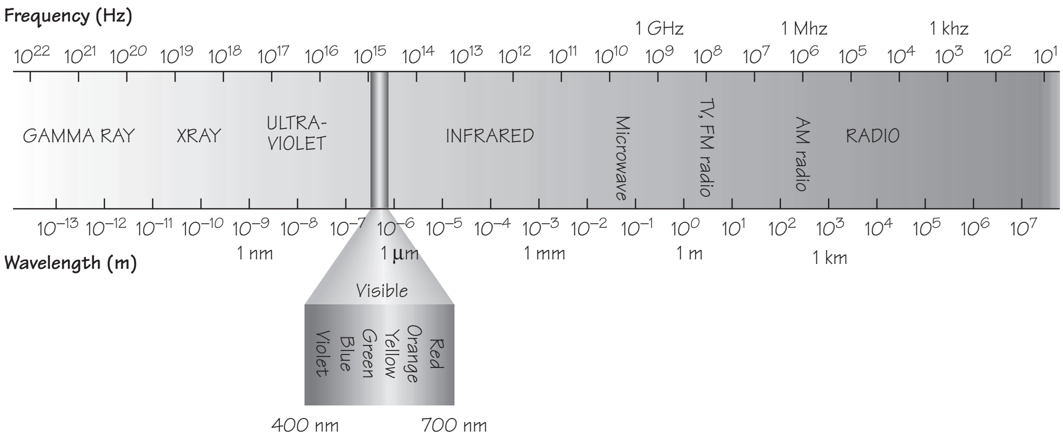

FIGURE 12.9 A chart of the electromagnetic spectrum, with visible light occupying the range between 400 nm and 700 nm in wavelength (1 nanometer = 10^{-9} m).

magnetic radiation, whatever its frequency, can be emitted only if energy is supplied to the source of radiation, which is, ultimately, a charge that is undergoing acceleration. This charge acceleration can be produced in many ways. For example, heating a material will increase the vibrational energy of charged particles. Also, one can vary the motion of charges on an electric conductor—an *antenna*—or cause a charged particle to change its direction. In these and other processes, work is done by the force that is applied to accelerate the electric charge. Some of the energy supplied to the antenna in doing this work is "radiated" away; that is, it propagates away from the source as an electromagnetic wave.

The work of Maxwell and Hertz opened up a new scientific view of nature. It also prepared for a rapid blooming of new technologies, such as radio, TV, radar, etc. We review below some of the indirect, technological consequences of a scientific advance.

Radio waves (λ = 10 m to 10,000 m; f = 10^4 Hz to 10^7 Hz). Electromagnetic waves in this region are reflected quite well by electrically charged layers of ions that exist in the upper atmosphere. This reflection makes it possible to detect radio waves at great distances from the source. Since radio signals have wavelengths from tens to thousands of meters, such waves can easily diffract around relatively small obstacles such as trees or buildings. But large hills and mountains may cast "dark" shadows.

Radio waves that can cross large distances, either directly or by relay, are very useful for carrying information. They are used not only for radio transmissions but also to carry cellphone communications via geographic "cells" centered around a single radio transmitter. A cellphone is technically a cellular radio transceiver, since it receives and sends radio signals.

In December 1901, the Italian inventor Guglielmo Marconi successfully detected radio waves sent from Newfoundland to Ireland. Marconi's work, perfected later on Cape Cod, Massachusetts, showed that long-distance radio communication was possible, because the waves were reflected by the previously unsuspected layers of ionized particles in the upper atmosphere and therefore could be received at great distances despite the curvature of the Earth's surface.

Radio communication is accomplished by changing the signal according to an agreed code that can be deciphered at the receiving end. The first radio communication was achieved by turning the signal on and off in an agreed pattern, such as Morse code (which is recognized today as a digital code). Later, sounds were coded by continuous variations in the amplitude (i.e., the intensity) of the broadcast wave. This is known as amplitude modulation, or AM. Later still, the information was coded as frequency variations in the broadcast wave, known as frequency modulation, or FM. In broadcast radio and television, the "decoding" is done in the receiver serving the loudspeaker or TV monitor, since the output message from the receiver takes the same form that it had at the transmitter. Radio stations regularly announce their frequencies in megahertz (MHz) for the FM band and kilohertz (kHz) for the AM band.

Because signals from different radio stations should not be received at the same spot on the dial, it is necessary to apportion the allowed frequencies of transmission within a region covered by radio signals. The International Telecommunication Union (ITU) controls radio transmission and other means of international communication. Within the United States, the Federal Communications Commission (FCC) regulates radio transmission. In order to reduce the interference of one station's signal with another, the FCC assigns suitable frequencies to radio stations (and other

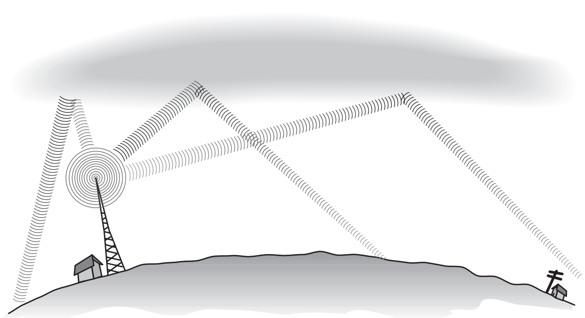

FIGURE 12.10 Radio waves bouncing off the ionosphere.

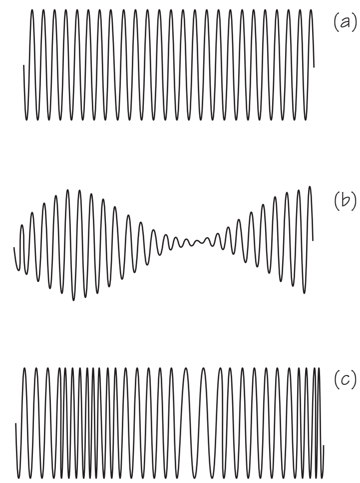

FIGURE 12.11 (a) A "carrier" radio wave; (b) AM (amplitude modulation): information is coded as variations in the amplitude (or intensity) of the carrier; (c) FM (frequency modulation): information is coded as variations in the frequency of the carrier.

transmitters). It also limits their power or the power radiated in particular directions, and may restrict the hours of transmission.

Television, FM, and Radar (λ about 1 m; f about 10^8 Hz). Waves at high frequencies of about 10^8 Hz are not reflected by the layers of electric charge in the upper atmosphere known as the *ionosphere*. Rather, the signals travel in nearly straight lines and pass into space. Thus, they can be used in communication between the Earth and orbiting satellites. But on Earth, TV signals cannot be received directly between points more than about 80 km apart, even if there are no mountains in the way. Instead, communications satellites are used to relay the signals, either directly to the receiver in a home equipped with a satellite dish, or to a cable-company receiver, which then relays the signal to its customers over a large region using cables.

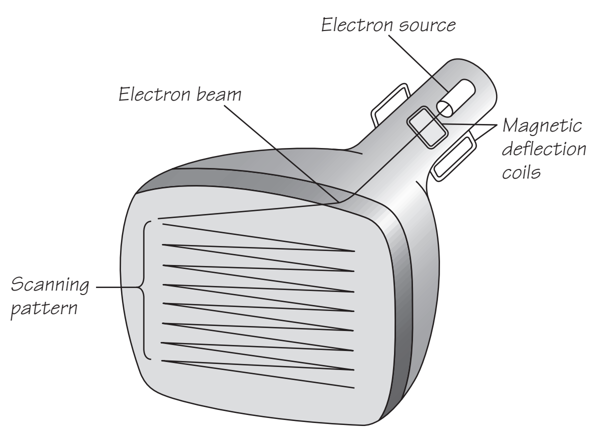

FIGURE 12.12 Schematic diagram of a TV picture tube.

■ TELEVISION

How It Works

Television—nearly every family in the United States owns at least one set, yet most do not know how it works.

The possibility of television emerged on the technological horizon with two developments: the discovery of *phosphors*, substances which glow with visible light when exposed to radiation, for example, when hit by a beam of electrons; and the use of radio waves to send signals from a broadcast station which could then be received in homes and be made to control thin beams of electrons. Combining these two elements allowed researchers, over the course of several decades, to develop one of the world's most widely used household appliances.

All television sets, except the recent plasma screens and digital sets, operate on the same general principles. A composite video signal, received from a broadcasting station or television cable, incorporates three parts: the luminance signal, which dictates the intensity, or brightness, of the electron beam; the chrominance signal, a sine wave that incorporates information about which colors the resulting image should be made up of; and the synchronization signal, which synchronizes the other signals to ensure they scan simultaneously.* Black and white televisions lack the chrominance signal, and in these, the intensity of the beam determines different shades of black and white on the screen.

The received *video* signal feeds into the cathode ray tube (CRT), the central feature of standard television sets. A "cathode" refers to a negatively charged end, and in the CRT, the cathode is a heated filament located inside a glass tube containing a vacuum. Electrons come off the cathode into the vacuum, forming a narrow beam, which is attracted by one or more positively charged "anodes." Inside a television's CRT, one anode focuses the beam while another accelerates the electrons from one end of the tube to the other, where they hit a flat screen at the end. The phosphor-coated screen glows briefly at whichever spot the electron beam hits it.

Engineers developed a way to control where the electron beam hits the screen by placing copper deflection coils inside the tube; these coils create magnetic fields that shift the beam in different directions. The electron beam quickly scans the screen line by line, eventually forming a still picture composed of 525 thin horizontal lines, which our brains interpret as a whole image. This scanning process occurs 60 times every second, although television sets now use a process called interlacing, which means that the beam only "paints" every other line of the screen each scan, but the eye processes images at a speed too slow to notice this effect.

On the black and white set, the flat screen at the end of the CRT is coated with a white phosphor which glows in different shades of white or gray each place the electrons hit it. Color television sets contain some additional features. Inside the CRT, three electron beams scan the screen simultaneously. The screen is coated with red, green, and blue phosphors arranged in tiny dots or stripes. A thin metal screen, the shadow mask, which contains small holes aligned with the phosphors, covers the screen to ensure that each electron beam strikes only phosphor stripes of the right color. The different electron beams directed to phosphors producing different colors scan the screen simultaneously, and light up various combinations of tiny red, green, and blue dots, or pixels (short for "picture elements"), which we see assembled into a fully colored picture. If you use a magnify-

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* D. Macauley, *The Way Things Work* (Boston, MA: Houghton Mifflin, 1998), p. 246.

ing glass close to a television screen, you will probably be able to see the individual pixels that make up the image.

Through this process, a television set composes rapidly one still image after another on the screen at the rate of at least 15 images, or frames, per second, which your brain perceives as a fluid moving scene.

TELEVISION: THE INVENTION

The research and development of television technology happened along two paths, mechanical and electronic.

Mechanical Television

Television was inspired by human vision, in which thousands upon thousands of electrical circuits are used to relay information in the optic nerve from the retina to the brain. Designs based on so many electrical circuits, however, were far too complicated to ever reach fruition. In 1880 Maurice Leblanc in France and W.E. Sawyer in the United States suggested instead that if each element of a picture could be rapidly scanned, electrical transmission of pictures could be achieved using only one circuit between the transmitter and receiver. Paul Nipkow of Germany adopted this scanning technique in 1884.

The picture to be televised is focused on a rotating disk. When the first aperture in the disk has scanned a line of the picture, the next aperture scans the parallel line directly below. At each rotation of the disk another line is scanned until the whole picture has been examined. In this design, more apertures mean more lines, and hence greater detail of the picture. As it passes through each aperture, the light differs according to the light and shade of the picture, it then passes through a photoelectric cell where it is changed into an electrical image, and then translated into electrical impulses. These impulses are then sent down a circuit to a receiver, where they produce light in something like a gas-discharge lamp. The light from this lamp is then projected onto another disk, similar to the transmitter, and by a reversal of the transmission process, the brightness of each segment is reproduced and the original picture is reconstructed. In order for this system to work, the rotation of the disks must be synchronized, and provided they are rotating at a sufficient speed, persistence of vision allows the observer to see a whole image rather than a series of moving segments.

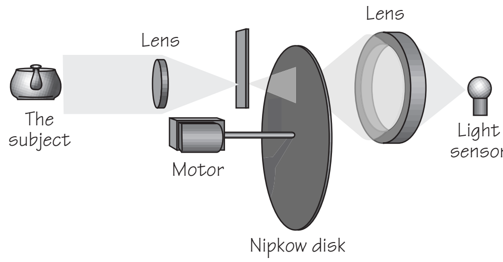


FIGURE 12.13 Diagram of Nipkow disk apparatus.

Until the arrival of electronic scanning, it was this mechanical system, characterized by the Nipkow disk, which dominated the development of television. However, the system was crude, with the small number of lines resulting in poor definition and the small number of rotations causing a flicker. Therefore research turned toward electronic systems.

Electronic Systems

One of the leading players in the development of electronic television was Vladimir Kosma Zworykin. He was convinced that electronic television was the path he should follow, and while working for the Radio Corporation of America (RCA), he developed the Iconoscope which used a CRT for transmitting images.

At the wide end of the Ionoscope is a sheet of mica, on one side of which is a signal plate, and the other a silver mosaic treated with cesium vapor and oxygen, in which each element is encircled by an aluminum oxide insulator. This combination of elements provides a surface from which electrons are easily liberated when exposed to light. When an image is focused onto the mosaic surface, it takes on a positive charge that corresponds to the light distribution. When the electron beam passes over the mosaic, the charge of each section changes in proportion to the amount of light that is falling on it. This change is transferred to the signal plate, which takes on a series of voltages corresponding to the light along the particular line.

Although it marked a major breakthrough in electronic television, the Iconoscope was not sensitive enough to produce consistently clear images, and in 1940 it was replaced by the Orthicon, based on a similar design but with a rigid set of squares. The Orthicon, however, was made obsolete in the same year, by a tube developed by Corning Glass Company, which was three to ten times more sensitive than the Orthicon and thirty to five hundred times more sensitive than the Iconoscope.

FIGURE 12.14 Vladimir Zworykin, one of the inventors of television, is shown here holding a cathode-ray tube.

At the beginning of the 1950s, television technology based on the electrical system had advanced so far that engineers began looking toward developing a color system. There were two possibilities. The first was a system based on a frame-by-frame sequential transmission of signals, each corresponding to the primary colors, but this design was incompatible with the current black and white transmissions. The more complex system proposed at the time was one in which signals representing the three primary colors were transmitted simultaneously. This second system was developed by the National Television Systems Committee (NTSC) in the United States and is now the basis for color systems all over the world. By the early 1960s, color television was becoming a consumer success in the United States.

Recent developments in television technology have focused on the development of High Definition (HDTV), in particular on the use of digital technology. Instead of conventional analog technology, which transmits signals in the form of waves, the new digital HDTV system transmit pictures as digital data, which is then translated by computers within the digital television. As well as clearer pictures and better sound, digital television also has the potential to transform and manipulate pictures as well as to receive them, and could perform the job of both a computer and a television set.

Further Reading

D.E. Fisher and M.J. Fisher, *Tube: The Invention of Television* (New York: Harcourt Brace, 1996).

Television, in which both sound and picture (in three primary colors) are transmitted, uses both frequency and amplitude modulations. The frequency of the wave is changed in a way that is analogous to the sound, while the picture is transmitted via amplitude modulations. This is called an *analogue wave*. However, in a recent development, the analogue TV signals are gradually being replaced by *digital* signals for digital TV. Here the analogue sound and picture waves are approximated by series of 1's and 0's (or, on and off voltages) that are converted into electromagnetic pulses and compressed at the sender, then transmitted to the receiver where they are decompressed and reconverted into continuous sound and light waves.

Signals at wavelengths of only about 1 m are not diffracted much around objects that have dimensions of several meters, such as cars, ships, or aircraft. Thus, the reflected portions of signals of wavelengths from 1 m down to 1 mm can be used to detect such objects. The interference between the direct waves and reflection of these waves by passing airplanes can distort a television picture considerably. The signal also may be radiated in the form of pulses. If so, the time t between the emission of a pulse and the reception of its echo measures the distance l of the reflecting object ($l = 2\, c/t$). This technique is called "*ra*dio *d*etection *a*nd *r*anging," or *radar* (see Section 8.9). By means of the reflection of a beam that is pulsed, both the direction and distance of an object, such as an aircraft, can be measured. This helps enormously in regulating traffic at busy airports. But initially it had an even more important role in alerting fighters in the United Kingdom during World War II of the approach of German aircraft, e.g., during the "Blitz" meant to destroy London.

Microwave radiation ($\lambda = 10^{-1}$ m to 10^{-4} m; $f = 10^9$ Hz to 10^{12} Hz). Electromagnetic waves in this region also do not bounce off the ionosphere, but instead pass easily right through it. These waves can thus be used for communicating with devices far beyond the Earth's atmosphere, such as those sent to explore space.

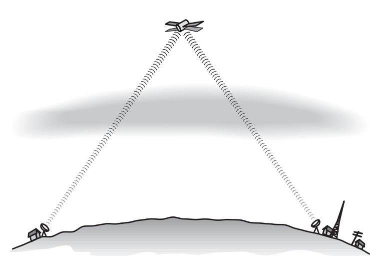


FIGURE 12.15 Satellites are used to relay microwaves all over the world. The microwaves can carry radio or TV information. (Not to scale.)

Microwave radiation also interacts strongly with the charged particles in ordinary matter, and thus has uses other than communication. When irradiated by microwaves, the matter absorbs the energy in the microwaves. This behavior is used in microwave ovens, in which the kinetic energy of the oscillating charges in food appears as heat, warming the food very quickly. Water, for example, readily absorbs radiation with a wavelength on the order of 10 cm. Thus, any moist substance placed in a region of intense microwave radiation of this wavelength (meat, soup, or a cake batter, for example) will become hot very quickly. Because the heat is generated within the substance itself, rather than conducted inward from the outside, foods can be cooked rapidly in a microwave oven. It is, however, important to keep the radiation confined to the oven because when such microwaves are emitted their radiation can damage living tissue.

Infrared radiation and the greenhouse effect (λ about 10^{-4} m to 10^{-6} m; f about 10^{12} Hz to 10^{14} Hz). Radiation in this region of the electromagnetic spectrum, just below the red end of the visible spectrum, is often called "thermal radiation," because it transmits heat. Because of the oscillation of charges within molecules due to heat energy, all warm objects, such as a glowing fireplace or warm-blooded creatures, emit infrared electromagnetic radiation. This is also how heat is transmitted from the Sun to the Earth, and it is one way in which living creatures can be detected at night by nocturnal predators or by humans using special "night vision" apparatus. Thus, warm objects and animals can be detected or photographed "in the dark" using infrared-sensitive equipment or film.

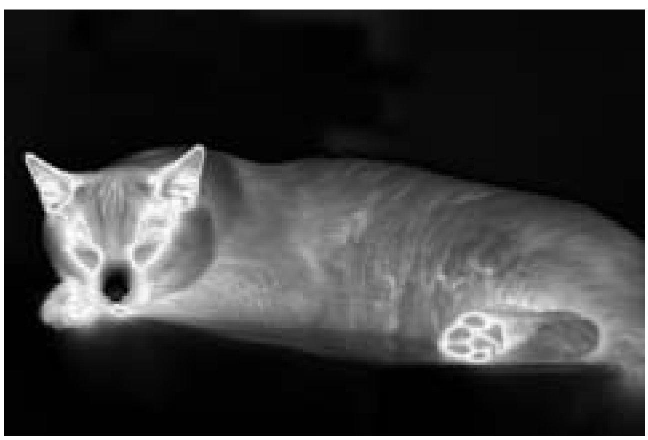


FIGURE 12.16 A photograph made with film sensitive only to infrared radiation.

In an actual greenhouse, the largest contribution to keep the interior heated is the reduction of convection, which is the same principle as used for wine-cooler jackets.

The environmental and technological problem of the phenomenon of *global warming* is associated with infrared radiation. Since the Earth is warmed by the Sun, the surface of the Earth also emits infrared radiation. Much of this radiation is dissipated into outer space, but some of it is naturally trapped by water vapor in the atmosphere. Like a blanket, the water vapor in the air reflects many of the infrared rays back to the Earth's surface, thus keeping the Earth's surface at just the right temperature for life to exist. This is known as the *greenhouse effect*, since greenhouses operate in the same way. The glass walls and roof of the greenhouse allow the Sun's visible rays to pass through, but they prevent the invisible infrared rays from escaping, thus warming the inside of the greenhouse where plants can grow year round. (You encounter the same effect when you leave the windows rolled up in a car parked in the sun.)

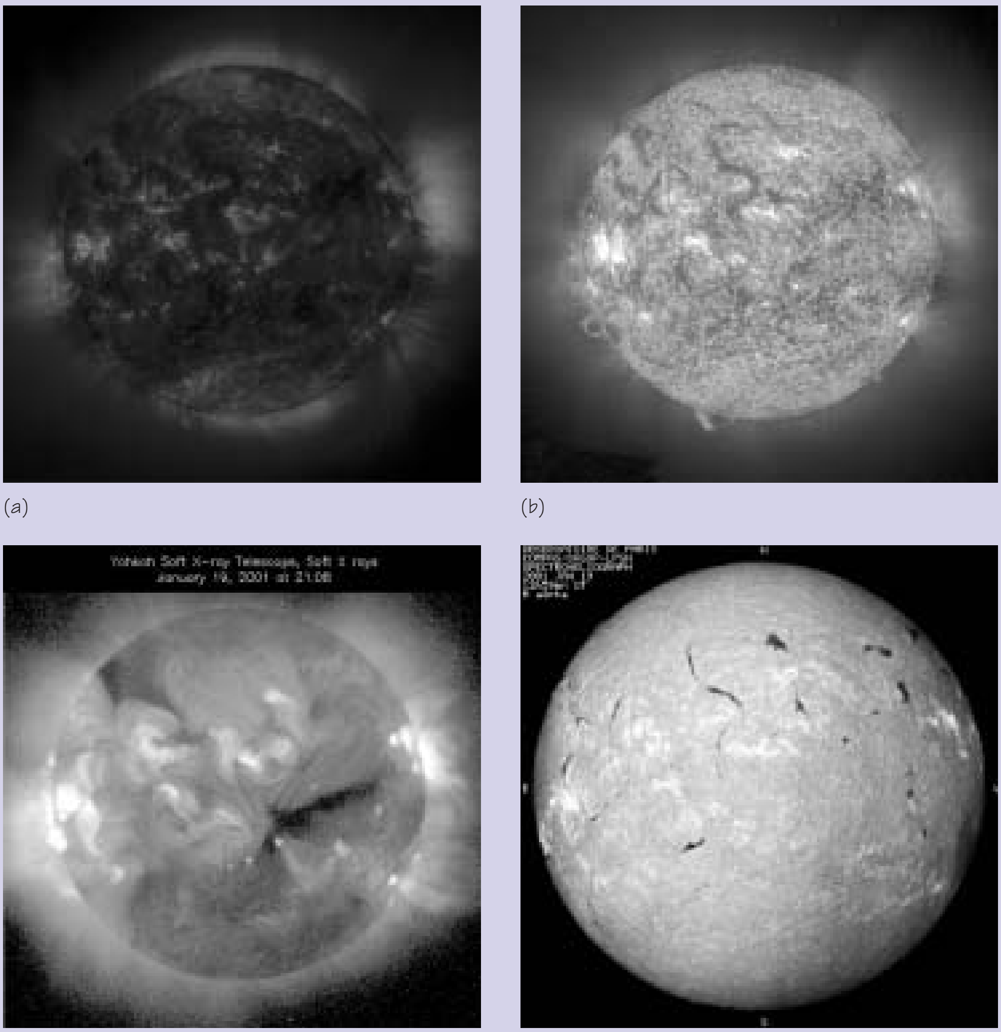
It has now been substantiated by scientists, including the U.S. National Academy of Sciences, that since the advent of the Industrial Revolution, much more of the infrared radiation emitted back into space by the Earth's surface is becoming trapped in the atmosphere by the gases produced through the burning of fossil fuels that run electric generators and transportation vehicles. The burning of these fuels produces carbon dioxide, sulfur dioxide, water vapor, and other gases and small particles. These gases allow the Sun's visible and ultraviolet rays to reach the ground, but reflect the infrared radiation emitted by the Earth's surface back to the Earth, keeping the infrared rays trapped in the atmosphere and thus causing global warming. (These gases also cause acid rain.)

This enhanced greenhouse effect accounts for an average rise in the Earth's temperature during the past century of only a degree or two Celsius, but scientists using computer models predict that this increase does have a major impact on the ecology on Earth, causing at different locations increased drought or rainfall, more powerful storms, and crop failures. They point to the fact that the average temperature of Earth during the last Ice Age was only about 5°C cooler than it is now. The unusual melting of glaciers and polar ice, the unusually warm winters and summers in recent decades, and the unusually large rainfalls and flooding around the world are signs of even more trouble ahead unless the burning of fossil fuels is curtailed.

During the 1990s a series of international meetings occurred in order to find a way to reduce the emission of "greenhouse gases." Unfortunately, the nations of the world could not agree because of economic reasons. The developing nations do not want to limit their growth, especially after the developed nations had already achieved their growth without limiting their

ASTRONOMY ACROSS THE SPECTRUM

The electromagnetic spectrum comprises more than the rainbow effect produced by passing white light through a prism. Electromagnetic radiation of different wavelengths provides different kinds of information. You are familiar with the effects of various parts of the spectrum: sunburn (ultraviolet rays) (a), visible light (d), heat (infrared) (b) and x rays (c). Scientists make use of electromagnetic radiations in such fields as astronomy, earth and life sciences, and communications.



(a) (b) (c) (d)

FIGURE 12.17

emissions. Some politicians and industrialists in the United States, the world's largest economy and thus the largest producer of greenhouse gases, feared the possible economic consequences of agreeing to a suggested 20% reduction in greenhouse-gas emissions by the year 2010. Further natural catastrophes related to possible climate change, and further evidence of global warming, may yet encourage the nations of the world to view the reduction in greenhouse gases as probably the better economic choice. In addition, it has been argued that the investment in devices and engines made to reduce the emission of "greenhouse gases" would stimulate the economy in a major way.

Visible light ($\lambda = 7 \times 10^{-7}$ m to 4×10^{-7} m; $f = 4 \times 10^{14}$ Hz to 8×10^{14} Hz). This small band of frequencies is known as visible light because the visual receptors in the human eye are sensitive only to these frequencies. If light within this band of frequencies is sent through a glass prism or through the raindrops in a cloud, it can be broken down into its constituent frequencies, which are observed by the human eye as the colors of the rainbow. These colors range from red at the low-frequency end (4×10^{14} Hz) to violet at the high-frequency end (8×10^{14} Hz). The main colors, in order, are: red, orange, yellow, green, blue, indigo, and violet (which may be remembered by the acronym ROY G BIV). (See Chapter 8, for more on the behavior of visible light.)

The visible-light frequencies are those at which the Sun copiously radiates energy. In the course of evolution, the human eye has taken advantage of light in that region. In the struggle for survival, humans have evolved as day creatures. However, many nocturnal predators, including cats, dogs, and some marsupials have developed the ability to use small amounts of visible light for night vision, and some are even able to see into the infrared region of light, which is invisible to human eyes.

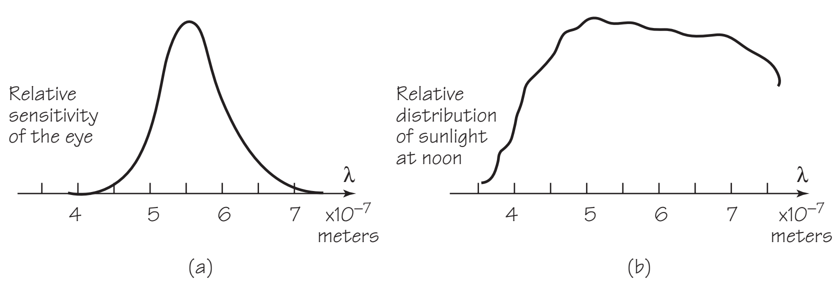


FIGURE 12.18 Sunlight and eye sensitivity versus wavelength.

Ultraviolet waves and ozone depletion (λ about 10^{-7} m to 10^{-8} m; *f* about 10^{15} Hz to 10^{16} Hz). Electromagnetic waves above the visible range—ultraviolet, X rays, and gamma rays—can damage living tissue, and some can cause cancer and genetic mutations. Although X rays and gamma rays occur naturally in our environment, they are much less abundant than ultraviolet rays, which are contained in the Sun's rays. Fortunately, a layer in the Earth's atmosphere provides some protection against the Sun's damaging ultraviolet rays. This layer contains a molecule called "ozone," a rare form of oxygen.

Normally two oxygen atoms chemically join to form a stable molecule, O_2. However, under certain circumstances, such as those caused by lightning, three oxygen atoms join together loosely to form the molecule, O_3, which is called ozone. At ground level, when ozone combines with exhaust from automobiles or other engines on a hot day, it produces smog that has serious health hazards. However, high in the atmosphere it forms a protection against ultraviolet rays. This molecule vibrates at the frequency of ultraviolet rays and can thus absorb or reflect these rays from the Sun back into space.

Unfortunately, man-made chemicals, widely used in industry, known as CFCs (chlorofluorocarbons), have been destroying the ozone layer since the 1930s, creating an "ozone hole" and allowing more of the damaging ultraviolet rays to reach the Earth's surface. This has caused a noticeable increase in skin cancers and eye cataracts in people, and the endangerment of some sea creatures and crops.

CFCs were developed in the 1930s for use as a coolant in refrigerators and air conditioners, and as a propellant in aerosol sprays. When used for these purposes under normal circumstances CFCs are essentially inert and very stable. Thus they seemed like ideal insulators, coolants, and propellants. However, during the 1980s it was discovered that when CFCs reach the upper atmosphere the chlorine in these molecules destroys ozone molecules in the atmosphere by taking away one of the three oxygen atoms, leaving ordinary oxygen, O_2, behind. Ultraviolet rays then break up the chlorine and oxygen, freeing the chlorine ion to destroy another ozone molecule. One chlorine ion can destroy thousands of ozone molecules. Studies at both the North and South poles of the Earth indicate that the destruction of ozone is worldwide.

The world reaction to the dangerous ozone depletion has been quite different to this problem compared with the reaction to global warming. This is mainly because the chemical industry had found a replacement for CFCs which would not cause any significant economic difficulty. The result was an international treaty that banned the production and sale of CFCs by

2000. Nevertheless, the chlorine already in the atmosphere can continue the destruction of the ozone layer for several decades. The result has been a steady increase in harmful effects of ultraviolet radiation. These effects are predicted to continue for decades to come until most of the chlorine previously emitted into the atmosphere is finally rendered harmless. In the meantime, physicians recommend that in open sunlight everyone wear sunglasses that actually filter out ultraviolet rays (in all forms), and not to stay in the Sun without wearing a hat and applying sunblock lotions to exposed skin.

X rays ($\lambda = 10^{-8}$ m to 10^{-17} m; $f = 10^{16}$ Hz to 10^{25} Hz). Atoms emit X radiation when electrons undergo transitions between the inner shells of the atoms. X rays are also produced by the sudden deflection or stopping of electrons when they strike a metal target. The maximum frequency of the radiation generated is determined by the energy with which the electrons strike the target. In turn, this energy is determined by the voltage through which the electrons are accelerated. So the maximum frequency increases with the accelerating voltage. The higher the frequency of the X rays, the greater is their power to penetrate matter. But the distance of penetration also depends on the nature of the material being penetrated. X rays are readily absorbed by bone, which contains calcium, while they pass much more easily through less dense organic matter such as flesh, which contains mainly the light atoms: hydrogen, carbon, and oxygen.

These properties of X rays, combined with their ability to affect a photographic plate, have led to some of the spectacular medical uses of X-ray

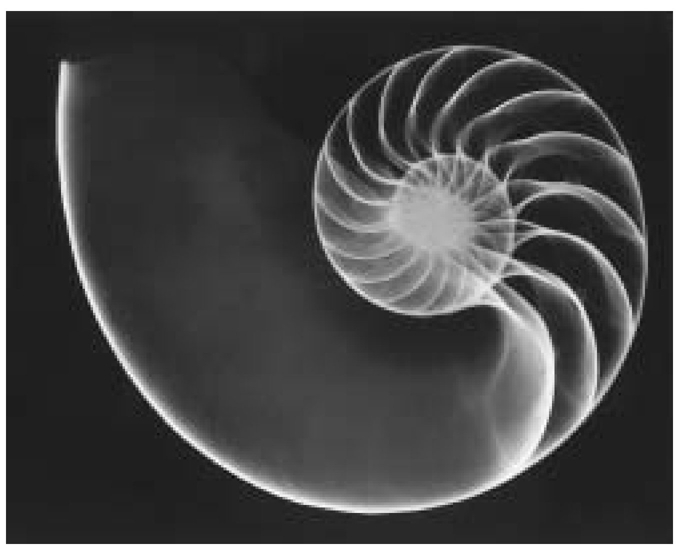


FIGURE 12.19 X-ray photograph of chambered nautilus sea shell.

photography. Because X rays can damage living cells and even cause genetic mutations, they have to be used with great caution and only by trained technicians. Since some kinds of diseased cells are injured more easily by X rays than are healthy cells, a carefully controlled X ray beam is sometimes used to destroy cancerous growths or other harmful cells.

X rays produce interference effects when they fall on a crystal in which atoms and molecules are arranged in a regular pattern. Different portions of the incident beam of X rays are reflected or diffracted from different planes of atoms in the crystal structure. These reflected rays can interfere constructively, and this fact can be used in either of two ways. If the spacing of the atoms in the crystal is known, the wavelength of the X rays can be calculated. Conversely, if the X ray wavelength is known, the distance between crystal planes, and thus the structure of the crystal, can be determined. X rays are now widely used by chemists, physicists, mineralogists, and biologists in studying the structure of crystals and complex molecules. (You will encounter these ideas again in Chapter 13.)

Gamma rays ($\lambda = 10^{-17}$ m and smaller; $f = 10^{25}$ Hz and higher). The gamma-ray region of the electromagnetic spectrum overlaps the X ray region. Gamma radiation is emitted mainly by the unstable nuclei of natural or artificial radioactive materials. They are also a component of so-called cosmic radiation, radiation streaming to the Earth from outer space. Gamma

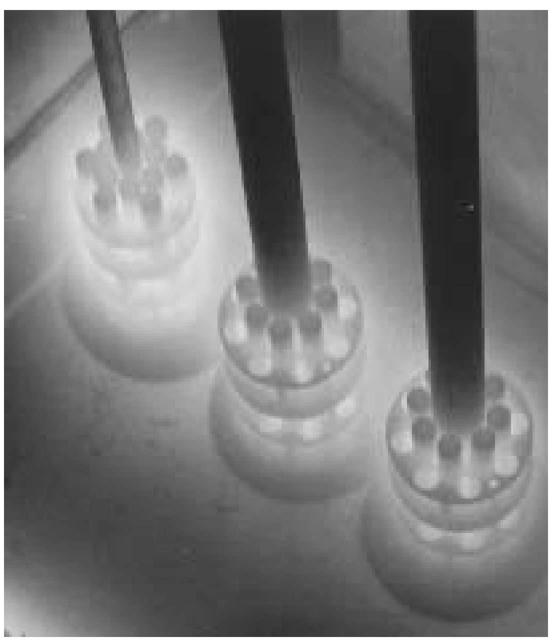


FIGURE 12.20 Čerenkov radiation in reactor. The glow in the photograph is caused when gamma rays emitted by radioactive cobalt cylinders interact with the surrounding pool of water.

rays are the most energetic radiation known, and, in cosmic radiation, they are produced by the most energy-intensive events in the Universe—the explosions of supernovae and other cataclysmic events. Many of the cosmic events that produce the observed gamma rays are not well understood. A series of gamma-ray sensitive satellites is presently studying these events. (You will learn more about gamma rays in Chapter 17.)

12.6 WHAT ABOUT THE ETHER NOW?

The "luminiferous ether" had been proposed specifically as a medium for the propagation of light waves. Maxwell found that the ether could also be thought of as a medium for transmitting electric and magnetic forces. Later, he realized that he could drop his specific model of the ether entirely if he focused on the mathematical form of the theory. Yet, just before his death in 1879, Maxwell wrote an article in which he still supported the ether (or aether) concept:

> Whatever difficulties we may have in forming a consistent idea of the constitution of the aether, there can be no doubt that the interplanetary and interstellar spaces are not empty, but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform body of which we have any knowledge. . . .

Maxwell was aware of the failures of earlier ether theories. Near the beginning of the same article he said:

> Aethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, till all space had been filled three or four times over with aethers. It is only when we remember the extensive and mischievous influence on science which hypotheses about aethers used formerly to exercise, that we can appreciate the horror of aethers which sober-minded men had during the 18th century. . . .

Maxwell had formulated his electromagnetic theory mathematically, independent of any particular model of the ether. Why, then, did he continue to speak of the "great ocean of aether" filling all space? It seemed unthinkable to Maxwell that there could be vibrations without something that vibrates, or waves without a medium. Also, to many nineteenth-century physicists the idea of “action at a distance” seemed absurd. How could one object exert a force on another body far away if something did not transmit the force? One body is said to act *on* another, and the word *on* gives the idea of contact. Thus, according to accepted ways of describing the world in common language, the ether seemed somehow necessary.

Yet 25 years after Maxwell’s death the ether concept had lost much of its support. Within another decade, it had vanished from the collection of useful concepts. In part, the success of Maxwell’s theory itself helped to undermine the general belief in the existence of an ether, simply because his equations did not depend on details of the ether’s structure. In fact, they could be taken to describe the relations between changes of electric and magnetic fields in space without any reference to the ether at all.

FIGURE 12.21 In this chapter, you have read about how mechanical models of light and electromagnetism faded away, leaving a model-less, mathematical (and therefore abstract) field theory. The situation has been likened to Lewis Carroll’s Cheshire Cat, which disappears leaving only its grin behind (illustration by John Tenniel).

Another difficulty with belief in the ether was that all attempts to detect the motion of the Earth relative to the ether failed (see Chapter 9). If light is a kind of vibration of an ether that fills all space, then light should travel at a definite speed relative to the ether. But the Earth must also be moving through the ether in its annual orbit around the Sun. Thus, the Earth should be moving like a ship, against an "ether wind" at some times, and with it at other times. Under these conditions, the apparent speed of light should be observed to differ. When the Earth and a beam of light are moving in the same direction through the ether, the observed speed of light should not be the same as when the Earth and the light are moving in opposite directions.

Theorists computed the time required for a pulse of light to make a round trip in a laboratory with and against the ether wind. They compared this interval with the time calculated for a round trip in the absence of an ether wind. The expected time difference was found to be very small; only 10^{-15} s for a round trip of 30 m. This is too short a time difference to measure directly, but it is of the same order as the time for one vibration of visible light. Therefore, the difference might be detected from observations of a properly produced interference pattern. In 1887, the American scientists Albert A. Michelson and Edward Morley used a device sensitive enough to detect an effect only 1% as great as that predicted by the ether theory. Neither this experiment nor the many similar experiments done since then have revealed the existence or expected effects of an ether wind.

Supporters of the ether concept offered various explanations for this unexpected result. For example, they suggested that objects moving at high speeds relative to the ether might change their size in just such a way as to make this relative speed undetectable. But even those who made such attempts to rescue the ether concept felt their proposals to be "ad hoc," forced, and artificial. Finally, a decisive development led scientists to abandon the ether concept. This breakthrough was not a specific experiment, but a brilliant proposal by a 26-year-old man.

The man was Albert Einstein, who, as discussed in Chapter 9, suggested that a new and deep union of mechanics and electromagnetism could be achieved without the ether model, on the basis of the two fundamental postulates of relativity theory: the relativity principle and the constancy of the speed of light. The price of accepting these postulates was, Einstein showed, the necessity of revising some common-sense notions of space and time. Einstein showed that Maxwell's equations are fully consistent with extending the principle of relativity to all physics. This was yet another great synthesis of previously separate ideas, like the syntheses forged by Copernicus, Newton, and Maxwell.

SOME NEW IDEAS AND CONCEPTS

classical physics
displacement current
electromagnetic spectrum
electromagnetic wave
global warming
greenhouse effect
ionosphere
ozone
spectrum
visible spectrum

FURTHER READING

R. Buderi, *The Invention that Changed the World* [Radar]. Sloan Technology Series (New York: Touchstone Books, 1998).
G. Cantor, D. Gooding, F.A. Frank, and J.L. James, *Michael Faraday* (Atlantic Highlands, NJ: Humanity Books, 1996).
D. Park, *The Fire within the Eye: A Historical Essay on the Nature and Meaning of Light* (Princeton: Princeton University Press, 1997).
C. Susskind, *Heinrich Hertz: A Short Life* (San Francisco: San Francisco Press, 1995).

STUDY GUIDE QUESTIONS

12.1 Faraday's Suggestion

1. What did Faraday suggest?
2. What was the motivation for this suggestion?

12.2 Maxwell's Principles of Electromagnetism

1. When there is a changing electric field, what else occurs (according to Maxwell)?
2. What is a displacement current?
3. What are the four principles of electromagnetism?

12.3 The Propagation of Electromagnetic Waves

1. What is an electromagnetic wave?
2. How is an electromagnetic wave formed?
3. What discovery did Maxwell make when he calculated the speed that electromagnetic waves should travel?
4. What did Maxwell infer from this result?
5. What is Maxwell's synthesis?
6. What is classical physics? Is it still valid today? Under what circumstances are revisions required?

12.4 Hertz's Experimental Confirmation

1. What predictions of Maxwell's did Hertz verify?
2. What did Hertz use as a detector of electromagnetic waves?
3. How does visible light fit into Maxwell's theory?
4. How do Faraday, Maxwell, and Hertz represent the stages we often observe in the formation of a new theory in science?

12.5 The Electromagnetic Spectrum

1. What is the electromagnetic spectrum and how does it differ from the visible spectrum?
2. List the types of electromagnetic waves discussed in this section. For each one, indicate where it is on the electromagnetic spectrum, and describe a use, or social impact, or technological application.
3. Why do ordinary radio waves not cast noticeable "shadows" behind such obstacles as trees or small buildings?
4. Why are satellites required for TV transmission over long distances, while some radio waves can be heard at great distances from the source?
5. How is the frequency of X rays related to their penetration of matter?
6. How do the wavelengths used in radar compare with the wavelengths of visible light?
7. What is global warming and why is it occurring, according to most scientists?
8. Why is global ozone depletion a cause for concern?
9. How does ozone depletion occur?
10. How have the nations of the world responded to each of these crises, and what is the reason for any difference?

12.6 What About the Ether Now?

1. Why did Maxwell (and others) adhere for a time to the concept of an ether?
2. Whose argument finally showed that the ether was an unnecessary hypothesis?
3. Did the demise of the ether idea lead to a demise of Maxwell's theory? Explain.

DISCOVERY QUESTIONS

1. A current in a conductor can be caused by a steady electric field. Can a displacement current in an insulator be similarly caused? Explain your answer briefly.
2. What is the "disturbance" that travels in each of the following waves?
   (a) water waves?
   (b) sound waves?
   (c) electromagnetic waves?

3. In Hertz's detector, it is the electric fieldstrength in the neighborhood of the wire that makes the sparks jump. How was Hertz able to show that the waves from the induction-coil-spark gap were polarized?
4. What evidence did Hertz obtain that his induction-coil-generated waves have many properties similar to visible light waves?
5. Give several factors that contributed to the 25-year delay in the general acceptance by scientists of Maxwell's electromagnetic wave theory.
6. What evidence is there for believing that electromagnetic waves carry energy? Does this suggest why the early particle theory of light had some success?
7. You are listening to a radio station while driving in a car when you notice something strange. The radio signal fades out at some points along the road, and later returns to the previous level. What is happening?
8. Examine the wavelengths and frequencies of several different electromagnetic waves. You may notice that as the frequency increases, the wavelength decreases. Why is this so?
9. Why must there be some federal control of the broadcast power, frequency, and direction of signals emitted by radio and TV stations, but no such controls on the distribution of newspapers and magazines?
10. If there are extraterrestrial beings of advanced civilizations, what method for gathering information about Earth-people might they have? Conversely, why is it far more probable that any contact with an extraterrestrial civilization, if it exists, will be made by receiving electromagnetic signals from it rather than actual "visits"?
11. Some scientists have been speculating about setting up an Earth colony on Mars. Mars is not hospitable to human life, but it does have a lot of direct sunlight which is not filtered much by the thin atmosphere there. How could the colonists make use of the sunlight to create a habitable environment? How could they protect themselves from some of the dangers of direct sunlight?
12. Why do you think the human eye is sensitive to the range of light wavelengths to which it is actually sensitive?
13. A sensitive thermometer placed in different parts of the visible light spectrum formed by a quartz prism will show a rise in temperature. This proves that all colors of light produce heat when absorbed. But the thermometer also shows an increase in temperature when it is placed in either of the two dark regions to either side of the end of the visible spectrum. Why is this?
14. During the eighteenth century many scientists were fascinated by what seemed to them a strange phenomenon. In their laboratory was the customary fireplace with a fire in it for warmth. A lens was located on a small table some distance across the room facing the fire. When a sheet of paper was placed behind the lens, the paper burst into flames, to the amazement of all who observed this. What was happening?
15. What was the principal reason for the loss of scientific support for the ether concept?
16. At many points in the history of science, the "natural" or common-sense way

of looking at things has changed greatly. Attitudes toward action-at-a-distance are a case in point. What are some other examples?

17. Can intuition be educated; that is, can feelings about the fundamental aspects of reality be changed? Use attitudes toward action-at-a-distance through the ether as one example, and give others.

Quantitative

1. An electron oscillating on an antenna produces an electromagnetic wave that vibrates at 10,000 Hz.
   (a) What are the wave's frequency, its period, and its wavelength?
   (b) What type of wave is this?
2. Obtain the frequency range of the FM dial on a radio. What is the corresponding range of wavelengths of the FM waves received by the radio?
3. How much time would elapse between the sending of a radar signal from the Earth to the Moon and the detection of its echo on Earth?