The Project Physics Course

Text and Handbook **4**

Light and Electromagnetism

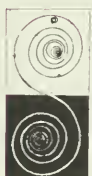# The Project Physics Course

Text and Handbook

UNIT **4** **Light and Electromagnetism**

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This Text and Handbook, Unit 4, is one of the
many instructional materials developed for the
Project Physics Course. These materials include
Texts, Handbooks, Teacher Resource Books,
Readers, Programmed Instruction Booklets, Film
Loops, Transparencies, 16mm films, and laboratory
equipment.

Acknowledgments, Text Section

P. 104 Maxwell, James Clerk, *The Scientific Papers of James Clerk Maxwell*, ed., Niven, W. D., Dover Publications, N.Y., 1965, p. 158.

P. 110 Maxwell, James Clerk, *The Scientific Papers of James Clerk Maxwell*, ed., Niven, W. D., Dover Publications, N.Y., 1965, p. 500.

P. 121 Maxwell, James Clerk, *The Scientific Papers of James Clerk Maxwell*, ed., Niven, W. D., Dover Publications, N.Y., 1965, p. 775 of Vol. II.

P. 121 Maxwell, James Clerk, *The Scientific Papers of James Clerk Maxwell*, ed., Niven, W. D., Dover Publications, N.Y., 1965, p. 763 of Vol. II.

P. 125 Carroll, Lewis, *The Complete Works of Lewis Carroll*, Random House, N.Y., 1939, pp. 66-67.

Pp. 126-127 Feynman, R. P., *The Feynman Lectures on Physics*, Feynman, R. P., Leighton, R. B., and Sands, M., Vol. 2, Addison-Wesley, 1964, pp. 9-10.

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Partial List of Staff and Consultants

The individuals listed below (and on the following pages) have each contributed in some way to the development of the course materials. Their periods of participation ranged from brief consultations to full-time involvement in the team for several years. The affiliations indicated are those just prior to or during the period of participation.

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Science is an adventure of the whole human race to learn to live in and perhaps to love the universe in which they are. To be a part of it is to understand, to understand oneself, to begin to feel that there is a capacity within man far beyond what he felt he had, of an infinite extension of human possibilities . . .

I propose that science be taught at whatever level, from the lowest to the highest, in the humanistic way. It should be taught with a certain historical understanding, with a certain philosophical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations.

I. I. RABI
Nobel Laureate in Physics

Preface

Background   The Project Physics Course is based on the ideas and research of a national curriculum development project that worked in three phases. First, the authors—a high school physics teacher, a university physicist, and a professor of science education—collaborated to lay out the main goals and topics of a new introductory physics course. They worked together from 1962 to 1964 with financial support from the Carnegie Corporation of New York, and the first version of the text was tried out in two schools with encouraging results.

These preliminary results led to the second phase of the Project when a series of major grants were obtained from the U.S. Office of Education and the National Science Foundation, starting in 1964. Invaluable additional financial support was also provided by the Ford Foundation, the Alfred P. Sloan Foundation, the Carnegie Corporation, and Harvard University. A large number of collaborators were brought together from all parts of the nation, and the group worked together for over four years under the title *Harvard Project Physics*. At the Project's center, located at Harvard University, Cambridge, Massachusetts, the staff and consultants included college and high school physics teachers, astronomers, chemists, historians and philosophers of science, science educators, psychologists, evaluation specialists, engineers, film makers, artists and graphic designers. The teachers serving as field consultants and the students in the trial classes were also of vital importance to the success of Harvard Project Physics. As each successive experimental version of the course was developed, it was tried out in schools throughout the United States and Canada. The teachers and students in those schools reported their criticisms and suggestions to the staff in Cambridge, and these reports became the basis for the subsequent revisions of the course materials. In the Preface to Unit 1 *Text* you will find a list of the major aims of the course.

We wish it were possible to list in detail the contributions of each person who participated in some part of Harvard Project Physics. Unhappily it is not feasible, since most staff members worked on a variety of materials and had multiple responsibilities. Furthermore, every text chapter, experiment, piece of apparatus, film or other item in the experimental program benefitted from the contributions of a great many people. On the preceding pages is a partial list of contributors to Harvard Project Physics. There were, in fact, many other contributors too numerous to mention. These include school administrators in participating schools, directors and staff members of training institutes for teachers, teachers who tried the course after the evaluation year, and most of all the thousands of students who not only agreed to take the experimental version of the course, but who were also willing to appraise it critically and contribute their opinions and suggestions.

The Project Physics Course Today. Using the last of the experimental versions of the course developed by Harvard Project Physics in 1964–68 as a starting point, and taking into account the evaluation results from the tryouts, the three original collaborators set out to develop the version suitable for large-scale publication. We take particular pleasure in acknowledging the assistance of Dr. Andrew Ahlgren of Harvard University. Dr. Ahlgren was invaluable because of his skill as a physics teacher, his editorial talent, his versatility and energy, and above all, his commitment to the goals of Harvard Project Physics.

We would also especially like to thank Miss Joan Laws whose administrative skills, dependability, and thoughtfulness contributed so much to our work. The publisher, Holt, Rinehart and Winston, Inc. of New York, provided the coordination, editorial support, and general backing necessary to the large undertaking of preparing the final version of all components of the Project Physics Course, including texts, laboratory apparatus, films, etc. Damon, a company located in Needham, Massachusetts, worked closely with us to improve the engineering design of the laboratory apparatus and to see that it was properly integrated into the program.

In the years ahead, the learning materials of the Project Physics Course will be revised as often as is necessary to remove remaining ambiguities, clarify instructions, and to continue to make the materials more interesting and relevant to students. We therefore urge all students and teachers who use this course to send to us (in care of Holt, Rinehart and Winston, Inc., 383 Madison Avenue, New York, New York 10017) any criticism or suggestions they may have.

F. James Rutherford
Gerald Holton
Fletcher G. Watson

Contents TEXT SECTION

It was inconceivable to many scientists that one body could directly affect another across empty space. They devised a variety of schemes to fill the space in between with something that would transmit the effect first with material "ether,"—later with mathematical "fields." Some of these schemes are illustrated on this page. Descartes, 17th century (bottom left); Euler, 18th century (top left); Maxwell, 19th century (top right). Above is a drawing copied from *The New York Times* (1967) representing the magnetic field around the earth. It is not the more symmetrical field the earth would have on its own, but as disturbed by the field due to streams of charged particles from the sun.

UNIT **4**

Light and Electromagnetism

PROLOGUE   The conviction that the world, and all that is in it,
consist of *matter in motion* drove scientists to search for mechanical
models that could account for light and electromagnetism. That is, they
tried to imagine how the effects of light, electricity, and magnetism
could be explained in detail as the action of some material objects.
(For example, the way light bounces off a mirror might be understood
if one imagines light to consist of particles that have some properties
similar to those of little balls.) Such mechanical models were useful for
a while, but in the long run had to be given up as far too limited. This
search, what was discovered, and the changes these discoveries
initiated in science — in technology and in society — form the subject
of this unit. In this Prologue we sketch the development of some of
these models and briefly indicate the effect of these developments on
our present ideas of the physical world.

From the seventeenth century on there were two competing models
for light, one depicting light as particles, the other depicting light as
waves. In the first half of the nineteenth century the wave model won
general acceptance, because it was better able to account for newly
discovered optical effects. Chapter 13 tells the story of the triumph of
the wave theory of light. The wave theory maintained its supremacy
until the early part of the twentieth century, when it was found (as we
shall see in Unit 5) that neither waves nor particles alone were sufficient
to account for all the behavior of light.

As experiments established that electric and magnetic forces have
some characteristics in common with gravitational forces, theories of
electricity and magnetism were developed which were modeled on
Newton's treatment of gravitation. The assumption that there are forces
between electrified and magnetized bodies which vary inversely with

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the square of the distance was found to account for many observations. The drafters of these theories assumed that bodies can exert forces over a distance without the necessity for one body to touch another.

Although action at-a-distance theories were remarkably successful in providing a quantitative explanation for some aspects of electromagnetism, these theories did not at the time provide a comprehensive explanation. Instead, the means of description that became widely accepted by the end of the nineteenth century, and that is now generally believed to be the best way to discuss *all* physical forces, is based on the idea of *fields*, an idea that we introduce in Chapter 14 and develop further in the last chapter of the unit.

Many scientists felt that action-at-a-distance theories, however accurate in prediction, failed to give a satisfactory physical explanation for how one body exerts a force on another. Newton himself was reluctant to assume that one body can act on another through empty space. In a letter to Richard Bentley he wrote:

> Tis unconceivable to me that inanimate brute matter should (without the meditation of something else wch is not material) operate upon & affect other matter without mutual contact; . . . And this is one reason why I desire you would not ascribe innate gravity to me. That gravity should be innate inherent & essential to matter so yt one body may act upon another at a distance through a vacuum wthout the mediation of any thing else by & through wch their action or force may be conveyed from one point to another is to me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it.

Some seventeenth-century scientists, less cautious in their published speculations than Newton was, proposed that objects are surrounded by atmospheres that extend to the most distant regions and serve to transmit gravitational, electric and magnetic forces from one body to another. The atmospheres proposed at this time were not made a part of a quantitative theory. In the nineteenth century, when the idea of an all-pervading atmosphere was revived, numerous attempts were made to develop mathematically the properties of a medium that would transmit the waves of light. The name "luminiferous ether" was given to this hypothetical "light-bearing" substance.

The rapid discovery of new electrical and magnetic effects in the first half of the nineteenth century acted as a strong stimulus to scientific imagination. Michael Faraday (1791-1867), who made many of the important discoveries, developed a model with assigned lines of force to the space surrounding electrified and magnetized bodies. Faraday showed how these lines of force could be used to account for many electromagnetic effects.

In a paper he wrote at age 17, William Thomson (1824-1907) showed how the equations used to formulate and solve a problem in electrostatics, could also be used to solve a problem in the flow of heat. At that time electrostatics was most simply and effectively treated by

considering that electrical forces can act at a distance, while the flow of heat was generally held to result from the action of parts that touch. With this paper Thomson showed that the same mathematical formulation could be used for theories based on completely different physical assumptions. Perhaps, then, it was more important to find correct mathematical tools than it was to choose a particular mechanical model.

James Clerk Maxwell (1831-1879), inspired by Faraday's physical models and by Thomson's mathematical demonstrations, undertook the task of developing a mathematical theory of electromagnetism. From the assumption of an imaginary ether filled with gears and idler wheels, Maxwell gradually worked his way to a set of equations that described the properties of electric and magnetic fields. These equations were later found to be remarkably successful. Not only did the equations describe accurately the electric and magnetic effects already known to occur, but they led Maxwell to predict new effects based on the idea of a propagating wave disturbance in electric and magnetic fields. The speed he predicted from such electromagnetic waves was nearly the same as the measured speed of light, which suggested to him that light might *be* an electromagnetic wave.

The field concept, in conjunction with the concept of energy, provides a way of treating the action of one body on another without speaking of action at a distance or of a material medium that transmits the action from one body to another. The concept of a field has proved its utility over and over again during the twentieth century.

Radio telescope at the National Radio Astronomy Observatory, Greenbank, West Virginia.

Light

13.1 Introduction

What is light? At first glance, this may seem to be a rather trivial question. After all, there is hardly anything that is more familiar to us. We see by means of light. We also live by light, for without it there would be no photosynthesis, and photosynthesis is the basic source of energy for most forms of life on earth. Light is the messenger which brings us most of our information about the world around us, both on the earth and out to the most distant reaches of space. Because our world is largely defined by light, we have always been fascinated by its behavior. How fast does it travel? How does it travel across empty space? What is color?

To the physicist, light is a form of energy. He can describe light by measurable values of speed, wavelengths or frequencies, and intensity of the beam. To him, as to all people, light also means brightness and shade, the beauty of summer flowers and fall foliage, of red sunsets and of the canvases painted by masters. These are different ways of appreciating light: one way is to regard its measurable aspects – which has been enormously fruitful in physics and in technology. The other is to ask about the aesthetic responses in us when we view the production of light in nature or art. Still another way of considering light is in terms of the bio-physical process of vision.

Because these aspects of light are not easily separated, problems raised about light in the early history of science were more subtle and more elusive than those associated with most other aspects of our physical experience. Early ideas on its nature were confused by a failure to distinguish between light and vision. This confusion is still evident in young children. When playing hide-and-go-seek, some of them "hide" by covering their eyes with their hands; apparently they think that they cannot be seen when they cannot see. The association of vision with light persists into the language of the adult world. We talk about the sun "peeping out of the clouds" or the stars "looking down."

SG 13.1

Some of the Greek philosophers believed that light travels in straight lines at high speed, and that it contains particles which stimulate the sense of vision when they enter the eye. For centuries after the Greek era, during which limited attention was paid to the nature of light, the particle model persisted. However, around 1500 Leonardo da Vinci, noting a similarity between sound echoes and the reflection of light, speculated that light might have a wave character.

A decided difference of opinion emerged among scientists of the seventeenth century about the nature of light. Some, including Newton, favored a model largely based on the idea of light as a stream of particles. Others, including Huygens, supported a wave model. By the late nineteenth century, however, there appeared to be overwhelming evidence that the observed characteristics of light could be explained by assuming that it had the nature of a wave motion; that is, by assuming a wave model. In this chapter we shall look at the question *How appropriate is a wave model in explaining the observed behavior of light?* That is, we shall take the wave model as a hypothesis, and examine the evidence that supports it. We must bear in mind that any scientific model, hypothesis or theory has two chief functions—to explain what is known, and to make predictions that can be subjected to experimental test. We shall look at both of these aspects of the wave model. The result will be very curious. The wave model turns out to work splendidly for all the properties of light known before the twentieth century. But in Chapter 18 we will find that for some purposes we must adopt a particle model. Then in Chapter 20 we will combine *both* models, joining together two apparently opposite theories.

We have already mentioned the ancient opinion—later proved by experiment—that light travels in straight lines and at high speed. Our daily use of mirrors convinced us that light can also be reflected. There are other characteristics of light—for example, it can be refracted, and it shows the phenomena of interference and diffraction. All of these properties you have studied earlier, when looking at the behavior of waves in Chapter 12. If necessary, it would therefore be well to refresh your memory about the basic ideas of that chapter before going on to the study of light. We shall, however, look also at some other phenomena—dispersion, polarization and scattering—which so far we have given little or no consideration. As we shall see, these also will fit into our wave model, and in fact will constitute strong experimental support for it.

Before going on to a discussion of these various characteristics of light's behavior and how they provide evidence in support of our hypothesis of a wave model for light, we shall first consider the propagation of light and two characteristics—reflection and refraction—which can be explained by both a corpuscular (particle) model and a wave model. The discussion in this text must, of course, be supplemented by experiments in your laboratory session

Light beams travel in straight lines
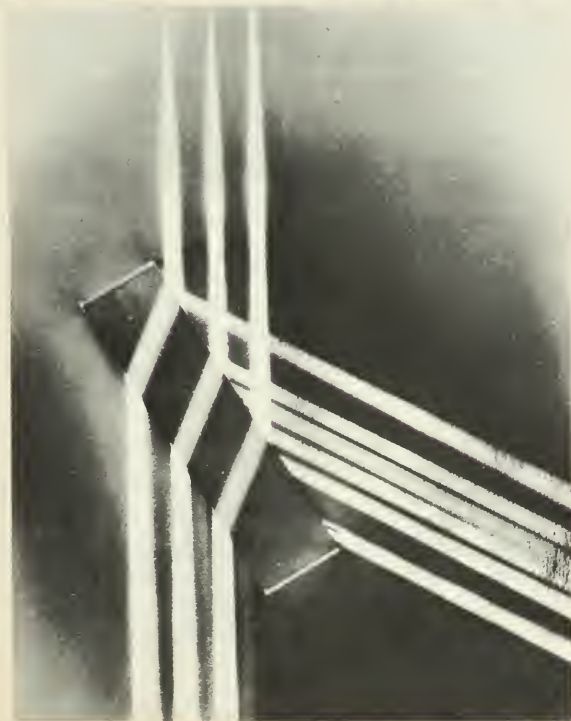
and wherever possible also by activities, selections from the readers, films and loops, transparencies, etc.

Indeed, this is a good moment to remind you of an important point: this course stresses the use of many media to learn physics. It therefore differs from many other courses with which you may be familiar, and which rely most heavily on a text only. In this course, on the contrary, the text will sometimes only motivate or put into context a part of the course that is much better learned by doing experiments, by class discussion etc., than by reading about them. This is particularly the case with optics, the science of light, and with electricity and magnetism – the subjects of Unit 4. This text will merely give a general map which you will fill out in a way that makes the study of physics more valid and exciting than reading alone.

13.2 Propagation of light

There is ample evidence that light travels in straight lines. The fact that one cannot see "around the corner" of an obstacle is one obvious example. The outline of a shadow cast by the sun is but one example of the sharply defined shadows cast by a large but very distant source. Similarly, sharp shadows are cast by a closer source of small dimensions. The distant sun or the nearby small source are approximate *point* sources of light; it is from such point sources that we get sharp shadows.

SG 13.2

Images as well as shadows can demonstrate that light travels in straight lines. Before the invention of the modern camera with its lens system, a light-tight box with a pinhole in the center of one face was widely used. As the *camera obscura,* the device was highly popular in the Middle Ages. Leonardo da Vinci probably used it as an aid in his sketching. In one of his manuscripts he says that "a small aperture in a window shutter projects on the inner wall of the room an image of the bodies which are beyond the aperture," and he includes a sketch to show how the straight-line propagation of light explains the formation of an image.
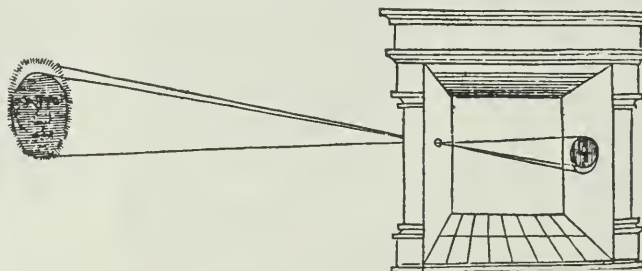
First published illustration of a *camera obscura*; observing a solar eclipse in January 1544, from a book by the Dutch physician and mathematician Gemma Frisius.

It is often convenient to use a straight line to represent the direction in which light travels. The convenient pictorial device of an infinitely thin *ray* of light is useful for thinking about light, but it does not correspond directly to anything that actually exists. A

light beam emerging from a good-sized hole in a screen is as wide
as the hole. You might expect that if we made the hole extremely
small we would get a very narrow beam of light—ultimately, just
a single ray. But we don't! Diffraction effects (such as you have
already observed for water and sound waves) appear when the
beam of light passes through a small hole (see below). So an
infinitely thin ray of light, although it is pictorially useful, cannot
be produced in practice. But we can still use the idea to represent
the direction in which a train of parallel waves is traveling.

An attempt to produce a "ray" of light. To make the pictures at the left, a parallel beam of red light was directed through increasingly narrow slits to a photographic plate. (Of course, the narrower the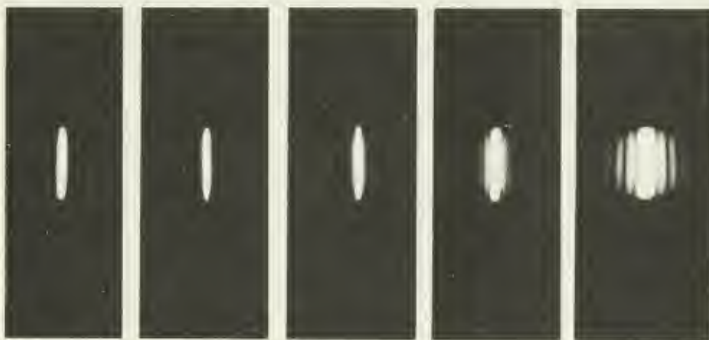 slit, the less the light that gets through. This was compensated for by longer exposures in these photographic exposures.) The slit widths, from left to right, were 1.5 mm, 0.7 mm, 0.4 mm, 0.2 mm, and 0.1 mm.

SG 13.3

Given that light seems to travel in straight lines, can we tell
how fast it goes? Galileo discussed this problem in his *Two New
Sciences* book (published 1638). He pointed out that everyday
experiences might lead us to conclude that the propagation of light
is instantaneous. But these experiences, when analyzed more
closely, really show only that light travels much faster than sound.
For example, "when we see a piece of artillery fired, at a great
distance, the flash reaches our eyes without lapse of time; but the
sound reaches the ear only after a noticeable interval." But how do
we really know whether the light moved "without lapse of time"
unless we have some accurate way of measuring the lapse of time?

Galileo then described an experiment by which the speed of
light might be measured by two persons on distant hills flashing
lanterns. (This experiment is to be analyzed in SG 13.4.) He
concluded that the speed of light is probably finite, not infinite, but
he was not able to estimate a definite value for it.

SG 13.4

Experimental evidence was first successfully related to a finite
speed for light by a Danish astronomer, Ole Römer. Detailed
observations of Jupiter's satellites had shown an unexplained
irregularity in the times between eclipse of the satellite by Jupiter's
disk. In September of 1676, Römer announced to the Academy of
Sciences in Paris that the eclipse of a satellite of Jupiter, which was
expected to occur at 45 seconds after 5:25 a.m. on the ninth of
November, would be ten minutes late. On November 9, 1676,
astronomers at the Royal Observatory in Paris, though skeptical of
Römer's mysterious prediction, made careful observations of the
eclipse and reported that it did occur late, just as Römer had
predicted.

Later, Römer revealed the theoretical basis of his prediction to the baffled astronomers at the Academy of Sciences. He explained that the originally expected time of the eclipse had been calculated on the basis of observations made when Jupiter was near the earth. But now Jupiter had moved to a distant position. The delay in the eclipse was simply due to the fact that light from Jupiter takes time to reach the earth, the time interval depending on the relative positions of Jupiter and the earth in their orbits. In fact, he estimated that it takes about 22 minutes for light to cross the earth's own orbit around the sun.

Shortly thereafter, the Dutch physicist Christiaan Huygens used Römer's data to make the first calculation of the speed of light. He combined Römer's value of 22 minutes for light to cross the earth's orbit with his own estimate of the diameter of the earth's orbit. (This distance could be estimated for the first time in the seventeenth century, as a result of the advances in astronomy described in Unit 2.) Huygens obtained a value which, in modern units, is about 2×10^8 meters per second. This is about two-thirds of the presently accepted value (see below). The error in Huygen's value was due mainly to Römer's overestimate of the time interval – we now know that it takes light only about 16 minutes to cross the earth's orbit.

The speed of light has been measured in many different ways since the seventeenth century. (See the article "Velocity of Light" in *Reader* 4.). Since the speed is very great, it is necessary to use either a very long distance or a very short time interval or both. The earlier methods were based on measurements of astronomical distances. In the nineteenth century, rotating slotted wheels and mirrors made it possible to measure very short time intervals so that distances of a few miles could be used. The development of electronic devices in the twentieth century allows measurement of even shorter time intervals. Consequently the speed of light is one of the most accurately known physical constants; but because of the importance of the value of the speed of light in modern physical theories, physicists are continuing to improve their methods of measurements.

As of 1970, the most accurate measurements indicate that the speed of light in vacuum is 299,792,500 meters per second. The uncertainty of this value is thought to be less than 300 meters per second, or 0.0001%. The speed of light is usually represented by the symbol c, and for most purposes it is sufficient to use the

approximate value $c = 3 \times 10^8$ meters per second.

Q1 Can a beam of light be made increasingly narrow by passing it through narrower and narrower slits?

Q2 What reason did Römer have for thinking that the eclipse of a particular satellite of Jupiter would be observed later than expected?

Q3 What was the most important outcome of Römer's work?

13.3 Reflection and refraction

What happens when a ray of light traveling in one medium (say air) hits the boundary of another medium (say glass)? The answers to this question depend on whether we adopt a particle or a wave theory of light and, therefore, give us a chance to test which theory is better.

We have already discussed reflection and refraction from the wave viewpoint in Chapter 12, so we need only recall the results obtained there.

1. A ray may be taken as the line drawn perpendicular to a wave's crest lines; a ray represents the direction in which a train of parallel waves is traveling.

2. In reflection, the angle of incidence (θ_i) is equal to the angle of reflection (θ_r).

3. Refraction involves a change of wavelength and speed of the wave as it goes into another medium. In particular, when the speed decreases the wavelength decreases, and the ray is bent in a direction toward a line perpendicular to the boundary. This bending toward the perpendicular is observed when a ray of light goes from air to glass.
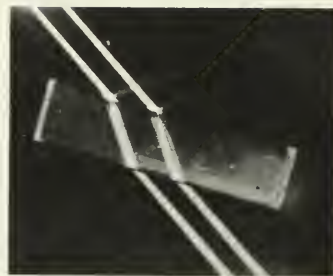
Two narrow beams of light, coming from the upper left, strike a block of glass. Can you account for the other effects?

SG 13.7–13.12
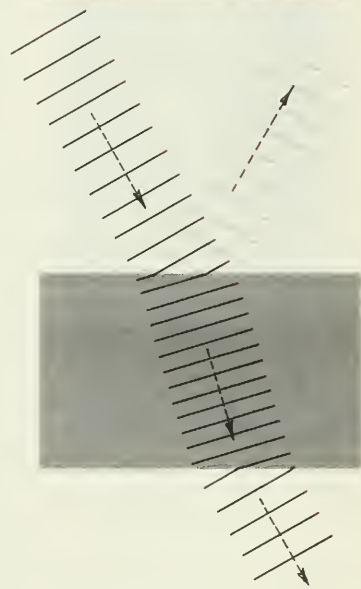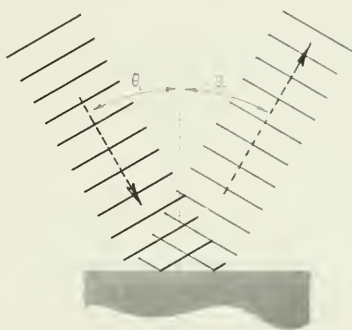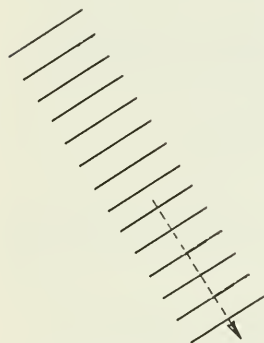
What about the particle model? To test this model, we must first consider the nature of the surface of glass. Though apparently smooth, it is actually a wrinkled surface. By means of a powerful microscope, it can be seen to have endless hills and valleys. If particles of light hit such a wrinkled surface, they would be scattered in all directions, not reflected and refracted as shown in the above figures. Therefore, Newton argued, there must actually be "some feature of the body which is evenly diffused over its surface and by which it acts upon the ray without immediate contact." Obviously this force was one which repelled the particles of light. A similar force, which attracted light particles instead of repelling them, could be used to explain refraction. As a particle of light approached a boundary of another medium, it would first have to overcome the repulsive force; if it did that, it would then meet an attractive force in the medium which would pull it into the medium. Since the attractive force would be a vector with a

The surface of a mirror as shown by
an electron microscope. The surface
is a three-micron thick aluminum film.
The magnification here is nearly
26,000. (μ stands for micron; where
$1\mu = 10^{-6}$ meter.)
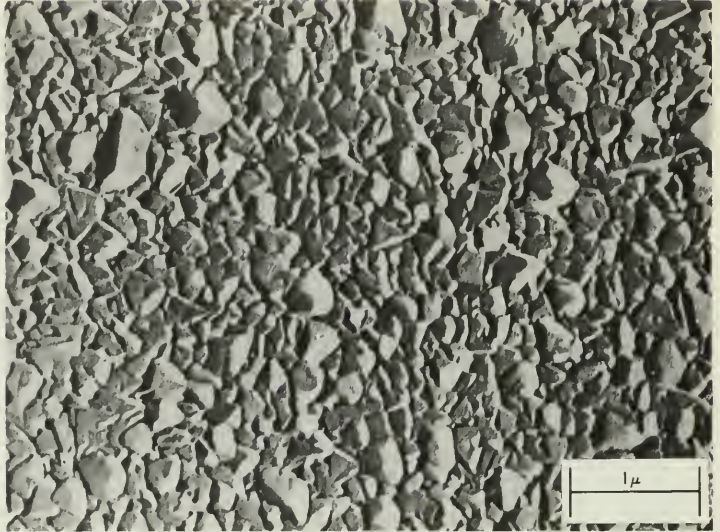
component in the direction of the original motion of the ray, the
light particle's speed would increase. So if the ray were moving at
an oblique angle to the boundary, its direction would change as it
entered the medium, toward the line perpendicular to the boundary.

According to the *particle* model, therefore, we can make the
following statements about reflection and refraction.

1.   A ray represents the direction in which the particles are
moving.

2.   In reflection, the angles of incidence and reflection are
equal. This prediction can be derived from the Law of Conservation
of Momentum (Chapter 9) applied to the interaction of the particles
with the repulsive power of the medium.

3.   Refraction involves a change of speed of the particles as
they go into another medium. In particular, when an attractive
power acts, *the speed increases* and the ray is bent into the
medium.

Comparing these features of the particle model with the
corresponding features of the wave model (above), we find that the
only difference is in the predicted speed for a refracted ray. When
we *observe* that a ray is bent toward the perpendicular line on
going into another medium – as is the case for light going from air
into water – then the particle theory predicts that light has a greater
speed in the second medium, whereas the wave theory predicts that
light has a *lower* speed.

You might think that it would be fairly easy to devise an
experiment to determine which prediction is correct. All one has to
do is measure the speed of light in water to compare it with the
speed of light in air. However, in the late seventeenth and early
eighteenth centuries, when the wave model was supported by
Huygens and the particle model by Newton, no such experiment

was possible. Remember that at that time the only available way of measuring the speed of light was an astronomical one. Not until the middle of the nineteenth century did Fizeau and Foucault measure the speed of light in water. The results agreed with the predictions of the wave model: the speed of light is less in water than in air.

Ironically, by the time these experiments were done, most physicists had already accepted the wave model for other reasons (see below). The Foucault-Fizeau experiments of 1850 were widely regarded as driving the last nail in the coffin of the Newtonian particle theory.

Q4   What evidence showed conclusively that Newton's particle model for light could not explain all aspects of refraction?

Q5   If light has a wave nature, what changes take place in the speed, wavelength, and frequency of light on passing from air into water?

13.4   Interference and diffraction

From the time of Newton until the early years of the nineteenth century, the particle theory of light was favored by most physicists, largely because of the prestige of Newton. Early in the nineteenth century, however, the wave theory was revived by Thomas Young. He found, in experiments made between 1802 and 1804, that light shows the phenomenon of *interference*. Interference patterns have been discussed in Sec. 12.6 in connection with water waves. Such patterns could not easily be explained by the particle theory of light. Young's famous "double-slit experiment" must be done in the lab rather than talked about; it provides convincing evidence that light has properties that can be explained only in terms of waves.

When a beam of light is split into two beams, and the split beams are then allowed to overlap, we find that the two wave trains interfere constructively in some places and destructively in others. To simplify the interpretation of the experiment, we will assume
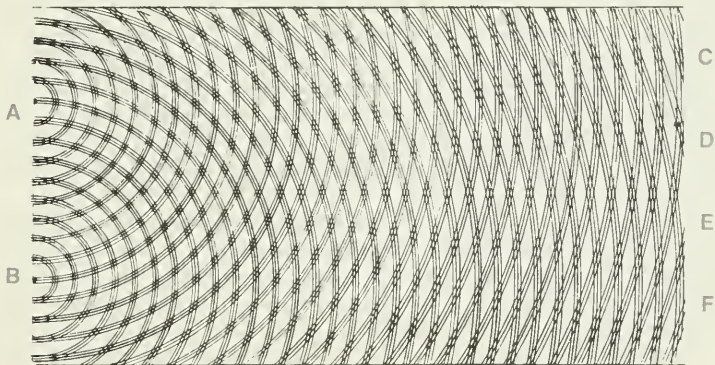
Thomas Young (1773-1829) was an English linguist, physician, and expert in many fields of science. At the age of fourteen he was familiar with Latin, Greek, Hebrew, Arabic, Persian, French, and Italian, and later was one of the first scholars successful at decoding Egyptian hieroglyphic inscriptions. He studied medicine in England, Scotland, and Germany. While still in medical school he made original studies of the eye, and later developed the first version of what is now known as the three-color theory of vision. He also did research in physiology on the functions of the heart and arteries, and studied the human voice mechanism, through which he became interested in the physics of sound and sound waves.

Young then turned to optics, and showed that many of Newton's experiments with light could be explained in terms of a simple wave theory of light. This conclusion was strongly attacked by some scientists in England who were upset by the implication that Newton might be wrong.

Thomas Young's original drawing showing interference effects in overlapping waves. The alternate regions of reinforcement and cancellation in the drawing can be seen best by placing your eye near the right edge and sighting at a grazing angle along the diagram.

A Polaroid photograph taken through a Project Physics magnifier placed about 30 cm behind a pair of closely spaced slits. The slits were illuminated with a narrow but bright light source.
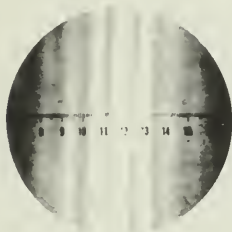
Augustin Jean Fresnel (1788-1827) was an engineer of bridges and roads for the French government. In his spare time he carried out extensive experimental and theoretical work in optics. Fresnel developed a comprehensive wave model of light that successfully accounted for reflection, refraction, interference, and polarization. He also designed a lens system for lighthouses that is still used today.

that the experiment is done with light that has a single definite wavelength λ.

Young used a black screen with a small hole punched in it to produce a narrow beam of sunlight in a dark room. In the beam he placed a second black screen with two narrow slits cut in it, close together. Beyond this screen he placed a white screen. The light coming through each slit was diffracted and spread out into the space beyond the screen. The light from each slit interfered with the light from the other, and the interference pattern could be seen where the light fell on the white screen. Where interference was constructive, there was a bright band on the screen. Where interference was destructive, the screen remained dark.

The fact that Young could actually find, by experiment, numerical values for the exceedingly short wavelength of light was quite astonishing. Here is his result:

> From a comparison of various experiments, it appears that the breadth of the undulations constituting the extreme red light must be supposed to be, in air, about one 36 thousandth of an inch, and those of the extreme violet about one 60 thousandth.

When Young announced his results that were based on the wave theory of light, he took special pains to show that Newton himself had made several statements favoring a theory of light that had some aspects of a wave theory even though Newton was generally considered a supporter of the particle theory. Nevertheless, Young was not taken seriously. It was not until 1818, when the French physicist Augustin Fresnel proposed a mathematical wave theory of his own, that Young's research began to get the credit it deserved. Fresnel also had to submit his work for approval to a group of physicists who were committed to the particle theory of light. One of them, the mathematician Simon Poisson, took Fresnel's wave equations and showed that if these equations really did describe the behavior of light, a very peculiar thing ought to happen when a small solid disk is placed in a beam of light. A white screen placed at certain distances behind the disk should have a bright spot in the center of the shadow, because diffraction of the light waves all around the edge of the round disk should lead to constructive interference at the center. In the particle theory of light, there was no room for ideas such as diffraction and constructive interference, and there could be no such bright spot. Since such a bright spot had never been reported, and furthermore since the idea of a bright spot in the center of a shadow sounded absurd on the face of it, Poisson announced gleefully to Fresnel that he had refuted the wave theory.

Fresnel accepted the challenge, however, and immediately arranged for this prediction to be tested by experiment. The result was that he could demonstrate that there *was* a bright spot in the center of the shadow, as predicted by Poisson on the basis of Fresnel's wave theory.

When the significance of the Young double-slit experiment and
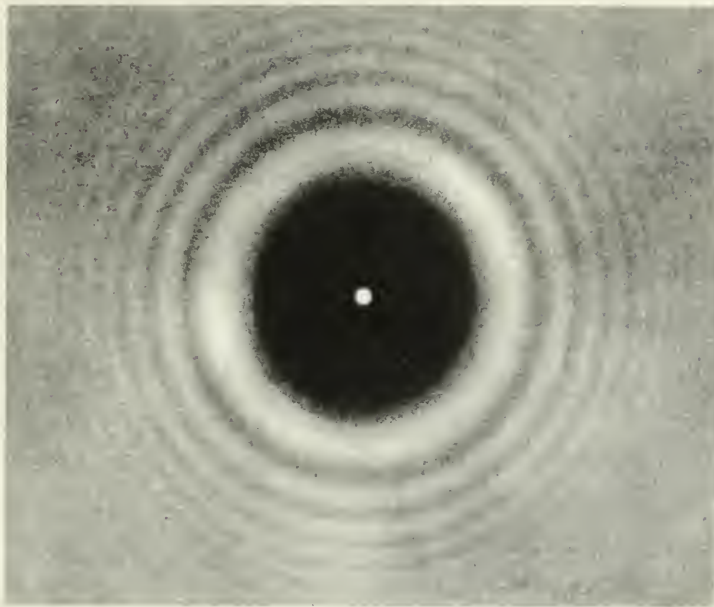
Diffraction pattern due to an opaque circular disk, showing the Poisson bright spot in the center of the shadow. Note also the bright and dark fringes of constructive and destructive interference. (You can make similar photographs yourself — see the activity "Poisson's Spot" in the *Handbook*.)

the Poisson bright spot was realized, support for the particle theory of light began to crumble away. By 1850 the validity of the wave model of light was generally accepted, and physicists had begun to concentrate on working out the mathematical consequences of this model and its application to all the different properties of light.

SG 13.15

Q6 How did Young's experiments support the wave model of light?

Q7 In what way is diffraction involved in Young's experiments?

Q8 What phenomenon was predicted by Poisson on the basis of Fresnel's wave theory?

13.5 Color

Man's early appreciation of color survives for our contemplation in the coloring agents found in prehistoric painting and pottery. But no scientific theory of color was developed before the time of Newton. Until then, most of the commonly accepted ideas about color had been advanced by artist-scientists, like da Vinci, who based their ideas on experiences with mixing pigments.

Unfortunately, the lessons learned in mixing pigment can rarely be applied to the mixing of colors of light. In early times, it was thought that light from the sun was "pure light," and that—as by refraction in glass—color came from adding impurity to this pure light.

Newton became interested in colors while he was still a student at Cambridge University, when he set out to construct an astro-

Diffraction and Detail

The photograph on the left shows the diffraction image of a point source of light. Diffraction by the camera lens opening has spread the light energy into a bright central disk surrounded by alternate dark and bright rings. The photographs below show an array of point sources, recorded through a progressively smaller and smaller hole. The array could represent a star cluster, surface detail on Mars, granules in living cells or simply specific points on some object.

The diffraction of the waves from the edges of the hole limits the detail of information that it is possible to receive. As the hole through which we observe the array below becomes smaller, the diffraction image of each point spreads out and begins overlapping the diffraction images of other points. When the diffraction patterns for the points overlap sufficiently, it is impossible to distinguish between them.

This problem of diffraction has many practical consequences. We obtain most of the information about our environment by means of waves (light, sound, radio, etc.) which we receive through some sort of hole: the pupil of the eye, the entrance to the ear or a microphone, the aperture of an optical telescope or radio telescope, etc. In all these cases, then, diffraction places a limit on the detail with which the sources of waves can be discriminated.

nomical telescope. One of the troublesome defects of the telescope was a fuzzy colored edge that always surrounded the image formed by the telescope lens. It was perhaps in an attempt to understand this particular defect that he began his extensive study of color.

In 1672, at the age of 29, Newton published a theory of the nature of color in the *Philosophical Transactions* of The Royal Society of London. This was his first published scientific paper. He wrote:

> . . . in the beginning of the Year 1666 (at which time I applyed myself to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phaenomena* of *Colours*. And in order thereto haveing darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my Prisme at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby . . . .
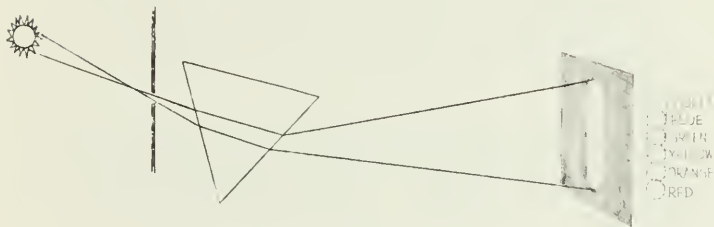
The drawing at the left is based on Newton's diagram of the refraction of sunlight by a prism.

The cylindrical beam of "white" sunlight from the circular opening passed through the prism and produced on the opposite wall an elongated patch of colored light, violet at one end, red at the other and showing a continuous gradation of colors in between. For such a pattern of colors, Newton invented the name *spectrum*.

But, Newton asked himself, from where do the colors come, and why is the image spread out in an elongated patch rather than circular? Seeking an explanation, Newton passed the light through different thicknesses of the glass, changed the size of the hole in the window shutter, and even placed the prism outside the window. But he found that none of these changes in conditions had any effect on the spectrum. To test whether some unevenness or irregularity in the glass produced the spectrum, he passed the colored rays from one prism through a similar second prism turned upside down. If some irregularity in the glass was responsible for spreading out the beam of light, then passing this beam through the second prism should spread it out even more. Instead, the second prism, when properly placed, served to bring the colors back together fairly well to form a spot of *white* light, as if the light had not passed through either prism.

By such a process of elimination, Newton convinced himself of

As is suggested in the diagram below, the recombination of colors by a second prism is not complete. Newton himself noted: "The prisms also must be placed very near to one another; for if their distance be so great, the colours begin to appear in the light, before its incidence on the second prism, these colours will not be destroyed by the contrary refractions of that prism."
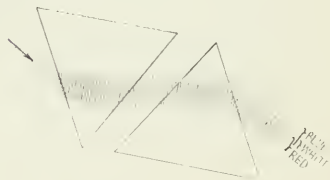
a belief that he probably had held from the beginning: white light is composed of colors. It is not the prism that manufactures or adds the colors; they were there all the time, but mixed up so that they could not be distinguished. When white light passes through a prism, each of the component colors is refracted at a different angle, so that the beam is spread into a spectrum.

As a further test of this hypothesis, Newton cut a small hole in a screen on which a spectrum was projected, so that light of a single color could be separated out and passed through a second prism. He found that the second prism had no further effect on this single-color beam, aside from refracting it more. Once the first prism had done its job of separating the colored components of white light, the second prism could not change the color of the components.

Summarizing his conclusions, Newton wrote:

> Colors are not *Qualifications of Light* derived from Refraction or Reflection of natural Bodies (as 'tis generally believed) but Original and Connate Properties, which in divers Rays are divers. Some Rays are disposed to exhibit a Red Colour and no other; some a Yellow and no other, some a Green and no other, and so of the rest. Nor are there only Rays proper and particular to the more Eminent Colours, but even to all their intermediate gradations.

Apparent colors of objects. So far Newton had discussed only the colors of rays of light, but in a later section of his paper he raised the important question: why do objects appear to have different colors? Why is the sky blue, the grass green, a paint-pigment yellow or red? Newton proposed a very simple answer:

> That the Colours of all Natural Bodies have no other Origin than this, that they . . . Reflect one sort of Light in greater plenty than another.

In other words, a red pigment looks red to us because when white sunlight falls on it, the pigment absorbs most of the rays of other colors of the spectrum and reflects mainly the red to our eyes.

According to Newton's theory, color is not a property of an object by itself, but depends on how the object reflects and absorbs the various colored rays that strike it. Newton justified this hypothesis by pointing out that an object may appear to have a different color when a different kind of light shines on it. For example, consider a pigment that reflects much more red light than green or blue light. When illuminated by white light, it will reflect mostly the red component of the white light, so it will appear red. But if it is illuminated with blue light, there is no red for it to reflect; it will reflect only very little of the blue light, so it will appear to be dark and slightly blue. Newton wrote:

> I have experimented in a dark Room, by illuminating those Bodies with uncompounded (pure) light of divers Colours. For by that means any Body may be made to

appear of any Colour. They have there no appropriate Colour, but ever appear of the Colour of the Light cast upon them, but yet with this difference, that they are most brisk and vivid in the Light of their own Day-light Colour.

SG 13.16

Reactions to Newton's theory. Newton's theory of color met with violent opposition at first. Other British scientists, especially Robert Hooke, objected that postulating a different kind of light for each color was unnecessary. It would be simpler to assume that the different colors were produced from pure white light by some kind of modification. Hooke, for example, proposed a color theory based on the wave model of light: ordinarily, in white light, the wave front is perpendicular to the direction of motion. (See Sec. 12.5 for a definition of wave front.) Colors are produced, according to Hooke, when refraction by another medium twists the wave front so that it is no longer perpendicular to the direction of motion.

Newton was aware of the fallacies in Hooke's theory, but he disliked public controversy. In fact, he waited until after Hooke's death in 1703 to publish his own book, *Opticks* (1704), in which he reviewed the properties of light.
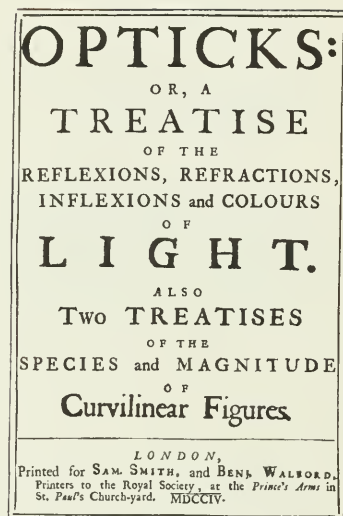
While Newton's *Principia* was a much more important work from a purely scientific viewpoint, his *Opticks* had considerable influence on the literary world. English poets, who celebrated the discoveries of their country's greatest scientist, and who were dimly aware of the significance of Newton's theory of gravity, could not grasp the technical details of the geometric axioms and proofs of the *Principia*. But Newton's theory of colors and light provided ample opportunity for poetic fancy, as in James Thomson's, "To the Memory of Sir Isaac Newton" (1727).

> . . . First the flaming red,
> Springs vivid forth; the tawny orange next;
> And next delicious yellow; by whose side
> Fell the kind beams of all-refreshing green.
> Then the pure blue, that swells autumnal skies,
> Ethereal played; and then, of sadder hue,
> Emerged the deepened indigo, as when
> The heavy-skirted evening droops with frost;
> While the last gleamings of refracted light
> Died in the fainting violet away.

Leaders of the nineteenth-century Romantic movement in literature, and the German "nature philosophers," did not think so highly of Newton's theory of color. The scientific procedure of dissecting and analyzing natural phenomena by experiments was distasteful to them. They preferred to speculate about the unifying principles of all natural forces, in the hope of being able to grasp nature as a whole. The German philosopher Friedrich Schelling wrote in 1802:

> Newton's *Opticks* is the greatest illustration of a
> whole structure of fallacies which, in all its parts, is
> founded on observation and experiment.

OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
L I G H T.
ALSO
Two **TREATISES**
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH. and BENJ. WALFORD.
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

Title page from the first edition of Newton's *Opticks* (1704), in which he described his theory of light.

SG 13.17

May ye chop the light in pieces
Till it hue on hue releases.
May ye other pranks deliver,
Polarize the tiny sliver
Till the listener overtaken,
Feels his senses numbed and
          and shaken –
Nay persuade us shall ye never
Nor aside us shoulder ever
Steadfast was our dedication –
We shall win the consummation

SG 13.18, 13.19

The Angstrom unit is named after Anders Jonas Angstrom, a Swedish astronomer who, in 1862 used spectroscopic techniques to detect the presence of hydrogen in the sun.

The amount of scattering of different waves by a tiny obstacle is indicated here for three wavelengths.

The German poet Goethe (mentioned in Chapter 11 in connection with Nature Philosophy) spent many years on a work intending to overthrow Newton's theory of colors, both by his own observations and by impassioned arguments. Goethe insisted on the purity of white light in its natural state. He rejected Newton's hypothesis that white light is a mixture of colors and suggested that colors are produced by the interaction of white light and its opposite, darkness. Although Goethe's observations on color perception were of some value to science, his theory of the physical nature of color could not survive scrutiny based on detailed experiment. Newton's theory of color remained firmly established, even in literature.

Q9 How did Newton show that white light was not "pure"?

Q10 Why could Newton be confident that, say, green light was not itself composed of different colors of light?

Q11 How would Newton explain the color of a blue shirt?

Q12 Why was Newton's theory of color attacked by the nature philosophers?

13.6 Why is the sky blue?

Newton suggested that the apparent colors of natural objects depend on which color is predominantly reflected or scattered to the viewer by the object. In general, there is no simple way of predicting from the surface structure and chemical composition, etc., what colors a solid or liquid will reflect or scatter. However, the blue color of the clear sky can be understood by a fairly simple argument.

As Thomas Young found (Sec. 13.4), different wavelengths of light correspond to different colors. The wavelength of light may be specified in units of Ångstrom (Å), equal to 10^{-10} meter; the range of the spectrum visible to humans is from about 7000 Å for red light to about 4000 Å for violet light.

Small obstacles can scatter the energy of an incident wave in all directions, and the amount of scattering depends on the wavelength. This fact can be demonstrated by experiments with water waves in a ripple tank. As a general rule, *the longer a wave is compared to the size of the obstacle, the less it is scattered by the obstacle.* For particles smaller than one wavelength, the amount of

scattering of light varies inversely with the fourth power of the wavelength. This means that, since the wavelength of red light is about twice the wavelength of blue light, the scattering of red light is about 1/16th as much as the scattering of blue light.

Now we can understand why the sky is blue. Light from the sun is scattered by air molecules and particles of dust in the sky. These particles are usually very small compared to the wavelengths of visible light, so light of short wavelengths — blue light — will be much more strongly scattered from the particles than light of longer wavelengths. When you look up into a clear sky, it is mainly this scattered light that enters your eye. The range of scattered short wavelengths (and the color sensitivity of the human eye) lead to the sensation of blue. If you look directly at the sun at sunset on a very hazy day, you receive light of longer wavelengths that has *not* been scattered out — so you perceive the sun as reddish.

If the earth had no atmosphere, the sky would appear black and stars would be visible by day. In fact, starting at altitudes of about ten miles, where the atmosphere becomes quite thin, the sky does look black and stars can be seen during the day, as has been reported by astronauts.

When the air contains dust particles or water droplets as large as the wavelength of visible light (about 10^{-6} meter), other colors than blue may be strongly scattered. For example, the quality of sky coloring changes with the water-vapor content of the atmosphere. On clear, dry days the sky is a much deeper blue than on clear days with high humidity. The intensely blue skies of Italy and Greece, which have been an inspiration to poets and painters for centuries, are a result of exceptionally dry air.
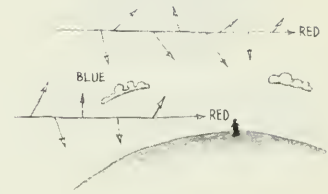
An observer looking at a sunset on a hazy day is receiving primarily *un-*scattered colors such as red; whereas if the observer looks overhead, he will be receiving primarily scattered colors, the most dominant of which is blue.

If light is scattered by particles considerably larger than one wavelength (such as the water droplets in a cloud), there isn't a very large difference in the scattering of different wavelengths, so we receive the mixture we perceive as white

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Q13 How does the scattering of light waves by tiny obstacles depend on the wavelength?

Q14 How would you explain the blue color of the earth's sky? What do you expect the sky to look like on the moon? Why?

13.7 Polarization

Newton could not accept the proposal of Hooke and Huygens that light is in many ways like sound — that is, that light is a wave propagated through a medium. Newton argued that light must also have some particle-like properties. He noted two properties of light that, he thought, could not be explained without thinking of light as having particle properties. First, a beam of light is propagated in straight lines, whereas waves such as sound spread out in all directions and go around corners. The answer to this objection could not be given until early in the nineteenth century, when Young was able to measure the wavelength of light and found it to be exceedingly small. Even red light, which has the longest wavelength of the visible spectrum, has a wavelength less than a thousandth of a millimeter. As long as a beam of light shines on objects or through holes of ordinary size (a few millimeters or more

Iceland Spar Crystal
Double Refraction
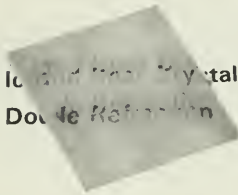
Iceland Spar Crystal
Double Refraction

in width), the light will appear to travel in straight lines. Diffraction and scattering effects don't become evident until a wave strikes an object whose size is about equal to or smaller than the wavelength.

Newton's second objection was based on the phenomenon of "polarization" of light. In 1669, the Danish scientist Erasmus Ba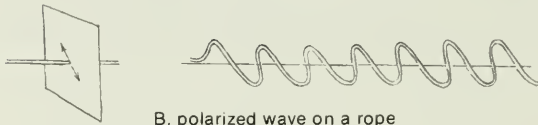rtholinus discovered that crystals of Iceland spar (calcite) had the curious property of splitting a ray of light into two rays. Thus small objects viewed through the crystal looked double.

Newton thought this behavior could be explained by assuming that the ray of light is a stream of particles that have different "sides"—for example, rectangular cross-sections. The double images, he thought, represent a sorting out of light particles which had entered the medium with different orientations.
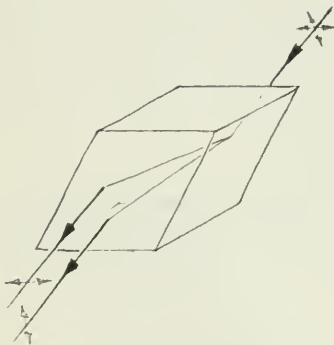
Around 1820, Young and Fresnel gave a far more satisfactory explanation of polarization, using a modified wave theory of light. Before then, scientists had generally assumed that light waves, like sound waves, must be *longitudinal.* (And, as Newton believed, longitudinal waves could not have any directional property.) Young and Fresnel showed that if light waves are *transverse,* this would account for the phenomenon of polarization.
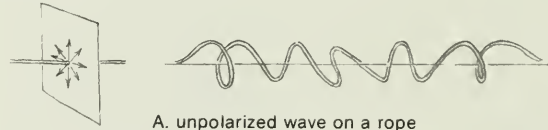
A. unpolarized wave on a rope

B. polarized wave on a rope

In Chapter 12, we stated that in a transverse wave, the motion of the medium itself is always perpendicular to the direction of propagation of the wave. That does not mean that the motion of the medium is always in the same direction; it could be in any direction in a plane perpendicular to the direction of propagation. However, if the motion of the medium *is* predominantly in one direction, for example, vertical, we say that the wave is polarized. (Thus a polarized wave is really the *simplest* kind of transverse wave; an unpolarized transverse wave is a more complicated thing, since it is a mixture of various transverse motions.) The way in which Iceland spar (a crystalline form of calcium nitrate) separates an unpolarized light beam into two polarized beams is sketched in the margin.

Scientific studies of polarization continued throughout the nineteenth century, but practical applications were frustrated because polarizing substances like Iceland spar were scarce and fragile. One of the best polarizers was "herapathite," or sulfate of iodo-quinine, a synthetic crystalline material. The needle-like crystals of herapathite absorb light which is polarized in the direction of the long crystal axis; the crystals absorb very little of the light polarized in a direction at 90° to the long axis. The crystals were so fragile that there seemed to be no way of using them.

Double refraction by a crystal of Iceland spar. The "unpolarized" incident light can be thought of as consisting of two polarized components. The crystal separates these two components, transmitting them through the crystal in different directions and with different speeds.

But in 1928, Edwin H. Land, while still a freshman student at college, invented a polarizing plastic sheet he called "Polaroid." His first polarizer consisted of a plastic film in which many microscopic crystals of herapathite were imbedded. When the plastic is stretched, the needle-like crystals line up in one direction, so that they all act on incoming light in the same way.

Some properties of a polarizing material are easily demonstrated. Hold a polarizing sheet – for example, the lens of a pair of polarizing sunglasses – in front of a light source and look at it through another polarizing sheet. Rotate the first sheet. You will notice that, as you do so, the light alternately brightens and dims; you must rotate the second sheet through an angle of 90° to go from maximum brightness to maximum dimness.

How can this be explained? If the light that strikes the first sheet is originally unpolarized – that is, a mixture of waves polarized in various directions – then the first sheet will transmit those waves that are polarized in one direction, and absorb the rest, so that the transmitted wave going toward the second sheet will be polarized in one direction. Whenever this direction happens to coincide with the direction of the long molecules in the second sheet, then the wave will be absorbed by the second sheet because it will set up vibrations within the molecules and lose most of its energy in this way. However, if the direction is perpendicular to the long axis of the molecules, the polarized light will go through the second sheet without much absorption.

Interference and diffraction effects required a wave model for light. To explain polarization phenomena, the wave model was made more specific by showing that light could be explained by transverse waves. This model for light explains well all the characteristics of light considered so far – but we shall see in Unit 5 that it turned out, nevertheless, to require further extension.

Later Land improved Polaroid by using polymeric molecules composed mainly of iodine in place of the herapathite crystals.

The eyes of bees and ants are sensitive to the polarization of scattered light from the clear sky, emitting a characteristic by the sun, even when the sun is low on the horizon or obscured. Following the bee's example, engineers have equipped airplanes with polarization indicators for use in arctic regions. (See Reader article "Popular Applications of Polarized Light.")

SG 13.20, 13.21

Q15 What two objections did Newton have to a wave model?

Q16 What phenomena have we discussed that are consistent with a wave model of light?

Q17 Have we proved that light can have *no* particle properties?

13.8   The ether

One thing seems clearly to be missing from the wave model for light. In Chapter 12, we discussed waves as a disturbance that propagates in some substance or "medium," such as a rope or water. What is the medium for the propagation of light waves?

Is air the medium for light waves? No, because light can pass through airless space – for example, the space between the sun or other stars and the earth. Even before it was definitely known that there is no air between the sun and the earth, Robert Boyle had tried the experiment of pumping almost all of the air out of a glass container and found that objects inside remained visible.

Since it was difficult to think of a disturbance without specifying what was being disturbed, it was natural to propose that a medium for the propagation of light waves existed. This medium was called the *ether*.

In the seventeenth and eighteenth centuries the ether was imagined to be an invisible fluid of very low density, which could penetrate all matter and fill all space. It might somehow be associated with the "effluvium" (something that "flows out") that was imagined to explain magnetic and electric forces. But light waves must be transverse in order to explain polarization, and usually transverse waves propagate only in a *solid* medium. A liquid or a gas cannot transmit transverse waves for any significant distance, for the same reason that you cannot "twist" a liquid or a gas. So nineteenth-century physicists assumed that the ether must be a solid.

As was stated in Chapter 12, the speed of propagation increases with the stiffness of the medium, and decreases with its density. Therefore, the ether was thought to be a very stiff solid with a very low density because the speed of propagation is very high, compared to other kinds of waves such as sound.

Yet, it seems absurd to say that a stiff, solid ether fills all space. We know that the planets move without slowing down, so apparently they encounter no resistance from a stiff ether. And, of course, we ourselves feel also no resistance when we move around in a space that transmits light freely.

Without ether, the wave-theory seemed improbable. But the ether itself had absurd properties. Until early in this century, this was an unsolved problem, just as it was for Newton and the poet Richard Glover who wrote, shortly after Newton's death:

> O had great Newton, as he found the cause
> By which sound rouls thro' th' undulating air,
> O had he, baffling time's resistless power,
> Discover'd what that subtile spirit is,
> Or whatsoe'er diffusive else is spread
> Over the wide-extended universe,
> Which causes bodies to reflect the light,
> And from their straight direction to divert
> The rapid beams, that through their surface pierce,
> But since embrac'd by th' icy arms of age,
> And his quick thought by times cold hand congeal'd,
> Ev'n NEWTON left unknown this hidden power . . . .

We shall see how, following Einstein's modification of the theory of light, the problem came to be solved.

Q18 Why was it assumed that an "ether" existed which transmitted light waves?

Q19 What remarkable property must the ether have if it is to be the mechanical medium for the propagation of light?

"Entrance to the Harbor", a painting by Georges Seurat (1888). Art historians believe that Seurat's techniques of pointillism, the use of tiny dots of pure color to achieve all effects in a painting, reflects his understanding of the physical nature of light.

13.1 The Project Physics learning materials particularly appropriate for Chapter 13 include:

Experiments

Refraction of a Light Beam

Young's Experiment — the Wavelength of Light

Activities

Thin Film Interference

Handkerchief Diffraction Grating

Photographing Diffraction Patterns

Poisson's Spot

Photographing Activities

Color

Polarized Light

Making an Ice Lens

Reader Articles

Experiments and Calculations Relative to Physical Optics

Velocity of Light

Popular Applications of Polarized Light

Eye and Camera

Lenses and Optical Instruments

In addition the following Project Physics materials can be used with Unit 4 in general:

Reader Articles

Action at a Distance

Maxwell's Letters: A Collection

Film

People and Particles

13.2 A square card, 3 cm on a side, is held 10 cm from a small penlight bulb, and its shadow falls on a wall 15 cm behind the card. What is the size of the shadow on the wall? (A diagram of the situation will be useful.)

13.3 The row of photographs on page 9 shows what happens to a beam of light that passes through a narrow slit. The row of photographs on page 126 of Chapter 12 shows what happens to a train of water wave that passes through a narrow opening. Both sets of photographs illustrate single-slit diffraction, but the photographs are not at all similar in appearance. Explain the difference in appearance of the photographs, and how they are similar.

13.4 An experiment to determine whether or not the propagation of light is instantaneous is described by Galileo as follows:

Let each of two persons take a light contained in a lantern, or other receptacle, such that by the interposition of the hand, the one can shut off or admit the light to the vision of the other. Next let them stand opposite each other at a distance of a few cubits and practice until they acquire such skill in uncovering and occulting their lights that the instant one sees the light of his companion he will uncover his own. After a few trials the response will be so prompt that without sensible error (svario) the uncovering of one light is immediately followed by the uncovering of the other, so that as soon as one exposes his light he will instantly see that of the other. Having acquired skill at this short distance let the two experimenters, equipped as before

take up positions separated by a distance of two or three miles and let them perform the same experiment at night, noting carefully whether the exposures and occultations occur in the same manner as at short distances; if they do, we may safely conclude that the propagation of light is instantaneous but if time is required at a distance of three miles which, considering the going of one light and the coming of the other, really amounts to six, then the delay ought to be easily observable . . . .

But later he states:

In fact I have tried the experiment only at a short distance, less than a mile, from which I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous, it is extraordinarily rapid . . . .

(a) Why was Galileo unsuccessful in the above experiment?

(b) How would the experiment have to be altered to be successful?

(c) What do you think is the longest time that light might have taken in getting from one observer to the other without the observers detecting the delay? Use this estimate to arrive at a lower limit for the speed of light that is consistent with Galileo's description of the result.

(d) Why do you suppose that the first proof of the finite speed of light was based on celestial observations rather than terrestrial observations?

13.5 A convenient unit for measuring astronomical distances is the *light year,* defined to be the distance that light travels in one year. Calculate the number of meters in a light year to two significant figures.

13.6 What time would be required for a space-ship having a speed of 1/1000 that of light to travel the 4.3 light years from the earth to the closest known star other than the sun, Proxima Centauri? Compare the speed given for the spaceship with the speed of approximately 10 km/sec maximum speed (relative to the earth) that a space capsule has on an earth-moon trip.

13.7 Newton supposed that the reflection of light off shiny surfaces is due to "some feature of the body which is evenly diffused over its surface and by which it acts upon the ray without contact." The simplest model for such a feature would be a repulsive force which acts only in a direction perpendicular to the surface. In this question you are to show how this model predicts that the angles of incidence and reflection must be equal. Proceed as follows:

(a) Draw a clear diagram showing the in-cident and reflected rays. Also show the angles of incidence and reflection (θ_1 and θ_2). Sketch a coordinate system on your diagram that has an x-axis parallel to the surface and a y-axis perpendicular to the

surface. Note that the angles of incidence and reflection are defined to be the angles between the incident and reflected rays and the y-axis.

(b) Supposing that the incident light consists of particles of mass m and speed v, what is the kinetic energy of a single particle? Write mathematical expressions for the x and y components of the momentum of an incident light particle.

(c) If the repulsive force due to the reflecting surface does no work on the particle and acts only perpendicular to the surface, which of the quantities that you have described in part (b) is conserved?

(d) Show algebraically that the speed u of the reflected particle is the same as the speed v of the incident particle.

(e) Write mathematical expressions for the components of the momentum of the reflected particle.

(f) Show algebraically that θ_1 and θ_2 must be equal angles.

13.8 Find the shortest path from point A to any point on the surface M and then to point B; Solve this by trial and error, perhaps by experimenting with a short piece of string held at one end by a tack at point A. (A possible path is shown but it is not necessarily the shortest one.) Notice that the shortest distance between A, M and B is also the *least-time* path for a particle traveling at a constant speed from A to M to B. What path would light take from A to M to B? Can you make a statement of the law of reflection in terms of this principle instead of in terms of angles?

13.9 What is the shortest mirror in which a 6-foot-tall man can see himself entirely? (Assume that both he and the mirror are vertical and that he places the mirror in the most favorable position.) Does it matter how far away he is from the mirror? Do your answers to these questions depend on the distance from his eyes to the top of his head?

13.10 Suppose the reflecting surfaces of every visible object were somehow altered so that they completely absorbed any light falling on them; how would the world then appear to you?

13.11 Objects are visible as a whole if their surfaces reflect light enabling our eyes to intercept cones of reflected light diverging from *each part* of the surface. The accompanying diagram shows such a cone of light (represented by 2 diverging rays) entering the eye from a book.

Draw clear straight-line diagrams to show how a pair of diverging rays can be used to help explain the following phenomena.

(a) The mirror image of an object appears to be just as far behind the mirror as the object is in front of the mirror.

(b) A pond appears shallower than it actually is.

(c) A coin placed in an empty coffee mug which is placed so that the coin cannot *quite* be seen becomes visible if the mug is filled with water.

13.12 Due to atmospheric refraction we see the sun in the evening for some minutes after it is really below the horizon, and also for some minutes before it is actually above the horizon in the morning.
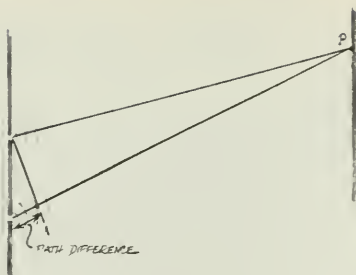
(a) Draw a simple diagram to illustrate how this phenomenon occurs.

(b) What would sunset be like on a planet with a very thick and dense (but still transparent) atmosphere?

13.13 In a particle theory of light, refraction could be explained by assuming that the particle was accelerated by an attractive force as it passed from air or vacuum toward a medium such as glass. Assume that this accelerating force could act on the particle *only* in a direction perpendicular to the surface, and use vector diagrams to show that the speed of the particle in the glass would have to be greater than in air.

13.14 Plane parallel waves of single-wavelength light illuminate the two narrow slits, resulting in an interference pattern of alternate bright and dark fringes being formed on the screen. The bright fringes represent zones of constructive
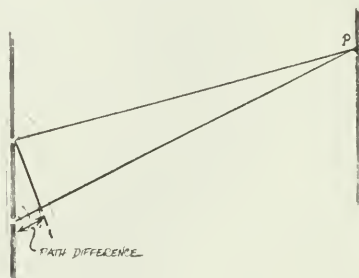
PATH DIFFERENCE

interference and hence appear at a point such as P on the diagram above only if the diffracted waves from the two slits arrive at P in phase. The diffracted waves will only be in phase at point P if the path difference is a whole number of wavelengths (that is, only if the path difference equals $m\lambda$ where $m = 0, 1, 2, 3 \ldots$).

27

How do you think it compares with the poem on p. 20 (a) as poetry? (b) as physics?

13.18 Green light has a wavelength of approximately 5×10^{-7} meters. What frequency corresponds to this wavelength? Compare this frequency to the carrier frequency of the radio waves broadcast by a radio station you listen to. (Hint: $\nu = f$.)

(a) What path difference results in destructive interference at the screen?

(b) The separation between two successive bright fringes depends on the wavelengths of the light used. Would the separation be greater for red light or for blue light?

(c) For a particular color of light, how would the pattern change if the distance of the screen from the slits is increased? (Hint: make two diagrams.)

(d) What changes occur in the pattern if the slits are moved closer together? (Hint: make two diagrams.)

(e) What happens to the pattern if the slits themselves are made more narrow?

13.15 Recalling diffraction and interference phenomena from Chapter 12, show that the wave theory of light can be used to explain the bright spot that can be found in the center of the shadow of a disk illuminated by a point source.

13.16 It is now a familiar observation that clothing of certain colors appears different in artificial light and in sunlight. Explain why.

13.17 Another poem by James Thomson (1728):

Meantime, refracted from yon eastern cloud,
Bestriding earth, the grand ethereal bow
Shoots up immense; and every hue unfold,
In fair proportion running from the red
To where the violet fades into the sky.

13.19 The arts sometimes reflect contemporary ideas in science; the following poem is an excellent example of this.
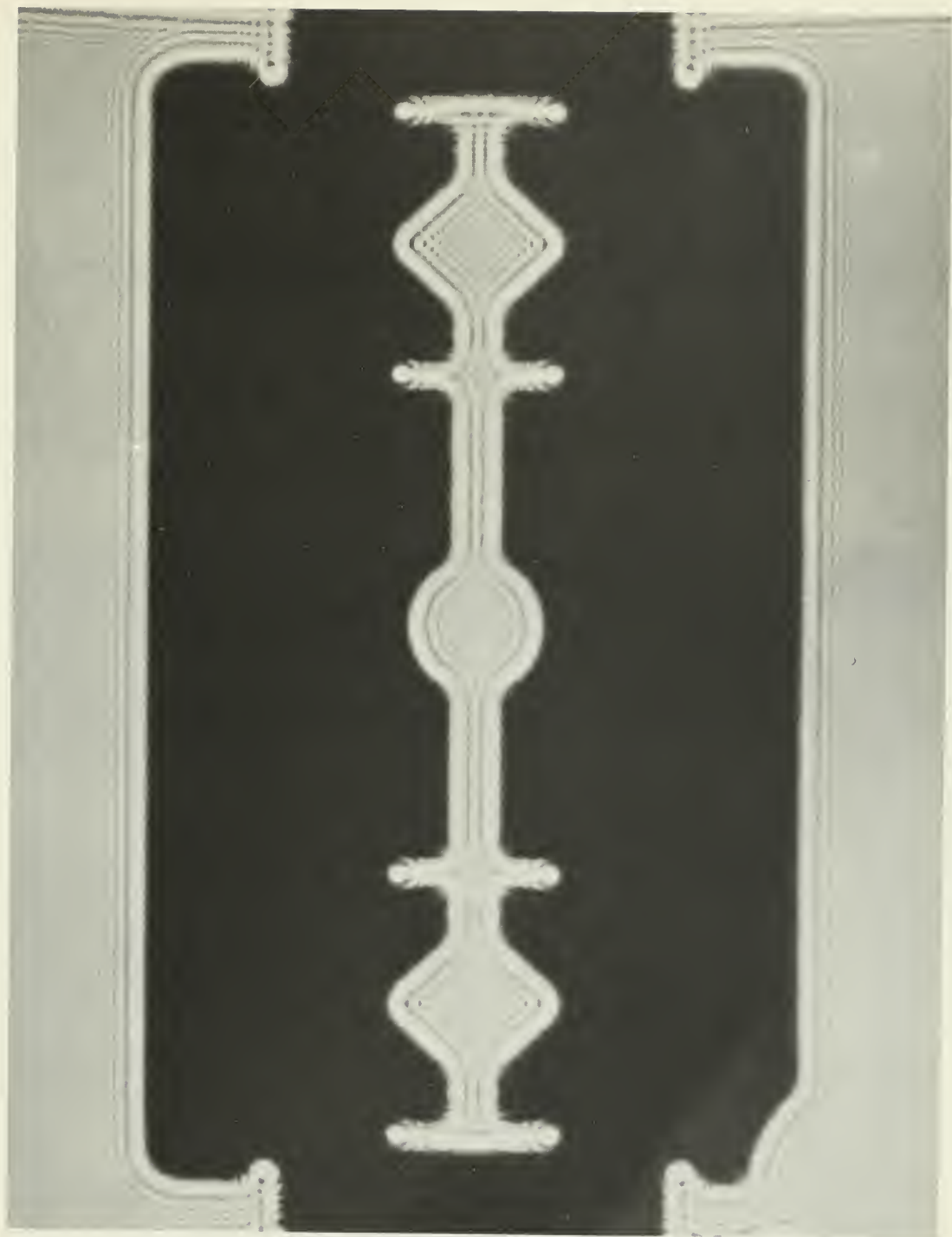
Some range the colours as they parted fly.
Clear-pointed to the philosophic eye;
The flaming red, that pains the dwelling gaze,
The stainless, lightsome yellow's gilding rays;
The clouded orange, that betwixt them glows,
And to kind mixture tawny lustre owers;
All-chearing green, that gives the spring its dye:
The bright transparent blue, that robes the sky;
And indigo, which shaded light displays,
And violet, which in the view decays.
Parental hues, whence others all proceed;
An ever-mingling, changeful, countless breed,
Unravel'd, variegated, lines of light,
When blended, dazzling in promiscuous white.
[Richard Savage (1697-1743), *The Wanderer*]

(a) Would you or would you not classify the poet Richard Savage as a "nature philosopher"? Why?

(b) Compare this poem with the one in SG 13.17 by James Thomson; which *poet* do you think displayed the better understanding of physics of his time? Which *poem* do you prefer?

13.20 One way to achieve privacy in apartments facing each other across a narrow courtyard while still allowing residents to enjoy the view of the courtyard and the sky above the courtyard is to use polarizing sheets placed over the windows. Explain how the sheets must be oriented for maximum effectiveness.

13.21 To prevent car drivers from being blinded by the lights of approaching autos, polarizing sheets could be placed over the headlights and windshields of every car. Explain why these sheets would have to be oriented the same way on every vehicle and must have their polarizing axis at 45° to the vertical.

Diffraction fringes around a razor blade.

Electric and Magnetic Fields

14.1 Introduction

The subject "electricity and magnetism" makes up a large part of modern physics and has important connections with almost all other areas of physics and chemistry. Because it would be impossible to study this subject comprehensively in the time available in an introductory course, we consider only a few main topics that will be needed as a foundation for later chapters. Major applications of the information in this chapter will appear later: the development of electrical technology (Chapter 15), the study of the nature of light and electromagnetic waves ,Chapter 16., and the study of properties of atomic and subatomic particles (Units 5 and 6).

SG 14.1

In this chapter we shall first treat electric charges and the forces between them—very briefly, because the best way to learn about that subject is not by reading but by doing experiments in the laboratory (see Experiment 33 in the *Handbook*). Next, we will show how the idea of a "field" simplifies the description of electric and magnetic effects. Then we will take up electric currents, which are made up of moving charges. By combining the concept of field with the idea of potential energy we will be able to establish quantitative relations between current, voltage, and power. These relations will be needed for the practical applications to be discussed in Chapter 15.

Finally, at the end of this chapter, we shall come to the relations between electricity and magnetism, a relation having important consequences both for technology and basic physical theory. We will begin by looking at a simple physical phenomenon: the interaction between moving charges and magnetic fields.

An inside view of "Hilac" (heavy ion linear accelerator) at Berkeley, California. In this device electric fields accelerate charged atoms to high energies.

14.2   The curious properties of lodestone and amber: Gilbert's *De Magnete*

Two natural substances, amber and lodestone, have aroused interest since ancient times. Amber is sap that long ago oozed from certain softwood trees, such as pine, and, over many centuries, hardened into a semitransparent solid ranging in color from yellow to brown. It is a handsome ornamental stone when polished, and it sometimes contains the remains of insects that were caught in the sticky sap. Ancient Greeks recognized a curious property of amber: if rubbed vigorously against cloth, it can attract nearby objects such as bits of straw or grain seeds.

Lodestone is a mineral that also has unusual properties. It attracts iron. Also, when suspended or floated, a piece of lodestone always turns to take one particular position – a north-south direction. The first known written description of the navigational use of lodestone as a compass in Western countries dates from the late twelfth century, but its properties were known even earlier in China. Today, lodestone would be called magnetized iron ore.

The histories of lodestone and amber are the early histories of magnetism and electricity. The modern developments in these subjects began in 1600 with the publication in London of William Gilbert's book *De Magnete*. Gilbert (1544-1603) was an influential physician, who served as Queen Elizabeth's chief physician. During the last twenty years of his life, he studied what was already known of lodestone and amber, made his own experiments to check the reports of other writers, and summarized his conclusion in *De Magnete*. The book is a classic in scientific literature, primarily because it was a thorough and largely successful attempt to test complex speculation by means of detailed experiments.
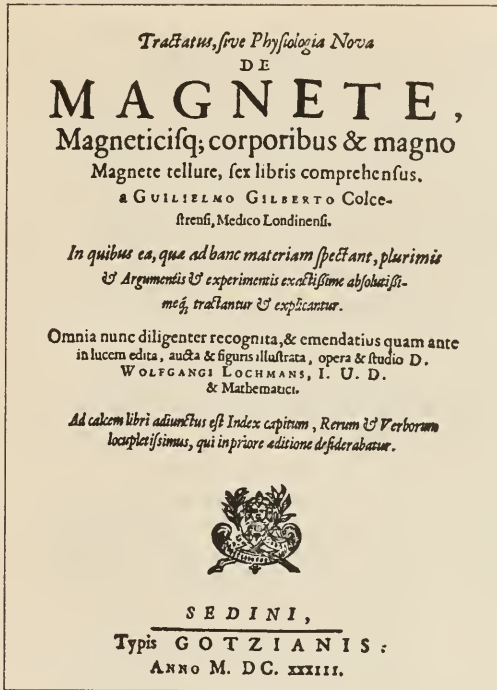
Gilbert's first task in his book was to review and criticize what had previously been written about lodestone. Gilbert reports various theories proposed to explain the cause of magnetic attraction; one of the most popular theories was suggested by the Roman author Lucretius:

Lucretius . . . was one of the early writers on atomic theory; see the Prologue to Unit 3.

> Lucretius . . . deems the attraction to be due to this, that as there is from all things a flowing out ("efflux" or effluvium") of minutest bodies, so there is from iron an efflux of atoms into the space between the iron and the lodestone – a space emptied of air by the lodestone's atoms (seeds); and when these begin to return to the lodestone, the iron follows, the corpuscles being entangled with each other.

Gilbert himself did not accept the effluvium theory as an explanation for magnetic attraction, although he thought it might apply to electrical attraction.

When it was discovered that lodestones and magnetized needles or bars of iron tend to turn so as to have a certain direction on the surface of the earth, many authors proposed explanations. But, says Gilbert,

Tractatus, sive Physiologia Nova
DE
MAGNETE,
Magneticisq; corporibus & magno
Magnete tellure, sex libris comprehensus.
a GUILIELMO GILBERTO Colce-
strensi, Medico Londinensi.

In quibus ea, quæ ad hanc materiam spectant, plurimis
& Argumentis & experimentis exactissime absolutissi-
meq, tractantur & explicantur.

Omnia nunc diligenter recognita, & emendatius quam ante
in lucem edita, aucta & figuris illustrata, opera & studio D.
WOLFGANGI LOCHMANS, I. U. D.
& Mathematici.

Ad calcem libri adiunctus est Index capitum, Rerum & Verborum
locupletissimus, qui in priore editione desiderabatur.

SEDINI,
Typis GOTZIANIS:
ANNO M. DC. XXXIII.

The title page of the third edition (1633) of Gilbert's book is reproduced above. Early in the book Gilbert makes the following statement:

> Before we expound the causes of magnetic movements and bring forward our demonstrations and experiments touching matters that for so many ages have lain hid . . . we must formulate our new and till now unheard-of view of the earth, and submit it to the judgment of scholars.

Gilbert proposed an elaborate analogy between the earth and a spherical lodestone. At the right are reproduced some of the drawings Gilbert used to illustrate his experiments with magnetized needles and spheres of iron and lodestone. Toward the end of the book, he presents the diagram at the right, which shows the angle at which a magnetic needle would "dip" toward the earth's surface (represented by the central circle) at different latitudes. The section of *De Magnete* in which this diagram appears is titled: *How to find . . . the latitude of any place by means of the following diagram, turned into a magnetic instrument, in any part of the world, without the help of the heavenly bodies, sun, planets, or fixed stars, and in foggy weather as well as in darkness.*
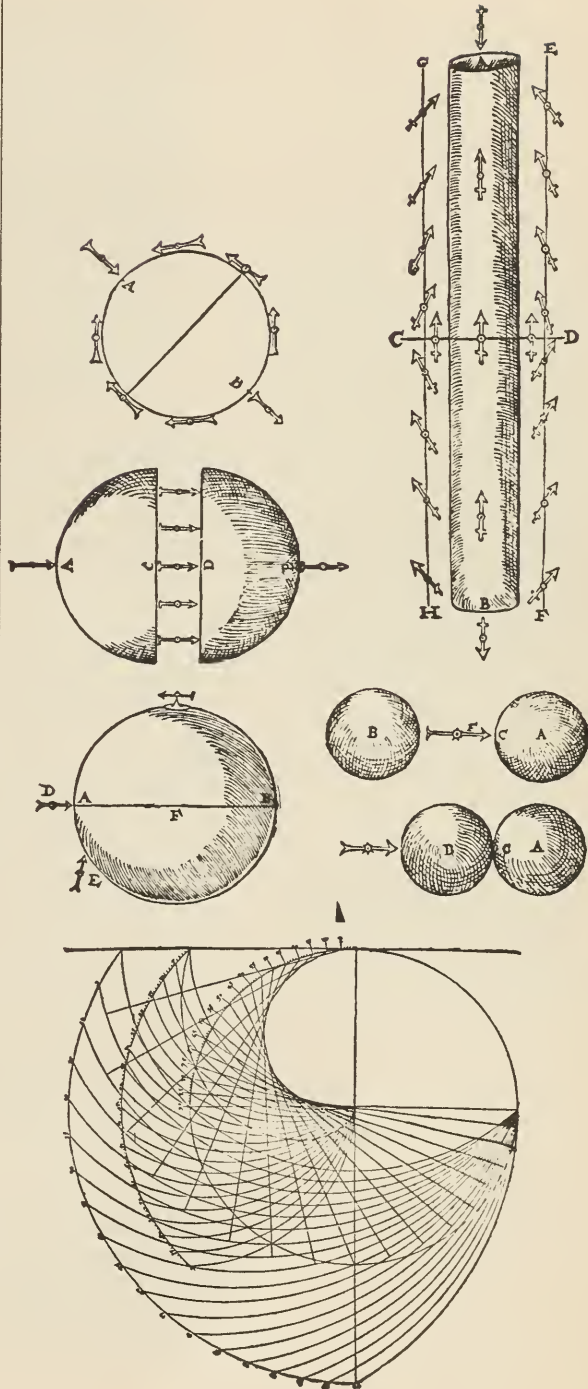
. . . they wasted oil and labor, because, not being practical
in the research of objects of nature, being acquainted
only with books, being led astray by certain erroneous
physical systems, and having made no magnetical experi-
ments, they constructed certain explanations on a basis
of mere opinions, and old-womanishly dreamt the things
that were not. Marcilius Ficinus chews the cud of ancient
opinions, and to give the reason of the magnetic direction
seeks its cause in the constellation Ursa . . . Paracelsus
declares that there are stars which, gifted with the lode-
stone's power, do attract to themselves iron . . . All these
philosophers . . . reckoning among the causes of the
direction of the magnet, a region of the sky, celestial
poles, stars . . . mountains, cliffs, vacant space, atoms,
attractional . . . regions beyond the heavens, and other
like unproved paradoxes, are world-wide astray from the
truth and are blindly wandering.

Gilbert himself proposed the real cause of the lining-up of a
magnetic needle or lodestone when suspended by itself: the earth
itself is a lodestone. Gilbert also did a rather ingenious experiment
to show that his hypothesis was a likely one: he prepared a large
piece of natural lodestone in the shape of a sphere, and showed
that a small magnetized needle placed on the surface of such a
lodestone will act in the same way as a compass needle does at
different places on the earth's surface. If the directions along which
the needle lines up are marked with chalk on the lodestone, they
will form meridian circles (similar to the lines of equal longitude
on a globe of the earth) which converge at two opposite ends that
may be called "poles." At the poles, the needle will point perpendic-
ular to the surface of the lodestone (see p. 33). Halfway between,
along the "equator," the needles will lie along the surface. Small
bits of iron wire placed on the surface of the spherical lodestone
line up along these same directions.

The discussion of these and other actions of magnets now
generally uses the idea that magnets set up "fields" all around
themselves. The field can then act on other objects near or distant.
Gilbert's description of the force exerted on the needle by his
spherical lodestone (which he called the "terrella," meaning "little
earth") was a step toward the modern field concept:

The immensely important idea of
"field" was introduced into physics
by Michael Faraday early in the
nineteenth century, and developed
further by Kelvin and Maxwell (see
Secs. 14.4 and 16.2).

The terrella's force extends in all directions . . . . But
whenever iron or other magnetic body of suitable size
happens within its sphere of influence it is attracted; yet
the nearer it is to the lodestone the greater the force with
which it is borne toward it.

"electric" comes from the Greek
word *electron*, meaning "amber."

Gilbert also included a discussion of electricity in his book. He
introduced the word *electric* as the general term for "bodies that
attract in the same way as amber." Gilbert showed that electric and
magnetic forces are different. For example, a lodestone always
attracts iron or other magnetic bodies, whereas an electric object
exerts its attraction only when it has been recently rubbed. On the

other hand, an electric object can attract small pieces of many different substances, whereas magnetic forces act only between a few types of substances. Objects are attracted to a rubbed electric object along lines directed toward one center region, but a magnet always has two regions (poles) toward which other magnets are attracted.

In addition to summarizing the then known facts of electricity and magnets, Gilbert's work suggested new research problems that were pursued by others for many years. For example, Gilbert thought that while the poles of two lodestones might either attract or repel each other, electric bodies could never exert repulsive forces. But in 1646, Sir Thomas Browne published the first account of electric repulsion. To systematize such observations a new concept, *electric charge*, was introduced. In the next section we will see how this concept can be used to describe the forces between electrically charged bodies.

Q1   How did Gilbert demonstrate that the earth behaves like a spherical lodestone?

Q2   How does the attraction of objects by amber differ from the attraction by lodestone?

14.3   Electric charges and electric forces

As Gilbert strongly argues, the facts of electrostatics (the effects of forces between electric charges at rest) must be learned in the laboratory rather than by just reading about them. This section, therefore, is only a brief outline to prepare for (or to summarize) your own experience with the phenomena.

The behavior of amber was discussed earlier: when it is rubbed it almost mysteriously acquires the property of picking up chaff, small bits of cork, paper or hair, etc. To some extent all materials show this effect when rubbed, including rods made of glass or hard rubber, or strips of plastic. There are two other important sets of basic observations: (a) where two rods of the same material have been rubbed with the same kind of cloth, the rods *repel* each other. Examples that were long ago found to work especially well are two glass rods rubbed with silk, or two hard rubber rods rubbed with fur; (b) but when two rods of *different* material have been rubbed — for example, a glass rod rubbed with silk, and a rubber rod rubbed with fur — the two rods may *attract* each other.

These and thousands of similar experimentally observable facts can be summarized in a systematic way by adopting a very simple model. Remember that the model we have been describing is not an experimental fact which you can observe separately. It is, rather, a set of invented ideas which help us describe and summarize what we can see happening. It is easy to forget this important difference between experimentally observable fact and invented explanations. Both are needed, but they are not the same thing! The model consists of the concept of "charge" and three rules. An object that

has been rubbed and acquired the property of attracting small bits of stuff is said to "be electrically charged" or to "have an electric charge." Further, we imagine that there are two kinds of charge, so that all objects showing electrical behavior have either one or the other of the two kinds of charge. The three rules are:

(1) There are only two kinds of electric charge.

(2) Two objects charged alike (that is, having the same kind of charge) repel each other.

(3) Two objects charged oppositely attract each other.

Another basic observation is that when two different uncharged materials are rubbed together (for example, the glass rod and the silk cloth) they will acquire opposite kinds of charge. Benjamin Franklin, who did many experiments with electric charges, proposed a mechanical model that would account for all these phenomena. In his model, charging an object electrically involved the transfer of an "electric fluid" that was present in all matter. When two objects were rubbed together, some electric fluid from one passed into the other; the one body would then have an extra amount of fluid and the other a lack of fluid. An excess of fluid produced one kind of electric charge—which Franklin called "positive." A lack of the same fluid produced the other kind of electric charge—which he called "negative."

Previously "two-fluid" models had been proposed, which involved both a "positive fluid" and a "negative fluid"; in normal matter, these two fluids were thought to be present in equal amounts that cancelled out each other's effects. When two different objects were rubbed together, there would be a transfer of fluids that would leave one with an unbalanced amount of positive fluid and the other with an unbalanced amount of negative fluid.

There was some dispute between advocates of one-fluid and two-fluid models, but nevertheless there was agreement to speak of the two kinds of electrical condition a charged body could be in as "+" or "−." It was not until the late 1890's that there was experimental evidence to give convincing support to any model of what "electric charge" actually was. There were, as it turned out, elements of truth in both one-fluid and two-fluid models. The story will be told in some detail in Unit 5. For the present, we can say that there are in fact two different material "fluids," but the "negative fluid" moves around much more easily than the "positive fluid," so most of the electric phenomena we have been discussing were in fact due to an excess or deficiency of the mobile fluid.

Franklin thought of the electric fluid as consisting of tiny particles, and that is the present view, too. Consequently, the word charge is commonly used as a plural, for example, in the statement "electric charges transfer from one body to another."

What is amazing in electricity, and indeed in other parts of physics, is that so few concepts are needed to deal with an infinitude of different observations. For example, it turns out we do not need to invent a third or fourth kind of charge in addition to "+" and "−." No observation of charged objects requires some

Benjamin Franklin (1706-1790), American statesman, inventor, scientist, and writer. He was greatly interested in the phenomena of electricity: his famous kite experiment and invention of the lightning rod gained him wide recognition. He is shown here observing the behavior of a bell whose clapper is connected to a lightning rod.

additional type of charge that might have to be called "÷" or "×."

Even the behavior of an *un*charged body can be understood in terms of + amd − charges. Any piece of matter large enough to be visible can be considered to contain a large amount of electric charge, both positive and negative. If the amount of positive charge is equal to the amount of negative charge, this piece of matter will appear to have no charge at all (that is to say, zero charge). So we can say that the effects of the positive and negative charges simply cancel each other when they are added together. (This is one advantage of calling the two kinds of charge positive and negative, rather than, for example, x and y.) When we talk about the electric charge on an object we usually mean the slight *excess* (or net) charge of either positive or negative charge existing on this object.

The electric force law. What is the "law of force" between electric charges? In other words, how does the force depend on the *amount of* charge, and on the *distance* between the charged objects?

The first evidence of the nature of the force law between electrical charges was obtained in an indirect way. About 1775, Benjamin Franklin noted that a small cork hanging near the outside of an electrically charged metal can is strongly attracted; but when he lowered the cork, suspended by a silk thread, into the can, he found that no electric force was experienced by the cork no matter what its position was inside the can.

Franklin did not understand why the walls of the can did not attract the cork when it was inside, whereas they did when it was outside. He asked his friend Joseph Priestley to repeat the experiment.

Priestley verified Franklin's results, and went on to make a brilliant inference from them. He remembered from Newton's *Principia* that Newton had proved that gravitational forces behave in a similar way. Inside a hollow planet, the net gravitational force on an object, obtained by adding up all the forces exerted by the parts of the planet, would be exactly zero. This is a result which can be deduced mathematically from the law that the gravitational force between any two individual pieces of matter is inversely proportional to the square of the distance between them. Priestley therefore proposed that electrical forces exerted by charges vary inversely as the square of the distance, just as do gravitational forces exerted by massive bodies. (Zero force inside a hollow conductor is discussed on p. 40.)

Priestley's proposal was based on bold reasoning by analogy. Such reasoning could not by itself *prove* that electrical forces are inversely proportional to the square of the distance between charges. But it strongly encouraged other physicists to test such an hypothesis by experiment.

The French physicist Charles Coulomb provided direct experimental confirmation of the inverse-square law for electric charges that Priestley had suggested. Coulomb used a *torsion balance* which he had invented. A diagram of the balance is shown on the following page. A horizontal, balanced insulating rod is shown

This experience with Newton's law of gravitation is affecting our discussion. We are assuming that the force depends only on a single property and on distance.

Joseph Priestley (1733–1804) a Unitarian minister and physical scientist was persecuted in England for his radical political ideas. One of his books was burned and a mob looted his house because of his sympathy with the French Revolution. He moved to America, the home of Benjamin Franklin, who had stimulated Priestley's interest in science. Primarily known for his identification of the gas oxygen as a separate element that is involved in combustion and respiration, he also experimented with electricity and contributed to the development of carbonated drinks (soda-pop).

Charles Augustin Coulomb (1738-1806) was born into a family of high social position and grew up in an age of political unrest. He studied science and mathematics and began his career as a military engineer. His book *The Theory of Simple Machines* gained him membership in the French Academy of Sciences. While studying machines Coulomb invented his torsion balance, with which he carried out intensive investigations on the mechanical forces due to electrical charges.

Suspension head

Fiber
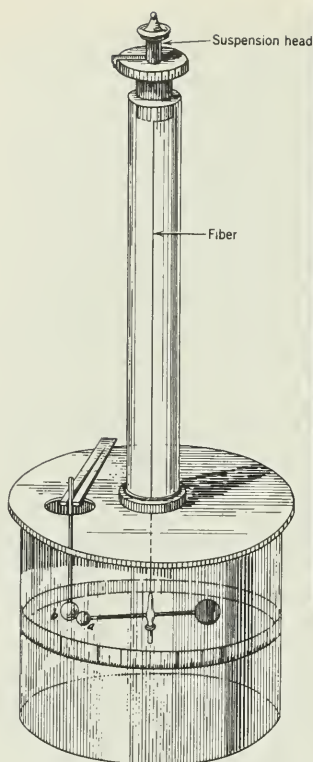
suspended by a thin silver wire, which twists when a force is exerted on the end of the rod. The twisting effect could be used to measure the force between a charged body A attached to one end of the rod and another charged body B placed near it.

By measuring the twisting effect for different separations between the centers of spheres A and B, Coulomb showed that the force between charged spheres varied in proportion to $1/R^2$:

$$F_{el} \propto \frac{1}{R^2}$$

Thus he directly confirmed the suggestion that the electrical force of repulsion for like charges, or attraction for unlike charges, varies inversely as the square of the distance between charges.

Coulomb also demonstrated how the magnitude of the electric force depends on their charges. There was not yet any accepted method for measuring quantitatively the amount of charge on an object (and nothing we have said so far would suggest how to measure the magnitude of the charge on a body). Yet Coulomb used a clever technique based on symmetry to compare the effects of different amounts of charge. He first showed that if a charged metal sphere touches an uncharged sphere of the same size, the second sphere becomes charged also—we may imagine that during

the moment of contact between the metal objects, some of the charge from the first "flows" over, or is "conducted" to, the second. Moreover, the two spheres after contact share the original charge *equally* (as demonstrated by the observable fact that they exert equal forces on some third, charged test body). In a similar way, starting with a given amount of charge on one sphere and sharing it by contact among several other identical but uncharged spheres, Coulomb could produce charges of one-half, one-quarter, one-eighth, etc., of the original amount. By thus varying the charges on the two spheres independently, he could show, for example, that when the two spheres are both reduced by one-half, the force between the spheres is reduced to one-quarter its previous value. In general, he found that the magnitude of the electric force is proportional to the *product* of the charges. If we use the symbols q_A and q_B for the net charges on bodies A and B, the magnitude F_{el} of the electric force that each exerts on the other is proportional to $q_A \times q_B$, and may be written as $F_{el} \propto q_A q_B$.

Coulomb summarized his results in a single equation which describes the electric forces that two small charged spheres A and B exert on each other:

$$F_{el} = k \, \frac{q_A q_B}{R^2}$$

where R is the distance between their centers and k is a constant whose value depends on the units of charge and length that are being used. This form of the law of force between two electric charges is now called Coulomb's Law. We shall discuss the value of k below. For the moment, note the beautiful fact that the equation has exactly the same form as Newton's Law of Universal Gravitation, though of course it arises from a completely different set of observations and applies to a completely different kind of phenomenon. Why this should be so is to this day a fascinating puzzle, and another token of the basic simplicity of nature.

The unit of charge. We can use Coulomb's Law to define a unit of charge. For example, we could arbitrarily let the magnitude of k be exactly 1, and define a unit charge so that two unit charges separated by a unit distance exert a unit force on each other. There exists a set of units based on this choice. However, in the system of electrical units we shall find more convenient to use, the "MKSA" system, the unit of charge is derived not from electrostatics but from the unit of current, the "ampere." The unit of charge is called the "coulomb," and is defined as the amount of charge that flows past a point in a wire in one second when the current is equal to one ampere.

The ampere, or "amp," is a familiar unit because it is frequently used to describe the current in electrical appliances. The effective amount of current in a common 100-watt light bulb is approximately one ampere, hence the amount of charge that goes through the bulb in one second is about 1 coulomb. So it might seem that the coulomb is a fairly small amount of charge. However, one coulomb

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The Project Physics documentary film *People and Particles* shows an experiment to see if Coulomb's law applies to charges at distances as small as 10⁻¹³ cm. It does!

Meter-Kilogram-Second-Ampere
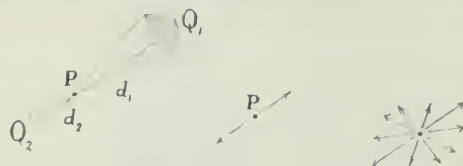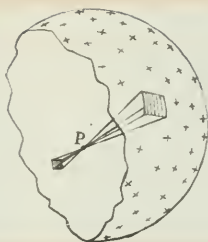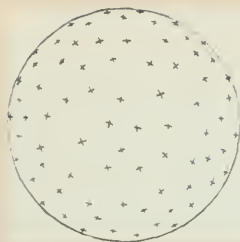
Consider any point charge P inside an even, spherical distribution of charges. For any small patch of charges with total charge Q_1 on the sphere there is a corresponding patch on the other side of P with total charge Q_2. But the areas of the patches are directly proportional to the squares of the distances from P, hence the total charges Q_1 and Q_2 are also *directly* proportional to the squares of the distances from P.

The electric field due to each patch of charge is proportional to the area of the patch, and *inversely* proportional to the square of the distance from P. So the distance and area factors cancel—the forces on P due to the two patches at P are exactly equal in magnitude. But the forces are also in opposite directions. So the net force on P is zero owing to Q_1 and Q_2.

Since this is true for all pairs of charge patches, the net electric field at P is zero.

Electric shielding

In general, charges on a closed conducting surface arrange themselves so that the electric force inside is zero just as they do on a sphere as shown in the diagrams above. Even if the conductor is placed in an electric field, the surface charges will rearrange themselves so as to keep the net force zero everywhere inside. Thus, the region inside any closed conductor is "shielded" from any *external* electric field. This is a very important practical principle.

Whenever stray electric fields might disturb the operation of some electric equipment, the equipment can be enclosed by a shell of conducting material. Some uses of electric shielding can be seen in the photographs of the back of a TV receiver, below.
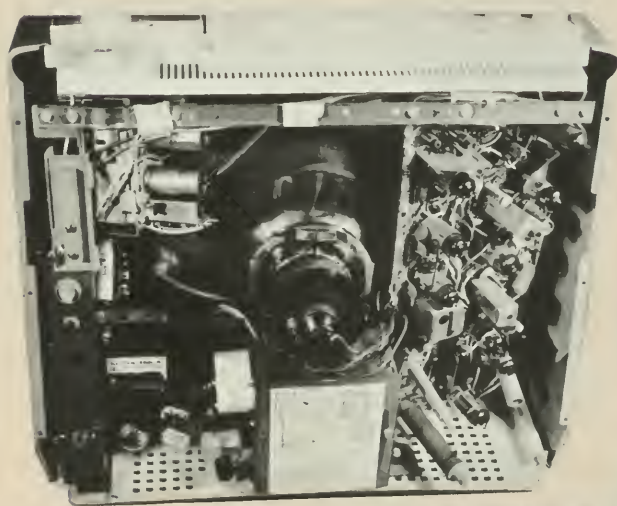
Closeup of a tube in the tuning section of the TV set on the left. Surrounding the tube is a collapsible metal shield. Partly shielded tubes can be seen elsewhere in that photo.

A section of shielded cable such as is seen in use in the photo above, showing how the two wires are surrounded by a conducting cylinder woven of fine wires.

of *net* charge all collected by itself in one place is unmanageably large! What happens in the light bulb is that each second one coulomb of the negative charges that are present in the wires move through its filament passing through a more or less stationary arrangement of positive charges. The *net* charge on the filament is zero at every moment.

If the coulomb (1 coul) is adopted as the unit of charge, then the constant k in Coulomb's law can be found experimentally, by measuring the force between known charges separated by a known distance. The value of k turns out to equal about nine billion newton-meters squared per coulomb squared (9×10^9 Nm²/coul²). This means that two objects, each with a *net* charge of one coulomb, separated by a distance of one meter, would exert forces on each other of nine billion newtons. This force is roughly the same as a weight of one million tons! We never observe such large forces, because we could not actually collect that much net charge in one place, or exert enough force to bring two such charges so close together. The mutual repulsion of like charges is so strong that it is difficult to keep a charge of more than a thousandth of a coulomb on an object of ordinary size. If you rub a pocket comb on your sleeve, enough, say to produce a spark as you touch a doorknob, the net charge on the comb will be far less than one millionth of a coulomb. Lightning discharges usually take place when a cloud has accumulated a net charge of a few hundred coulombs distributed over its very large volume.

Electrostatic induction. We have noted, and you have probably observed, that an electrically charged object can often attract small pieces of paper even though the paper has no net charge itself. (By itself it exerts no force on other pieces of paper.) At first sight it might appear that this attraction is not covered by Coulomb's law, since the force ought to be zero if either q_A or q_B is zero. However, we can explain the attraction if we recall that uncharged objects contain equal amounts of positive and negative electric charges. When an electrified body is brought near a neutral object, its effect can be to rearrange the positions of some of the charges in the neutral object. For example, if a negatively charged comb is held near a piece of paper, some of the positive charges in the paper will shift toward the side of the paper nearest the comb, and a corresponding amount of negative charge will shift toward the other side. The paper still has no net electric charge, but some of the positive charges are then slightly *closer* to the comb than the corresponding negative charges are, so the attraction to the comb is greater than the repulsion. (Remember that the force gets weaker with the square of the distance, according to Coulomb's law; it would be down to one fourth if the distance were twice as large.) Hence there will be a net attraction of the charged body for the neutral object. This explains the old observation of the effect rubbed amber had on chaff and the like.

A charged body *induces* a shift of charge on the neutral body. Thus the rearrangement of electric charges inside or on the surface

A stroke of lightning is, on the average, about 40,000 amperes, and transfers about 1 coulomb of charge between the cloud and the ground.

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of a neutral body due to the influence of a nearby object is called *electrostatic induction.* In Chapter 16 we will see how the theory of electrostatic induction played an important role in the develop-

ment of the theory of light.

Q3 In the following sentences, circle what is invented language to deal with observation.

(a) Like charges repel each other. A body that has a net positive charge repels any body that has a net positive charge. That is, two glass rods that have both been rubbed will tend to repel each other. A body that has a net negative charge repels any other body that has a net negative charge.

(b) Unlike charges attract each other. A body that has a net positive charge attracts any body that has a net negative charge and vice versa.

Q4 What experimental fact led Priestley to propose that electrical force and gravitational forces change with distance in a similar way?

Q5 What two facts about the force between electric charges did Coulomb demonstrate?

Q6 If the distance between two charged objects is doubled, how is the electrical force between them affected?

Q7 Are the coulomb and ampere both units of charge?

14.4 Forces and fields

Gilbert described the action of the lodestone by saying it had a "sphere of influence" surrounding it. By this he meant that any other magnetic body coming inside this sphere will be attracted, and the strength of the attractive force will be greater at places closer to the lodestone. In modern language, we would say that the lodestone is surrounded by a *magnetic field.*

Because the word "field" is used in many ways, we shall discuss some familiar fields, and then proceed gradually to develop the idea of physical fields as used in science. This is a useful exercise to remind us that most terms in physics are really adaptations — with important changes — of commonly used words. Velocity, acceleration, force, energy, and work are examples you have already encountered in this course.

One ordinary use of the concept of field is illustrated by the "playing field" in various sports. The football field, for example, is a place where teams compete according to rules which confine the significant action to the area of the field. The field in this example is a *region of interaction.*

In international politics, we speak of spheres or fields of influences. A field of political influence is also a region of inter-action; unlike a playing field, it has no sharp boundary line. A country usually has greater influence on some countries and less influence on others. So in the political sense, "field" implies also an *amount* of influence, which can be stronger in some places and

weaker in others. Furthermore, the field has a *source* — the country that exerts the influence.

   We shall see there are similarities here to the concept of field as used in physics, but there is an important difference: to define a field in the physical sense, it must be possible to assign a numerical value of field strength to every point in the field. This part of the field idea will become clearer if we discuss now some situations which are more directly related to the study of physics. First we will talk about them in everyday language; then we will introduce the terminology of physics.

The Situation	*Description of your experience*
(a) You are walking along the sidewalk toward a street lamp at night.	"The brightness of light is increasing."
(b) You stand on the sidewalk as an automobile moves down the street with its horn blaring.	"The sound gets louder and then softer."
(c) On a hot summer day, you walk barefoot out of the sunshine and into the shade on the sidewalk.	"The sidewalk is cooler here than in the sunshine."

We can describe these experiences in terms of fields:

   (a) The street lamp is surrounded by a field of illumination. The closer you move to the lamp, the stronger the field of illumination at the point where you are, as seen by your eye or by a light-meter you might be carrying. For every place near the street lamp, we could assign a number that represents the strength of illumination at that place.

   (b) The automobile horn is surrounded by a sound field. In this case you are standing still in your frame of reference (the sidewalk), and a pattern of field values goes past you with the same speed as the car. We can think of the sound field as steady but moving with the horn. At any instant we could assign a number to each point in the field to represent the intensity of sound. At first the sound is faintly heard as the weakest part of the field reaches you. Then the more intense parts of the field go by, and the sound seems louder. Finally, the loudness diminishes as the sound field and its source (the horn) move away.
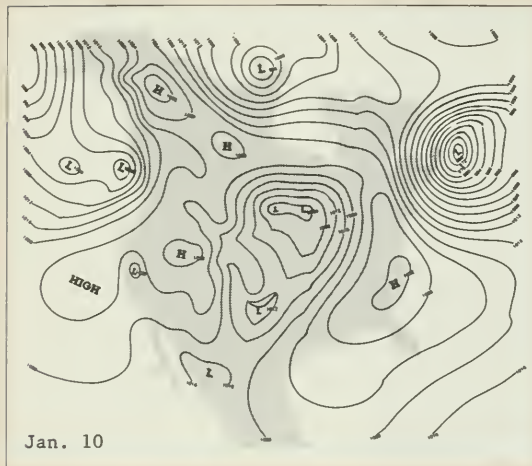
   (c) In this case you are walking in a temperature field which is intense where the sidewalk is in the sunshine and weaker where it is in the shade. Again, we could assign a number to each point in the field to represent the temperature at that point.

   Notice that the first two of these fields are each produced by a single source. In (a) the source is a stationary street lamp, in (b) it is a moving horn. In both cases the field strength gradually increases as your distance from the source decreases. But in the third case (c) the field is produced by a complicated combination of influences: the sun, the clouds in the sky, the shadow cast by nearby buildings, and other factors. Yet giving the description of the field
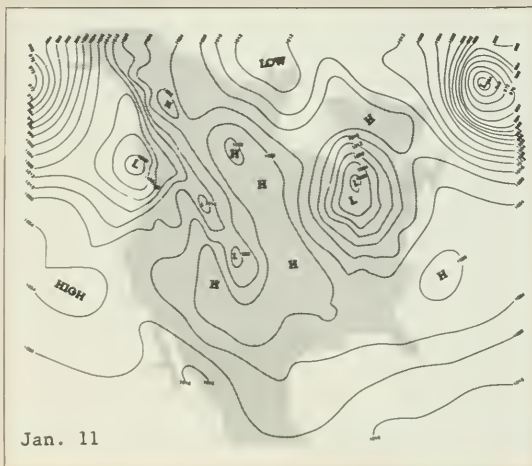
Pressure and velocity fields

These maps, adapted from those of the U.S. Weather Bureau, depict two fields, air pressure at the earth's surface and high-altitude wind velocity, for two successive days. Locations at which the pressure is the same are connected by lines. The set of such pressure "contours" represents the overall field pattern. The wind velocity at a location is indicated by a line (showing direction) and feather lines—one for every 10 mph. (The wind velocity over the tip of Florida, for example, is a little to the east of due north and is approximately 30 mph.)

Air pressure at the earth's surface   **High altitude wind velocity**

itself is just as simple as for a field produced by a single source: one numerical value is associated with each point in the field.

So far, all examples were simple *scalar* fields—no direction was involved in the value of the field at each point. On the opposite page are maps of two fields for the layer of air over the surface of North America for two consecutive days. There is a very important difference between the field mapped at the left and that mapped at the right; the air pressure field (on the left) is a scalar field, while the wind velocity field (on the right) is a *vector* field. For each point in the pressure field, there is a single number, a scalar quantity which gives the value of the field at that point. But for each point in the wind velocity field the value of the field is given by both a numerical magnitude and a direction, that is, by a vector.

These field maps are particularly useful because they can be used more or less successfully to predict what the conditions of the field might be on the next day. Also, by superimposing the maps for pressure and velocity on each other, we could discover how the fields are related to each other.

SPECIMEN STATION MODEL

Wind speed (21 to 25 miles per hour)

Direction of wind. (From the north-west.)

Temperature in degrees Fahrenheit.

Total amount of clouds. (Sky completely covered)

Visibility (3/4 miles)

Present weather (Continuous slight snow in flakes.)

Dewpoint in degrees Fahrenheit

Cloud type (Low fractostratus and/or fractocumulus)

Height of cloud base (300 to 599 feet)

Cloud type (High cirrus)

Part of sky covered by lowest cloud (Seven or eight tenths)

Cloud type (Middle oltocumulus)

Barometric pressure at sea level Initial 9 or 10 omitted (1024 7 millibars)

Amount of barometric change in past 3 hours (In tenths of millibars)

Barometric tendency in past 3 hours (Rising)

Sign showing whether pressure is higher or lower than 3 hours ago

Time precipitation began or ended (Began 3 to 4 hours ago)

Weather in past 6 hours (Rain)

Amount of precipitation in last 6 hours

Key for a U.S. Weather Bureau Map.

The term "field" actually can be used by physicists in three different senses: (1) the value of the field at a point in space, (2) the collection of all values, and (3) the region of space in which the field has values. In reading the rest of this chapter, it will not be difficult to decide which meaning is appropriate each time the term is used.

The gravitational force field. Before returning to electricity and magnetism, and to illustrate further the idea of a field, we take as an example the gravitational force field of the earth. Recall that the force $\vec{F}_{grav}$ exerted by the earth on some object above the surface of the earth, for example upon a stone or other small object used as a test object or "probe," acts in a direction toward the center of

the earth. The field of force of gravitational attraction set up by the earth is a *vector* field, and could be represented by arrows pointing toward the center of the earth. In the illustration, a few such arrows are shown, some near, some far from the earth.

The strength or magnitude of the gravitational force field of the earth's attraction on another body at any chosen point depends on the distance of the point from the center of the earth, since, according to Newton's theory, the magnitude of the gravitational attraction is inversely proportional to the square of the distance R:

$$F_{\text{grav}} = G \times \frac{Mm}{R^2}$$

where M is the mass of the earth, m is the mass of the test body, R is the distance between the centers of earth and the other body, and G is the universal gravitational constant.

F_{grav} depends on the mass of the test body. It would be convenient to define a field that depends only on the properties of the source and not also on the mass of the particular test body on which the force acts. If this were possible, we could think of the field as existing in space and having a definite magnitude and direction at every point, regardless of what the mass of the test body might be, or even regardless of whether there is any test body present at all. As it happens, such a field is easy to define. By slightly rearranging the equation for Newton's law of gravitation, we can write:

$$F_{\text{grav}} = m \left(\frac{GM}{R^2} \right)$$

We then define the gravitational field strength $\vec{g}$ around a spherical body of mass M to have a magnitude GM/R^2 and a direction the same as the direction of $\vec{F}_{\text{grav}}$, so that:

$$\vec{F}_{\text{grav}} = m\vec{g}$$

Thus $\vec{g}$ at a point in space is determined by the source mass M and the distance R from the source, but does *not* depend on the mass of any test object.

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However, the gravitational force at a point in space is usually determined by more than one source. For example, the moon is acted on by the sun as well as by the earth, and to a smaller extent by the other planets. In order to be able to define the field due to any configuration of massive bodies, we can take $\vec{F}_{\text{grav}}$ to be the *net* gravitational force due to *all* sources with an influence in that region of space. We then *define* $\vec{g}$ in such a way that we can still write the simple relationship $\vec{F}_{\text{grav}} = m\vec{g}$. That is, we define $\vec{g}$ by the equation:

$$\vec{g} = \frac{\vec{F}_{\text{grav}}}{m}$$

Thus the gravitational field strength at a point in space is the *ratio* of the net gravitational force $\vec{F}_{\text{grav}}$ which would act on a test body at that point to the mass m of the test body.
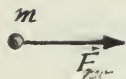
Electric fields. The strength of any force field can be defined in a similar way. According to Coulomb's law, the electric force one relatively small charged body exerts on another depends on the product of the *charges* of the two bodies. For a charge q placed at any point in the electric field set up by a charge Q, Coulomb's law describing the force F_{el} experienced by q can be written as:

$$F_{el} = k\frac{Qq}{R^2} \qquad \text{or} \qquad F_{el} = q\frac{kQ}{R^2}$$

As in the case of the gravitational field we discussed earlier, the expression for force has here been broken up into two parts. One part, kQ/R^2 which depends only on the charge Q of the source and distance R from it is given the name "the electric field strength due to Q." The second part, q, is a property of the body being acted on. Thus we *define* the electric field strength $\vec{E}$, due to charge Q, to have magnitude kQ/R^2 and the same direction of $\vec{F}_{el}$. The electric force is then the product of the test charge and the electric field strength:

$$\vec{F}_{el} = q\vec{E} \qquad \text{and} \qquad \vec{E} = \frac{\vec{F}_{el}}{q}$$

We consider this equation to *define* $\vec{E}$ for an electric force field. Thus the electric field strength $\vec{E}$ at a point in space is the *ratio* of the net electric force $\vec{F}_{el}$ which would act on a test charge placed at that point to the magnitude q of the test charge. This definition can be used whether the electric field being considered is due to a single point charge or due to a complicated distribution of charges.

So far we have passed over a complication that we did not encounter in dealing with gravitation. There are two kinds of electric charge, positive (+) and negative (−), and the forces they experience when placed in the same electric field are opposite in direction. Long ago the arbitrary choice was made of defining the direction of the vector $\vec{E}$ to be the same as the direction of the force exerted by the field on a *positive* test charge. If we are given the direction and magnitude of the field vector $\vec{E}$ at a point, then by definition the force vector $\vec{F}_{el}$ acting on a charge q is $\vec{F}_{el} = q\vec{E}$. A positive charge, say +0.00001 coulombs, placed at this point will experience a force $\vec{F}_{el}$ in the same direction as $\vec{E}$ at that point. A negative charge, say −0.00001 coulombs, will experience a force of the same magnitude as before but in the opposite direction. Changing the sign of q from + to − automatically changes the direction of $\vec{F}_{el}$ to the opposite direction.
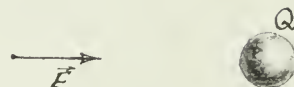
The reason is that the same kind of superposition principle holds which we have already seen so many times the fields set up by separate sources superpose and add vectorially.

SG 14.7
SG 14.8

SG 14.9

Q8   What is the difference between a scalar field and a vector field? Give examples of each.

Q9   Describe how one can find, by experiment, the magnitude and the directions of :
(a) the gravitational field at a certain point in space
(b) the electric field at a certain point in space.

Q10   Why would the field strengths $\vec{g}$ and $\vec{E}$ for the test bodies be unchanged if m and q were doubled?
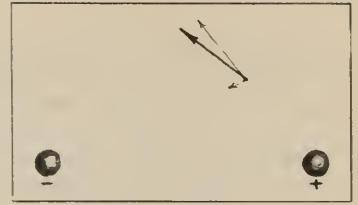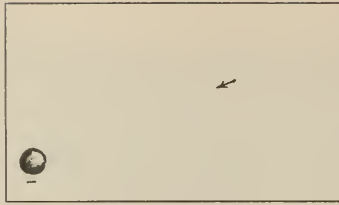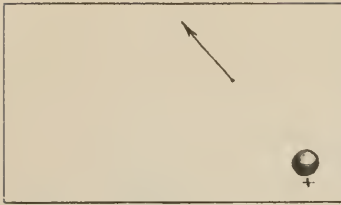
Only rarely will we be interested in the electric field of a single charged sphere. If we want to be able to calculate the field values for a complicated array of charges, without actually taking some small test charge and moving it around in the field to measure the force, we need a rule for adding the fields set up by separate sources. A wide variety of experiments indicates that, at any point in an electric field, the field strength produced by several sources is just the vector sum of the field strengths produced by each source alone.

A simple example is that of finding the net electric field strength produced by a pair of spheres with equal charges of opposite sign. The first frame above indicates the field strength at a point P which would result from the presence of the (+) charge alone. The second frame shows the field strength at the same point which would result from the presence of the (−) charge alone. (The point P happens to be twice as far from the center of the positive charge, so the field strength is only $\frac{1}{4}$ as great in the second frame.) When both (+) and (−) charges are present, the net electric field strength at the point P is the vector sum of the individual electric field strengths, as indicated in the third frame.
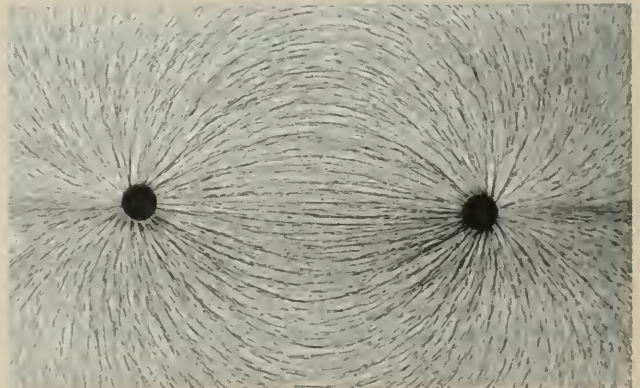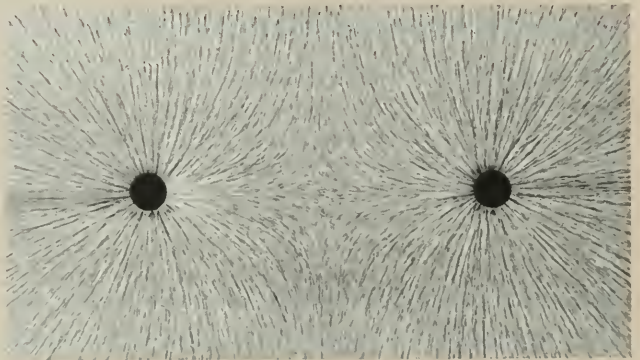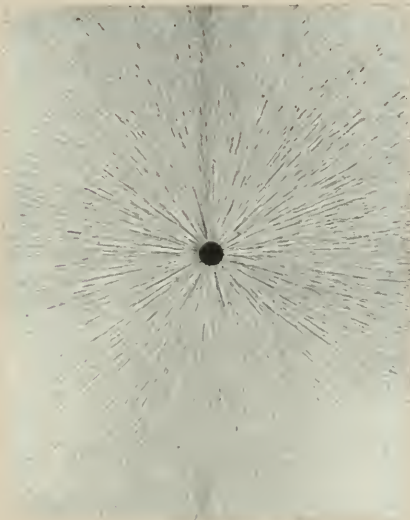
The photograph above shows bits of fine thread suspended in oil. At center is a charged object. Its electric field induces opposite charges on the two ends of each bit of thread which then tend to line up end-to-end along the direction of the field.
Top right: equal like charges.
Bottom right: equal opposite charges.
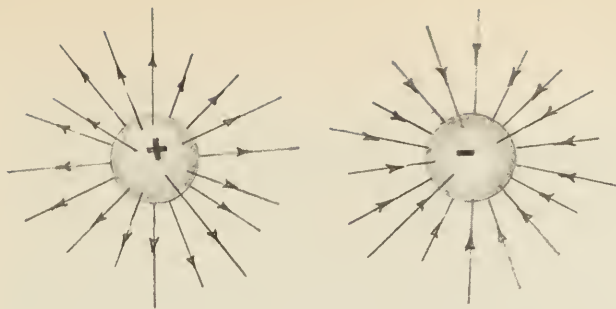
The "map" of a three-dimensional electric field is not easy to draw. A vector value can be assigned to the electric field strength $\vec{E}$ at every point in space, but obviously we cannot illustrate that—such a map would be totally black with arrows. A convention which has been used for many years in physics is to draw a small number of all the infinitely many possible lines that indicate the *direction* of the field. For example, the field around a charged sphere could be represented by a drawing like these above. Notice that the lines, which have been drawn symmetrically around the sphere, are more closely spaced where the field is stronger. The lines can be drawn in three dimensions so that the density of lines in a given region represents the strength of the field in that region. These lines, therefore, represent both the local direction and local strength of the field, and are called "lines of
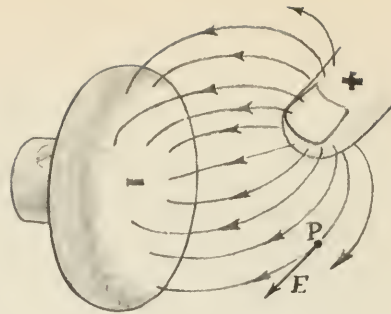
force." Around a single charged sphere the lines of force are straight and directed radially away from or toward the center. When charges are distributed in a more complicated way, the lines of force in the region around them may be curved. The direction of the field strength $\vec{E}$ at a point is the *tangent* to the curved line of force at that point. Above, for example, we have drawn the lines of force that represent the electric field between a charged fingertip and the oppositely charged surface of a doorknob. The electric field vector $\vec{E}$ at point P would be directed along the tangent to the curved line of force at P, and represented by the arrow at P. Note the difference: each line of force only shows direction, and terminates at a charged object or goes off to infinity. But the electric field vector $\vec{E}$ at each point P is represented by an arrow of length drawn to scale to indicate magnitude E.
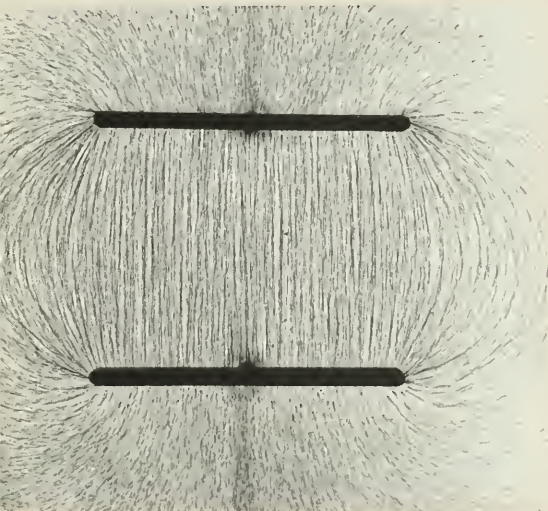
Oppositely charged plates. (Notice the *uniformity* of the field *between* the plates as compared with the *nonuniformity* at the *ends* of the plates.)
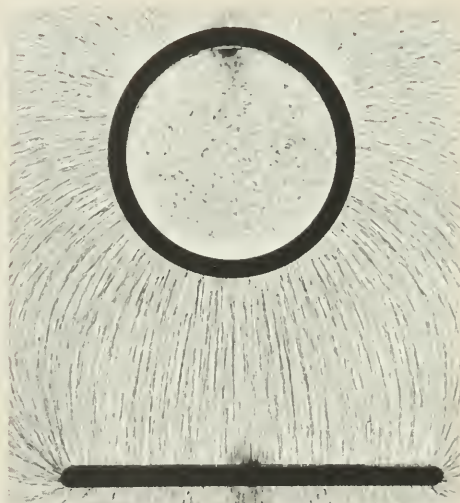
Oppositely charged cylinder and plate. (Notice the absence of field inside the cylinder, as indicated by lack of alignment of the fibers.)

Q11   A negatively charged test body is placed in an electric field where the vector $\vec{E}$ is pointing downward. What is the direction of the force on the test body?

14.5   The smallest charge

In Sec. 14.3 we mentioned the fact that an electrified comb can pick up a small piece of paper, so that in this case the electric force on the paper must exceed the gravitational force exerted on the paper by the earth. This observation indicates that electric forces in general are strong compared to gravitational forces. Another illustration of the same point is the fact that we can balance the gravitational force on an object, only big enough to be seen in a microscope (but still containing several billion atoms) with the electrical force on the same object when the object has a net electric charge of only a single electron. (The electron is one of the basic components of the atom. Other properties of atoms and electrons will be discussed in Unit 5.) This fact is the basis of a method of measuring the electron's charge in an experiment first done by the American physicist Robert A. Millikan in 1909. Although a description of Millikan's experiment will be postponed until Sec. 18.3, its basic principle will be discussed here because it provides such a vivid connection between the ideas of force, field, and charge.

Millikan used fine droplets of oil from an atomizer which become charged as they are formed in a spray. The oil was convenient because of the low rate of evaporation of the droplet.

Suppose a small body of mass m — a droplet of oil or a small plastic sphere — carries a net negative electric charge of magnitude q. If we place the negatively charged body in an electric field E directed downwards, a force F_{el} of magnitude qE will be exerted on the body in the upward direction. Of course there will also be a downward gravitational force $F_{grav} = mg$ on the object. The body will accelerate upward or downward, depending on whether the electric force or the gravitational force is greater. By adjusting the magnitude of the electric field strength $\vec{E}$, that is by changing the source that sets up $\vec{E}$ — we can balance the two forces.

$$\vec{F}_{el} = q\vec{E}$$

$$q \bigcirc m$$

$$\vec{F}_{grav} = m\vec{g}$$

When $m\vec{g}$ and $q\vec{E}$ are balanced, frictional forces remain until the body stops moving.

What happens when the two forces are balanced? Remember that if a zero net force acts on a body it will have no acceleration — though it can still be moving with some constant velocity. However, in this case air resistance is also acting as long as the drop moves at all, and will soon bring the drop to rest. (When the oil drop is stationary, no frictional forces of air resistance act on it). The drop will then be in equilibrium and will be seen to be suspended in mid-air. When this happens, we record the magnitude of the electric field strength $\vec{E}$ which we had to apply to produce this condition.

If the electric force balances the gravitational force, the following must hold:

$$qE = mg$$

We can calculate the charge q from this equation if we know the quantities E, m and g, since

$$q = \frac{mg}{E}$$

This allows us to find, in the laboratory, what values of charge q
a small test object such as an oil drop can carry. If you do this, you
will find the remarkable fact that *all possible charges in nature
are made up of whole multiples of some smallest charge* which
we call the *magnitude of the charge on an electron*. By repeating
the experiment many times with a variety of small charges, the
value of the smallest charge can be found, which is the charge on
one electron (q_e). This is in effect what Millikan did. He obtained
the value of $q_e = 1.6024 \times 10^{-19}$ coulomb for the electron charge.
(For most purposes we can use the value 1.6×10^{-19} coulomb.) This
value agrees with the results of many other experiments done
since then. No experiment has yet revealed the existence of a
smaller unit of charge. (Some physicists have speculated, however
that there might be $\frac{1}{3}q_e$ associated with a yet-to-be found subatomic
particle that has been given the name "quark.")

The magnitude of the charge on the
electron is symbolized by q and its
sign is negative. Any charge q is
therefore given by $q = nq$ where n
is the whole number of individual
charges, each of magnitude q.

SG 14.12 - 14.14

Q12   How can the small oil droplets or plastic spheres used in
the Millikan experiment experience an electric force *upward* if
the electric field is directed *downward*?

Q13   What do the results of the Millikan experiment indicate
about the nature of electric charge?

14.6   Early research on electric charges

For many centuries the only way to charge objects electrically
was to rub them. In 1663, Otto von Guericke made and described
a machine that would aid in producing large amounts of charge
by rubbing:

> . . . take a sphere of glass which is called a phial, as large
> as a child's head; fill it with sulphur that has been
> pounded in a mortar and melt it sufficiently over a fire.
> When it is cooled again break the sphere and take out the
> globe and keep it in a dry place. If you think it best, bore
> a hole through it so that it can be turned around an iron
> rod or axle . . . .

When he rested his hand on the surface of the sulphur globe
while rotating it rapidly, the globe acquired enough charge to
attract small objects.

By 1750 electrical machines were far more powerful and
vigorous research on the nature of electricity was going on in many
places. Large glass spheres or cylinders were whirled on axles
which were in turn supported by heavy wooden frames. A stuffed
leather pad was sometimes substituted for the human hands. The
charge on the globe was often transferred to a large metal object
(such as a gun barrel) suspended nearby.

These machines were powerful enough to deliver strong
electrical shocks and to produce frightening sparks. In 1746 Pieter
van Musschenbroek, a physics professor at Leyden, reported on

Franklin's drawing of a Leyden jar, standing on an insulating block of wax. The rod in the stopper was connected to a conducting liquid in the bottle. A charge given to the ball would hold through the non-conducting glass wall an equal amount of the opposite charge on the metal foil wrapped around the outside. It can hold a large charge because positive charges hold negative charges on the other side of a nonconducting wall.

an accidental and very nearly fatal discovery in a letter which begins, "I wish to communicate to you a new, but terrible, experiment that I would advise you never to attempt yourself." Musschenbroek was apparently trying to conduct the electrical genie into a bottle, for he had a brass wire leading from a charged gun barrel to a jar filled with water (see illustration on p. 51). A student was holding the jar in one hand and Musschenbroek was cranking the machine. When the student touched the brass wire with his free hand he received a tremendous shock. They repeated the experiment, this time with the student at the crank and Musschenbroek holding the jar. The jolt was even greater than before (the student must have been giving his all at the crank). Musschenbroek wrote later that he thought ". . . it was all up with me . . . ." and that he would not repeat the experience even if offered the whole kingdom of France. Word of the experiment spread rapidly, and the jar came to be called a Leyden jar. Such devices, because of their capacity for storing electric charge, are now called capacitators.

The Leyden jar came to Benjamin Franklin's attention. He performed a series of experiments with it, and published his analysis of its behavior in 1747. In these experiments Franklin first showed that the effects of different kinds of charge (which we have called positive and negative) can cancel each other. Because of this cancellation he concluded that positive and negative charges were not substantially different. Franklin thought that only *one* kind of electricity need be imagined to explain all phenomena. He considered a body to be charged positively when it had an excess of "electric fire," and to be charged negatively when it had a shortage of it. However, this view is no longer held—both positive and negative electric charges do exist in their own right. But Franklin's theory was sufficient to account for most facts of electrostatics known in the eighteenth century.

Franklin's theory also yielded the powerful and correct idea that electric charge is neither created nor destroyed. Charges occurring on objects are due to the rearrangement of electric charges—an act of redistribution rather than creation. Similarly, positive and negative charges can cancel or neutralize each other's effect without being destroyed. This is the modern principle of *conservation of charge*, which is taken to be as basic a law of nature as are the conservation principles of momentum and of energy. The Law of Conservation of Electric Charge can be stated, *the net amount of electric charge in a closed system remains constant, regardless of what reactions occur in the system. Net amount of charge* is defined as the difference in amounts of + and − charge. (For example, a net charge of + 1 coulomb would describe 1 coulomb of positive charge all by itself, or a composite of 11 coulombs of positive charge and 10 coulombs of negative charge.) If the + and − are taken to be actual numerical signs, instead of only convenient labels for two different kinds of charge, then the *net* charge can be called the *total* charge; adding charges with + and − signs will in effect give the difference between the amounts

Capacitors, familiar to anyone who has looked inside a radio, are descendents of the Leyden jar. They have many different functions in modern electronics.

of positive and negative charge. The principle of conservation of electric charge is widely useful—from designing circuits (see the *Reader 4* article, "Ohm's Law") to analyzing subatomic reaction (see the Project Physics supplementary unit *Elementary Particles*).

Electrostatic equipment of the 1700's.

An interesting implication of the electric charge conservation law is that it allows the possibility that charges can appear or disappear suddenly in a closed system—as long as there are equal amounts of + and − charge. (An example of just such a spontaneous appearance of charges is a central part of the experiment in the Project Physics film *People and Particles*.)

Q14 What experimental fact led Franklin to propose that there is only one kind of "electric fire"?

14.7 Electric currents

Touching a charged object to one end of a chain or gun barrel will cause the entire chain or barrel to become charged. The obvious explanation is to imagine that the charges move through the object. Electric charges move easily through some materials—called *conductors*. Metal conductors were most commonly used by the early experimenters, but salt solutions and very hot gases also conduct charge easily. Other materials, such as glass and dry fibers, conducted charge hardly at all and are called non-conductors or *insulators*. Dry air is a fairly good insulator. (But damp air is not— which is why you may have difficulty in keeping charges on objects if you do electrostatic experiments on a humid day.) But if the charge is great enough, the air around it will become conducting all of a sudden, letting a large amount of charge shift through it. The heat and light caused by the sudden rush of charge produces a "spark." Sparks were the first obvious evidence of moving charges.

SG 14.15

Count Alessandro Volta (1745-1827) was given his title by Napoleon in honor of his electrical experiments. He was Professor of Physics at the University of Pavia, Italy. Volta showed that the electric effects previously observed by Luigi Galvani, in experiments with frog legs, were due to the metals and not to any special kind of "animal electricity." See the article "A Mirror for the Brain" in *Reader 4* for an account of this controversy.
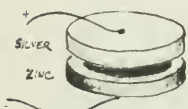
Voltaic "cell"

Voltaic "pile" or battery

Until late in the eighteenth century, an appreciable movement of flow of charge or an *electric current,* could be produced only by discharging a Leyden jar. Such currents last only for the brief time it takes for the jar to discharge.

In 1800, Alessandro Volta discovered a much better way of producing electric currents. Volta demonstrated that if different metals, each held with an insulating handle, are put into contact and then separated, one will have a positive charge and the other a negative charge. Volta reasoned that a much larger charge could be produced by stacking up several pieces of metal in alternate layers. This line of thought led him to undertake a series of experiments which produced an amazing finding, reported in a letter to the Royal Society in England in March of 1800:

> Yes! the apparatus of which I speak, and which will doubtless astonish you, is only an assemblage of a number of good conductors of different sorts arranged in a certain way. 30, 40, 60 pieces or more of copper, or better of silver, each in contact with a piece of tin, or what is much better, of zinc, and an equal number of layers of water or some other liquid which is a better conductor than pure water, such as salt water or lye and so forth, or pieces of cardboard or of leather, etc. well soaked with these liquids. . . .
>
> I place horizontally on a table or base one of the metallic plates, for example, one of the silver ones, and on this first plate I place a second plate of zinc; on this second plate I lay one of the moistened discs; then another plate of silver, followed immediately by another of zinc, on which I place again a moistened disc. I thus continue in the same way coupling a plate of silver with one of zinc, always in the same sense, that is to say, always silver below and zinc above or *vice versa,* according as I began, and inserting between these couples a moistened disc; I continue, I say, to form from several of these steps a column as high as can hold itself up without falling.

Volta showed that one end, or "terminal," of the pile was charged positive, and the other charged negative. He found that when wires are attached to the first and last disk of his apparatus (which he called a "battery"); it produced electricity with effects exactly the same as the electricity produced by rubbing amber, by friction in electrostatic machines, or by discharging a Leyden jar.

But most important of all, Volta's battery provided a means of producing a more or less *steady* electric current for a long period of time. Unlike the Leyden jar, it did not have to be charged from the outside after each use. Thus the properties of electric currents as well as static electric charges could be studied in the laboratory in a controlled manner.

Q15   In what ways was Volta's battery superior to a Leyden jar?

14.8   Electric potential difference

The sparking and heating produced when the terminals of an electric battery are connected show that energy from the battery has been transformed into light, sound, and heat energy. The battery converts chemical energy to electrical energy which, in turn, is changed to other forms of energy (such as heat) in the conducting path between the terminals. In order to understand electric currents and the way electric currents can be used to transport energy, we shall need a new concept that goes by the common name "voltage."

First recall something we learned in mechanics (Unit 3): Change in potential energy is equal to the work required to move an object frictionlessly from one position to another (Sec. 10.2). For example, the gravitational potential energy is greater when a book is on a shelf than it is when the book is on the floor; the increase in potential energy is equal to the work done raising the book from floor to shelf. This difference in potential energy depends on three factors: the mass m of the book, the magnitude of the gravitational strength field g, and the difference in height d between the floor and the shelf.

In a similar way, the *electric* potential energy is changed when work is done on an electric test charge in moving it from one point to another in an electric field, and again, this change of potential energy $\Delta(PE)$ can be directly measured by the work that was done. The magnitude of this change in potential energy will of course depend on the magnitude of the test charge q. So if we divide $\Delta(PE)$ by q, we get a quantity that does not depend on how large q is, but depends only on the intensity of the electric field and the location of the beginning and end points. This new quantity is called "electric potential difference." *Electric potential difference is defined as the ratio of the change in electrical potential energy $\Delta(PE)$ of a charge q to the magnitude of the charge.* In symbols,

$$V = \frac{\Delta(PE)}{q}$$

The units of electric potential difference are those of energy divided by charge, or joules per coulomb. The abbreviation for joules/coul is *volt*; hence the electrical potential difference (or "voltage") between two points is 1 volt, if 1 joule of work is done in moving 1 coulomb of charge from one of the points to the other.

$$1 \text{ volt} = 1 \text{ joule/coulomb}$$

The potential difference between two points in a steady electric field depends on the location of the points, but not on the *path* followed by the test charge. The path can be short or long, direct or tortuous — the same work is done per unit charge, just as a mountaineer does the same work per pound of mass in his pack against the gravitational field from bottom to top of his climb, whether he climbs up directly or spirals up along the slopes. Thus
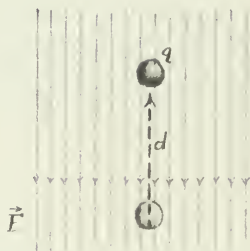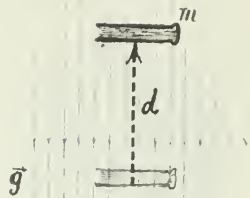
As is true for gravitational potential energy there is no absolute zero level of electric potential energy — the difference in potential energy is the significant quantity. The symbol V is used both for potential difference as in the equation at the left and as an abbreviation for volt the unit of potential difference (as in 1 V = 1 J/coul).

SG 14.15 – 14.21

A 1½-volt cell is one which has a potential difference of 1½-volts between its two terminals. (This type of cell is often called a "battery," although technically a battery is the name for a group of connected cells.)

it is possible to speak of the electrical potential difference between two points in a field, just as it is possible to speak of the difference in gravitational potential energy between two points (as we did in Sec. 10).

We begin to see the great influences of this definition of potential difference in a simple case. Let us calculate the potential difference between two points in a uniform electric field, such as the electric field used in the Millikan experiment. Consider two points in a uniform electric field of magnitude E produced by oppositely charged parallel plates. The work that must be done in moving a positive charge q from one point to the other directly against the lines of electric force is the product of the force q exerted on the charge ($F_{el} = qE$), and the distance d through which the charge is moved. Thus,

$$\Delta(PE) = qEd$$

Substituting this expression for $\Delta(PE)$ in the definition of electric potential difference gives for the simple case of a uniform field,

$$V = \frac{\Delta(PE)}{q}$$
$$= \frac{qEd}{q}$$
$$= Ed$$

In practice it is easier to measure electric potential difference V (with a volt-meter) than it is to measure electric field strength E. The relationship above is most often useful in the alternative form $E = V/d$ which can be used to find the intensity of a uniform field.

Electric potential energy, like gravitational potential energy, can be converted into kinetic energy. A charged particle placed in an electric field, but free of other forces, will accelerate — it will move so as to increase its kinetic energy at the expense of the electric potential energy. (In other words, the electric force on the charge acts in such a way as to push it toward a region of lower potential energy.) A charge q, "falling" through a potential difference V, increases its kinetic energy by qV if nothing is lost by friction (that is, in a vacuum tube). The increase in kinetic energy is equal to the decrease of potential energy; the sum of the two at any moment remains constant. This is just one particular case of the general principle of energy conservation, when only electric forces are acting.

The conversion of electric potential energy to kinetic energy finds application in the *electron accelerators* (of which a common example is a television picture tube). An electron accelerator usually begins with an "electron gun" which consists of two basic parts: a wire and a metal can in an evacuated glass tube. The wire is heated red-hot to cause electrons to escape from its surface. The nearby can is charged positively, producing an electric field between the hot wire and the can. The electric field accelerates the electrons through the vacuum toward the can. Many electrons will
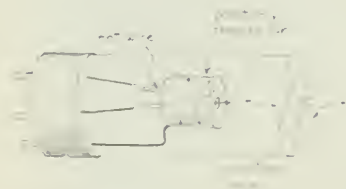
Electrically charged particles (electrons) are accelerated in an "electron gun" as they cross the potential difference between a hot wire (filament) and can in an evacuated glass tube.

stick to the can, but some go shooting through a hole in one end of it. The stream of electrons emerging from the hole can be further accelerated or focused by additional cans. (You can make such an electron gun for yourself in the laboratory experiment Electron Beam Tube.) Such a beam of charged particles has a wide range of uses both in technology and in research. For example, it can be used to make a fluorescent screen glow, as in a television picture tube or an electron microscope. Or it can be used to knock atoms apart, producing interesting particles (to study) and x-rays (for medical purposes or further research). When moving through a potential difference of one volt, an electron with a charge of 1.6×10^{-19} coulomb increases its kinetic energy by 1.6×10^{-19} joules. This amount of energy is called an "electron volt," abbreviated eV. Multiples are 1 KeV (= 1000 eV), 1 MeV (= 10^6 eV) and 1 Bev (= 10^9 eV). Energies of particles in accelerators are commonly expressed in such multiples (see Chapter 19). In a TV tube, the electrons in the beam are accelerated across an electric potential difference of about 20,000 volts — so they each have an energy of about 20 KeV. The largest accelerator being constructed now is designed to give (for research purposes) charged particles with kinetic energies of 200 BeV.

Q16   How is the electric potential difference, or "voltage," between two points defined?
Q17   Does the potential difference between two points depend on the path followed in taking a charge from one to the other? Does it depend on the magnitude of the charge moved?
Q18   Is the electron volt a unit of charge, or voltage, or what?

Particle accelerators come in a wide variety of shapes and sizes. They can be as common as a 1000-volt tube in an oscilloscope or 20,000-volt TV "guns" (see photos on p. 70–71 in Study Guide), or as spectacular as the one shown below (or the Cambridge Electron Accelerator which was the scene for two Project Physics films, *People and Particles* and *Synchrotron*)

K : kilo- (10)
M : mega- (10)
B : billion (10)
(B is often replaced by G · giga-)

SG 14.22

Left: the site of Stanford University's 2-mile electron accelerator, in which electrons are given kinetic energies as great as 20 BeV.
Right: a section of the evacuated tube through which the electrons travel. The electrons are accelerated in steps by electric fields in a long line of accelerating cavities, similar to those in the photograph on p. 30.

14.9   Electric potential difference and current

The acceleration of an electron in a vacuum by an electric field is the simplest example of the effect of a potential difference on a charged particle. A more familiar example is electric current in a metal wire. Chemical changes inside the battery produce an electric field which continually drives charges to the terminals, one charged negatively, the other positive. The "voltage" of the battery tells us how much energy per unit charge is available when the electric field between the terminals is allowed to move charges in any external path from one terminal of the battery to the other.

The relation between current and potential difference might seem to be more complicated in a wire than a vacuum tube because electrons in a metal do not move freely as they would in an evacuated tube, but are continually interacting with the atoms of the metal. However, there is a simple relation, originally found by experiment by George Wilhelm Ohm, which is at least approximately valid in the case of most metallic conductors: *the total current I in a conductor is proportional to the potential difference V applied between the two ends of the conductor.* If we use the symbol I for the current and V for the applied potential difference, we can write the relationship as

$$I \propto V$$
$$\text{or} \qquad I = constant \times V$$

This simple proportionality is called *Ohm's Law*. It is usually written in the form

$$I = \frac{V}{R}$$

where R is a constant called the *resistance* of the conducting path. Thus, Ohm's law assumes that the amount of the resistance of a given conducting path does not depend on current or voltage. The resistance does depend on the material and dimensions of the path, such as the length and diameter of the wire. The resistance is not strictly a constant for any conducting path—it varies with changes in temperature, for example.

Ohm's law is a good empirical approximation in practical technical work, but it does not have the status and generality of such laws as the law of universal gravitation or Coulomb's law. In this course, we will use it mainly in lab work and in connection with the discussion of electric light bulbs and power transmission in Chapter 15.

In metallic conductors the moving charge is the negative electron, with the positive "mother" atom fixed. But all effects are the same as if positive charges were moving in the opposite direction. By an old convention, this is the direction usually chosen to describe the direction of current.

Close-up of part of the electric circuit in the TV set pictured on p. 40. These "resistors" have a fairly constant voltage-to-current ratio. (The value of the ratio is indicated by colored stripes.)

SG 14.23

Q19   How does the current in a metallic conductor change if the potential difference between the ends of the conductor is doubled?

Q20   What does it mean to say a resistor has a resistance of 5 *megohms* (5×10^6 ohms)?

Q21   How would you test whether Ohm's law applies to a given piece of wire?

14.10   Electric potential difference and power

If the charge could move freely from one terminal to the other in an evacuated tube, the work done on the charge would simply increase the kinetic energy of the charge. However, if the charge moves through some material such as a wire or resistor, it will transfer energy to the material by colliding with atoms; thus at least some of the work will go into heat energy. If, for example, the battery is forcing charges through the filament wire in a flashlight bulb, the electric energy carried by the charges is dissipated in heating the filament. (The hot filament radiates energy, a small fraction of which is in the form of visible light.) Recall now that "voltage" (electric potential difference) is the amount of *work* done per unit of charge transferred per unit *time.* So the product of voltage and current will be the amount of *work* done per unit *time*:

$$V \text{ (joules/coulomb)} \times I \text{ (coulombs/sec)} = VI \text{ (joules/sec)}$$

But work done per unit time is called *power* (as defined in Sec. 10.6 of Unit 3 Text). The unit of power, equal to 1 joule/sec, is called a "watt." Using the definition of ampere (1 coulomb/sec) and volt (1 joule/coulomb), we can write the power P:

$$P \text{ (watts)} = V \text{ (volts)} \times I \text{ (amperes)}$$

What energy transformation does this work accomplish? As the positive charge moves to a lower potential level, it does work against material by colliding with its atoms, and the electrical energy associated with it is converted into heat energy. If V is the voltage between the two ends of some material carrying a current I, the power dissipated in the material as heat will be given by $P = VI$. This can be equally well expressed in terms of the resistance of the material substituting IR for V:

$$P = IR \times I$$
$$P = I^2R$$

Joule was the first to find experimentally that the heat produced by a current is proportional to the square of the current. This discovery was part of his series of researches on conversion of different forms of energy (described in Sec. 10.8). The fact that the rate of dissipation of energy is proportional to the *square* of the current has great significance in making practical use of electric energy, as we will see in the next chapter.

Example A small flashlight bulb connected to a 1.5-volt cell will have a current of about 0 1 ampere in its filament. At what rate is electric work being done to heat the filament in the bulb?
$P \quad VI$
$\quad = 1.5 \text{ volts} \times 0 1 \text{ amps}$
$\quad = 0.15 \text{ watts}$
(Only a small fraction of this power goes into the visible light energy radiated from the filament)

SG 14.24 – 14.27

Q22   What happens to the electrical energy used to move charge through a conducting material?
Q23   How does the power dissipated as heat in a conductor change if the current in the conductor is doubled?

14.11 Currents act on magnets

Since early in the eighteenth century there were reports that lightning had changed the magnetization of compass needles and had made magnets of knives and spoons. Some believed that they had magnetized steel needles by discharging a Leyden jar through them. These reports suggested that electricity and magnetism are intimately related in some way. But the casual observations were not followed up with deliberate, planned experiments that might have had an impact on the development of concepts and theory.

None of these early reported occurrences surprised adherents of the Nature Philosophy current in Europe at the start of the nineteenth century. They were convinced that all the observed phenomena in nature were different manifestations of a single force. Their metaphysical belief in the unity of physical forces would, in fact, lead them to expect that electrical and magnetic forces were associated or related in some way.

The first concrete evidence of a connection between electricity and magnetism came in 1820, when Oersted performed a momentous series of experiments. (See illustrations on next page.) Oersted placed a magnetic compass needle directly beneath a long horizontal conducting wire. He had placed the wire along the earth's magnetic north-south line, so that the magnetic needle was naturally aligned parallel to the wire. When the wire was connected to the terminals of a battery, the compass needle swung toward an east-west orientation—nearly perpendicular to the wire! While charge at rest does not affect a magnet, charge in motion (a current) does exert an odd kind of force on a magnet.

Oersted's results were the first instance ever found in which a force was observed that did not act along a line connecting the sources of the force (as forces do between planets, or between electric charges, or between magnetic poles). The force that the current-carrying wire exerts on a magnetic pole is not along the line from the wire to the pole: the force that must be acting on the pole to twist is necessarily acting *perpendicular* to such a line. The magnetic needle is *not* attracted to or repelled by the wire that carries the current; it is *twisted* sidewise by forces on its poles.

The way a current affects a compass needle certainly seemed peculiar. No wonder it had taken so long before anyone found the connection between electricity and magnetism. Closer examination revealed more clearly what was happening in all these experiments. The long straight current-carrying wire sets up a magnetic field that turns a small magnet so that the north-south line on the magnet is tangent to a circle whose center is at the wire and whose plane lies *perpendicular* to the wire. Thus, the current produces a *circular* magnetic field, not a *central* magnetic field as had been expected.

We define the direction of the magnetic field vector $\vec{B}$ at each point to be the same as the direction of the force on the north-seeking pole of a compass needle placed at that point. The force
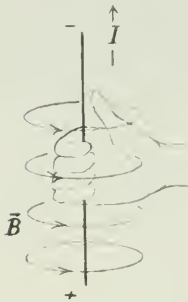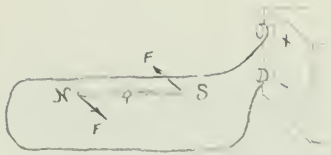
A useful rule: if the thumb points in the direction of the flow of charge, the fingers curl in the direction of the lines of the magnetic field $\vec{B}$. The magnitude of $\vec{B}$ is discussed in Sec. 14.13. Use the right hand for positive charge flow, left hand for negative charge flow.

Hans Christian Oersted (1777-1851), a Danish physicist, studied the writings of the Nature Philosopher Schelling and wrote extensively on philosophical subjects himself. In an essay published in 1813, he predicted that a connection between electricity and magnetism would be found. In 1820 he discovered that a magnetic field surrounds an electric current when he placed a compass under a current-carrying wire. In later years he vigorously denied the suggestion of other scientists that his discovery of electromagnetism had been accidental.
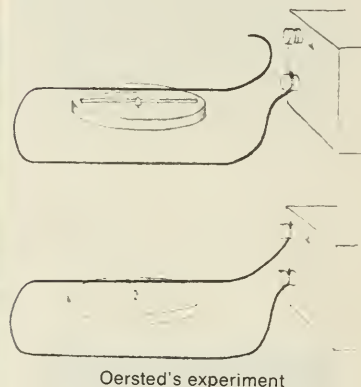
Oersted's experiment

To make the photograph below, a thick wire was inserted vertically through a horizontal sheet of cardboard, and tiny slivers of iron were sprinkled on a sheet. A strong current through the wire creates a magnetic field which causes the slivers to become magnetized and to line up in the direction of the field. Note that the magnetic lines of force encircle the wire.
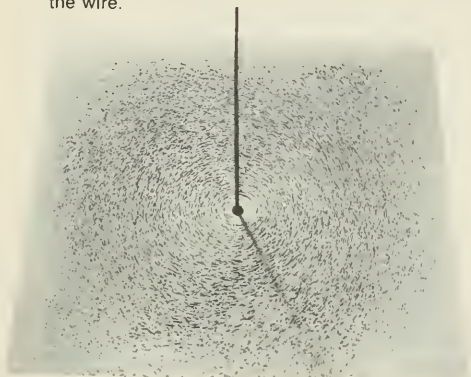
Left: an array of tiny compasses on a sheet of cardboard placed perpendicular to a brass rod. Right: when there is a strong current in the rod, the compass needles are deflected from their normal north-south line by the magnetic field set up by the current. This experiment, too, indicates that the lines of magnetic force due to the current are circular around the rod.

Needle-like iron oxide crystals in the magnetic field of a bar magnet. The bar magnet is under the paper on which the iron oxide has been spread.
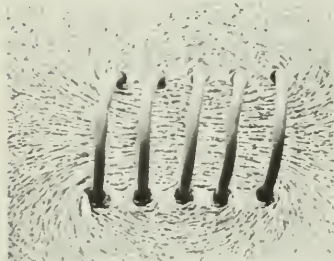
Iron filings in the magnetic field produced by current in a coil of wire.

SG 14.28

André-Marie Ampère (1775-1836) was born in a village near Lyons, France. There was no school in the village and Ampère was self-taught. His father was executed during the French Revolution, and Ampère's personal life was deeply affected by his father's death. Ampère became a professor of mathematics in Paris and made important contributions to physics, mathematics, and the philosophy of science. His self-portrait is reproduced above.

on the south-seeking pole will be in a direction exactly opposite to the field direction. A compass needle will respond to the opposite forces on its ends by turning until it points as closely as possible in the direction of the field. We can get a clue to the "shape" of the magnetic field set up all around a current by sprinkling tiny slivers of iron on a sheet of paper through which the current-carrying wire is passing. The slivers become magnetized and serve as tiny compass needles to indicate the direction of the field. Since the slivers also tend to link together end-to-end, the pattern of slivers indicates magnetic lines of force around any current-carrying conductor or for that matter around a bar magnet. These lines form a pictorial representation of the magnetic field.

An example of such pictorialization is finding the "shape" of magnetic field produced by a current in a *coil* of wire, instead of a straight piece of wire. To do this, we bend the wire into a loop so that it goes through the paper in two places. The magnetic effects of the different parts of the wire on the iron slivers combine to produce a field pattern similar to that of a bar magnet. (See pp. 64 and 65.)

Q24   Under what conditions can electric charges affect magnets?
Q25   What was surprising about the force a current exerted on a magnet?
Q26   How do we know that a current produces any magnetic field near it? What is the "shape" of the field anywhere near a straight conductor?

14.12   Currents act on currents

Oersted's discovery is a typical case of the rare occasion when a discovery opens up an exciting new subject of research. In this case. no new equipment was needed. At once, scores of people in laboratories throughout Europe and America began intensive studies on the magnetic effects of electric currents. The work of Andre-Marie Ampère (1775-1836) stands out among all the rest. Ampère came to be called the "Newton of electricity" by James Clerk Maxwell, who some decades later was to construct a complete theory of electricity and magnetism. Ampère's work is filled with elegant mathematics; without describing his theory in detail. we can trace some of his ideas and review some of his experiments.

Ampère's thoughts raced forward as soon as he heard Oersted's news. He began with a line of thought somewhat as follows: since magnets exert forces on each other, and since magnets and currents also exert forces on each other, can it be that currents exert forces on other currents? Although it is tempting to leap forward with a reply, the answer is not necessarily yes. Arguing from symmetry is inviting and often turns out to be right, but it is

not logically or physically necessary. Ampère recognized the need to let experiment provide the answer. He wrote:

> When M. Oersted discovered the action which a current exercises on a magnet, one might certainly have suspected the existence of a mutual action between two circuits carrying currents; but this was not a necessary consequence; for a bar of soft iron also acts on a magnetised needle, although there is not mutual action between two bars of soft iron.

And so Ampère put his hunch to the test. On September 30, 1820, within a week after word of Oersted's work reached France, Ampère reported to the French Academy of Sciences that he had indeed found that two parallel current-carrying wires exert forces on each other even though they showed no evidence of electric charges.

Ampère made a thorough study of the forces between currents, and how they depend on the distance between the wires and their relative orientations as well as on the amount of current. In the laboratory you can repeat these experiments and work out the "force law" between two currents. We will not need to go into the quantitative details here, except to note that the force between currents can be used to measure how much current flows. In fact, the magnetic force between currents is nowadays the preferred way to *define* the unit of current, which is called the *ampere* (as mentioned in Sec. 14.3). One ampere is defined as the amount of current in each of two long straight parallel wires set one meter apart, which causes force of exactly 2×10^{-7} newtons on each meter of the wires.

Replica of Ampère's current balance. The essential part is a fixed horizontal wire (foreground), and just behind it, hanging from a hinged support, a shorter segment of wire. Current is produced in both wires, and the force between them is measured.

Q27 What was Ampère's hunch?

Summary of Electric Units

Quantity	Symbol	Unit
current	I	The *ampere* is the fourth fundamental unit in the so-called MKSA system (meter, kilogram, second, ampere) which is now widely used by physicists. For definition, see last paragraph.
charge	Q	The *coulomb* is defined as the amount of charge that flows in one second, when the current is 1 ampere.
potential difference	V	The *volt* is defined as the electric potential difference between two points such that 1 joule of work is done in moving 1 coulomb of charge between those points.
electric power	P	The *watt* is defined as the rate of energy flow (or work done per second, or "power") which corresponds to 1 joule per second. Thus a current of 1 ampere due to a potential difference of 1 volt corresponds to 1 watt of power. The *kilowatt* is equal to 1000 watts.
work	W	The *kilowatt-hour* is the amount of energy expended (work done) when one kilowatt of power is used for one hour. It is equal to 3,600,000 joules (1000 joules/sec × 3600 sec).
resistance	R	The *ohm* is defined as the resistance of a material which allows a current of just 1 ampere to pass through if the potential difference across the material is 1 volt.
electric field	$\vec{E}$	Electric field can be expressed either in terms of the force experienced by a unit charge (newtons per coulomb), or in terms of the rate at which the electric potential difference increases (volts per meter).
magnetic field	$\vec{B}$	The magnitude of magnetic field is defined in terms of the force experienced per meter of length by a conductor carrying a current of 1 ampere. The units are thus newtons per ampere-meter. Another common unit is the *gauss*, which equals 10^{-4} newtons/amp. meter.

Magnets and fields

The diagrams at the right represent the magnetic field of a current in a loop of wire. In the first diagram, some lines of force due to opposite sides of the loops have been drawn separately. One example is given of how the two fields add at point *P*. Some lines of force for the total field are drawn in the second diagram. Below at the right is a photograph of iron filings in the magnetic field of an actual current loop. Below at the left is the field of a series of coils, or helix.

In many applications, from doorbells to cyclotrons, magnetic fields are produced by coils of wire wound around iron cores. When a current is switched on, the iron core becomes magnetized and increases the strength of the field of the coil alone by a factor of 10^2 or 10^3. Such devices are called *electromagnets*.
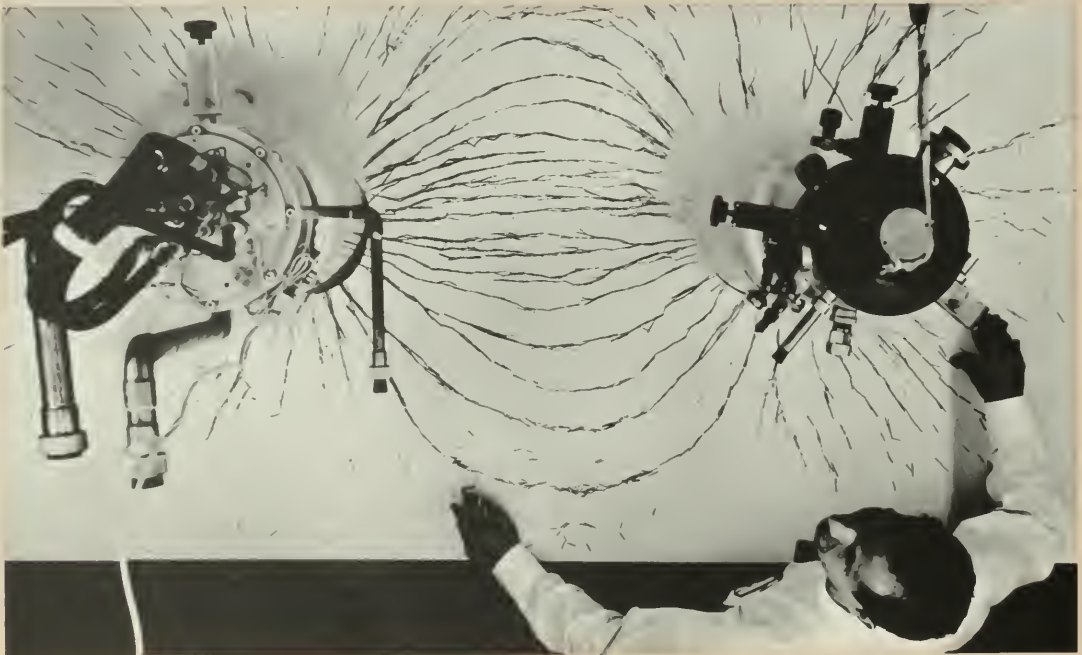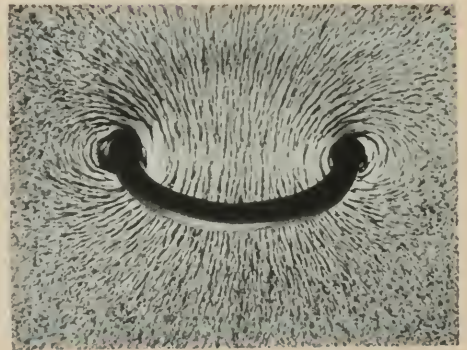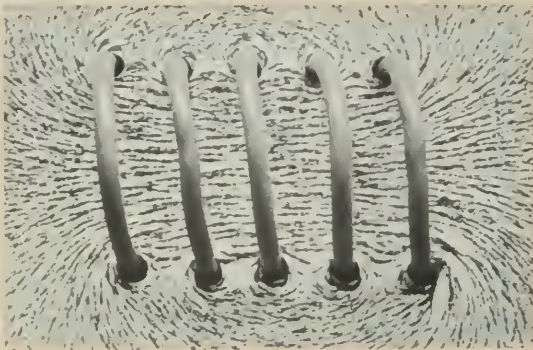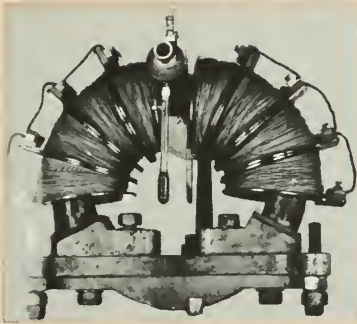
This electromagnet was used early in this century to deflect a beam of charged atoms sent through the tube at the top, in the gap between two sets of coils. It appears again in Unit 6.

A modern electromagnet used in research when strong uniform fields are required.

The first electromagnet, invented by William Sturgeon in England in 1824, could lift a weight of nine pounds. In 1832, Joseph Henry constructed an electromagnet at Princeton which could hold up a weight of 3,600 pounds. Modern electromagnets (see above) which can typically lift 50,000 pounds of iron are widely used in industry, for example, to sort or load scrap metal.
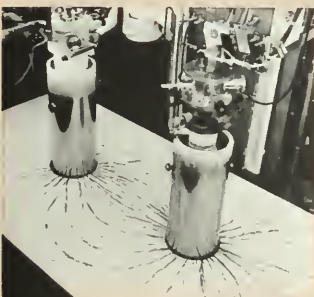
In the two pictures at the left, iron nails line up in a strong magnetic field produced by large currents in superconducting coils, kept at 4° above absolute zero by liquid helium.

14.13   Magnetic fields and moving charges

In the last two sections we discussed the interactions of currents with magnets and with each other. The description of these phenomena is greatly simplified by the use of the concept of magnetic field.

As we saw in studying Coulomb's law, electrically charged bodies exert forces on each other. When the charged bodies are at rest, we say that the forces are "electric" forces, or Coulomb forces, and we imagine "electric fields" which are responsible for them. But when the charged bodies are moving with respect to us (as for example when two parallel wires carry currents), new forces *in addition to* the electric forces are present. We call these new forces "magnetic" and attribute them to "magnetic fields" set up by the moving charges.

The magnetic interaction of moving charged bodies is not as simple as the electric interaction. As we saw in the description of Oersted's experiment, the direction of the force exerted by a current on a magnet needle is perpendicular both to the direction of the current and to the line between the magnet and current. For the moment, however, we will not be concerned about the forces on current-carrying conductors. Instead, we will consider the behavior of individual, freely moving electric charges in an external magnetic field. We believe, after all, that the force on a wire is due to the force on the moving electric charges in it. Once we have established some simple rules for the behavior of free charged particles, we will return to wires again in the next chapter. There you will see how the simple rules are sufficient to understand the operation of electric generators and electric motors – and how these inventions transformed western civilization. But seeking simple rules is not the only reason for considering individual charged particles. The behavior of individual charged particles in a magnetic field is basic to understanding a wide range of phenomena, from television picture tubes to cyclotrons and radiation belts around the earth.

The rules summarized in the remainder of the section are best learned in the laboratory. All you need is a magnet and a device to produce a beam of charged particles – for example, the "electron gun" described in Sec. 14.8. (Recommended procedures are described in the experiment Electron Beam Tube in the *Handbook.*)

The force on a moving charged body. Suppose we have a fairly uniform magnetic field $\vec{B}$ (which may be produced either by a bar magnet or by a current in a coil), and we study how this external field acts on a moving, charged body. We find by experiment that the charge experiences a force, and that the force depends on three quantities: the charge q on the body, the velocity $\vec{v}$ of the body, and the strength of the external field $\vec{B}$ through which the body is moving. The force depends not only on the *magnitude* of the velocity, but also on its *direction*. If the body is moving in a direction *perpendicular* to the field $\vec{B}$, the magnitude of the force is proportional to each of these quantities, that is,

(a) When q moves with velocity $\vec{v}$ perpendicular to $\vec{B}$ we find that

(b)   there is a force $\vec{F}$ as shown, proportional to q, v, and B.
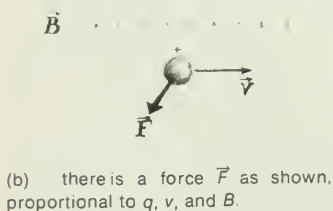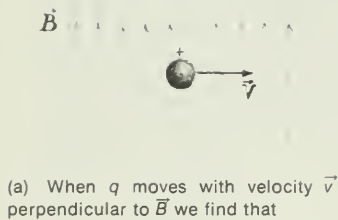
$$F \propto qvB$$

which we can also write as

$$F = kqvB$$

where k is a proportionality constant that depends on the units chosen for F, q, v, and B. If the charge is moving in a direction *parallel* to $\vec{B}$, there is no force! For all other directions of motion, the force is between the full value and zero. In fact, the force is found to be proportional to the *component* of the velocity perpendicular to the field direction. $v_\perp$. Hence we can write a more general expression for the force:

$$F \propto qv_\perp B$$
$$\text{or} \qquad F = kqv_\perp B$$

where k is the same constant as before. *The direction of the force is always perpendicular to the direction of the field and is also perpendicular to the direction of motion of the charged body.*

The force exerted by an external magnetic field on a moving charged particle can be used to *define* the unit of magnetic field $\vec{B}$, by taking the proportionality constant in the last equation equal to one. This definition of the unit of $\vec{B}$ will be convenient here since we will be mainly concerned with how magnetic fields act on moving charges (rather than with forces between bar magnets). So in the special case when $\vec{B}$ and $\vec{v}$ are *at right angles* to each other, the magnitude of the deflecting force becomes simply

$$F = qvB$$

The path of a charged body in a magnetic field. The force on a moving charged body in a magnetic field is always "off to the side," that is, perpendicular to its direction of motion at every moment. Therefore, the magnetic force does not change the *speed* of the charged body, but it does change the direction of the velocity vector. If a charged body is moving exactly perpendicular to a uniform magnetic field, there will be a constant sideways push and the body will move along a circular path, in a plane perpendicular to the direction of the magnetic field. If B is strong enough. the particle will be trapped in a circular orbit (as in the upper sketch a in the margin).

What happens if the charged body's velocity has some component along the direction of the field but is not exactly parallel to it? The body will still be deflected into a curved path, but at the same time, the component of its motion *along* the field will continue undisturbed; so the particle will trace out a coiled (helical) path, (as in the lower sketch b in the margin). If the body is initially moving exactly parallel to the magnetic field, there is no deflecting force on it at all, since in this case, $v_\perp$ is zero.

Some important examples of the deflection of charged particles by magnetic fields to be discussed in Units 5 and 6 will include particle accelerators and bubble chambers. Here we will mention one important example of the "coiled" motion: the Van Allen radiation belts. A stream of charged particles, mainly from the

(c) If $\vec{v}$ is not $\perp$ to $\vec{B}$, there is a smaller force, proportional to $v_\perp$ instead of v.

A useful rule: if your fingers point along $\vec{B}$, and your thumb along $\vec{v}$, $\vec{F}$ will be in the direction your palm would push. For positive charges use the right hand, and for negative use the left hand.

SG 14.29
SG 14.30

SG 14.31   b

sun but also from outer space, continually sweeps past the earth. Many of these particles are deflected into spiral paths by the magnetic field of the earth, and are subsequently "trapped" in the earth's field. The extensive zones containing the rapidly moving trapped particles are called the Van Allen belts. When some of the particles from these zones work their way toward the earth's magnetic poles and hit the atmosphere, they excite the atoms of the gases to radiate light. This is the cause of the aurora ("northern lights" and "southern lights").

In this chapter we have discussed the interaction between currents and magnets and between magnetic fields and charged particles. At first reading, many students consider this topic to be a very abstract part of pure physics. Yet as you should see at once in the next chapter, and again in Chapter 16, the study of these interactions has had important social and practical consequences for the whole civilized world.

Q28 Which of the following affect the *magnitude* of the deflecting force on a moving charged particle?
   (a) the component of the velocity parallel to the magnetic field
   (b) the component of the velocity perpendicular to the field
   (c) the magnetic field $\vec{B}$ itself
   (d) the magnitude of the charge
   (e) the sign of the charge
Q29 Which of the items in the preceding question affect the direction of the deflecting force on the charged particle?
Q30 Why does the deflecting force on a moving charged particle not change the speed of the charged particle? Does it ever do any work on it?
Q31 What are differences between deflecting forces on a charged object due to gravity, due to an electric field, and due to a magnetic field?

A simplified sketch of a variety of paths taken by charged particles in the earth's magnetic field. The Van Allen belts are regions of such trapped particles.

The American physicist James A. Van Allen directed the design of instruments carried by the first American satellite Explorer I. See his article "Radiation Belts Around the Earth," in *Reader 4*.

SG 14.32, 14.33

The aurora photographed from Alaska. The glow is produced when the upper atmosphere is excited by charged particles trapped in the earth's magnetic field.

14.1 The Project Physics learning materials particularly appropriate for Chapter 14 include:
Experiments
Electric Force I
Electric Forces II
Currents, Magnets, and Forces
Electron Beam Tube
Activities
Detecting Electric Fields
Voltaic Pile
An 11¢ Battery
Measuring Magnetic Field Intensity
More Perpetual Motion Machines
Additional Activities Using the Electron
   Beam Tube
Inside a Radio Tube
An Isolated North Magnetic Pole?
Reader Articles
Radiation Belts Around the Earth
A Mirror for the Brain

14.2 How much must you alter the distances between two charged objects in order to keep the force on them constant, if you also
  (a) triple the net charge on each?
  (b) halve the net charge on each?
  (c) double the net charge on one and halve the net charge on the other?

14.3 How far apart in air must two charged spheres be placed, each having a net charge of 1 coulomb, so that the force on them is 1 newton?

14.4 If electrostatic induction does not involve the addition or subtraction of charged particles, but instead is just the separation, or redistribution, of charged particles, how can you explain the fact that attraction results from induction?

14.5 A carbon-coated (and therefore conducting) ping-pong ball hanging by a nylon (nonconducting) thread from a ring stand is touched with a finger to remove any slight charge it may have had. Then a negatively charged rod is brought up close to but *not touching* the ball. While the rod is held there the ball is momentarily touched with a finger; then the rod is removed. Does the ball now have a net charge? How would you test whether it has. If you think it has, make a few simple sketches to show how it became charged, indicating clearly what kind of charge it has been left with.

14.6 (a) Calculate the strength of the gravitational field of the moon at a point on its surface. The mass of the moon is taken to be 7.3×10^{22} kg and its radius is 1.74×10^6 m.
  (b) Calculate the gravitational field at a point near the surface of a small but extremely dense star, LP357-186, whose radius is 1.5×10^6 m and whose density is about 10^{12} kg/m³.
  (c) The gravitational field of any uniform spherical shell is zero inside the shell.

Use this principle together with Newton's gravitational force law and the formula for the volume of a sphere ($\frac{4}{3}\pi r^3$) to find out how the gravitational field at a point P *inside* a solid spherical planet depends on the distance r from the center. (Assume the planet's density is uniform throughout.)
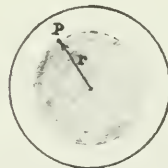
14.7 We speak of an electric field exerting a force on a charged particle placed in the field. What has to be true about this situation in view of the fact that Newton's third law holds in this case too?

14.8 The three spheres A, B and C are fixed in the positions shown. Determine the direction of the net electrical force on sphere C, which is positively charged, if

Ⓐ

Ⓒ

Ⓑ

  (a) A and B carry equal positive charges.
  (b) A and B have charges of equal magnitude, but the charge on B is negative, and on A is positive.

14.9 An electric field strength exists at the earth's surface of about 100 N/coul, directed downward.
  (a) What is the net charge on the earth? (As Newton had shown for gravitational forces, the field of a uniformly charged sphere can be calculated by assuming all of the charge is concentrated at its center).
  (b) Because the earth is a conductor, most of the net charge is on the surface. What, roughly, is the average amount of net charge per square meter of surface? Does this seem large or small, compared to familiar static charges like those that can be produced on combs?

14.10 In oscilloscope tubes, a beam of electrons is deflected as it is passed between two pairs of oppositely charged plates. Each pair of plates, as can be seen in the photograph at the top of the following page, is shaped something like the
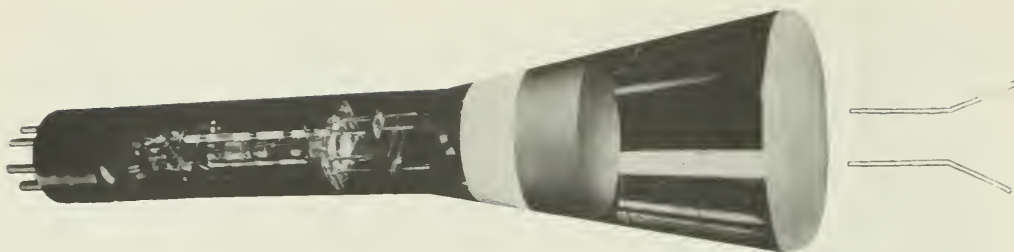
sketch to the right of the photograph. Sketch in roughly what you think the lines of force in the electric field between a pair of such oppositely charged plates would be like.

14.11 Is air friction acting on the moving oildrop a help or a hindrance in the experiment described for measurement of the charge of the electron. Explain your answer briefly.

14.12 The magnitude of the electron's charge will be seen later to be 1.6×10^{-19} coulomb. How many electrons are required to make 1 coulomb of charge?

14.13 Calculate the ratio of the electrostatic force to the gravitational force between two electrons a distance of 10^{-10} meters apart. (The mass of the electron is approximately 10^{-30} kg; recall that $G = 6.7 \times 10^{-11}$ N·m²/kg².)

14.14 Because electrical forces are similar in some respects to gravitational forces, it is reasonable to imagine that charged particles such as the electron, may move in stable orbits, around other charged particles. Then. just as the earth is a "gravitational satellite" of the sun, the electron would be an "electric satellite" of some *positively* charged particle that has a mass so large compared to the electron that it can be assumed to remain stationary at the center of the electron's orbit. Suppose the particle has a charge equal in magnitude to the charge of the electron, and that the electron moves around it in a circular orbit.
  (a) The centripetal force acting on the moving electron is provided by the electrical (Coulomb) force between the electron and the positively charged particle. Write an equation representing this statement, and from this equation derive another equation that shows how the kinetic energy of the electron is related to its distance from the positively charged particle.
  (b) Calculate the kinetic energy of the electron if the radius of its orbit were 10^{-10} meters.
  (c) What would be the speed of the electron if it had the kinetic energy you calculated in part (b)? (The mass of the electron is approximately 10^{-30} kg.)

14.15 A hard-rubber or plastic comb rubbed against wool can often be shown to be charged.

Why does a metal comb not readily show a net charge produced by rubbing unless it is held by an insulating handle?

14.16 What is the potential difference between two points in an electric field if 6×10^{-4} joules of work were done against the electric forces in moving 2×10^{-5} coulombs of charge from one point to the other?

14.17 If there is no potential difference between any points in a region, what must be true of
  (a) the electric potential energy and
  (b) the electric field in that region?

14.18 Electric field intensity, $\vec{E}$ can be measured in either of two equivalent units: newtons-per-coulomb, and volts-per-meter. Using the definitions of volt and joule, show that newton is actually the same as volt/meter. Can you give the reason for the equivalence in words?

14.19 By experiment. if the distance between the surfaces of two conducting spheres is about 1 cm, an electric potential difference of about 30,000 volts between them is required to produce a spark in ordinary air. (The higher the voltage above 30,000 V. the "fatter" the spark for this gap distance.) What is the minimum electric field strength (in the gap between the surfaces) necessary to cause sparking?

14.20 The gap between the two electrodes in an automobile sparkplug is about 1 mm (39 thousandths of an inch). If the voltage produced between them by the ignition coil is about 10,000 volts, what is the approximate electric field strength in the gap?

14.21 One can think of an electric battery as "pumping" charges onto its terminals up to the point where electric potential difference between the terminals reaches a certain value, where those charges already there repel newcomers from inside the battery; usually the value is very close to the voltage marked on the battery.

What would happen if we connected two or more batteries in a sequence? For example. the

battery on the right, below, maintains terminal C at an electric potential 6 volts higher than

(a)
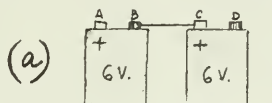
terminal D. This is what the + indicates under C — its electric potential is higher than the other terminal of the same battery. The battery on the left maintains terminal A at a potential 6 volts higher than terminal B. If we connect B to C with a good conductor, so that B and C are at the same potential level, what is the potential difference between A and D? What would the potential difference be between the extreme left and right terminals in the following set-ups?

(b)

(c)
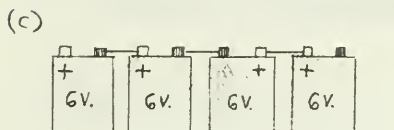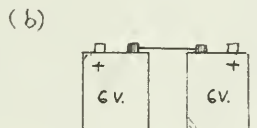
14.22 (a) What kinetic energy will an electron gain in an evacuated tube if it is accelerated through a potential difference of 100 volts. State your answer in electron volts and also in joules. (The magnitude of the charge on the electron is 1.6×10^{-19} coulomb.)
(b) What speed will it acquire due to the acceleration? (The mass of the electron is 10^{-30} kg.)

14.23 Suppose three resistors are each connected to a battery and to a current meter. The following table gives two of three quantities related by Ohm's law for three separate cases. Complete the table.

	Voltage	Current	Resistance
(a)	2 volts		0.5 ohms
(b)	10 volts	2 amps	
(c)		3 amps	5 ohms

14.24 The electric field at the earth's surface can increase to about 10^4 volts/meter under thunder clouds.
(a) About how large a potential difference between ground and cloud does that imply?
(b) A set of lightning strokes can transfer as much as 50 coulombs of charge. Roughly how much energy would be released in such a discharge?

14.25 "Physics International's B^2 Pulsed Radiation Facility is now producing the world's most intense electron beam (40,000 amps/4 MeV) as a routine operation. With this beam PI can precisely deposit upwards of 5,000 joules of energy in 30 nanoseconds." (*Physics Today*, Dec. 1966).
The "4MeV" means that the charges in the beam have an energy that would result from being accelerated across a potential difference of 4 million volts. A "nanosecond" is a billionth of a second. Are these published values consistent with one another? (Hint: calculate the power of the beam in two different ways.)

14.26 An electron "gun" includes several electrodes, kept at different voltages, to accelerate and focus the electron beam. Nonetheless, the energy of electrons in the beam that emerges from the gun depends only on the potential difference between their source (the hot wire) and the final accelerating electrode. In a color-tv picture tube, this potential difference is 20 to 30 kilovolts. A triple gun assembly (one each for red, blue, and green) from a color set is shown in the photograph below.
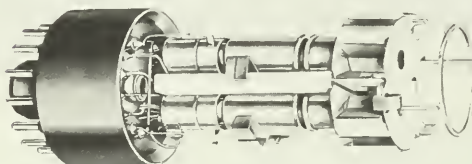
If the beam in a TV tube is accelerated through 20,000 volts and constitutes an average current on the order of 10^{-3} amps, roughly what is the power being dissipated against the screen of the tube?

14.27 Calculate the power dissipated in each of the three circuit elements of question 14.23.

14.28 A student who wished to show the magnetic effect of a current on a pocket compass, slowly slid the compass along the tabletop toward a wire lying on the table and carrying a constant current. He was surprised and puzzled by the lack of any noticeable turning effect on the compass needle. How would you explain his unexpected result?

14.29 The sketch shows two long, parallel wires, lying in a vertical north-south plane (the view here is toward the west). A horizontal compass is located midway between the two wires. With no current in the wires, the needle points N. With 1 amp in the upper wire, the needle points NW.

(a) What is the direction of this one ampere current?

(b) What current (magnitude and direction) in the lower wire would restore the compass to its original position?

14.30 The deflecting force on a charged particle moving perpendicularly to a uniform magnetic field is always perpendicular to its velocity vector, hence it is directed at every moment toward a single point — the center of the circular path the particle follows.

(a) Knowing that the magnetic force (given by the expression qvB) therefore provides a centripetal force (which is always given by mv^2/R), show that the radius of the circle R is directly proportional to the momentum of the particle mv.

(b) What information would you need to determine the ratio of the particle's charge to its mass?

14.31 By referring to the information given in the last problem:

(a) Find an equation for the period of the circular motion of a charged particle in a uniform magnetic field.

(b) Show mathematically that the radius of the helical path will be smaller where the magnetic field strength is greater.

(c) Use the right hand rule to show that the direction of the deflecting force on the particle is such as to oppose the movement of the particle into the region of stronger field.

14.32 If the energy of charged particles approaching the earth (say from the sun) is very great, they will not be trapped in the Van Allen belts, but rather they will be somewhat deflected, continuing on past or into the earth. The direction of the lines of force of the earth's magnetic field is toward the earth's north end. If you set up a detector for positively charged particles on the earth, would you expect to detect more particles by directing it slightly toward the east or slightly toward the west?
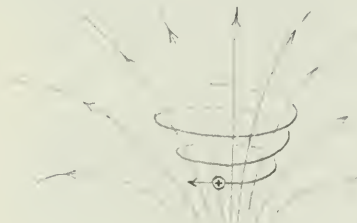
14.33 William Gilbert in *De Magnete* recorded that a piece of amber that had been rubbed attracted smoke rising from a freshly extinguished candle, the smoke particles having been charged by passing through the ionized gases of the flame. After the development of electric machines, experiments were done on the discharges from sharp or pointed electrodes like needles, called corona discharges, and Hohlfeld found in 1824 that passing such a discharge through a jar filled with fog, cleared the fog from the jar. A similar experiment was performed by Guitard only using tobacco smoke. The corona discharge in these experiments ionized the gas which in turn charged the water droplets of the fog or the smoke particles.

However, no successful industrial precipitator came until Cottrell, using the electric generator, high voltage transformer, and mechanical rectifier developed in the last decades of the nineteenth century, achieved both a strong corona discharge and a high potential difference between the discharge electrode and the collecting electrode. Since that time many electrostatic precipitators have been built by electrical and chemical engineers to collect many kinds of particulate matter, the most important of which being fly ash from the burning of coal in the electrical power industry itself.

exhaust gases without suspended particles

charged particles are driven by electric field to walls and deposit there

intense field near wire ionizes gas, which gives charge to particles

neutral particles are attracted to center wire

dc high voltage

exhaust gases and suspended particles
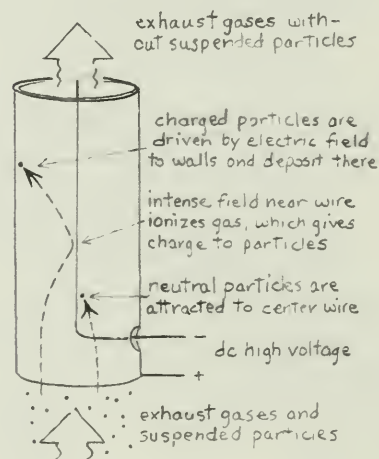
What are the implications of this technological development for control of pollution? Is it widely used? If not, why not?

A before-and-after example of the effect of electrostatic precipitators. The principle is described in SG 14.32 on the opposite page.

Faraday and the Electrical Age

15.1 The problem: getting energy from one place to another

In Chapter 10 we discussed the development of the steam engine in the eighteenth and nineteenth centuries, which enabled Europe and America to make use of the vast stores of energy contained in coal, wood and oil. By burning fuel, chemical energy can be converted into heat energy. Then by using this heat energy to make steam and letting the steam expand against a piston or a turbine vane, heat energy can be converted to mechanical energy. In this way a coal-fueled steam engine can be used to run machinery.

But steam engines suffered from two major defects; the mechanical energy was available only at the place where the steam engine was located, and practical steam engines were then big, hot, and dirty. As a result of the widespread use of machines run by steam engines, people were crowded together in factories, and their homes stood in the shadow of the smoke stacks. It was possible also to use steam engines for transportation by making locomotives; locomotives could be astonishing and powerful, but were limited by their size and weight (and added further to polluting the air).

These defects in the practical use of steam power might be partially avoided by using one central power plant from which energy could be sent out, for use at a distance by machines of any desired size and power, at the most useful locations. After Volta's development of the battery, many scientists and inventors speculated that electricity might provide such a means of distributing energy and running machines. But the energy in batteries is quickly used up, unless it is delivered at a feeble rate. A better way of generating electric currents was needed. As we shall see, when this was found it changed the whole shape of life at home, in factories, on the farm, and in offices. And it changed also the very appearance of cities and landscapes.

In this chapter we will see an example of how discoveries in basic physics have given rise to new technologies—technologies

which have revolutionized and benefited modern civilization,
though not without bringing some new problems in their turn.

In retrospect, the first clue to the wide use of electricity came
from Oersted's discovery that a magnetic needle is deflected by a
current. A current can exert a force on a magnet; thus it was
natural that speculations arose everywhere that somehow a magnet
could be used to produce a current in a wire. (Such reasoning from
symmetry is common in physics — and often is useful.) Within a few
months after the news of Oersted's discovery reached Paris, the
French physicists Biot, Savart, and Ampère had begun research on
the suspected interactions of electricity and magnetism. (Some of
their results were mentioned in Chapter 14.) A flood of other
experiments and speculations on electromagnetism from all over
the world was soon filling the scientific journals. Yet the one crucial
discovery — the continuous and ample generation of electric current
— still eluded everyone.

Ampère also sensed that electricity
might transmit not only energy but
also *information* to distant places.

15.2   Faraday's early work on electricity and lines of force

A valuable function of scientific journals is to provide for their
readers comprehensive survey articles on recent advances in
science, as well as the usual more terse announcements of the
technical details of discoveries. The need for a review article is
especially great after a large burst of activity such as that which
followed Oersted's discovery of electromagnetism in 1820.

In 1821 the editor of the British journal *Annals of Philosophy*
asked Michael Faraday to undertake a historical survey of the
experiments and theories of electromagnetism which had appeared
in the previous year. Faraday, who had originally been apprenticed
to a bookbinder, was at that time an assistant to the well-known
chemist Humphry Davy. Although Faraday had no formal training
in science or mathematics, he was eager to learn all he could. He
agreed to accept the assignment, but soon found that he could not
limit himself merely to reporting what others had said they had
done. He felt he had to repeat the experiments in his own laboratory,
and, not being satisfied with the theoretical explanations proposed
by other physicists, he started to work out his own theories and
plans for further experiments. Before long Faraday launched a
series of researches in electricity that was to make him one of the
most famous physicists of his time.

Faraday's first discovery in electromagnetism was made on
September 3, 1821. Repeating Oersted's experiment (described in
Sec. 14.11), he put a compass needle at various places around a
current-carrying wire. Faraday was particularly struck by the fact
that the force exerted by the current on each pole of the magnet
would tend to carry the pole along a circular line around the wire.
As he expressed it later, the wire is surrounded by *circular lines
of force* or a circular magnetic field. Faraday then constructed an
"electromagnetic rotator" based on this idea. It worked. Though
very primitive, it was the first device for producing continuous
motion owing to the action of a current — the first electric motor.

Faraday also designed an arrangement in which the magnet was fixed and the current-carrying wire rotated around it. (If a current can exert a force on a magnet, a magnet should be able to exert an equal force on a current, according to Newton's third law.) As in many other cases, Faraday was guided by the idea that for every effect of electricity on magnetism, there must exist a converse effect of magnetism on electricity – though it was not always so obvious what form the converse effect would take.

Q1 Why is the magnetic pole of Faraday's "electromagnetic rotator" pushed in a circle around a fixed wire?

15.3 The discovery of electromagnetic induction

Armed with his "lines of force" picture for visualizing electric and magnetic fields, Faraday joined in the search for a way of producing currents by magnetism. Scattered through his diary in the years after 1824 are many descriptions of such experiments. Each report ended with a note: "exhibited no action" or "no effect."

Finally, in 1831, came the breakthrough. Like many discoveries which have been preceded by a period of preliminary research and discussion among scientists, this one was made almost simultaneously by two scientists working independently in different countries. Faraday was not quite the first to produce electricity from magnetism; electromagnetic induction, as it is now called, was actually discovered first by an American scientist, Joseph Henry. Henry was teaching mathematics and philosophy at an academy in Albany, New York, at the time. Unfortunately for the reputation of American science, teachers at the Albany Academy were expected to spend all their time on teaching and administrative duties, with no time left for research. Henry had hardly any opportunity to follow up his discovery, which he made during a one-month vacation. He was not able to publish his work until a year later; and in the meantime Faraday had made a similar discovery and published his results.

Faraday is known as the discoverer of "electromagnetic induction" (production of a current by magnetism) not simply because he established official priority by first publication, but primarily because he conducted exhaustive investigations into all aspects of the subject. His earlier experiments and his ideas about lines of force had suggested the possibility that a current in one wire ought somehow to be able to induce a current in a nearby wire. Oersted and Ampère had shown that a *steady* electric current produced a *steady* magnetic field around the circuit carrying the current. One might think that a steady electric current could somehow be generated if a wire were placed near or around a magnet, although a very strong magnet might be needed. Or a steady current might be produced in one wire if a very large steady current exists in another wire nearby. Faraday tried all these possibilities, with no success.

Two versions of Faraday's electromagnetic rotator. In each, the cup was filled with mercury so that a large current can be passed between the base and overhead support.
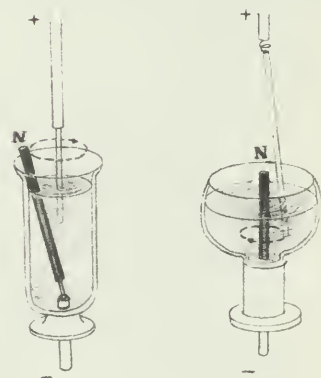
In one version (left) the north end of a bar magnet revolves along the circular electric lines of force surrounding the fixed current. In the other version (right), the rod carrying the current revolves around the fixed bar magnet – moving always perpendicular to the magnetic lines of force coming from the pole of the magnet.

Michael Faraday (1791-1867) was the son of an English blacksmith. In his own words:

> My education was of the most ordinary description, consisting of little more than the rudiments of reading, writing and arithmetic at a common day-school. My hours out of school were passed at home and in the streets.

At the age of twelve he went to work as an errand boy at a bookseller's store. Later he became a bookbinder's assistant. When Faraday was about nineteen he was given a ticket to attend a series of lectures given by Sir Humphry Davy at the Royal Institution in London. The Royal Institution was an important center of research and education in science, and Davy was Superintendent of the Institution. Faraday became strongly interested in science and undertook the study of chemistry by himself. In 1813, he applied to Davy for a job at the Royal Institution and Davy hired him as a research assistant. Faraday soon showed his genius as an experimenter. He made important contributions to chemistry, magnetism, electricity and light, and eventually succeeded Davy as superintendent of the Royal Institution.

Because of his many discoveries, Faraday is generally regarded as one of the greatest of all experimental scientists. Faraday was also a fine lecturer and had an extraordinary gift for explaining the results of scientific research to non-scientists. His lectures to audiences of young people are still delightful to read. Two of them, "On the Various Forces of Nature" and "The Chemical History of a Candle," have been republished in paperback editions.

Faraday was a modest, gentle and deeply religious man. Although he received many international scientific honors, he had no wish to be knighted, preferring to remain without title.

Faraday's laboratory at the Royal Institution.

Part of a page in Faraday's diary where he recorded the first successful experiment in electromagnetic induction, August 29, 1831. (About $\frac{1}{2}$ actual size.)

The solution Faraday found in 1831 came in good part by accident. He was experimenting with two wire coils that had been wound around an iron ring (see illustration in the margin). He noted that a current appeared in one coil only while the current in the other coil was being switched on or off. When a current was turned on in coil A, a current was indeed induced in coil B, but it lasted only for a moment. As soon as there was a steady current in the coil A, the current in the coil B disappeared. But when the current in the coil A was turned off, again there was a momentary current induced in coil B.

To summarize Faraday's result: a current in a stationary wire can induce a current in another stationary wire only while it is *changing*. But a steady current in one wire cannot induce a current in another wire.

Faraday was not satisfied with merely observing and reporting this curious and important result. Guided by his concept of "lines of force," he tried to find out what were the essential factors involved in electromagnetic induction, as distinguished from the merely accidental arrangement of his first experiment.

According to Faraday's theory, the changing current in coil A would change the lines of magnetic force in the whole iron ring, and that change in lines of magnetic force in the part of the ring near coil B would induce a current in B. But if this was really the correct explanation of induction, Faraday asked himself, shouldn't it be possible to produce the same effect in another way? In particular:

1. Is the iron ring really necessary to produce the induction effect, or does the presence of iron merely intensify an effect that would also occur without it?
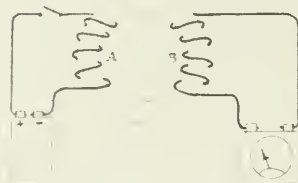
2. Is coil A really necessary, or could current be induced merely by changing the magnetic lines of force through coil B in some other way, such as by moving a simple magnet relative to the wire?

Faraday answered these questions almost immediately by further experiments. First, he showed that the iron ring was not necessary; starting or stopping a current in one coil of wire would induce a momentary current in a nearby coil with only air (or vacuum) between the coils. (See top figure at the left) Second, he found that when a bar magnet was inserted into or removed from a coil of wire, a current was induced at the instant of insertion or removal. (See second figure at the left) In Faraday's words,

> A cylindrical bar magnet . . . had one end just inserted into the end of the helix cylinder; then it was quickly thrust in the whole length and the galvanometer needle moved; then pulled out again the needle moved, but in the opposite direction. The effect was repeated every time the magnet was put in or out . . . .

Note that this is a primitive *electric generator*: it provides electric current by having some mechanical agent move a magnet.

Having done these and many other experiments, Faraday stated his general principle of electromagnetic induction: changing lines of magnetic force can cause a current to be generated in a wire. The needed "change" in lines of force can be produced either by (a) a magnet moving relative to a wire (Faraday found it convenient to speak of wires "cutting across" lines of force) or (b) a changing current (in which case the lines of force changing would "cut across" the wire). He later used the word *field* to refer to the arrangement and intensity of lines of force in space. We can say, then, that a current can be induced in a circuit by variations in a magnetic field around the circuit. Such variations may be caused SG 15.4 either by relative motion of wire and field, or just by the change in SG 15.5 intensity of the field.

So far Faraday had been able to produce only momentary surges of current by induction. That of course would hardly be an improvement over batteries as a source of current. Is it possible to produce a continual current by electromagnetic induction? To do this one has to create a situation in which magnetic lines of force are *continually changing* relative to the conductor. If a simple magnet is used, the relative change can be produced either by moving the magnet or by moving the conductor. This is just what Faraday did: he turned a copper disk between the poles of a magnet. (See illustration in margin.) A steady current was produced in a circuit connected to the disk through brass brushes. This device (called the "Faraday disk dynamo") was the first constant-current electric generator. Although this particular arrangement did not turn out to be very practical, at least it showed that continuous generation of electricity was possible.

These first experimental means of producing a continuous current were important not only for clarifying the connection between electricity and magnetism; they also suggested the
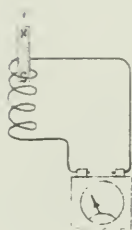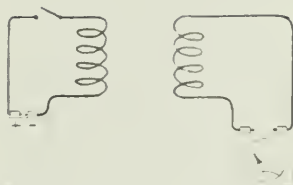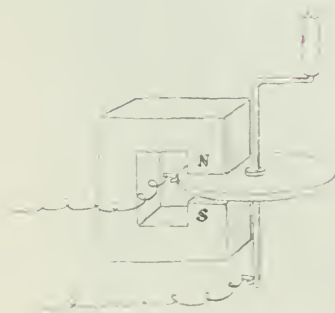
possibility of generating electricity eventually on a large scale. The production of electrical current involves changing energy from one form to another. When electrical energy appears, it is at the cost of some other form of energy; in the electric battery, chemical energy — the energy of formation of chemical compounds — is converted into electrical energy. Although batteries are useful for many portable applications (automobiles and flashlights for example) it is not practical to produce large amounts of electrical energy by this means. There is, however, a vast supply of mechanical energy available from many sources that could produce electrical energy on a large scale if some reasonably efficient means of converting mechanical energy into electrical energy were available. This mechanical energy may be in the form of wind, or water falling from high elevation, or continuous mechanical motion produced, for example, by a steam engine. The discovery of electromagnetic induction showed that, at least in principle, it was feasible to produce electricity by mechanical means. In this sense Faraday can rightly be regarded as initiating the modern electrical age.

But, although Faraday realized the practical importance of his discoveries, his primary interest was in basic science, the search for laws of nature and for a deeper understanding of the relationship between the separate experimental and theoretical findings. Though he appreciated the need for applied science, such as the eventual perfection of specific devices, he left the development of the generator and the motor to others. On the other hand, the inventors and engineers who were interested in the practical and profitable applications of electricity at that time did not know much about physics, and most of the progress during the next fifty years was made by trial and error. In following the development of modern electrical technology, as a case study in the long range effects of scientific work, we will see several problems that could have been solved much earlier if a physicist with Faraday's knowledge had been working on them.

Q2 Why is Faraday considered the discoverer of electromagnetic induction?

Q3 What is the general definition of electromagnetic induction?

15.4   Generating electricity by the use of magnetic fields: the dynamo

Faraday had shown that when a conducting wire moves relative to a magnetic field, a current is produced. Whether it is the wire or the magnetic field that moves doesn't matter; what counts is the relative motion of one with respect to the other. Once the principle of electromagnetic induction had been discovered, the path was open to try all kinds of combinations of wires and magnets in relative motion. We shall describe one basic type of generator (or "dynamo," as it was often called) which was frequently used in the nineteenth century and which is still the basic model for many generators today.
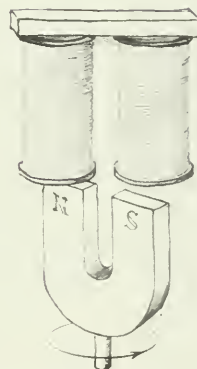
One generator of 1832 had a permanent horseshoe magnet rotated by hand beneath two stationary coils.

Alternating-current generator.

CURRENT

TIME
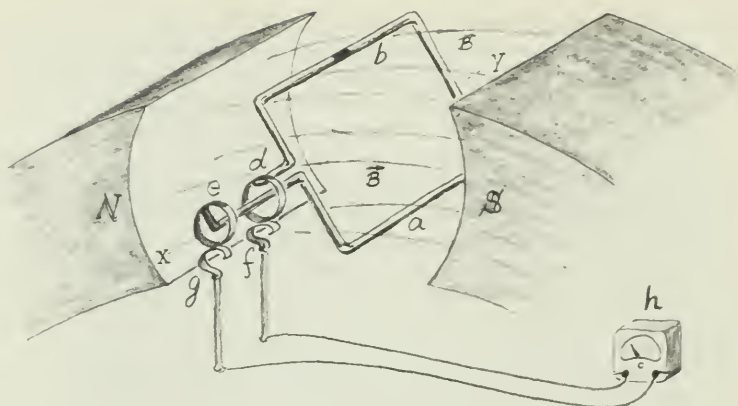
This form of generator is basically a coil of wire that can be rotated in a magnetic field. The coil is connected to an external circuit by sliding contacts. In the diagram on the left, the "coil" made for simplicity out of a single rectangular loop of wire is made to rotate around an axis XY between the north and south poles of a magnet. Two conducting rings d and e are permanently attached to the loop, and therefore, also rotate around the axis; conducting brushes f and g are provided to complete a circuit through a meter at h that indicates the current produced. The complete circuit is *abdfhgea*. (Note that the wire goes from a through ring d without touching it and connects to e.)

Initially the loop is at rest, and no charge flows through it. Now suppose we start to rotate the loop. The wire's long sides a and b will have a component of motion perpendicular to the direction of the magnetic lines of force; that is, the wire "cuts across" lines of force. This is the condition for an electric current to be induced in the loop. The greater the rate at which the lines are cut, the greater the induced current is.

Now, to get a better understanding of what is going on in the wire, we will describe its operation in terms of force on the charges whose movement constitutes the current. Because the charges in the part of the loop labeled b are being physically moved together with the loop across the magnetic field, they experience a magnetic force given by qvB (as described in Sec. 14.13). As a consequence these charges in the wire will be pushed "off to the side" by the
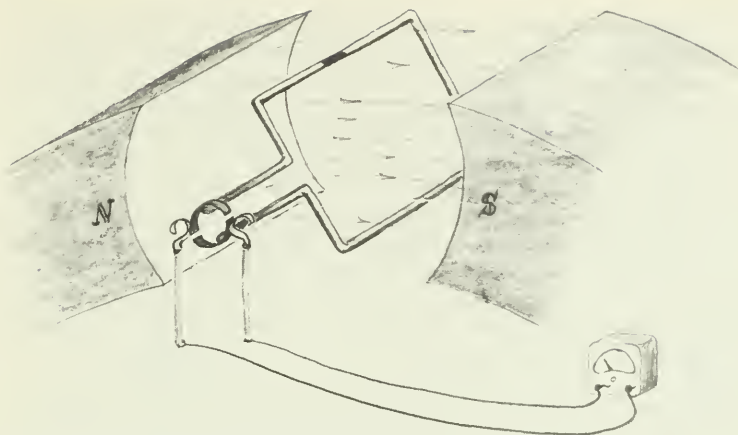
Direct-current generator.

magnetic field through which they are moving; "off to the side" in this situation is *along the wire.*

What about side *a*? That side of the loop is also moving through the field and "cutting" lines of force, but in the opposite direction. So the charges in *a* experience a push along the wire in the opposite direction compared to those in *b*. This is just what is needed; the two effects reinforce each other in generating a current around the whole loop.

The generator we have just described produces what is called *alternating current* (abbreviated ac), because the current periodically reverses (alternates) its direction. At the time this kind of generator was first developed, in the 1830's, alternating current could not be used to run machines. Instead, *direct current* (dc) was desired.

In 1832, Ampère announced that his instrument-maker, Hippolyte Pixii, had solved the problem of generating direct current. Pixii modified the ac generator by means of an ingenious device called the *commutator* (from the word commute, to interchange, or to go back and forth). The commutator is a split cylinder inserted in the circuit so that the brushes *f* and *g*, instead of always being connected to the same part of the loop, as in the previous figure, reverse connections each time the loop passes through the vertical position. Just as the direction of current induced in the loop is at the point of reversing, the contacts reverse; as a result, the current in the outside circuit is always in the same direction.
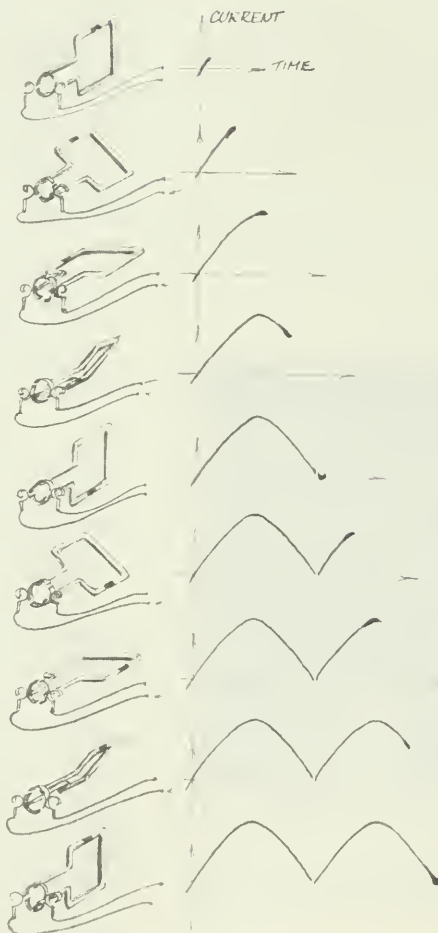
Although the current in the outside circuit is always in the same direction, it is not constant, but fluctuates rapidly between zero and its maximum value, as shown in the marginal drawings on page 83. Many sets of loops and commutators are connected together on the same shaft in such a way that their induced currents reach their maximum and zero values at different times; the *total* current from all of them together is then more uniform.

Whether a generator delivers alternating or direct current (ac or dc), the electric power (energy per unit time) it produces at every instant is given by the same equation we developed in Sec. 14.10. For example, suppose that a wire (for example, the filament wire in a light bulb) with resistance R is substituted for the meter (at h). If the current generated in the circuit at a given time is I, the electrical energy per unit time delivered to the wire is given by I^2R. For alternating current, the power output varies from instant to instant, but the *average* output power is simply $(I^2)_{av}R$. This electrical energy of course does not appear by itself, without any source of energy; that would violate the laws of conservation of energy. In our generator, the "source" of this energy is of course the mechanical energy that must be provided to the rotating shaft to keep the coils rotating in the magnetic field. This mechanical energy is provided by a steam or gasoline engine, or by water power, wind power, etc. The generator is thus a device for converting mechanical to electrical energy.

The current continually reverses direction so, in one sense, the average value for I is zero; charge is moved back and forth in the wire, but not transferred through it. I^2 is always positive, however.

Q4   What is the position of a rotating loop when it generates maximum current? minimum? Why?

Q5   What is the purpose of the commutator?

Q6   Where does the energy delivered by the generator come from?

15.5   The electric motor

The biggest initial obstacle to the use of motors was the difficulty of providing cheap electric current to run the motor. The chemical energy in batteries was quickly exhausted. The dynamo, invented almost, simultaneously by Faraday and Henry in 1832, was at first no more economical than the battery. It was only another "philosophical toy." Design of electric generators that used mechanical power to produce electrical power depended on understanding the details of operation, and this took nearly 50 years. The intervening period was one of numerous inventions that aroused great temporary enthusiasm and ambitious plans, followed by disillusion resulting from unanticipated practical difficulties. But the hope of a fortune to be made by providing cheap power to the world spurred on each new generation of inventors, and knowledge about the physics and technology of electromagnetic systems gradually accumulated.

In fact, it was a chance event that marks the beginning of the electric power age – an accidental discovery at the Vienna Exhibition

of 1873. It is of course not quite accurate to ascribe the beginnings of an era to one man, in one place, performing one act, at one time. In reality, with many men thinking about and experimenting in a particular scientific field, what does happen is that the situation becomes favorable for a breakthrough, and sometimes a seemingly trivial chance event is all that is needed to get things going. In this case, as the story goes, an unknown workman at the exhibition just happened to connect two dynamos together. The current generated by one dynamo went through the coils of the other dynamo which then ran as an electric motor on the electricity generated by the first.
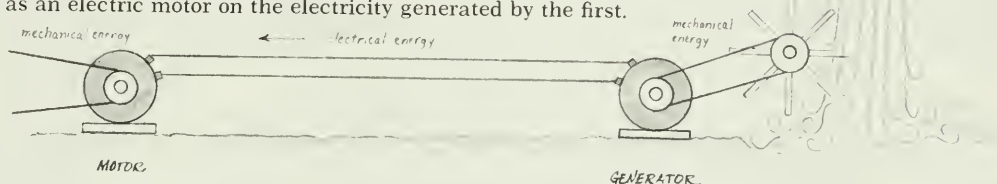
This accidental discovery, that a generator could be used to function as a motor, was immediately utilized at the exhibition in a spectacular public demonstration: a small artificial waterfall was used to drive the generator. Its current then drove the motor, which in turn operated a pump to spray water from a fountain. Thus electromagnetic induction was first used to convert mechanical energy into electrical energy by means of a generator; the electrical energy could be transmitted over a considerable distance and converted back into mechanical energy by a motor. This is the basic operation of a modern electrical transmission system: a turbine driven by steam or falling water drives a generator which converts the mechanical energy to electrical energy; conducting wires transmit the electricity over long distances to motors, toasters, electric lights, etc., which convert the electrical energy to mechanical energy, heat or light.

SG 15.10, 15.11

The development of electrical generators shows the interaction of science and technology in a different light than did the development of steam engines. As was pointed out in Chapter 10, the early steam engines were developed by practical inventors who had no knowledge of what we now consider to be the correct theory of heat (thermodynamics). In fact, it was the development of the steam engine and attempts by Sadi Carnot and others to improve its efficiency through theoretical analysis, that was one of the major historical factors leading to the establishment of thermodynamics. In that case, the advance in technology came before the advance in science. But in the case of electromagnetism a large amount of scientific knowledge was built up by Ampère, Faraday, Kelvin and Maxwell before there was any serious success in practical application. The scientists who understood electricity better than anyone else were not especially interested in commercial applications, and the inventors who hoped to make huge profits from electricity knew very little of the theory. Although after Faraday announced his discovery of electromagnetic induction people started making generators to produce electricity immediately, it was not until 40
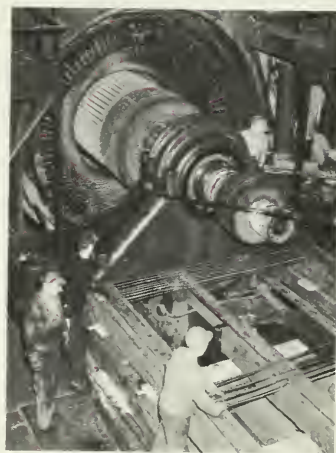
Assembling a commercial generator. As in almost all large generators, the coils of wire in which current is induced are around the outside, and electromagnets are rotated on the inside.

Water-driven electric generators producing power at the Tennessee Valley Authority. The plant can generate electric energy at a rate of over 100,000,000 watts.

years later that inventors and engineers became sufficiently familiar with such necessary concepts as lines of force and field vectors. With the introduction of the telegraph, telephone, radio and alternating-current power systems, the amount of mathematical knowledge needed to work with electricity became quite large, and universities and technical schools started to give courses in electrical engineering. In this way there developed a group of specialists who were familiar with the physics of electricity and also knew how to apply it.

Q7 How would you make an electric motor out of a generator?
Q8 What prevented the electric motor from being an immediate economic success?
Q9 What chance event led to the beginning of the electric power age?

15.6   The electric light bulb

The growth of the electric industry has been largely due to the public demand for electrical products. One of the first of these to be commercially successful in the United States was the electric light bulb. It is an interesting case of the interrelation between physics, industry and society.

At the beginning of the nineteenth century, illumination for buildings and homes was provided by candles and oil lamps. Street lighting in cities was practically nonexistent, in spite of sporadic attempts to hang lights outside houses at night. The natural gas industry was just starting to change this situation, and the first street lighting system for London was provided in 1813 when gas lights were installed on Westminster Bridge. However, the introduction of gas lighting in factories was not entirely beneficial in its social effects, since it enabled employers to extend an already long and difficult working day into a longer one still.

In 1801, the British chemist Humphry Davy noted that a brilliant spark or arc appeared when he broke contact between two carbon rods which were connected to the two terminals of a battery. This discovery led to the development of the "arc light."

The arc light was not practical for general use until the steam-driven electrical generators had replaced expensive batteries as a source of electric current. In the 1860's and 1870's, arc lights began to be used for street lighting and lighthouses. However, the arc light was too glaring and too expensive for use in the home. The carbon rods burned up in a few hours because of the high temperatures produced by the arc, and the need for frequent service and replacement made this system inconvenient. (Arc lights are still used for some high intensity purposes such as spotlights in theaters.)

As Humphry Davy and other scientists showed, light can be produced simply by producing a current in a wire (often called a filament) to heat it to a high temperature. This method is known as incandescent lighting. The major technical drawback was that the material of the filament gradually burned up. The obvious solution was to enclose the filament in a glass container from which all the air had been removed. But this was easier said than done. The vacuum pumps available in the early nineteenth century could not produce a sufficiently good vacuum for this purpose. It was not until 1865, when Hermann Sprengel in Germany invented an exceptionally good vacuum pump, that the electric light bulb in its modern form could be developed. (The use of Sprengel's pump by Crookes and others was also vital in scientific experiments leading to the discoveries in atomic physics which we will discuss in Chapter 18.)

Thomas Edison was not the first to invent an incandescent light using the Sprengel pump, nor did he discover any essentially new scientific principles. What he did was develop a light bulb which could be used in homes, and (even more important) a distribution system for electricity. His system not only made the light bulb practical but also opened the way for mass consumption of electrical energy in the United States.

Edison started from the basic assumption that each customer must be able to turn on and off his own light bulbs without affecting the other bulbs connected to the circuit. This meant that the bulbs must be connected "in parallel"—like the rungs of a ladder rather than "in series."

Davy's arc lamp

Demonstrations of the new electric light during a visit of Queen Victoria and Prince Albert to Dublin, Ireland. From *Illustrated London News*, August 11, 1849.
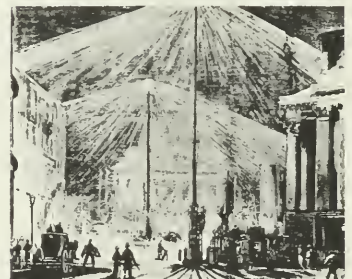
In the late 1800's, dynamo powered arc-lamps were used in some European cities.

Thomas Alva Edison (1847-1931) was born at Milan, Ohio, and spent most of his boyhood at Port Huron, Michigan. His first love was chemistry, and to earn money for his chemical experiments, he set up his own business enterprises. Before he was fifteen, he ran two stores in Port Huron, one for periodicals and the other for vegetables; hired a newsboy to sell papers on the Grand Trunk Railway running between Port Huron and Detroit; published a weekly newspaper; and ran a chemical laboratory in the baggage car of the train. His financial empire was growing rapidly when, in 1862, a stick of phosphorus in his laboratory caught fire and destroyed part of the baggage car. As a result, his laboratory and newspaper equipment were evicted from the train, and he had to look for another base of operations.

It was not long before his bad luck with the phosphorus was offset by a piece of good luck: he was able to save the life of the son of the station agent by pulling him out of the path of an oncoming train. In gratitude, the station agent taught Edison the art of telegraphy, and thus began Edison's career in electricity.

At the right are shown two portraits of Edison. On the opposite page is a copy of the drawing that accompanied his patent on the incandescent lamp. The labeled parts are the carbon filament (a), thickened ends of filament (c), platinum wires (d), clamp (h), leading wires (x), copper wires (e), tube to vacuum pump (m).

The choice of parallel rather than series circuits—a choice
based on the way Edison thought the consumer would want to
use the system—had important technical consequences. In a series
circuit, the same current would go through each bulb. In a parallel
circuit, only part of the total current available from the source goes
through any one bulb. To keep the total current needed from being
too large, the current in each bulb would have to be small.

As was pointed out in Chapter 14, the heating effect of a current
depends on both the resistance of the wire and the amount of
current it carries. The rate at which heat energy is produced is
I^2R; that is, it goes up directly as the resistance, but increases as
the *square* of the current. Therefore, most inventors used high-
current, low-resistance bulbs, and assumed that parallel circuits
would not be practical. But Edison realized that a small current
can have a large heating effect if the resistance is high enough.

So Edison began a search for a suitable high-resistance,
non-metallic substance for his filaments. To make such a filament,
he first had to bake or "carbonise" a thin piece of a substance; then
he would seal it inside an evacuated glass bulb with wires leading
out. His assistants tried more than 1,600 kinds of material: "paper
and cloth, thread, fishline, fiber, celluloid, boxwood, coconut-shells,
spruce, hickory, hay, maple shavings, rosewood, punk, cork, flax,
bamboo, and the hair out of a redheaded Scotchman's beard." His
first successful high-resistance lamp was made with carbonized
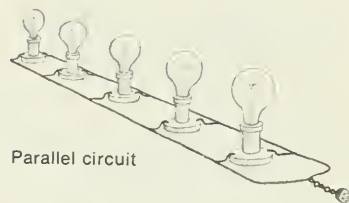
Parallel circuit
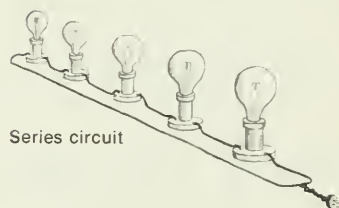
Series circuit

SG 15.12, 15.13

See the article "The Invention of
the Electric Light" in *Reader 4*.

T. A. EDISON.
Electric-Lamp.

No. 223,898.   Patented Jan. 27, 1880.

Fig 1

Fig 2

Fig 3

Witnesses   *Inventor*
Chas. Smith   *Thomas A. Edison*
Geo. T. Pinckney,   *By Lemuel W. Serrell*
                                              atty.
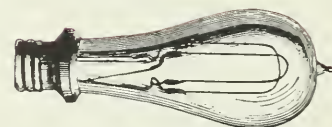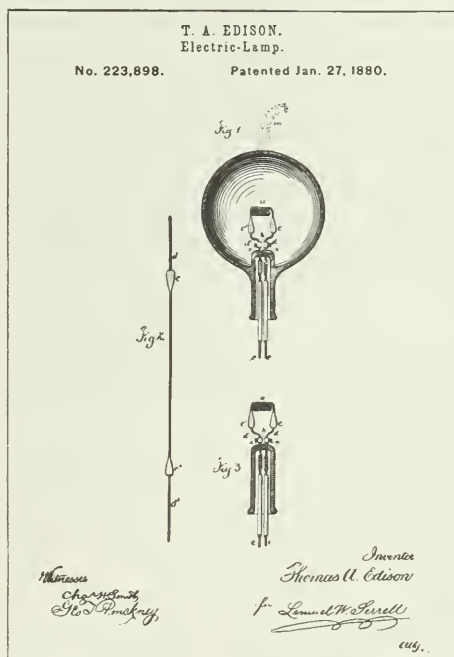
One type of Edison lamp. Note the
familiar filament and screw-type base.

Drawing (about $\frac{1}{2}$ size) that accom-
panied Edison's patent application.

EDISON'S LIGHT.

The Great Inventor's Triumph in Electric Illumination.

A SCRAP OF PAPER.

It Makes a Light, Without Gas or Flame, Cheaper Than Oil.

TRANSFORMED IN THE FURNACE.

Complete Details of the Perfected Carbon Lamp.

FIFTEEN MONTHS OF TOIL.

Story of His Tireless Experiments with Lamps, Burners and Generators.

SUCCESS IN A COTTON THREAD.

The Wizard's Byplay, with Bodily Pain and Gold "Tailings."

HISTORY OF ELECTRIC LIGHTING.

The near approach of the first public exhibition of Edison's long looked for electric light, announced to take place on New Year's Eve at Menlo Park, on which occasion that place will be illuminated with the new light, has revived public interest in the great inventor's work, and throughout the civilized world scientists and people generally are anxiously awaiting the result. From the beginning of his experiments in electric lighting to the present time Mr. Edison has kept his laboratory guardedly closed, and no authoritative account (except that published in the HERALD some months ago relating to his first patent) of any of the important steps of his progress has been made public—a course of procedure the inventor found absolutely necessary for his own protection. The HERALD is now, however, enabled to present to its readers a full and accurate account of his work from its inception to its completion.

A LIGHTED PAPER.

Edison's electric light, incredible as it may appear, is produced from a little piece of paper—a tiny strip of paper that a breath would blow away. Through

First newspaper account of Edison's invention (New York Herald, December 21, 1879).

cotton thread, enclosed in a high-vacuum sealed bulb. It burned continuously for two days before it fell apart. This was in October 1879. The following year, Edison produced lamps with filaments made from Bristol board, bamboo, and paper.

The Edison Electric Light Company began to install lighting systems in 1882. After only three years of operation, the Edison company had sold 200,000 lamps. It had a virtual monopoly of the field, and began to pay handsome dividends to its stockholders.

The electric light bulb had undergone some modification since Edison's original invention. For example, the carbonized filaments of the older lamps have been replaced in newer bulbs by a thin wire of tungsten, which has the advantages of greater efficiency and longer life.

The widespread use of light bulbs (confirming the soundness of Edison's theory about what people would buy) led to the rapid development of systems of power generation and distribution. The need for more power for lighting spurred the invention of better generators, the replacement of direct harnessing of water power, and the invention of the steam turbine. Then, success in providing larger quantities of energy at lower cost made other uses of electricity practical. Once homes were wired for electric lights, the current could be used to run sewing machines, vacuum cleaners, washing machines, toasters, and (later on) refrigerators, freezers, radios and television sets. Moreover, once electric power was available for relatively clean public transportation, cities would grow rapidly in all dimensions—through elevators that made high-rise buildings practical, and through electric tramways and subways that provided people rapid transporation from their homes to their jobs and to markets.

We have now become so accustomed to the more sophisticated and spectacular applications of electricity that it is hard to realize the impact of something as simple as the electric light bulb. But most people who lived through the period of electrification—for example, in the 1930's and 1940's in many rural areas of the United States—agreed that the one single electrical appliance that made the greatest difference in their own daily lives was the electric light bulb.

Q10 Why were arc lights not used for illuminating homes?
Q11 What device was essential to the development of the incandescent lamp?
Q12 Why did Edison require a substance with a high resistance for his light bulb filaments?
Q13 What were some of the major effects the introduction of electric power had on everyday life?

15.7   Ac versus dc, and the Niagara Falls power plant

In Sec. 15.5 we stated that the usual form of electric generator produces alternating current, but that it can be changed into direct

current by the use of a commutator. The reason for converting ac into dc was the general belief among practical engineers, held throughout most of the nineteenth century, that only dc was useful in the applications of electricity. However, as the demand for electric power increased, some of the inherent disadvantages of dc became evident. One disadvantage was the fact that the commutator complicated the mechanical design of the generator, especially if the ring had to be rotated at high speed. This difficulty was even more serious after the introduction of steam turbines in the 1890's, since turbines work most effectively when run at high speeds. Another disadvantage was the fact that there was no convenient way to change the voltage of direct current.

One reason for wanting to change the voltage which drives the current in a transmission system involves the amount of power lost in heating the transmission wires. The power output of a generator depends, as we showed in Sec. 14.10, on the output voltage of the generator as well as on the amount of current:

$$P_{\text{total}} = VI$$

The same total power can be transmitted with smaller I if V is larger. Now, when there is a current I in a transmission wire of resistance R, the amount of power expended as heat in the transmission wires is proportional to the resistance and to the square of the current:

$$P_{\text{heat loss}} = I^2R$$

The power finally available to consumers is $P_{\text{total}} - P_{\text{heat loss}}$. This means that for transmission lines of a given resistance R, one wants to make the current I as small as possible in order to minimize the power loss in transmission. Obviously, therefore, electricity should be transmitted at low current and at high voltage.

On the other hand, for most of the applications of electricity, especially in homes, it is neither convenient nor safe to use high voltages. Also, most generators cannot produce electricity at very high voltages (which would require excessively high speeds of the moving parts). Therefore we need some way of "stepping up" the electricity to a high voltage for transmission, and some way of "stepping it down" again for use at the other end, where the consumer uses the power. In short, we need a *transformer*.

A transformer can easily be made by a simple modification of Faraday's induction coil (Sec. 15.4). Faraday was able to induce a current in a coil of wire (which we call the *secondary* coil) by winding this coil around one side of an iron ring, and then changing a current in another coil (the *primary* coil) which is wound around the other side of the ring. A current is induced in the secondary coil when the primary current changes. If the primary current is changing all the time, then a current will continually be induced in the secondary—an alternating current in the primary coil (as from a generator without a commutator) will induce an alternating current in the secondary coil.
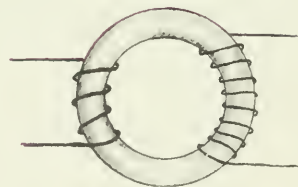
A steady current (dc) in the primary induces no current at all in the secondary; transformers work on ac.

We need just one additional fact to make a useful electric transformer: if the secondary has more turns than the primary, the alternating voltage produced across the secondary coil will be *greater* than across the primary; if the secondary has fewer turns than the primary, the alternating voltage produced across the secondary will be *lower* than the voltage across the primary. This fact was discovered by Joseph Henry, who built the first transformer in 1838.

SG 15.15-15.17

The first ac system was demonstrated in Paris in 1883. An experimental line which powered arc and incandescent lighting, through transformers, was installed in a railway line in London in 1884, and another one shortly afterward in Italy. An American engineer, George Westinghouse, saw the system exhibited in Italy and purchased the American patent rights for it. Westinghouse had already gained a reputation by his invention of the railway air brake, and had set up a small electrical engineering company in Pittsburgh in 1884. After making some improvements in the design and construction of transformers, the Westinghouse Electric Company set up its first commercial installation to distribute alternating current for incandescent lighting in Buffalo, New York, in 1886.

At the time of the introduction of the Westinghouse ac system in the United States, the Edison Electric Light Company held almost a complete monopoly of the incandescent lighting business. The Edison Company had invested large amounts of money in providing dc generating plants and distribution systems for most of the large cities. Naturally Edison was alarmed by a new company which claimed to produce the same kind of electric power for illumination with a much cheaper system. There was a bitter public controversy, in which Edison attempted to show that ac is unsafe because of the high voltage used for transmission. In the middle of the dispute, the New York State Legislature passed a law establishing electrocution as a means of capital punishment, and this seems to have helped in arousing some of the popular fear of high voltage.

SG 15.18

Nevertheless, the Westinghouse system continued to grow, and since there were no spectacular accidents, the public accepted ac as being reasonably safe. The invention of the "rotary converter" (essentially an ac motor driving a dc generator) made it possible to convert ac into dc for use in local systems already set up with dc equipment, or to power individual dc motors. Consequently the Edison company (later merged into General Electric) did not have to go out of business when ac was generally adopted.

The final victory of the ac system was assured in 1893, when the decision was made to use ac for the new hydroelectric plant at Niagara Falls. In 1887, businessmen in Buffalo had pledged $100,000 to be offered as a prize "to the Inventors of the World" who would design a system for utilizing the power of the Niagara River "at or near Buffalo, so that such power may be made practically available for various purposes throughout the city." The contest attracted world-wide attention, not only because of the large prize but also because large quantities of electrical power

had never before been transmitted over such a distance – it was
20 miles from Niagara Falls to Buffalo. The success or failure of
this venture would influence the future development of electrical
distribution systems for other large cities.

It was a close decision whether to use ac or dc for the Niagara
Falls system. The demand for electricity in 1890 was mainly for
lighting, which meant that there would be a peak demand in the
evening; the system would have to operate at less than full capacity
during the day and late at night. Some engineers proposed that,
even though ac could be generated and transmitted more efficiently,
a dc system would be cheaper to operate if there were much
variation in the demand for electricity. This was because *batteries*
could be used to back up the generators in periods of peak demand.
Thomas Edison was consulted, and without hesitation he recom-
mended dc. But the Cataract Construction Company, which had
been formed to administer the project, delayed making a decision.

The issue was still in doubt in 1891 when, at the International
Electrical Exhibition in Frankfort, Germany, an ac line carrying
sizable quantities of power from Frankfort to Lauffen (a distance
of 110 miles) was demonstrated. Tests of the line showed an
efficiency of transmission of 77%. That is, for every 100 watts fed
in at one end of the line, only 23 were wasted by heating effects in
the line, and the other 77 were delivered as useful power. The
success of this demonstration reinforced the gradual change in
expert opinion in favor of ac over dc, and the Cataract Company
finally decided to construct an ac system.

After the ac system had been established, it turned out that the
critics had been wrong in their prediction about the variation of
demand for electricity throughout the day. Electricity was to have
many uses besides lighting. In the 1890's, electric motors were
already being used for street railway cars, sewing machines and
elevators. Because of these diverse uses, the demand for electricity
was spread out more evenly during each 24-hour period. In the
particular case of the Niagara Falls power plant, the source of
energy – the flow of water down the Niagara River – made it possible
to produce energy continuously without much extra cost. (The
boiler for a steam turbine would either have to be kept supplied
with fuel during the night, or shut down and started up again in
the morning.) Since hydroelectric power was available at night at
low cost, new uses for it became possible. The Niagara Falls plant
attracted electric furnace industries, continually producing such
things as aluminum, abrasives, silicon and graphite. Previously
the electrochemical processes involved in these industries had been
too expensive for large-scale use, but cheap power now made them   SG 15.19
practical. These new industries in turn provided the constant
demand for power which was to make the Niagara project even
more profitable than had originally been expected.

The first transmission of power to Buffalo took place in
November 1896. By 1899, there were eight 5,000-horsepower
units in operation at Niagara, and the stockholders of the Cataract
Construction Company had earned a profit of better than 50% on

Wilson Dam (Tennessee Valley Authority), Alabama
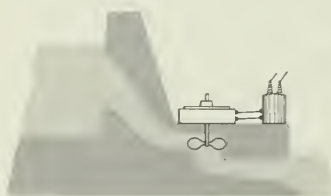
The general principle of hydro-electric power generation is shown in this sketch: water flowing from a higher to lower level turns turbine blades attached to a generator shaft. The details of construction vary widely.
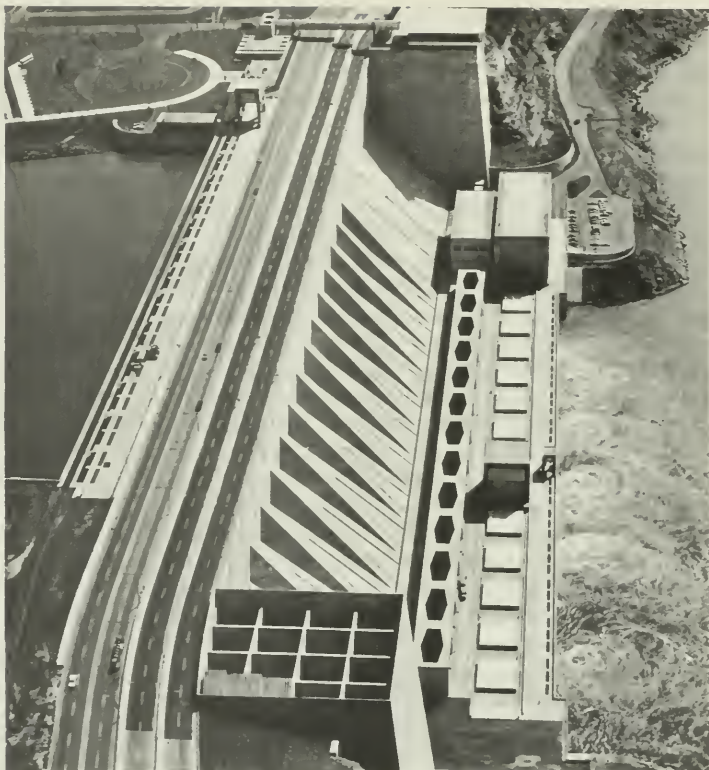
Niagara Power Plant

their investment. By this time the electrochemical industries, which had not figured in the original plans at all, were using more power than lighting and motors together.

As a postscript to the story of ac versus dc, it should be mentioned that dc is now coming back into favor for long-distance transmission of electric power at very high voltages. The reasons for this turnabout are explained in an article, "The Future of Direct Current Power Transmission," reprinted in *Reader 4*.

Q14 Give one reason why it is more economical to transmit electric power at high voltage and low current than at low voltage and high current.

Q15 Why won't transformers operate if steady dc is furnished for the primary coil?

15.8 Electricity and society

Many times during the last hundred years, enthusiastic promoters have predicted that a marvelous future is in store for us all. We need only stand back and watch the application of electricity to all phases of life. First, the backbreaking physical

labor that has been the lot of 99% of the human race throughout
the ages (and still is for most of mankind today) will be handed
over to machinery run by electricity; the average citizen will have
nothing to do except supervise machinery for a few hours a day,
and then go home to enjoy his leisure. Moreover, the old saying
that "a woman's work is never done" will be forgotten, since
electric machines will do all the cleaning, laundering and ironing,
preparation of food and washing of dishes, leaving the woman free
to do a greater variety of things than the chores of the housewife.

A second social purpose of electrical technology was conceived
by President Franklin D. Roosevelt and others who believed that
country life is in some sense more natural and healthy than city
life. In the nineteenth century, largely through the steam engine,
a source of power came into use that could take over most work
done by humans and animals – but only at the price of concentrating
people in the cities, close to the power generating plant. Now that
electrical transmission of power at a distance was possible, people
could go back to the countryside without sacrificing the comforts
of city life. Heating, lighting and refrigeration by electricity would
make life easier and more sanitary in previously difficult climates.
One of the major achievements of Roosevelt's administration in the
1930's was the rural electrification program, which provided loans
for rural cooperatives to install their own electrical generating and
distribution systems in areas where the private power companies
had previously found it unprofitable to operate. Federal power
projects such as the Tennessee Valley Authority also assisted in the
campaign to make electricity available to everyone. By making
country life a bit more luxurious and reducing the physical labor
involved in farming, electrification should have helped to reverse
the migration of people from rural to urban areas.

A third effect of electricity might be to help unite a large   SG 15.20
country into a single social unit by providing rapid transportation,
and even more rapid communication between the different parts.
Human society evolves much as do the biological organisms: all
parts develop in step and increase their interdependence. It follows
that telephone communications and modern civilization had to
develop together. The telephone would be most valuable in a
complicated cosmopolitan society and, as is now recognized, a
sophisticated society cannot operate without a communication
system something like the telephone.

Having taken care of such problems for a large part of the
population – getting work done, finding out what's going on and
so being able in principle to respond in time to do something about
it, leading a healthier and more comfortable life through the use
of refrigeration and air conditioning, man now comes face to face
with a new problem, or rather, a problem that was encountered
before by only a tiny fraction of the world's population. Thanks to
advances in science and related technology, many people no longer
have to spend almost all of their time working for the bare
necessities of life. Now, what is it that we really want to do?
Whatever it might be, electricity, it would seem, might help us do it
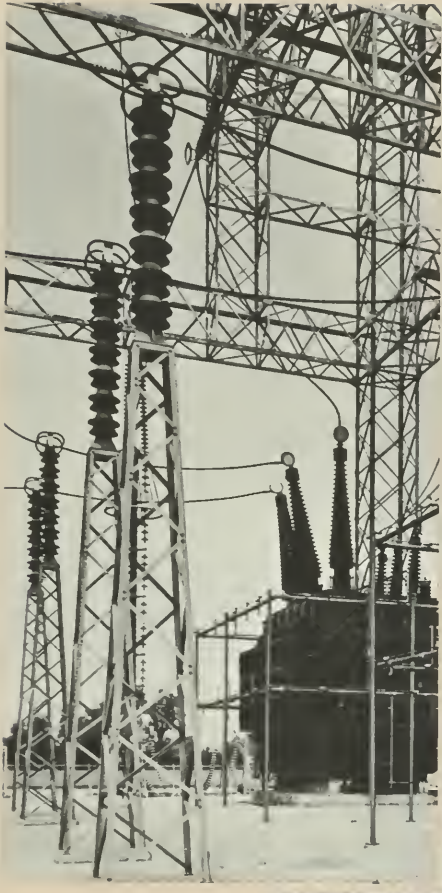
Commercial Distribution of Electric Power

The commercial distribution of ac electric power requires elaborate transmission facilities. Generator output voltages of about 10^4 volts are stepped up to about 10^5 volts for transmission, stepped down to about 10^4 volts for local distribution, and further stepped down to about 10^2 volts by neighborhood power-pole transformers. Within the home, it may be stepped down further (often to 6 volts for doorbells and electric trains) and stepped up by transformers in radio and TV sets for operating high-voltage tubes.
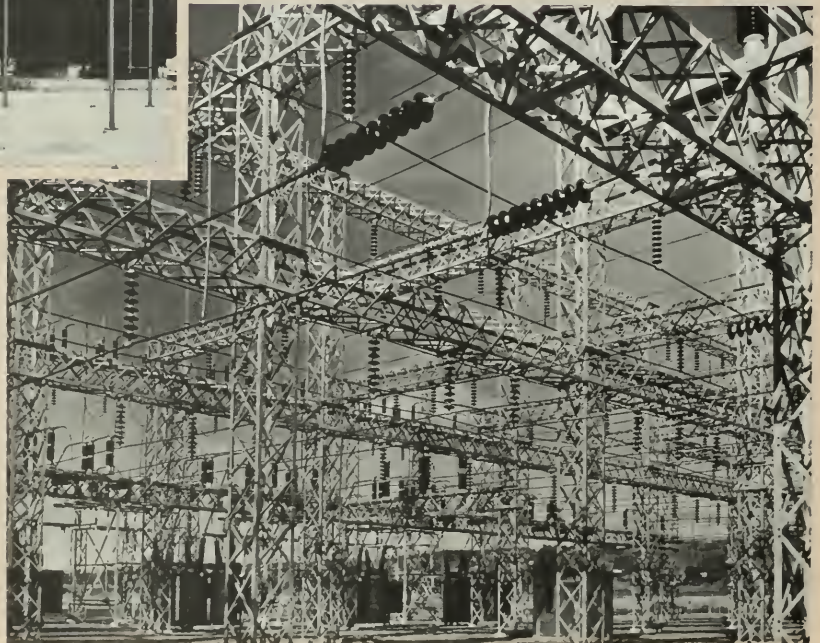
Major electric transmission lines in the United States. In many cases several lines are represented by a single line on the map. Not shown are the small-capacity lines serving widely scattered populations in the mountainous and desert areas. In the densely populated areas, only the high-voltage lines are shown.

The interdependence of our modern system of electrical power distribution was dramatically demonstrated at about 5 p.m. on November 9, 1965, when a faulty electrical relay in Canada caused a power failure and total blackout throughout most of the northeastern part of the United States.

better. With electric lighting, we can read books at night, or attend meetings, plays, concerts or games in large public buildings. None of these things were impossible before electrical illumination was developed, but candles and gas lamps were messy, hard on the eyes, and (when used on a large scale) expensive and hazardous. With the telegraph, telephone, radio and television we can quickly learn the news of events throughout the world, benefit from exchanging facts and opinions with other people and to some degree share the cultural treasures of the world.

A less optimistic opinion. Wonderful as all this seems, a variety of skeptics take a much dimmer view of the "progress" cited above. One might argue, for example, that by exploiting the resources of fossil fuel (coal, oil and gas) to do work, industries in the more advanced countries have used up in only 200 years most of the reserves of chemical energy that have been accumulated over the last two hundred million years. Moreover, few of them have rarely done so with enough social conscience to avoid polluting the air with vast amounts of smoke and ash, except when forced to do so by outraged public opinion. Other skeptics claim that a social system has been created in which the virtues of "honest toil and pride of workmanship" have begun to be endangered by a working life of monotonous triviality for much of the population, and chronic unemployment for some of the rest. The rise in the standard of living and acquisition of new gadgets and luxuries by many of those living in the wealthier, industrial countries have not often been fulfilling real human and social needs, but were too frequently manipulated by advertising campaigns and planned obsolescence. Therefore they have not brought tranquility of spirit, but often only created a demand for more and more material possessions. Meanwhile, the materially less fortunate people are separated by a wider and wider gap from the richer ones, and look on in growing envy and anger.

As for the labor-saving devices sold to the modern housewife, have they really made things much easier for her? Housewives in upper- and middle-income families work usually just as much as before, for what appliances now do used to be done in such homes largely by servants. To be sure, the social changes that accompanied industrialization and electrification have also generated many new jobs for women (and men) with little training, and these jobs are more attractive than domestic service. This is on the plus side. But families with low incomes, if they can afford to buy one major electrical appliance, usually do not choose labor-saving gadgets but a television set—and most of what comes out of *that*, our skeptic says, still contributes little to a better life!

The decentralization of population which electricity was supposed to produce has come about, but in an unexpected way. The upper- and middle-income inhabitants of cities have indeed been able to escape to the suburbs where they do enjoy all the convenience and pleasures of the electrical age. But they have left behind them urban ghettoes crowded with minority groups whose frustration at being deprived of the benefits of the "affluent

society" is only aggravated by scenes of suburban life presented to them on television. As for the farmer, modern technology has made large scale agriculture into a new kind of industry that has no place for the small landholder.

Electrical communications and rapid transcontinental transportation have bound us into a close-knit, interdependent social system. But this has its disadvantages too. Thus, an electronic computer may be used by an employer or a state to dredge up all a man's past mistakes.

Electricity: good or bad? The point of such criticisms is that it illustrates the other half of the total story: electricity, like any other area of technological improvement based on scientific discovery is neither good nor bad by itself. Electricity increases enormously the possibilities open to us, but choices still have to be made among them on the basis of value systems outside the framework of science or technology. The decisions about the large-scale applications of electricity cannot be left to the experts in physics or engineering, or to the public or private utilities, or to government agencies. They must be made by citizens who have taken the trouble to learn something about the physical forces that play such an important role in modern civilization – whether in the field of electrification, or the coming large-scale use of nuclear power, or the introduction of automation and other uses of computers, or whatever lies over the horizon.

SG 15.21

Electric power lines in New York State

15.1 The Project Physics learning materials particularly appropriate for Chapter 15 include:

Activities
Faraday Disk Dynamo
Generator Jump Rope
Simple Meters and Motors
Simple Motor-generator Demonstration
Physics Collage
Bicycle Generator
Lapis Polaris, Magnes

Reader Articles
Systems, Feedback, Cybernetics
The Electronic Revolution
The Invention of the Electric Light
High Fidelity
The Future of Direct Power Transmission

15.2 What sources of energy were there for industry before the electrical age? How was the energy transported to where it was needed?

15.3 Oersted discovered that a magnetic needle was affected by a current. Would you expect a magnetic needle to exert a force on the current? Why? How would you detect this force?

15.4 In which of these cases will electromagnetic induction occur?
(a) A battery is connected to a loop of wire held near another loop of wire.
(b) A battery is disconnected from a loop of wire held near another loop of wire.
(c) A magnet is moved through a loop of wire.
(d) A loop of wire is held in a steady magnetic field.
(e) A loop of wire is moved across a magnetic field.

15.5 Describe a set-up for producing induced currents by means of a magnetic field, and spell out how the set-up differs from one for producing a field by means of a current.

15.6 It was stated on p. 84 that the output of a dc generator can be made smoother by using multiple windings. If each of two loops were connected to commutators as shown what would the output current of the generator be like?
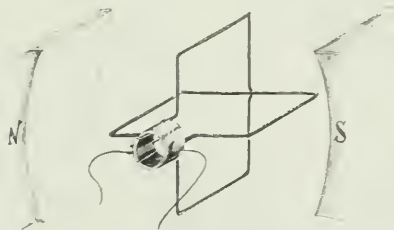
Multiple commutator segments of an automobile generator.

15.7 Refer to the simple ac generator shown on p. 82. Suppose the loop is being rotated counter-clockwise by some externally applied mechanical force. Consider the segment b as it is pictured in the third drawing, moving *down* across the magnetic field.

A useful rule: if your fingers point along B, and your thumb along $\vec{v}$, $\vec{F}$ will be in the direction your palm would push. For positive charges use the right hand, and for negative use the left hand.
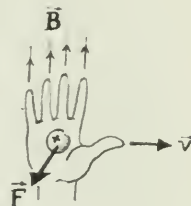
(a) Use the hand rule to determine the direction of the current induced in b.
(b) The induced current is an additional motion of charges, and they move also across the external magnetic field; thus an additional magnetic force acts on segment b. Use the hand rule to determine the direction of the additional force – but *before* doing so try to guess the direction of the force.
(c) Determine the direction of the additional force on charges in the segment labeled a, which is moving upwards across the field.

15.8 Why is a generator coil harder to rotate when it is connected to an appliance to which it provides current, such as a lamp, than when it is disconnected from any load?

15.9 Suppose two bar magnets, each held by one end at the same level but a few feet apart, are dropped simultaneously. One of them passes through a closed loop of wire. Which magnet reaches the ground first? Why?

15.10 Sketch a situation in which a wire is perpendicular to a magnetic field, and use the hand rule to find the direction of the force on the current. Imagine the wire moves sideways in response to the force. This sideways motion is an additional motion across the field, and so each charge in the wire experiences an additional

force. In what direction is the additional force on the charges?

15.11 Connect a small dc motor to a battery through a current meter. By squeezing on the motor shaft, vary the speed of the motor. On the basis of your answer to question 15.10 can you explain the effect that the speed of the motor has on the current?

15.12 A dozen Christmas-tree lights are connected in series and plugged into a 120-volt wall outlet.

(a) If each lamp dissipated 10 watts of heat and light energy, what is the current in the circuit?
(b) What is the resistance of each lamp?
(c) What would happen to these lamps if they were connected in parallel across the 120-volt line? Why?

15.13 Suppose we wanted to connect a dozen 10-watt lamps in *parallel* across a 120-volt line, what resistance must each lamp have in this case? To determine the resistance, proceed by answering the following questions:
(a) What current will there be in each lamp?
(b) What is the resistance of each lamp?
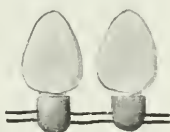
Compare the total current for this string of 10-watt lamps with the total current in the string of lamps in the previous question.

15.14 A man who built his own boat wanted to equip it with running lights and an interior light using a connecting wire with a resistance of $\frac{1}{5}$ ohm. But he was puzzled about whether a 6-volt system or a 12-volt system would have less heating loss in the connecting wires. Suppose that his interior lamp is to be a 6-watt lamp. (A

6-watt lamp designed for use in 6-volt systems has a resistance of 6 ohms.)
(a) If it were to operate at its full 6-volt, 6-watt rating, what current would the lamp require?
(b) If the current calculated in (a) were the actual current, what power loss would there be in the connecting wires?
(c) What would be the answers to (a) and (b) if he used a 12-volt battery and a 12 volt, 6 watt bulb?
(d) Because of the resistance of the connecting wires, the lamps described will not actually operate at full capacity. Recalculate parts (a) and (b) to determine what would be the actual currents, power losses, and power consumptions of the lamps.

15.15 A transformer for an electric train is used to "step down" the voltage from 120 volts to 6 volts. As in most transformers, the output power from the secondary coil is only a little less than the input power to the primary coil. Suppose the current in the primary coil were $\frac{1}{4}$ amp, what would be the current in the secondary coil?

15.16 For a transformer, the ratio of the secondary voltage to the primary voltage is the same as the ratio of the number of turns of wire on the secondary coil to the number of turns of wire on the primary coil. If a transformer were 100 per cent efficient, the output power would equal the input power; assume such is the case, and derive an expression for the ratio of the secondary current to the primary current in terms of the turn ratio.

15.17 On many transformers thicker wire (having lower resistance) is used for one of the coils than for the other. Which would you expect has the thicker wire, the low-voltage coil or the high-voltage coil?

15.18 Comment on the advisability and possible methods of getting out of a car over which a high-voltage power line has fallen.

15.19 What factors made Edison's recommendation for the use of dc for the Niagara Falls system in error?

15.20 Write a report comparing the earliest electric automobiles with those being developed now.

15.21 What were some of the major effects (both beneficial and detrimental) of electricity on society?

Radio telescope in Alaska, framed by Northern Lights

Electromagnetic Radiation

16.1 Introduction

On April 11, 1846, a distinguished physicist, Sir Charles Wheatstone, was scheduled to give a lecture at the Royal Institution in London. Michael Faraday was to introduce Wheatstone to the expectant audience of fashionable ladies and gentlemen. But 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 felt obliged to give the lecture himself. As a result, we now have on record some of Faraday's speculations which, as he later admitted, he would never have made public had he not suddenly been forced to speak for an hour.

Faraday, ordinarily so careful to confine his remarks to his experiments, used this occasion to disclose his speculations on the nature of light. They can best be understood if we recognize that Faraday, like Oersted before him, believed that all the forces of nature are somehow connected. Therefore electricity and magnetism, for example, could not be separate things that just happen to exist in the same universe; they must really be different forms of the same basic phenomenon. This metaphysical conviction was parallel to that coming out of the speculations of Schelling and other German nature philosophers at the beginning of the nineteenth century, and had inspired Oersted to search in the laboratory for a connection between electricity and magnetism. Eventually he found it, in his discovery that an electric current in a conductor can turn a nearby magnet.

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

SG 16.1

Nature philosophy was discussed in the Epilogue to Unit 2 *Text* in Sec. 10.9 and its effect on Oersted in Sec. 14.11

Having convinced himself by this experiment that there is a definite connection between light and magnetism, Faraday could not resist going one step further in his impromptu lecture the following year. He suggested that perhaps light itself is a vibration of magnetic lines of force. If two charged or magnetized objects are connected by an electric or magnetic line of force, then Faraday reasoned, if one of them moves, a disturbance would be transmitted along the line of force. Furthermore, if light waves were vibrations of lines of force, then one does not need to imagine that space is filled with an elastic substance – ether, in order to explain the propagation of light. The lines of force could replace the conception of the ether, if one could show that lines of force have the elastic properties needed for wave transmission.

Faraday could not make this idea more precise because he lacked the mathematical skill needed to prove that waves could be propagated along lines of electric or magnetic force. Other physicists in Britain and Europe who might have been able to develop a mathematical theory of electromagnetic waves did not understand Faraday's concept of lines of force, or at least did not consider them a good basis for a mathematical theory. It was not until ten years later that James Clerk Maxwell, a Scottish mathematical physicist who had just completed his B.A. degree at Cambridge University, saw the value of the idea of lines of force and started using mathematics to express Faraday's concepts.

Magnetic lines of force indicate the direction of magnetic force on a north magnetic pole. (The force on a south pole is in the opposite direction.)

16.2   Maxwell's formulation of the 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.

James Clerk Maxwell, in the 1860's, developed a mathematical theory of electromagnetism in which he added to and generalized these principles so that they applied to electric and magnetic fields in conductors, in insulators, even in space free of matter.

Maxwell proceeded by putting Faraday's theory of electricity and magnetism into mathematical form. In 1855, less than two years after completing his undergraduate studies, Maxwell presented to the Cambridge Philosophical Society a long paper entitled, "On Faraday's Lines of Force." Maxwell described how these lines are constructed:

Electric lines of force indicate the direction of electric force on a positive test charge. (The force on a negative charge is in the opposite direction.)

> . . . 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.

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 ten years, Maxwell created his own models
of electric and magnetic induction. In developing his theory,
Maxwell first proposed a mechanical model to visualize the relations
among the electrical and magnetic quantities observed experi-
mentally by Faraday and others. Maxwell then expressed the
operation of the model in a group of equations. These equations,
giving the relations between the electric and magnetic fields, came
to be the most useful way to represent the theory, and their power
allowed him to feel free 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 equations) is one of the high
points of the course; but it will require vector calculus.

Maxwell's work contained an entirely new idea of far-reaching
consequences: *an electric field that is changing with time gen-
erates a magnetic field.* Not only do *currents in conductors* produce
fields around them, but *changing electric fields in insulators* such
as glass or air or the ether also produce magnetic fields.

It is one thing to accept this newly stated connection between
electric and magnetic fields; it is another task, both harder and
more interesting, to understand the physical necessity for such a
connection. The paragraphs below are intended to make it seem
reasonable.

An uncharged insulator (such as glass, wood, paper, rubber)
contains equal amounts of negative and positive charge. In the
normal state these charges are distributed evenly so that 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. None of the charges in an
insulating material (in contrast to a conductor) are 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
due to the electric field. If the strength of the field is increased,
the charges will be displaced further. The changing displacement
of charges that accompanies a changing electric field in an
insulator constitutes a current. Maxwell called this current a
displacement current. Maxwell assumed that this momentary
displacement current in an insulator is just as effective in sur-
rounding itself with a magnetic field as a conduction current of the
same magnitude.

In an insulator, the displacement current (the rate at which the
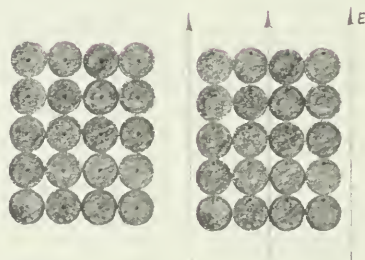
When an electric field is set up in
an insulating material, (as in the dia-
gram at the right, above) the + and −
charges, which are bound to one
another by attraction, are displaced.
This displacement constitutes a cur-
rent. (The + charges are represented
by dots, and − charges by shaded
circles.)

SG 16.3

charge displacement changes) 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 then assumed that this model, developed for matter, also applies to *space free of matter* (at first glance apparently an absurd idea) and therefore, that under all circumstances an *electric field that is changing with time surrounds itself with a magnetic field*. This principle was a new prediction of Maxwell's. Previously it was thought that the only current that produced a magnetic field was the current in a conductor. The additional magnetic field that Maxwell said would arise from a changing electric field, even in empty space, is so small in comparison to the magnetic field produced by the current in the conductors of the apparatus that it was not at that time possible to measure it directly. But, as we shall see, Maxwell predicted consequences that soon *could* be tested.

According to Maxwell's theory, therefore, the two basic principles of electromagnetism, as inherited from earlier scientists, should be expanded by adding a third:

3. *A changing electric field in space produces a magnetic field.* The induced magnetic field vector $\vec{B}$ is a plane perpendicular to the changing electric field vector $\vec{E}$. The magnitude of $\vec{B}$ depends on the rate at which $\vec{E}$ is changing.

Thus, consider a pair of conducting plates connected to a source of current, as shown at the left. As charges are moved onto or away from plates through the conductors connecting them to the source, the strength of the electric field $\vec{E}$ in the space between the plates changes with time. This changing electric field produces a magnetic field $\vec{B}$ as shown. The strength of $\vec{B}$ at a given moment varies with distance from the region between the plates. (Of course, only a few of the infinitely many lines for $\vec{E}$ and $\vec{B}$ are shown.)

An additional principle was known before Maxwell, but it 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 $\vec{E}$ is in a plane perpendicular to the changing magnetic field vector $\vec{B}$. The magnitude of $\vec{E}$ depends on the rate at which $\vec{B}$ is changing. Consider the changing magnetic field produced by, say, temporarily increasing the current

A changing electric field produces a magnetic field

When the electric field $\vec{E}$ between a pair of charged plates starts to increase in intensity, a magnetic field $\vec{B}$ is induced. The faster $\vec{E}$ changes, the more intense $\vec{B}$ is. When $\vec{E}$ momentarily has reached its maximum value, $\vec{B}$ has decreased to zero momentarily. When $\vec{E}$ diminishes, a $\vec{B}$ field is again induced, in the opposite direction, falling to zero as $\vec{E}$ returns to its original strength.

A changing magnetic field produces an electric field

When the magnetic field $\vec{B}$ between the poles of an electromagnet starts to increase, an electric field $\vec{E}$ is induced. The faster $\vec{B}$ changes, the more intense $\vec{E}$ is. When $\vec{B}$ momentarily has reached its maximum value, $\vec{E}$ has decreased to zero momentarily. When $\vec{B}$ diminishes, an $\vec{E}$ field is again induced, in the opposite direction, falling to zero as $\vec{B}$ returns to its original strength.
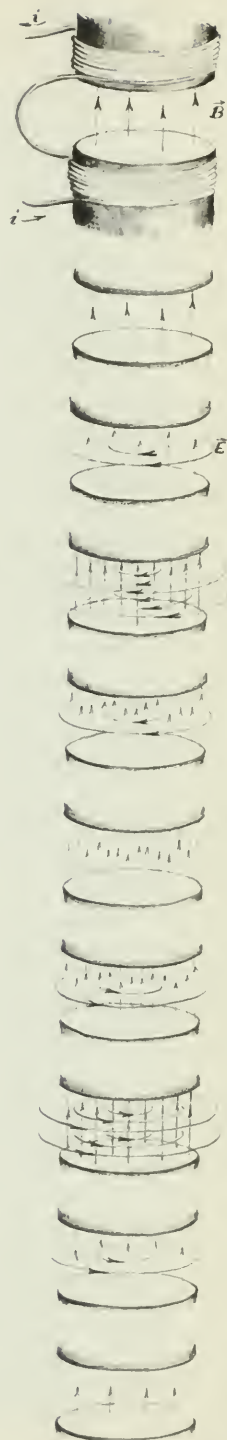
in an electromagnet, as shown along the right side of the opposite
page. This changing magnetic field induces an electric field in the
region around the magnet. If a conductor happens to be aligned in
the direction of the induced electric field, the free charges in the
conductor will move under its influence, producing a current in the
direction of the induced field. This electromagnetic induction had
been discovered experimentally by Faraday, as we noted in Sec. 15.3.

Maxwell's ideas of the total set of relations between electric
and magnetic fields were not at once directly testable. When the
crucial test came, it concerned his prediction of the existence of
waves, waves travelling as interrelating electric and magnetic fields
— electromagnetic waves.

Q1   What did Maxwell propose is generated when there is a
changing electric field?
Q2   What is a displacement current?
Q3   What are the four principles of electromagnetism?

16.3   The propagation of electromagnetic waves

Suppose we create, in a certain region of space, an electric
field that changes with time. As we have just seen, according to
Maxwell's theory, an electric field $\vec{E}$ that fluctuates in time simul-
taneously induces a magnetic field $\vec{B}$ that also varies with time
(as well as with distance from the region where we created the
changing electric field). Similarly, a magnetic field that is changing
with time simultaneously induces an electric field that changes
with time (as well as with distance from the region where we
created the changing magnetic field).

As Maxwell realized and correctly predicted, mutual induction
of time- and space-changing electric and magnetic fields should
allow the following unending sequence of events: a time-varying
electric field in one region produces a time- and space-varying
magnetic field at points near this region. But this *magnetic*
field produces a time- and space-varying *electric* field in the
surrounding space. And *this* electric field, produces time- and
space-varying magnetic fields, in its neighborhood, and so on. Thus
if an electromagnetic disturbance is started at one location, say by
vibrating charges (as may be imagined to exist in a hot gas, or in
the transmitter wire of a radio or television station), the disturbance
can travel to distant points through the mutual generation of the
electric and magnetic fields. The fluctuation of interlocked electric
and magnetic fields propagate through space in the form of an
"electromagnetic wave," a disturbance in the electric and magnetic
field intensities in space.

In Chapter 12 it was shown that waves occur when a distur-
bance 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 further along the rope and at a later time. Dropping a pebble
into a pond produces a disturbance that moves away from the

See The Relationship of Electricity
and Magnetism in *Reader 4.*

The electric and magnetic field
changes occur together much like
the "action and reaction of
Newton's third law

SG 16.4, 16.5
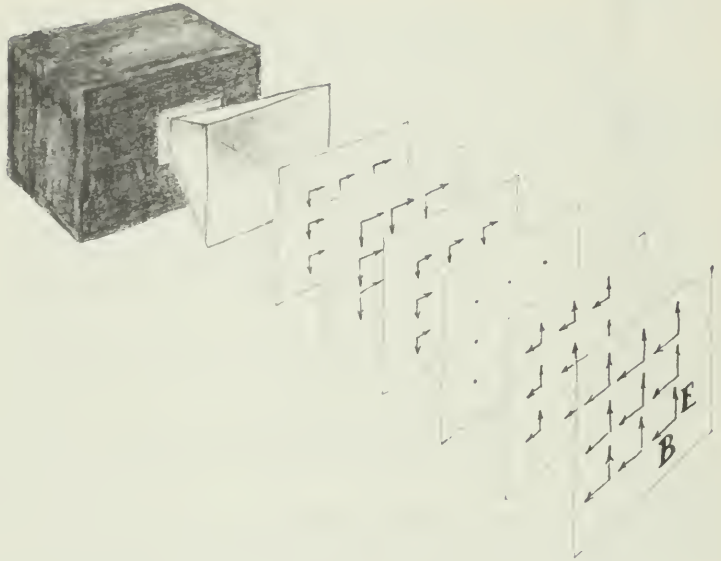
Electric oscillations in a vacuum-tube circuit are led onto a rod in a conducting "horn" and generate in the horn a variation in electric and magnetic fields that radiates away into space. This drawing is an instantaneous "snapshot" of almost plane wavefronts directly in front of such a horn.

source as a result of the action of one part of the water on the neighboring parts. 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.

What determines the speed with which the electromagnetic waves travel? Recall first that in the case of mechanical waves in a rope, or in water, the speed of propagation is determined by the stiffness of the material and the density of the material. Speed increases with increasing stiffness, but decreases with increasing density. This relation between wave speed, stiffness, and density holds for both of these mechanical wave motions, and for many other types of waves. Here we can only sketch out in barest outline how Maxwell proceeded beyond this point. Assuming that something analogous to this relation would hold for electromagnetic waves, 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 electric and magnetic fields, he was guided by his mechanical model representing the ether in which 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 had already been performed five years earlier by the German scientists Weber and Kohlrausch. Using their published values, Maxwell

1700	1750	1800	1831	1850	1879	1900

MAXWELL

Historical Events

- Peace of Utrecht
- French and Indian War
- French Revolution
- Louisiana Purchase
- War of 1812
- Battle of Waterloo
- Monroe Doctrine
- Communist Manifesto
- American Civil War
- Emancipation Proclamation
- Franco-Prussian War
- Spanish-American War

Government

- NAPOLEON I (NAPOLEON BONAPARTE)
- GEORGE WASHINGTON
- QUEEN VICTORIA
- PETER THE GREAT
- ABRAHAM LINCOLN

Science and Technology

- BENJAMIN FRANKLIN
- JOSEPH HENRY
- CHARLES AUGUSTIN DE COULOMB
- CHARLES ROBERT DARWIN
- ALESSANDRO VOLTA
- ALBERT MICHELSON
- SIR ISAAC NEWTON
- JOHANN KARL FRIEDRICK GAUSS
- JOSEPH PRIESTLEY
- LORD KELVIN (WILLIAM THOMSON)
- DANIEL BERNOULLI
- MICHAEL FARADAY
- CHARLES FRANCOIS DUFAY
- ANDRÉ MARIE AMPÈRE
- SIGMUND FREUD
- LUIGI GALVANI
- LOUIS PASTEUR
- HANS CHRISTIAN OERSTED
- THOMAS YOUNG
- HEINRICH HERTZ
- GEORG SIMON OHM

Philosophy and Theology

- JEAN JACQUES ROUSSEAU
- KARL MARX
- IMMANUEL KANT
- JOHN DEWEY
- FRANÇOIS MARIE AROUET DE VOLTAIRE
- FRIEDRICH WILHELM NIETZSCHE

Literature

- JOHANN WOLFGANG VON GOETHE
- ÉMILE ZOLA
- SAMUEL JOHNSON
- PERCY BYSSHE SHELLEY
- LEO NIKOLAEVICH TOLSTOY
- HENRY FIELDING
- ROBERT BURNS
- ALFRED TENNYSON
- ALEXANDER POPE
- SAMUEL TAYLOR COLERIDGE
- MARK TWAIN (SAMUEL L. CLEMENS)
- WILLIAM BLAKE
- GEORGE BERNARD SHAW

Art

- THOMAS GAINSBOROUGH
- EDGAR DEGAS
- WILLIAM HOGARTH
- CLAUDE MONET
- FRANCISCO GOYA
- VINCENT VAN GOGH
- JOSEPH MALLORD WILLIAM TURNER

Music

- JOHANN SEBASTIAN BACH
- WOLFGANG AMADEUS MOZART
- FRANZ PETER SCHUBERT
- JOHANNES BRAHMS
- GEORGE FREDERICK HANDEL
- LUDWIG VON BEETHOVEN
- PETER ILYICH TCHAIKOVSKY
- ANTONIO VIVALDI
- RICHARD WAGNER

calculated that the speed of the supposed electromagnetic waves should be about 311,000,000 meters per second. 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 Fizeau had measured the speed of *light*, and had obtained a value of about 315,000,000 meters per second. 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 critical significance for physics seemed obvious to him and, making an enormous, ingenious leap of the imagination, he wrote:

> The velocity of the transverse undulations in our hypo-
> thetical 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.*

Here then was an explanation of light waves, and at the same time joining of the previously separate sciences of electricity, magnetism, and optics. Realizing the great significance of his discovery, Maxwell turned his efforts to making the theory mathematically elegant and freeing it from his admittedly artificial model.

Maxwell's synthesis of electromagnetism and optics, after it had been experimentally confirmed (see Sec. 16.4), was seen as a great event in physics. In fact, physics had known no greater time since the 1680's when Newton was writing his monumental work on mechanics. Although Maxwell's electromagnetic theory grew up in Maxwell's mind in a Newtonian, mechanical framework, it leapt out of that framework and became another great general physical theory, a theory independent of its mechanical origins. Like Newtonian mechanics, Maxwell's electromagnetic field theory was spectacularly successful. We will see something of that success in the next few sections. The success went in two different directions: the practical and the conceptual. Practically it led to a whole host of modern developments, such as radio and television. On the conceptual 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. As we will note later, Maxwell's work led eventually to the special theory of relativity, and other physical theories were nourished by it also. Eventually results accumulated that did not fit Maxwell's theory; something more was needed. Starting about 1925, after a quarter century of discovery and improvisation, the development of quantum mechanics led to an enlarged synthesis that included Maxwell's electromagnetism.

With better measurements we now know that both Maxwell's predicted speed and Fizeau's measured speed should have come to just under 3×10^8 m/sec.

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. Hence in the terminology of Chapter 12, electromagnetic waves are *transverse*. And as we noted in Chapter 13 it was long known that light waves are transverse.

For a general survey of the development of physical ideas leading up to Maxwell's theory see the article by Einstein and Infeld, "The Electromagnetic Field" in *Reader 4*.

See also "James Clerk Maxwell, Part II" and "Maxwell's Letters, a Collection" in *Reader 4*.

Q4 What discovery did Maxwell make upon calculating the speed with which electromagnetic disturbances should travel?
Q5 What is Maxwell's synthesis?

16.4 Hertz's experiments

Did Maxwell's theoretical result 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 equal to the speed of light certainly suggested that there is *some* connection between electricity and light; no one would seriously argue that it was only a coincidence. But stronger evidence was needed before the rest of Maxwell's theory, with its curious displacement current, could be accepted.

What further evidence would be sufficient 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 connection between their separate parts. To a modern physicist who has learned Maxwell's theory from recent textbooks, the other theories that were proposed in the nineteenth century would all seem much more complicated and artificial. But at the time, Maxwell's theory was not appealing to the minds of those physicists who were not accustomed to thinking in terms of fields. It could only be accepted in preference to other theories if it could be used to predict some *new* property of electromagnetism or light.

Maxwell himself made two such predictions from his theory. Unfortunately, he did not live to see them verified experimentally in 1888; for he died at the age of 48, in 1879. Maxwell's most important prediction was that electromagnetic waves of many different frequencies could exist. All such waves would be propagated through space at the speed of light. Light itself would correspond to waves of only a small range of frequencies (from 4×10^{14} cycles/sec to 7×10^{14} cycles/sec), those that are detectable by the human eye.

To test this prediction, it was necessary to invent apparatus that could both produce and detect electromagnetic waves, preferably those of frequencies other than light frequencies. This was first done by the German physicist Heinrich Hertz. In 1886, Hertz noticed a peculiar effect produced during the sparking of an induction coil. As was well-known, sparks sometimes jump in the air gap between the terminals of an induction coil (see drawing). You will recall (Chapter 15) that an induction coil can be used to produce high voltages if there are many more turns of wire on one side than 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 be formed momentarily by ionization of the air molecules in the gas and a short burst of electricity may pass through, attended by a visible spark. Each visible spark produced by an induction coil is actually a series of many small sparks, jumping rapidly back and forth (oscillating) between the terminals. Hertz found he could control the frequency of oscillation of the jumping spark by the size and shape of metal plates attached to the spark gap of the induction coil.
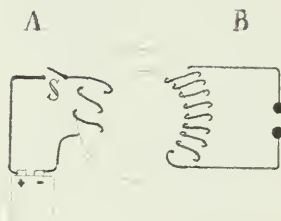
Operation of the induction coil: Starting and stopping the current in coil A with a vibrating switch S produces a rapidly changing magnetic field in the iron core. This rapidly changing field induces high voltage peaks in the many-turn coil B, and can cause a spark to jump across the air gap. Spark coils for use in car engines operate in this way.
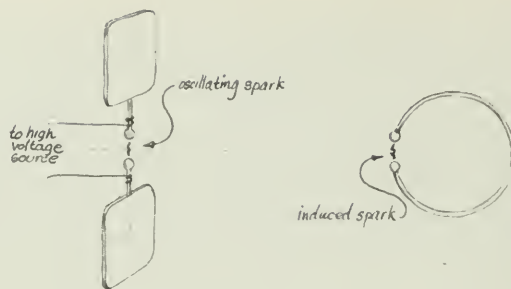
SG 16.6

Heinrich Hertz (1857-1894) was born in Hamburg, Germany. During his youth he was mainly interested in languages and the humanities, but was attracted to science after his grandfather gave him some 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 he devoted himself to the study of electromagnetism, including the recent and still generally unappreciated work of Maxwell. Two years later he started his famous experiments on electromagnetic waves. During the course of this work, Hertz made another discovery—the photoelectric effect—which has had a profound influence on modern physics. We shall study this effect in Chapter 18 (Unit 5).

Now Hertz observed that when a simple piece of wire was bent so that there was a short gap between its two ends, and was held not far from an induction coil, *a spark would jump across the air gap in the wire just when a spark jumped across the terminals of the induction coil.* This was a curious new phenomenon. He reasoned that as the spark jumps back and forth across the gap of the induction coil it must be setting up rapidly changing electric and magnetic fields. According to Maxwell's theory, these changes will propagate through space as electromagnetic waves. (The frequency of the waves will be the same as the frequency of oscillations of the sparks.) When the electromagnetic waves pass over the bent piece of wire, they will set up rapidly changing electric and magnetic fields there, too. A strong electric field produces a spark in the 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. This wire, therefore, serves as a detector of the electromagnetic waves generated by the induction coil. Hertz's observation of the induced spark was the first solid clue that electromagnetic waves do exist.

If this interpretation is correct, and waves travel through space from the induction coil, then there must be a short delay between the appearance of the first and second spark. The spark in the detector cannot occur at exactly the same instant as the spark in the induction coil because even travelling at the speed of light it takes finite time interval for the wave to go from one place to the other. In 1888 Hertz measured the speed of these electromagnetic waves and found it to be, as Maxwell had predicted, the same as the speed of light.

In subsequent experiments, Hertz showed that the electromagnetic radiation 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, and the angle of reflection is equal to the angle of incidence. The electromagnetic radiation can be focused by concave metallic mirrors. It shows diffraction effects when it passes through an opening in a screen. All interference phenomena can be shown including standing waves. Also, electromagnetic waves are refracted in passing through prisms made of glass, wood, plastic and other non-conducting material. All these
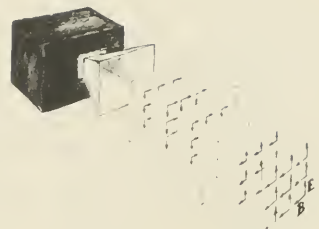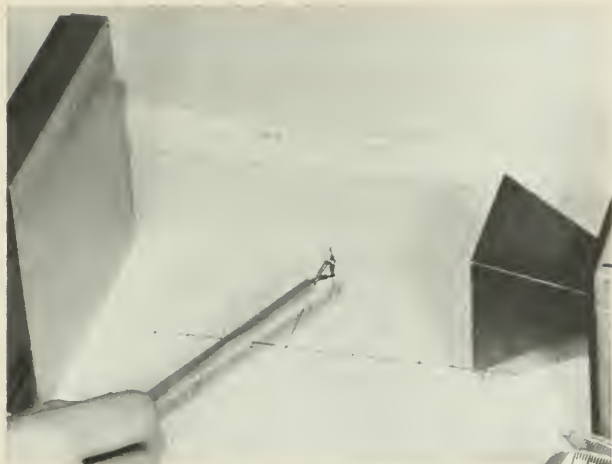
Electromagnetic radiation of a few centimeters wavelength is generated by oscillating electric fields inside the metal horn. Experiments with this radiation show phenomena similar to those observed for water waves and sound waves. Below is a record of measurements of the intensity of a standing interference pattern of electromagnetic waves in front of a flat reflecting surface. The intensity was measured by the current induced in a small detector on the end of a probe, as shown in the photograph.
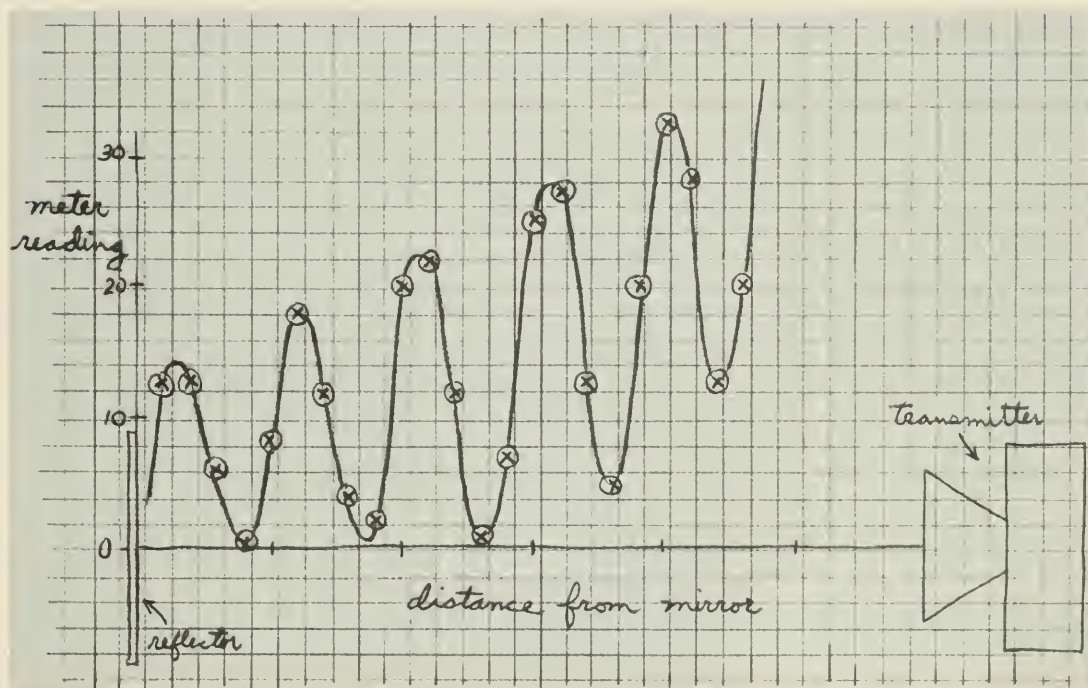
experiments, (with more modern apparatus), can be done in your school laboratory.

Hertz's experiments provided dramatic confirmation of Maxwell's electromagnetic theory. They showed that electromagnetic waves actually exist, that they travel with the speed of light, and that they have the familiar characteristics of light. There was now rapid acceptance of Maxwell's theory by mathematical physicists, who applied it with great success to the detailed analysis of a wide range of phenomena.

SG 16.7

Maxwell also predicted that electromagnetic waves will exert a pressure on any surface that reflects or absorbs them. This pressure is very small, and experimentally it is extremely difficult to distinguish it from the pressure caused by air currents set up by heating of the surface that absorbs the waves. The technical difficulties involved in testing this prediction were not solved until 1899, when Lebedev in Russia and, two years later, Nichols and Hull in the United States, finally confirmed the existence of radiation pressure. They found that this pressure has exactly the value predicted by Maxwell's theory.

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

SG 16.8

Q6   What predictions of Maxwell's were verified by Hertz?
Q7   What did Hertz use as a detector of electromagnetic waves?

16.5   The electromagnetic spectrum

Hertz's induction coil produced electromagnetic radiation with a wavelength of about 1 meter, about a million times the wavelength of visible light. Later experiments showed that a very wide and continuous variation in the wavelength (and frequency) of electromagnetic waves is possible; the entire possible range is called the *electromagnetic spectrum.* A range of frequencies from about 1 cycle/sec to 10^{25} cycles/sec, corresponding to a wavelength range from 10^8 meters to 10^{-17} meters, has been studied and many frequency regions have been put to practical use.

Light, heat, radio waves, and x rays are names given to the radiations in certain regions in the electromagnetic spectrum. Each of these names denotes a region in which radiation is produced or observed in a particular way. For example, light may be perceived directly through its effect on the retina of the eye, but to detect radio waves we need electronic equipment. The named regions overlap; for example, some radiation is called "ultraviolet" or "x ray," depending on how it is produced.

All the 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. They all carry energy;

FREQUENCY (CYCLES/SEC) / WAVELENGTH (METERS) chart — RADIO, MICROWAVE, INFRARED, VISIBLE, ULTRAVIOLET, X-RAYS, GAMMA RAYS; A.C. POWER, AM, TV FM, RADAR.
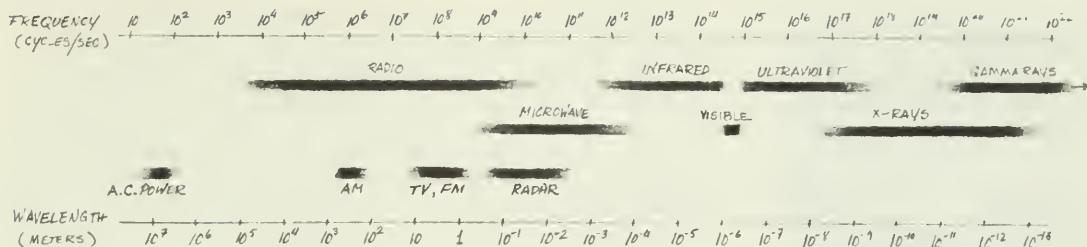
when they are absorbed, the absorber is heated. Electromagnetic radiation, whatever its frequency, can be emitted only by a process in which energy is supplied to the source of radiation. There is now overwhelming evidence that electromagnetic radiation originates from accelerated charges, as Faraday had speculated. This charge acceleration may be produced in many ways: by heating materials to increase the vibrational energy of charged particles, by varying the motion of charges on an electric conductor (an antenna), or by causing a charged particle to change its direction. In these and other processes some of the energy supplied to the antenna (that is, the work done by the force that is applied to accelerate the electric charge) is "radiated" away – propagating away from the source in the electromagnetic wave that is generated.

The work of Maxwell and Hertz opened up not only a new window to the scientific view of nature, but also prepared for a rapidly blooming set of new technologies, such as radio, TV, radar, etc. As we have done before – for example in the chapter on electric motors and generators, let us look at least briefly at these indirect consequences of a scientific advance.

Radio. Electromagnetic waves of frequencies of 10^4 to 10^7 cycles/sec are reflected quite well by electrically charged layers in the upper atmosphere. This reflection makes it possible for radio waves to be detected at great distances from the source. 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.
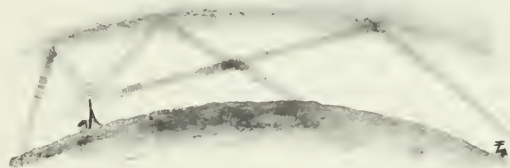
Radio waves that can transverse large distances, either directly or by relay, are very useful for conveying information. Communication is accomplished by changing the signal in some way following an agreed code that can be deciphered by the recipient. The first radio communication was achieved by turning the signal on and off in an agreed pattern, such as Morse code. Later, sounds could be

A chart of the electromagnetic spectrum.

SG 16.9

See "The Electronic Revolution" in Reader 4.

SG 16.10
SG 16.11
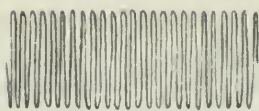
A "carrier" radio wave.
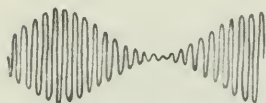
AM (amplitude modulation): information is coded as variations in the amplitude of the carrier.
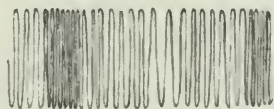
FM (frequency modulation): information is coded as variations in the frequency of the carrier.

coded by continuous variations in the amplitude of the broadcast wave (AM). Later still, the information was coded as frequency variations in the broadcast wave (FM). In broadcast radio and television, the "decoding" is done in the receiver serving the loudspeaker or TV picture tube, so that the output message from the receiver takes the same form that it had at the transmitter.

Because signals from different stations should not be received at the same spot on the dial, it is necessary to restrict their transmission. The International Telecommunication Union (ITU) controls radio transmission and other means of international communication. Within the United States, the Federal Communications Commission (FCC) is the government agency that regulates radio transmission. In order to reduce the interference of one stations's signal with another, the FCC assigns suitable frequencies to radio stations, limits their power or sometimes the power radiated in particular directions, and may restrict the hours of transmission.

Television and radar. Television and FM broadcasting stations operate at frequencies of about 10^8 cycles/sec or wavelengths of about one meter. Waves at these frequencies are not reflected by the layers of electric charge in the upper atmosphere; the signals travel in nearly straight lines and pass into space instead of following the curvature of the earth. Thus, they can be used to link the earth to stations on the moon, for example. On the other hand, coaxial cables or relay stations are necessary to transmit signals between points on the earth separated by more than about 50 miles, even if there are no mountains. Signals can be transmitted from one distant place to another, including from one continent to another by relay satellites.

Satellites are used to relay microwaves all over the world. The microwaves can carry radio or TV information.

SG 16.12–16.18
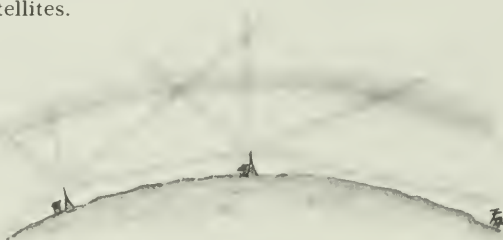
These signals, having wavelengths of about a meter, are not diffracted much around objects which have dimensions of several meters, such as cars, ships, or aircraft. The reflected portion of signals of wavelengths from one meter down to as short as one millimeter are used to detect aircraft, ships, and other objects. The interference between the direct waves and reflection of these waves by passing airplanes can produce a very noticeable and annoying movement and flicker of the television picture. If the radiated signal is in the form of pulses, the time from the emission of a pulse to the reception of its echo measures the distance of the reflecting object. This technique is called *RAdio Detection And Ranging*, or RADAR. By means of the reflection of a pulsed beam, that is pulsed, both the direction and distance of an object can be measured.

Infrared radiation. Electromagnetic waves with wavelengths of 10^{-1} to 10^{-4} meters are often called microwaves. The shorter the wavelengths, the more difficult it becomes to construct circuits that oscillate and generate significant energy of radiation. However, electromagnetic waves shorter than about 10^{-4} meters are emitted copiously by the very atoms of hot bodies. This "radiant heat" is usually called *infrared* rays, because most of the energy is in the wavelengths slightly longer than the red end of the visible band of radiation. While associated mainly with heat radiation, they do have some properties which are the same as those of visible light. The shorter of the infrared waves affect specially treated photographic film, and photographs taken with infrared radiation show some interesting effects. Since scattering of small particles in the atmosphere is very much less for long wavelengths (Sec. 13.6), infrared rays can penetrate through smoky haze dense enough to block visible light.

Visible light. The visual receptors in the human eye are sensitive to electromagnetic radiation with wavelengths between about 7×10^{-7} and 4×10^{-7} meters. Radiation of these wavelengths is usually light, or more explicitly, visible light. The peak sensitivity of the eye is in the green and yellow parts of the spectrum, near the peak of solar radiation which reaches the earth's surface.

A photograph made with film sensitive only to infrared radiation.

SG 16.19
SG 16.20

SG 16.21
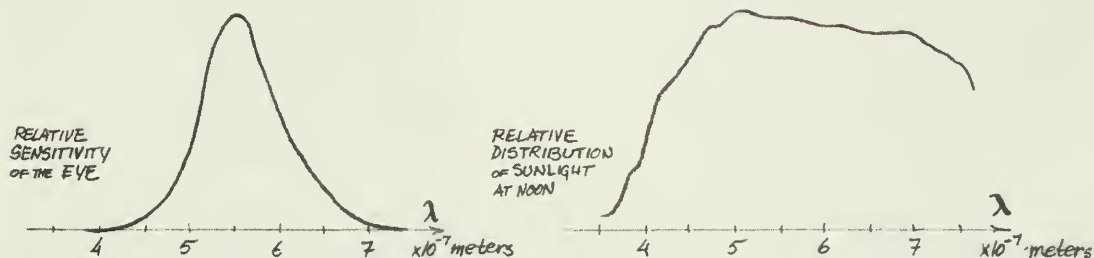
Ultraviolet light. Electromagnetic waves shorter than the visible violet are called *ultraviolet.* The ultraviolet region of the spectrum is of just as much interest in spectrum study as the visible and infrared because it includes radiations that are characteristic of many kinds of atoms. Ultraviolet light, like visible light, can also cause photochemical reactions in which radiant energy is converted directly into chemical energy. Typical of these reactions are those which occur in silver bromide in the photographic process, in the production of ozone in the upper atmosphere, and in the production of a dark pigment, known as melanin, in the skin.

X rays. This radiation (wavelengths from about 10^{-8} meters to 10^{-17} meters) is commonly 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, and that energy is determined by the voltage through which they are accelerated (Sec. 14.8). So

Electromagnetic waves generally are produced in the *acceleration* of charged particles.
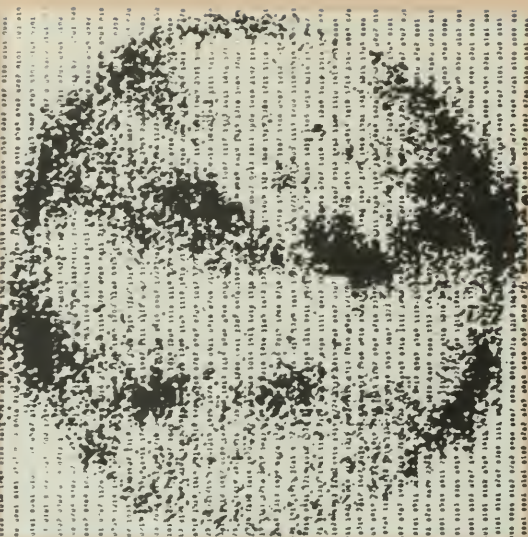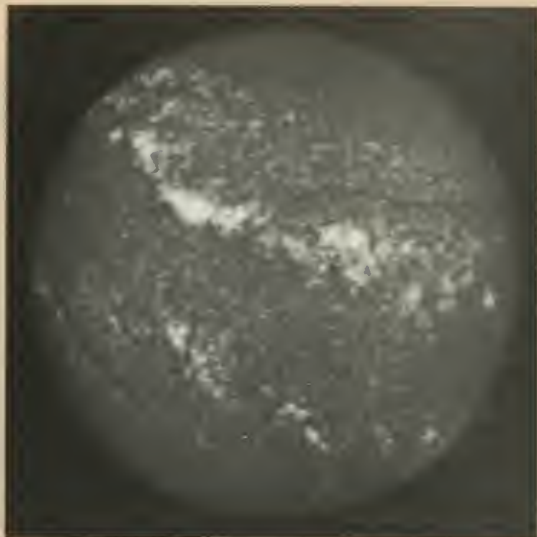
Astronomy Across the Spectrum

Electromagnetic radiation of different wavelengths brings us different kinds of information. Above are two views of the sun on Oct. 25, 1967: at the left is a photo taken in *violet* light; at the right is a computer plot of intensity of very short *ultraviolet* emission. The UV doesn't penetrate the earth's atmosphere; the information displayed here was collected by the Orbiting Solar Observatory satellite shown at the right. Below are three views of the sun on Mar. 17, 1965. At the left is a photograph in red light; at the right is an image formed by *x rays*; on the next page is an intensity contour map made from the image. The x-ray telescope was raised

above the earth's atmosphere by an Aerobee rocket. Longer-wavelength radiations such as radio and
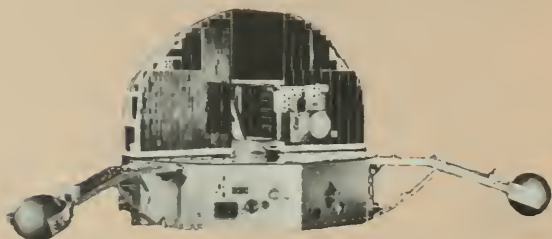
infrared are able to penetrate interstellar dust. Radio telescopes come in a great variety of shapes and sizes. Above is shown the huge Arecibo telescope in Puerto Rico; it has a fixed reflector but a moveable detector unit. To the right are a photograph and a diagram of a precise steerable antenna, the Haystack antenna in Massachusetts. Information collected with this instrument at 3.7 cm wavelength led to the upper contour map at right. This map of radio brightness is of the portion of the sky around the center of our galaxy; the area covered is about that of the full moon. The *infrared* brightness of the same portion of sky is shown in the bottom contour map.
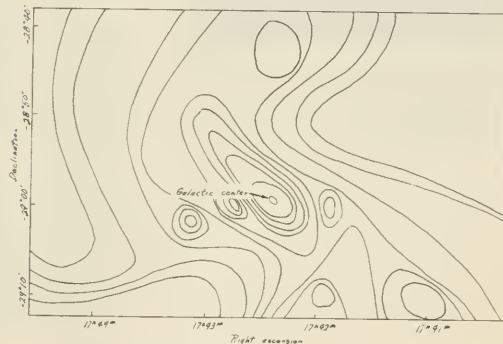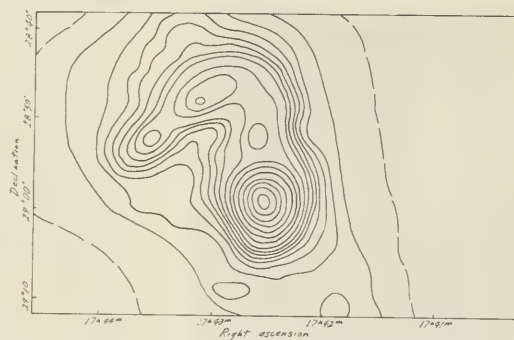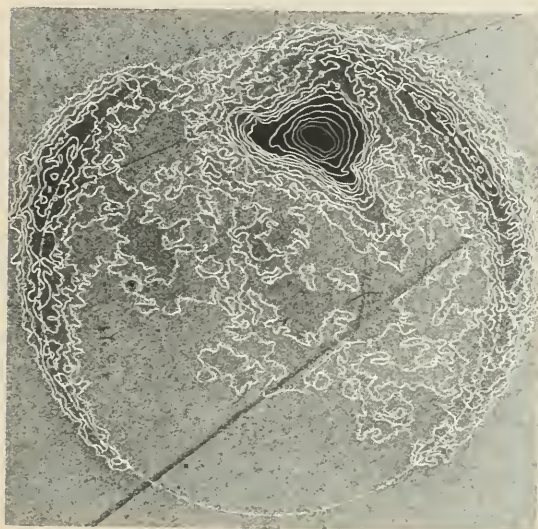
X-ray photos of (left) a Chambered Nautilus sea shell, and (right) a jet engine.
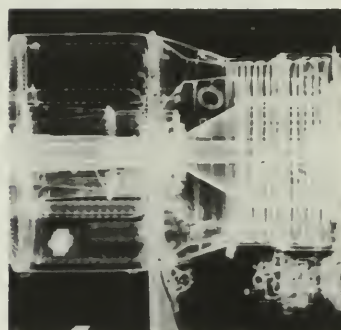
the maximum frequency increases with the accelerating voltage. The higher the frequency of the x rays, the greater is their power to penetrate matter; the distance of penetration also depends on the nature of the material being penetrated. X rays are quite readily absorbed by bone (which contains calcium), whereas they pass much more readily through lower density organic matter (such as flesh) containing mainly the light atoms hydrogen, carbon, and oxygen. This fact, combined with the ability of x rays to affect a photographic plate, leads to some of the medical uses of x-ray photography. Because x rays can damage living cells they should be used with great caution and only by trained technicians. Some kinds of diseased cells are injured more easily by x rays than are healthy cells, and so a carefully controlled x-ray beam can be used in therapy to destroy cancer 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. The reflected portions of the incident beam of x rays from successive planes of atoms in the crystal structure 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 crystalline substance, can be determined. Hence, rays are now widely used by chemists, mineralogists and biologists seeking information about the structure of crystals and complex molecules.

Gamma rays. The gamma-ray region of the electromagnetic spectrum overlaps the x-ray region (see p. 120). Gamma radiation is emitted mainly by the unstable nuclei of natural or artificial radioactive materials. We shall be considering gamma rays further in Unit 6.

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

Q8 Why do radio waves not cast noticeable shadows behind such obstacles as trees or small buildings?

Q9 Why are relay stations often needed in transmitting television signals?

Q10 How is the frequency of x rays related to their penetration of matter?

SG 16.22

Q11   How do the wavelengths used in RADAR compare to the
wavelengths of visible light?

Q12   How does the production of x rays differ from that of
gamma rays?

16.6   What about the ether now?

The luminiferous ether had been postulated specifically to
serve as a medium for the propagation of light waves. Maxwell
found that the same ether could also be thought of as a medium to
transmit electric and magnetic forces, but also that he could
dispense with the concept entirely if he focused on the form of the
theory. Yet, just before his death in 1879, Maxwell wrote an article
in which he still supported the ether 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. . . .

Why, after he had succeeded in formulating his electromagnetic
theory mathematically in a way that made it independent of any
detailed model of the ether, did Maxwell continue to speak of the
"great ocean of aether" filling all space? Like all men, Maxwell
could go only so far in changing his view of the world. It was
almost unthinkable that there could be vibrations without some-
thing that vibrates—that there could be 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, with the word *on* conveying the idea
of contact. Thus, according to accepted ways of describing the
world using the common language, the postulate of the ether
seemed somehow necessary.

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, and 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?" His intuition developed from mechanisms, from a toy top to a commercial steam engine, until he had satisfied his curiosity about how they worked. On the abstract side, 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 occurences. While Maxwell was still at the Edinburgh Academy, he wrote a paper on "Oval Curves," some pages from which are reproduced on this page. A summary of this paper was published in the proceedings of the Royal Society of Edinburgh when he was only fourteen years old. By the time he was seventeen he had published three papers on the results of his original research. In the 1870's he organized the Cavendish Laboratory at Cambridge University, which became a world center for physics research for the next several decades.

He was one of the main contributors to the kinetic theory of gases, to two other important branches of physics, 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 Isaac Newton and that of Albert Einstein.

Yet twenty-five years after Maxwell's death the ether concept had lost much of its support, and within another decade, it was dropped from the physicists' collection of useful concepts. In part, the success of Maxwell's theory itself, with its indifference to details of the ether's constitution, helped to undermine the general belief in the existence of an ether. Maxwell's equations could be considered to give the relations between changes of electric and magnetic fields in space without making any reference to the ether.

Another difficulty with the belief in the existence of the ether was the failure of all attempts to detect the motion of the earth with respect to the ether. If light is a kind of vibration of the ether that pervades all space, then light should travel at a definite speed relative to the ether. But it seemed reasonable to assume that the earth is moving through the ether as it makes its annual orbit around the sun. That is, 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, from the speed when the earth and light are moving in opposite directions through the ether.

When the time for light to make a round trip with and against the ether wind is computed, and is compared with the time calculated for a round trip in the absence of an ether wind, the expected time difference is found to be very small: only 10^{-15} seconds for a round trip of 30 meters. Although this is too short a time difference to measure directly, it is of the same order as the time for one vibration of visible light. It was therefore thought it might be detected from observations of an appropriately produced interference pattern. In 1887 the American scientists Albert Michelson and Edward Morley used a device that was so sensitive that it should have been able to detect an effect only one percent as great as that expected on the basis of the other theory. Neither this experiment nor the many similar experiments done since then have revealed an ether wind.

In an attempt to preserve the idea of an ether, 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. The artificiality of such attempts to rescue the ether concept was felt even by those who made these proposals. The conclusive development that led scientists to forego the ether concept was not a specific experiment, but a brilliant proposal, by a young man of 26 years, that a new and deep union of mechanics and electromagnetism could be achieved without the ether model. The man was Albert Einstein. A few brief remarks must suffice here to provide a setting for your further study of relativity at a later time.

In 1905, Einstein showed that the equations of electro-magnetism can be written to fit the same principle of relativity that holds for mechanics. As you recall from Sec. 4.4, the Galilean

principle of relativity states that the same laws of mechanics apply in each of two frames of reference which have a constant velocity relative to each other. Thus it is impossible, according to this principle, to tell by any kind of mechanical experiment whether or not one's laboratory (reference frame) is at rest or is moving with constant velocity. The principle is illustrated by the common experience that within a ship, car, plane or train moving at a constant speed in a straight line, the observer finds that objects move, or remain at rest, or fall or respond to applied force in just the same way they do when these conveyances are at rest. Galileo, a convinced Copernican, used this principle to argue that the motion of objects with respect to the earth (for example the fall of a stone along the side of a tower) gives no indication whether the earth is fixed and the sun in motion, or the sun fixed and the earth moving.

Einstein conjectured that this principle of relativity applied not only to mechanics but to all of physics, including electromagnetism. A main reason for this assumption appears to have been his feeling that nature cannot be so lopsided that a principle of relativity should apply only to *part of* physics. Then he added a second basic conjecture, the statement that *the speed of any light beam moving through free space is the same for all observers,* even when they are moving relative to each other or relative to the light sources. This bold intuition resolved the question of why the motion of observers with respect to the ether did not show up in experiments on the speed of light. In fact, Einstein simply rejected the ether and all other attempts to provide a "preferred frame of reference" for light propagation. The price of making these assumptions 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 analogous to those of Copernicus, Newton, and Maxwell.

What then, was the role played by the elaborate theories of ether that were at the base of much of nineteenth-century physics? It would certainly be unjust to say that the ether conception was useless, since it guided the work of Maxwell and others, and also had useful by-products in contributing to an understanding of the elastic properties of matter. We should consider the early mechanical models used for light and electricity as the scaffolding which is needed to erect a building; once the building is completed, providing the construction is sound, the scaffolding can be torn down and taken away.

Indeed the whole conception of explanation by means of mechanism, while intuitively appealing, has been found insufficient in modern physics and has been largely abandoned. Important developments in twentieth-century physics that have demonstrated the inadequacy of mechanical explanation will be discussed in Units 5 and 6.

Einstein in 1912.

See Einstein's essay, *On the Method of Theoretical Physics* in *Reader 4*

Some of the other immense consequences of Einstein's theory of relativity will be discussed in Unit 5.

Q13 Why did Maxwell (and others) cling to the concept of an ether?

Q14 Whose argument finally showed that the ether was an unnecessary hypothesis?

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 might be likened to that of the Cheshire Cat, in a story written by the Reverend Charles Dodgson, a mathematics teacher at Oxford, in 1862. Some excerpts are reproduced below.
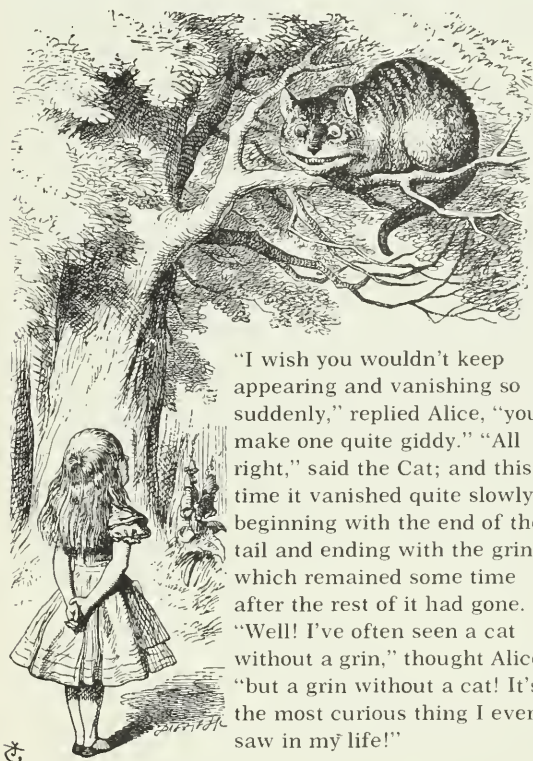
"I wish you wouldn't keep appearing and vanishing so suddenly," replied Alice, "you make one quite giddy." "All right," said the Cat; and this time it vanished quite slowly beginning with the end of the tail and ending with the grin, which remained some time after the rest of it had gone. "Well! I've often seen a cat without a grin," thought Alice, "but a grin without a cat! It's the most curious thing I ever saw in my life!"

[*Alice's Adventures in Wonderland*, Chapter VI]

EPILOGUE In this unit we have followed a complex but coherent story — how light and electromagnetism became comprehensible, first separately and then together. The particle model of light accounted for the behavior of light by showing that moving particles, on experiencing strong forces at a boundary, can be thought of as bouncing back or swerving in just the direction that light is observed to be reflected and refracted. The wave model also accounted well for these and other effects by treating light as transverse waves in a continuous medium. These rival models of light provided a substantial mechanical analogy for light viewed either as corpuscles or waves.

The approach through mechanical analogy worked, up to a point, in explaining electricity and magnetism. Both Faraday and Maxwell made use of mechanical models for electric and magnetic lines of force. Maxwell used these models as guides to the development of a mathematical theory of electromagnetism that, when completed, went well beyond the models — and that also explained light as an electromagnetic wave phenomenon.

The electric and magnetic fields of Maxwell's theory cannot be made to correspond to the parts of any mechanical model. Is there, then, any way we can picture in our minds what a field "looks like?" Here is the response of the Nobel Prize-winning American physicist Richard Feynman to this question:

> I have asked you to imagine these electric and magnetic fields. What do you do? Do you know how? How do I imagine the electric and magnetic field? What do I actually see? What are the demands of scientific imagination? Is it any different from trying to imagine that the room is full of invisible angels? No, it is not like imagining invisible angels. It requires a much higher degree of imagination to understand the electromagnetic field than to understand invisible angels. Why? Because to make invisible angels understandable, all I have to do is to alter their properties a *little bit* — I make them slightly visible, and then I can see the shapes of their wings and bodies, and halos. Once I succeed in imagining a visible angel, the abstraction required — which is to take almost invisible angels and imagine them completely visible — is relatively easy. So you say, "Professor, please give me an approximate description of the electromagnetic waves, even though it may be slightly inaccurate, so that I too can see them as well as I can see almost invisible angels. Then I will modify the picture to the necessary abstraction."
>
> I'm sorry that I can't do that for you. I don't know how. I have no picture of this electromagnetic field that is in any sense accurate. I have known about the electromagnetic field a long time — I was in the same position 25 years ago that you are now, and I have had 25 years of experience thinking about these wiggling waves. When I start describing the magnetic field moving through space, I speak of the E- and B-fields and wave my arms and you may imagine that I can see them. I'll tell you what I can see. I see some kind of vague shadowy wiggling lines — here and there is an E and B

written on them somehow, and perhaps some of the lines
have arrows on them—an arrow here or there which
disappears when I look too closely at it. When I talk about
the fields swishing through space, I have a terrible confusion
between the symbols I use to describe the objects and the
objects themselves. I cannot really make a picture that is
even nearly like the true waves. So if you have some
difficulty in making such a picture, you should not be
worried that your difficulty is unusual.

[A more extended excerpt of this discussion may be found in *Reader 4.*]

   We can summarize the general progression represented by the
development of mechanics and electromagnetism by saying that
physical theories have become increasingly abstract and mathematical.
Newton banished the celestial machinery of early theories by sub-
stituting a mathematical theory using the laws of motion and the
inverse-square law. Maxwell developed a mathematical theory of
electromagnetism that, as Einstein showed, did not require any
all-pervading material medium. We are seeing here a growing but quite
natural disparity between common-sense ideas that develop from direct
human experiences and the subtle mathematical abstractions developed
to deal with effects that we cannot sense directly.

   Yet these highly abstract theories do ultimately have to make sense
when couched in ordinary language, and they do tell us about the
things we can see and touch and feel. They use abstract language,
but have concrete tests and by-products. They have made it possible
to devise the equipment that guides space probes to other planets and
to design and operate the instruments that enable us to communicate
with these probes. Not only are these theories at the base of all practical
developments in electronics and optics, but they now also contribute
to our understanding of vision and the nervous system.

   Maxwell's electromagnetic theory and the interpretation given to
electromagnetism and mechanics by Einstein in the special theory of
relativity produced a profound change in the basic philosophical
viewpoint of the Newtonian cosmology. (In this sense, Unit 4 marks a
kind of watershed between the "old" and "new" ways of doing physics.)
While it is too early to hope for a comprehensive statement of these
changes, some aspects of a new cosmology can already be detected.
For this purpose, we must now give further attention to the behavior
of matter, and to the atomic theories developed to account for
this behavior.
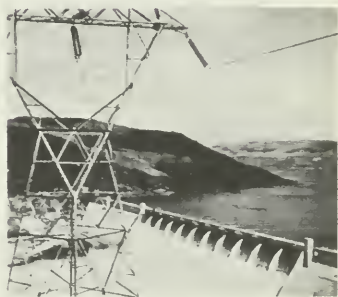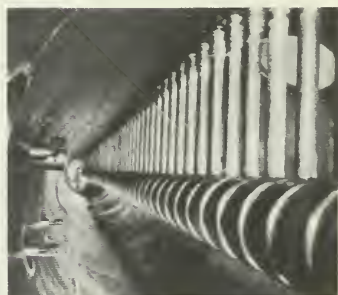
16.1 The Project Physics learning materials particularly appropriate for Chapter 16 include:

Experiment
Electromagnetic radiation
Activities
Microwave Transmission System
Science and the Artist—the Story Behind a New Science Stamp
Bell Telephone Science Kits
Good Reading
Reader Articles
James Clerk Maxwell, Part II
On the Induction of Electric Current
The Relationship of Electricity and Magnetism
The Electromagnetic Field
Film Loop
Standing Electromagnetic Waves
Transparency
The Electromagnetic Spectrum

16.2 What inspired Oersted to look for a connection between electricity and magnetism?

16.3 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.

16.4 What causes an electromagnetic wave to be initiated? to be propagated?

16.5 What is the "disturbance" that travels in each of the following waves:
(a) water waves
(b) sound waves
(c) electromagnetic waves

16.6 In Hertz's detector, it is the electric field strength in the neighborhood of the wire that makes the sparks jump. How could Hertz show that the waves from the induction coil spark gap were polarized?

16.7 What evidence did Hertz obtain that his induction-coil-generated waves have many properties similar to visible light waves?

16.8 Give several factors that contributed to the twenty-five year delay in the general acceptance by scientists of Maxwell's electromagnetic wave theory.

16.9 What evidence is there for believing that electromagnetic waves carry energy? Since the energy travels in the direction of wave propagation, how does this suggest why the early particle theory of light had some success?

16.10 What is the wavelength of an electromagnetic wave generated by the 60 cycles/sec alternating current in power lines?

16.11 How short are "short-wave" radio waves? (Look at the frequencies indicated on the dial of a short-wave radio.)

16.12 Electric discharges in sparks, neon signs, lighting, and some atmospheric disturbances produce radio waves. The result is "static" or noise in AM radio receivers. Give other likely sources of such static.

16.13 Why is there federal control on the broadcast power and direction of radio and TV stations, but no comparable controls on the distribution of newspapers and magazines?

16.14 If there are extraterrestial beings of advanced civilizations, what method for gathering information about earth-people would be available to them?

16.15 Why can radio waves be detected at greater distances than the waves used for television and FM broadcasting?

16.16 Some relay satellites have a 24-hour orbit, to stay above the same point as the earth turns below it. What would the radius and location of the orbit of such a "synchronous" orbit be? (Refer to Unit 2 for whatever principles or constants you need.)

16.17 Explain why airplanes passing overhead cause "flutter" of a TV picture.

16.18 How much time would elapse between the sending of a radar signal to the moon and the return of the echo?

16.19 Refer to the black-and-white photograph on p. 117 that was taken using film sensitive only to the infra-red. How do you account for the appearance of the trees, clouds, and sky?

16.20 What do you think is the reason for the eye to be sensitive to the range of light wavelengths that it is?

16.21 A sensitive thermometer placed in different parts of the visible light spectrum formed by a quartz prism will show a rise in temperature. This shows that all colors of light produce heat when absorbed. But the thermometer also shows an increase in temperature when its bulb is placed in either of the two dark regions to either side of the end of the visible spectrum. Why is this?

16.22 For each part of the electromagnetic spectrum discussed in Sec. 16.5, list the ways in which you have been affected by it. Give examples of things you have done with radiation in that frequency range, or of effects it has had on you.

16.23 What is the principal reason for the loss of support for the ether concept?

16.24 At many points in the history of science the "natural" or "intuitively" obvious way of looking at things has changed radically. Our

attitudes toward action-at-a-distance are a case in point. What are some other examples?

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

16.26 Explain the analogy of the cat-less grin given at the end of Chapter 16.

16.27 Write a brief essay on any two of the five pictures on pages 126 and 127, explaining in some detail what principles of physics they illustrate. (Select first the main principle at work in each of the situations shown here. Also you need not limit yourself to the principles discussed in this unit.)

16.28 In a couple of pages, summarize how this unit built up the story (and physical details) of the theory of light—from the particle model of light, to the model of light as a material wave in a material ether, to the joining of the initially separate disciplines of electricity and magnetism, first with each other and then with the theory of light in the general electromagnetic theory of Maxwell.

When signals are led to several antennas, the interference among their radiated waves can result in the broadcast power being restricted to certain directions. This elaborate antenna array is a U.S. Navy installation at Cutler, Maine.

The Project Physics Course

Handbook 4

Light and Electromagnetism

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Contents HANDBOOK SECTION

Chapter 13 Light

EXPERIMENT 32
REFRACTION OF A LIGHT BEAM

You can easily demonstrate the behavior of a light beam as it passes from one transparent material to another. All you need is a semicircular plastic dish, a lens, a small light source, and a cardboard tube. The light source from the Millikan apparatus (Unit 5) and the telescope tube with objective lens (Units 1 and 2) will serve nicely.

Making a Beam Projector

To begin with, slide the Millikan apparatus light source over the end of the telescope tube (Fig. 13-1). When you have adjusted the bulb-lens distance to produce a parallel beam of light, the beam will form a spot of constant size on a sheet of paper moved toward and away from it by as much as two feet.

Make a thin flat light beam by sticking two pieces of black tape about 1 mm apart over the lens end of the tube, creating a slit. Rotate the bulb filament until it is parallel to the slit.
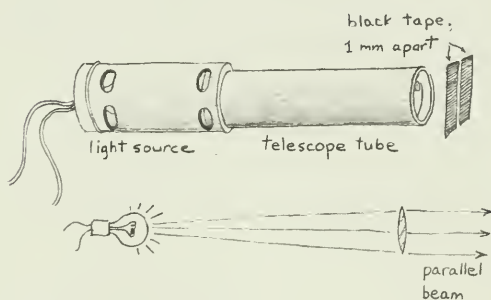
Fig. 13-1

When this beam projector is pointed slightly downward at a flat surface, a thin path of light falls across the surface. By directing the beam into a plastic dish filled with water, you can observe the path of the beam emerging into the air. The beam direction can be measured precisely by placing protractors inside and outside the dish, or by placing the dish on a sheet of polar graph paper. (Fig. 13-2)
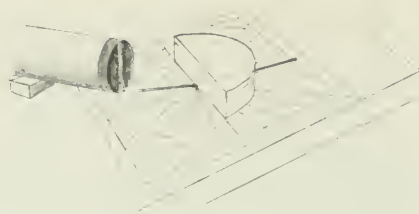
Fig. 13-2

Behavior of a Light Beam at the Boundary Between Two Media

Direct the beam at the center of the flat side of the dish, keeping the slit vertical. Tilt the projector until you can see the path of light both before it reaches the dish and after it leaves the other side.

To describe the behavior of the beam, you need a convenient way of referring to the angle the beam makes with the boundary. In physics, the system of measuring angles relative to a surface assigns a value of 0° to the perpendicular or straight-in direction. The angle at which a beam strikes a surface is called *angle of incidence*; it is the number of degrees away from the straight-in direction. Similarly, the angle at which a refracted beam leaves the boundary is called the *angle of refraction*. It is measured as the deviation from the straight-out direction. (Fig. 13-3)
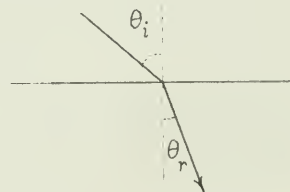
Fig. 13-3

Note the direction of the refracted beam for a particular angle of incidence. Then direct the beam perpendicularly into the rounded side of the dish where the refracted beam came out. (Fig. 13-4) At what angle does the beam now come out on the flat side? Does reversing the path like this have the same kind of effect for all angles?

Q1 Can you state a general rule about the
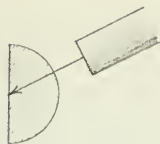
Fig. 13-4

passage of light beams through the medium?
Q2 What happens to the light beam when it reaches the edge of the container along a radius?

Change the angle of incidence and observe how the angles of the reflected and refracted beams change. (It may be easiest to leave the projector supported in one place and to rotate the sheet of paper on which the dish rests.) You will see that the angle of the *reflected* beam is always equal to the angle of the incident beam, but the angle of the *refracted* beam does not change in so simple a fashion.

Refraction Angle and Change in Speed

Change the angle of incidence in 5° steps from 0° to 85°, recording the angle of the refracted beam for each step. As the angles in air get larger, the beam in the water begins to spread, so it becomes more difficult to measure its direction precisely. You can avoid this difficulty by directing the beam into the round side of the dish instead of into the flat side. This will give the same result since, as you have seen, the light path is reversible.
Q3 On the basis of your table of values, does the angle in air seem to increase in proportion to the angle in water?
Q4 Make a plot of the angle in air against the angle in water. How would you describe the relation between the angles?

According to both the simple wave and simple particle models of light, it is not the ratio of angles in two media that will be constant, but the ratio of the *sines* of the angles. Add two columns to your data table and, referring to a table of the sine function, record the sines of the angles you observed. Then plot the sine of the angle in water against the sine of the angle in air.
Q5 Do your results support the prediction made from the models?
Q6 Write an equation that describes the relationship between the angles.

According to the wave model, the ratio of the sines of the angles in two media is the same as the ratio of the light speeds in the two media.
Q7 According to the wave model, what do your results indicate is the speed of light in water?

Color Differences

You have probably observed in this experiment that different colors of light are not refracted by the same amount. (This effect is called *dispersion*.) This is most noticeable when you direct the beam, into the round side of the dish, at an angle such that the refracted beam leaving the flat side lies very close to the flat side. The different colors of light making up the white beam separate quite distinctly.
Q8 What color of light is refracted most?
Q9 Using the relation between sines and speeds, estimate the difference in the speeds of different colors of light in water.

Other Phenomena

In the course of your observations you probably have observed that for some angles of incidence no refracted beam appears on the other side of the boundary. This phenomenon is called *total internal reflection*.
Q10 When does total internal reflection occur?

By immersing blocks of glass or plastic in the water, you can observe what happens to the beam in passing between these media and water. (Liquids other than water can be used, but be sure you don't use one that will dissolve the plastic dish!) If you lower a smaller transparent container upside-down into the water so as to trap air in it, you can observe what happens at another water-air boundary. (Fig. 13-5) A round container so placed will show what effect an air-bubble in water has on light.
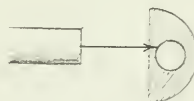
Fig. 13-5

Q11 Before trying this last suggestion, make a sketch of what you think will happen. If your prediction is wrong, explain what happened.

EXPERIMENT 33 YOUNG'S EXPERIMENT – THE WAVELENGTH OF LIGHT

You have seen how ripples on a water surface are diffracted, spreading out after having passed through an opening. You have also seen wave interference when ripples, spreading out from two sources, reinforce each other at some places and cancel out at others.

Sound and ultrasound waves behave like water waves. These diffraction and interference effects are characteristic of all wave motions. If light has a wave nature, must it not also show diffraction and interference effects?

You may shake your head when you think about this. If light is diffracted, this must mean that light spreads around corners. But you learned in Unit 2 that "light travels in straight lines." How can light both spread around corners and move in straight lines?

Simple Tests of Light Waves

Have you ever noticed light spreading out after passing through an opening or around an obstacle? Try this simple test: Look at a narrow light source several meters away from you. (A straight-filament lamp is best, but a single fluorescent tube far away will do.) Hold two fingers in front of one eye and parallel to the light source. Look at the light through the gap between them. (Fig. 13-6) Slowly squeeze your fingers together to decrease the width of the gap. What do you see? What happens to the light as you reduce the gap between your fingers to a very narrow slit?
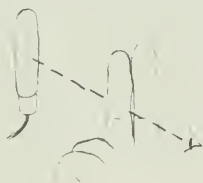
Fig. 13-6

Evidently light *can* spread out in passing through a very narrow opening between your fingers. For the effect to be noticeable, the opening must be small in comparison to the wavelength. In the case of light, the opening must be much smaller than those used in the ripple tank, or with sound waves. This suggests that light is a wave, but that it has a much shorter wavelength than the ripples on water, or sound or ultrasound in the air.

Do light waves show interference? Your immediate answer might be "no." Have you ever seen dark areas formed by the cancellation of light waves from two sources?

As with diffraction, to see interference you must arrange for the light sources to be small and close to each other. A dark photographic negative with two clear lines or slits running across it works very well. Hold up this film in front of one eye with the slits parallel to a narrow light source. You should see evidence of interference in the light coming from the two slits.

Two-slit Interference Pattern

To examine this interference pattern of light in more detail, fasten the film with the double slit on the end of a cardboard tube, such as the telescope tube without the lens. Make sure that the end of the tube is light-tight, except for the two slits. (It helps to cover most of the film with black tape.) Stick a piece of translucent "frosted" tape over the end of a narrower tube that fits snugly inside the first one. Insert this end into the wider tube, as shown in Fig. 13-7.
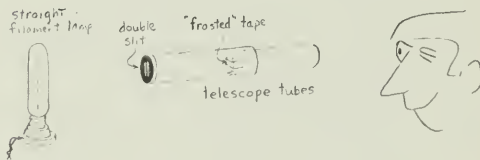
Fig. 13-7

Set up your double tube at least 5 feet away from the narrow light source with the slits parallel to the light source. With your eye about a foot away from the open end of the tube, focus your eye on the *screen*. There on the screen is the interference pattern formed by light from the two slits.

Q1 Describe how the pattern changes as you move the screen farther away from the slits.

Q2 Try putting different colored filters in

front of the double slits. What are the differ-
ences between the pattern formed in blue
light and the pattern formed in red or yellow
light?

Measurement of Wavelength

Remove the translucent tape screen from the
inside end of the narrow tube. Insert a mag-
nifying eyepiece and scale unit in the end
toward your eye and look through it at the light.
(See Fig. 13-8) What you see is a magnified
view of the interference pattern in the plane
of the scale. Try changing the distance be-
tween the eyepiece and the double slits.
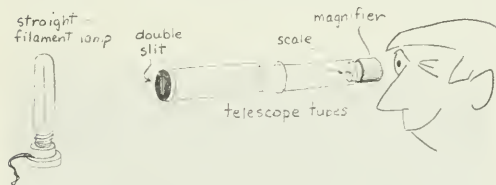
Fig. 13-8

In Experiment 31, you calculated the wave-
length of sound from the relationship

$$\lambda = \frac{x}{\ell} d$$

The relationship was derived on page 120 of
Text Chapter 12. There it was derived for
water waves from two in-phase sources, but
the mathematics is the same for any kind of
wave. (Use of two closely-spaced slits gives a
reasonably good approximation to in-phase
sources.)

Fig. 13-9

Use the formula to find the wavelength of
the light transmitted by the different colored
filters. To do so, measure x, the distance be-
tween neighboring dark fringes, with the mea-
suring magnifier (Fig. 13-10). (Remember that
the smallest divisions on the scale are 0.1 mm.)
You can also use the magnifier to measure d,
the distance between the two slits. Place the
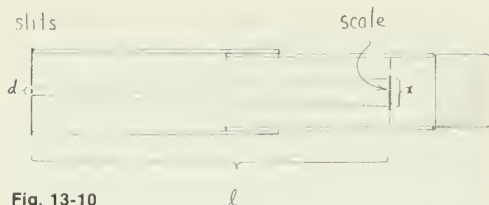
Fig. 13-10 ℓ

film against the scale and then hold the film
up to the light.) In the drawing, ℓ is the dis-
tance from the slits to the plane of the pattern
you measure.

The speed of light in air is approximately
3×10^8 meters/second. Use your measured
values of wavelength to calculate the approxi-
mate light *frequencies* for each of the colors
you used.

Discussion

Q3   Why couldn't you use the method of
"standing waves" (Experiment 31, "Sound")
to measure the wavelength of light?
Q4   Is there a contradiction between the
statement, "Light consists of waves" and the
statement, "Light travels in straight lines"?
Q5   Can you think of a common experience in
which the wave nature of light is noticeable?

Suggestions for Some More Experiments

1. Examine light diffracted by a circular hole
instead of by a narrow slit. The light source
should now be a small point, such as a distant
flashlight bulb. Look also for the interference
effect with light that passes through two small
circular sources—pinholes in a card—instead
of the two narrow slits. (Thomas Young used
circular openings rather than slits in his orig-
inal experiment in 1802.)
2. Look for the diffraction of light by an ob-
stacle. For example, use straight wires of
various diameters, parallel to a narrow light
source. Or use circular objects such as tiny
spheres, the head of a pin, etc., and a point
source of light. You can use either method of
observation—the translucent tape screen, or
the magnifier. You may have to hold the mag-
nifier fairly close to the diffracting obstacle.

Instructions on how to photograph some
of these effects are in the activities that follow.

ACTIVITIES

THIN FILM INTERFERENCE

Take two *clean* microscope slides and press them together. Look at the light they reflect from a source (like a mercury lamp or sodium flame) that emits light at only a few definite wavelengths. What you see is the result of interference between light waves reflected at the two inside surfaces which are almost, but not quite, touching. (The thin film is the layer of air between the slides.)

This phenomenon can also be used to determine the flatness of surfaces. If the two inside surfaces are planes, the interference fringes are parallel bands. Bumps or depressions as small as a fraction of a wavelength of light can be detected as wiggles in the fringes. This method is used to measure very small distances in terms of the known wavelength of light of a particular color. If two very flat sides are placed at a slight angle to each other, an interference band appears for every wavelength of separation. (Fig. 13-11)

How could this phenomenon be used to measure the thickness of a very fine hair or very thin plastic?
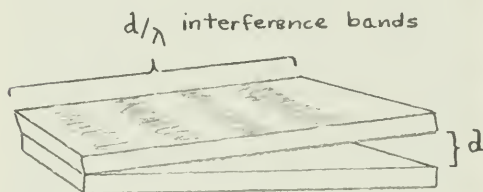
Fig. 13-11

An alternative is to focus an ordinary camera on "infinity" and place it directly behind the magnifier, using the same setup as described in Suggestions for Some More Experiments on page 237.

HANDKERCHIEF DIFFRACTION GRATING

Stretch a linen or cotton handkerchief of good quality and look through it at a distant light source, such as a street light about one block away. You will see an interesting diffraction pattern. (A window screen or cloth umbrella will also work.)

PHOTOGRAPHING DIFFRACTION PATTERNS

Diffraction patterns like those pictured here can be produced in your lab or at home. The photos in Figs. 13-12 and 13-13 were produced with the setup diagrammed in Fig. 13-14.
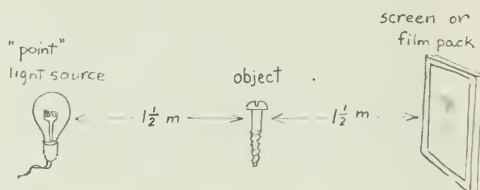
Fig. 13-12

Fig. 13-13

Fig. 13-14

To photograph the patterns, you must have a darkroom or a large, light-tight box. Figure 13-13 was taken using a Polaroid 4 × 5 back on a Graphic press camera. The lens was removed, and a single sheet of 3000-ASA-speed Polaroid film was exposed for 10 seconds; a piece of cardboard in front of the camera was used as a shutter.

As a light source, use a $1\frac{1}{2}$-volt flashlight bulb and AA cell. Turn the bulb so the end of the filament acts as a point source. A red (or blue) filter makes the fringes sharper. You can see the fringes by examining the shadow on the screen with the 10x magnifier. Razor blades, needles, or wire screens make good objects.

POISSON'S SPOT

A bright spot can be observed in a photograph of the center of some shadows, like that shown in the photograph, Fig. 13-15. To see this,
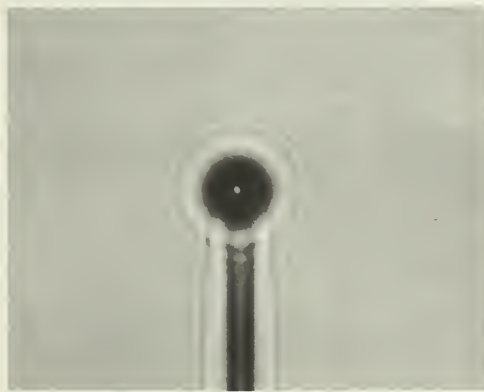
Fig. 13-15

set up a light source, obstacle, and screen as shown in Fig. 13-16. Satisfactory results require complete darkness. Try a two-second exposure with Polaroid 3000-ASA-film.
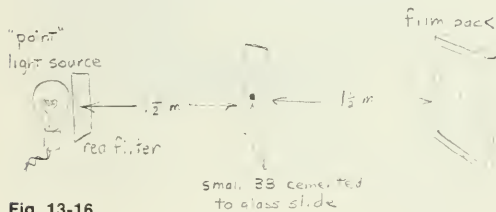
Fig. 13-16

PHOTOGRAPHIC ACTIVITIES

The number of photography activities is limitless, so we shall not try to describe many in detail. Rather, this is a collection of suggestions to give you a "jumping-off" point for classroom displays, demonstrations, and creative work.

(a) History of photography

Life magazine, December 23, 1966, had an excellent special issue on photography. How the world's first trichromatic color photograph was made by James Clerk Maxwell in 1861 is described in the Science Study Series paperback, *Latent Image,* by Beaumont Newhall. Much of the early history of photography in the United States is discussed in *Mathew Brady,* by James D. Horan, Crown Publishers.

(b) Schlieren photography

For a description and instructions for equipment, see *Scientific American*, February 1964, p. 132-3.

(c) Infrared photography

Try to make some photos like that shown on page 14 of your Unit 4 *Text.* Kodak infrared film is no more expensive than normal black and white film, and can be developed with normal developers. If you have a 4 × 5 camera with a Polaroid back, you can use 4 × 5 Polaroid infrared film sheets. You may find the Kodak Data Book M-3, "Infrared and Ultraviolet Photography," very helpful.

COLOR

One can easily carry out many intriguing experiments and activities related to the physical, physiological, and psychological aspects of color. Some of these are suggested here.

(a) Scattered light

Add about a quarter-teaspoon of milk to a drinking glass full of water. Set a flashlight about two feet away so it shines into the glass. When you look through the milky water toward the light, it has a pale orange color. As you move around the glass, the milky water appears to change color. Describe the change and explain what causes it.

(b) The rainbow effect

The way in which rainbows are produced can be demonstrated by using a glass of water as a

large cylindrical raindrop. Place the glass on a piece of white paper in the early morning or late afternoon sunlight. To make the rainbow more visible, place two books upright, leaving a space a little wider than the glass between them, so that the sun shines on the glass but the white paper is shaded (Fig. 13-17). The rainbow will be seen on the backs of the books. What is the relationship between the arrangement of colors of the rainbow and the side of the glass that the light entered? This and other interesting optical effects are described in *Science for the Airplane Passenger*, by Elizabeth A. Wood, Houghton-Mifflin Co., 1968.
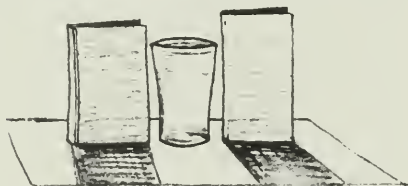
Fig. 13-17

(c) Color vision by contrast (Land effect)
Hook up two small lamps as shown in Fig. 13-18. Place an obstacle in front of the screen
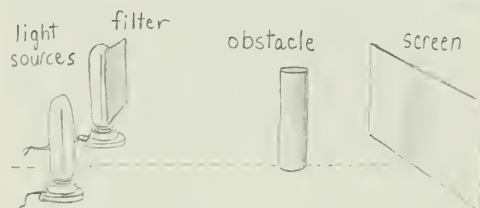
Fig. 13-18

so that adjacent shadows are formed on the screen. Do the shadows have any tinge of color? Now cover one bulb with a red filter and notice that the other shadow appears green by contrast. Try this with different colored filters and vary the light intensity by moving the lamps to various distances.

(d) Land two-color demonstrations
A different and interesting activity is to demonstrate that a full-color picture can be created by simultaneously projecting two black-and-white transparencies taken through a red and a green filter. For more information see *Scientific American*, May 1959; September 1959; and January 1960.

POLARIZED LIGHT

The use of polarized light in basic research is spreading rapidly in many fields of science. The laser, our most intense laboratory source of polarized light, was invented by researchers in electronics and microwaves. Botanists have discovered that the direction of growth of certain plants can be determined by controlling the polarization form of illumination, and zoologists have found that bees, ants, and various other creatures routinely use the polarization of sky light as a navigational "compass." High-energy physicists have found that the most modern particle accelerator, the synchrotron, is a superb source of polarized x-rays. Astronomers find that the polarization of radio waves from planets and from stars offers important clues as to the dynamics of those bodies. Chemists and mechanical engineers are finding new uses for polarized light as an analytical tool. Theoreticians have discovered shortcut methods of dealing with polarized light algebraically. From all sides, the onrush of new ideas is imparting new vigor to this classical subject.

A discussion of many of these aspects of the nature and application of polarized light, including activities such as those discussed below, can be found in *Polarized Light,* by W. A. Shurcliff and S. S. Ballard, Van Nostrand Momentum Book #7, 1964.

(a) Detection
Polarized light can be detected directly by the unaided human eye, provided one knows what to look for. To develop this ability, begin by staring through a sheet of Polaroid at the sky for about ten seconds. Then quickly turn the polarizer 90° and look for a pale yellow brush-shaped pattern similar to the sketch in Fig. 13-19.
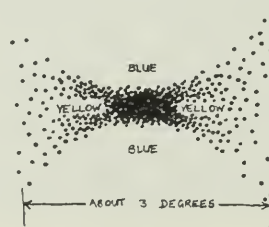
Fig. 13-19

The color will fade in a few seconds, but another pattern will appear when the Polaroid is again rotated 90°. A light blue filter behind the Polaroid may help.

How is the axis of the brush related to the direction of polarization of light transmitted by the Polaroid? (To determine the polarization direction of the filter, look at light reflected from a horizontal non-metallic surface, such as a table top. Turn the Polaroid until the reflected light is brightest. Put tape on one edge of the Polaroid parallel to the floor to show the direction of polarization.) Does the axis of the yellow pattern always make the same angle with the axis of polarization?

Some people see the brush most clearly when viewed with circularly polarized light. To make a circular polarizer, place a piece of Polaroid in contact with a piece of cellophane with its axis of polarization at a 45° angle to the fine stretch lines of the cellophane.

(b) Picket fence analogy

At some time you may have had polarization of light explained to you in terms of a rope tied to a fixed object at one end, and being shaken at the other end. In between, the rope passes through two picket fences (as in Fig. 13-20), or through two slotted pieces of cardboard. This analogy suggests that when the slots are parallel the wave passes through, but when the slots are perpendicular the waves are stopped. (You may want to use a rope and slotted boards to see if this really happens.)

Place two Polaroid filters parallel to each
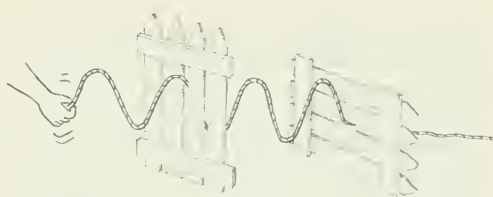
Fig. 13-20

other and turn one so that it blacks out the light completely. Then place a third filter between the first two, and rotate it about the axis of all three. What happens? Does the picket fence analogy still hold?

A similar experiment can be done with microwaves using parallel strips of tinfoil on cardboard instead of Polaroid filters.

MAKE AN ICE LENS

Dr. Clawbonny, in Jules Verne's *The Adventures of Captain Hatteras,* was able to light a fire in −48° weather (thereby saving stranded travelers) by shaping a piece of ice into a lens and focusing it on some tinder. If ice is clear, the sun's rays pass through with little scattering. You can make an ice lens by freezing water in a round-bottomed bowl. Use boiled, distilled water, if possible, to minimize problems due to gas bubbles in the ice. Measure the focal length of the lens and relate this length to the radius of the bowl. (Adapted from *Physics for Entertainment,* Y. Perelman, Foreign Languages Publishing House, Moscow, 1936.)

B.C.   By John Hart

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EXPERIMENT 34   ELECTRIC FORCES I

If you walk across a carpet on a dry day and then touch a metal doorknob, a spark may jump across between your fingers and the knob. Your hair may crackle as you comb it. You have probably noticed other examples of the electrical effect of rubbing two objects together. Does your hair ever stand on end after you pull off your clothes over your head? (This effect is particuarly strong if the clothes are made of nylon, or another synthetic fiber.)

Small pieces of paper are attracted to a plastic comb or ruler that has been rubbed on a piece of cloth. Try it. The attractive force is often large enough to lift scraps of paper off the table, showing that it is stronger than the gravitational force between the paper and the entire earth!

The force between the rubbed plastic and the paper is an electrical force, one of the four basic forces of nature.

In this experiment you will make some observations of the nature of the electrical force. If you do the next experiment, Electric Forces II, you will be able to make quantitative measurements of the force.

Forces between Electrified Objects

Stick an 8-inch length of transparent tape to the tabletop. Press the tape down well with your finger leaving an inch or so loose as a handle. Carefully remove the tape from the table by pulling on this loose end, preventing the tape from curling up around your fingers.

To test whether or not the tape became electrically charged when you stripped it from the table, see if the non-sticky side will pick up a scrap of paper. Even better, will the paper jump up from the table to the tape?

Q1   Is the tape charged? Is the paper charged?

So far you have considered only the effect of a charged object (the tape) on an uncharged object (the scrap of paper). What effect does a charged object have on another charged object? Here is one way to test it.

Charge a piece of tape by sticking it to the table and peeling it off as you did before. Suspend the tape from a horizontal wood rod, or over the edge of the table. (Don't let the lower end curl around the table legs.)

Now charge a second strip of tape in the same way and bring it close to the first one. It's a good idea to have the two non-sticky sides facing.

Q2   Do the two tapes affect each other? What kind of force is it—attractive or repulsive?

Hang the second tape a few inches away from the first one. Proceed as before and electrify a third piece of tape. Observe the reaction between this and your first two tapes. Record

all your observations. Leave only the first tape hanging from its support—you will need it again shortly. Discard the other two tapes.

Stick down a new piece of tape (A) on the table and stick another tape (B) over it. Press them down well. Peel the stuck-together tapes from the table. To remove the net charge the pair will have picked up, run the nonsticky side of the pair over a water pipe or your lips. Check the pair with the original test strip to be sure the pair is electrically neutral. Now carefully pull the two tapes apart.

Q3   As you separated the tapes did you notice any interaction between them (other than that due to the adhesive)?

Q4   Hold one of these tapes in each hand and bring them slowly towards each other (non-sticky sides facing). What do you observe?

Q5   Bring first one, then the other of the tapes near the original test strip. What happens?

Mount A and B on the rod or table edge to serve as test strips. If you have rods of plastic, glass, or rubber available, or a plastic comb, ruler, etc., charge each one in turn by rubbing on cloth or fur and bring it close to A and then B.

Although you can't prove it from the results of a limited number of experiments, there seem to be only two classes of electrified objects. No one has ever produced an electrified object that either attracts or repels *both A and B* (where A and B are themselves electrified objects. The two classes are called positive (+) and negative (−). Write out a general statement summarizing how all members of the same class behave with each other (attract, repel, or remain unaffected by) and with all members of the other class.

A Puzzle

Your system of two classes of electrified objects was based on observations of the way charged objects interact. But how can you account for the fact that a charged object (like a rubbed comb) will attract an *un*charged object (like a scrap of paper)? Is the force between a charged body (either + or −) and an uncharged body always attractive, always repulsive, or is it sometimes one, sometimes the other?

Q6   Can you explain how a force arises between charged and uncharged bodies and why it is always the way it is? The clue here is the fact that the negative charges can move about slightly—even in materials called non-conductors, like plastic and paper (see Sec. 14.5 *Text*).
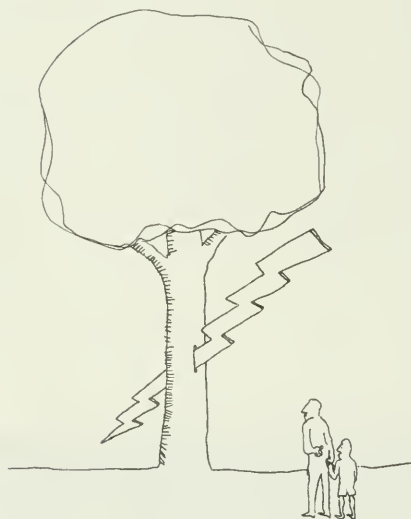
EXPERIMENT 35
ELECTRIC FORCES II—COULOMB'S LAW

You have seen that electrically charged objects exert forces on each other, but so far your observations have been qualitative; you have looked but not measured. In this experiment you will find out how the amount of electrical force between two charged bodies depends on the amounts of charge and on the separation of the bodies. In addition, you will experience some of the difficulties in using sensitive equipment.

The electric forces between charges that you can conveniently produce in a laboratory are small. To measure them at all requires a sensitive balance.

Constructing the Balance

(If your balance is already assembled, you need not read this section—go on to "Using the balance.") A satisfactory balance is shown in Fig. 14-1.

Coat a small foam-plastic ball with a conducting paint and fix it to the end of a plastic sliver or toothpick by stabbing the pointed end into the ball. Since it is very important that the plastic be clean and dry (to reduce leakage of charge along the surface); *handle the plastic slivers as little as possible, and then only with clean, dry fingers.* Push the sliver into one end of a soda straw leaving at least an inch of plastic exposed, as shown at the top of Fig. 14-2.

Next, fill the plastic support for the balance with glycerin, or oil, or some other liquid. Cut a *shallow* notch in the top of the straw about 2 cm from the axle on the side away from the sphere—see Fig. 14-2.
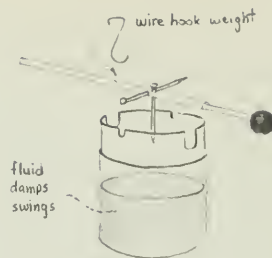
Fig. 14-2

Locate the balance point of the straw, ball, and sliver unit. Push a pin through the straw at this point to form an axle. Push a second pin through the straw directly in front of the axle and perpendicular to it. (As the straw rocks back and forth, this pin moves through the fluid in the support tube. The fluid reduces the swings of the balance.) Place the straw on the support, the pin hanging down inside the vial. Now adjust the balance, by sliding the plastic sliver slightly in or out of the straw, until the straw rests horizontally. If necessary, stick small bits of tape to the straw to make it balance. Make sure the balance can swing freely while making this adjustment.

Finally, cut five or six small, equal lengths of thin, bare wire (such as #30 copper). Each should be about 2 cm long, and they *must all be as close to the same length as you can make them.* Bend them into small hooks (Fig. 14-2) which can be hung over the notch in the straw or hung from each other. These are your "weights."

Mount another coated ball on a pointed plastic sliver and fix it in a clamp on a ring stand, as shown in Fig. 14-1.
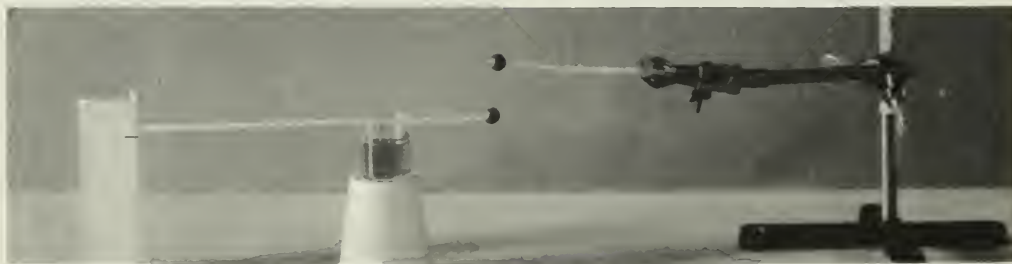
Fig. 14-1

Using the Balance

Charge both balls by wiping them with a rubbed plastic strip. Then bring the ring-stand ball down from above toward the balance ball.

Q1 What evidence have you that there is a force between the two balls?

Q2 Can you tell that it is a force due to the charges?

Q3 Can you compare the size of electrical force between the two balls with the size of gravitational force between them?

Your balance is now ready, but in order to do the experiment, you need to solve two technical problems. During the experiment you will adjust the position of the ring-stand sphere so that the force between the charged spheres is balanced by the wire weights. The straw will then be horizontal. First, therefore, you must check quickly to be sure that the straw *is* balanced horizontally each time. Second, *measure* the distance between the centers of the two balls, yet you cannot put a ruler near the charged balls, or its presence will affect your results. And if the ruler isn't close to the spheres, it is very difficult to make the measurement accurately.

Here is a way to make the measurement. With the balance in its horizontal position, you can record its balanced position with a mark on a folded card placed near the end of the straw (at least 5 cm away from the charges). (See Fig. 14-1.)

How can you avoid the parallax problem? Try to devise a method for measuring the distance between the centers of the spheres. Ask your teacher if you cannot think of one.

You are now ready to make measurements to see how the force between the two balls depends on their separation and on their charge.

Doing the Experiment

From now on, work as quickly as possible but move carefully to avoid disturbing the balance or creating air currents. It is not necessary to wait for the straw to stop moving before you record its position. When it is swinging slightly,

but *equally*, to either side of the balanced position, you can consider it balanced.

Charge both balls, touch them together briefly, and move the ring-stand ball until the straw is returned to the balanced position. The weight of one hook now balances the electric force between the charged spheres at this separation. Record the distance between the balls.

Without recharging the balls, add a second hook and readjust the system until balance is again restored. Record this new position. Repeat until you have used all the hooks — but don't reduce the air space between the balls to less than $\frac{1}{2}$ cm. Then quickly retrace your steps by removing one (or more) hooks at a time and raising the ring-stand ball each time to restore balance.

Q4 The separations recorded on the "return trip" may not agree with your previous measurements with this same number of hooks. If they do not, can you suggest a reason why?

Q5 Why must you not recharge the balls between one reading and the next?

Interpreting Your Results

Make a graph of your measurements of force F against separation d between centers. Clearly F and d are inversely related; that is, F increases as d decreases. You can go further to find the relationship between F and d. For example, it might be $F \propto 1/d$, $F \propto 1/d^2$, or $F \propto 1/d^3$, etc.

Q6 How would you test which of these best represents your results?

Q7 What is the actual relationship between F and d?

Further Investigation

In another experiment you can find how the force F varies with the charges on the spheres, when d is kept constant.

Charge both balls and then touch them together briefly. Since they are nearly identical, it is assumed that when touched, they will share the total charge almost equally.

Hang four hooks on the balance and move the ring-stand ball until the straw is in the balanced position. Note this position.

CHAPTER 14

Touch the upper ball with your finger to discharge the ball. If the two balls are again brought into contact, the charge left on the balance ball will be shared equally between the two balls.

Q8 What is the charge on each ball now (as a fraction of the original charge)?

Return the ring-stand ball to its previous position and find how many hooks you must remove to restore the balance.

Q9 Can you state this result as a mathematical relationship between quantity of charge and magnitude of force?

Q10 Consider why you had to follow two precautions in doing the experiment:

(a) Why can a ruler placed too close to the charge affect results?

(b) Why was it suggested that you get the spheres no closer than about $\frac{1}{2}$ cm?

Q11 How might you modify this experiment to see if Newton's third law applies to these electric forces?
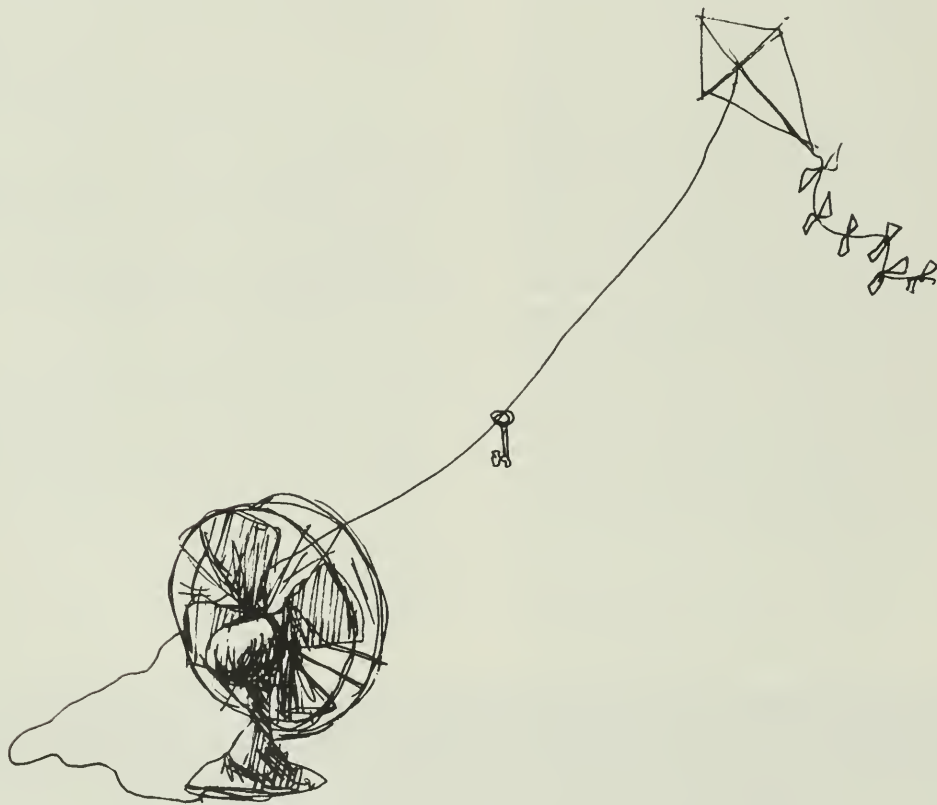
EXPERIMENT 36
FORCES ON CURRENTS

If you did Experiment 35, you used a simple but sensitive balance to investigate how the electric force between two charged bodies depends on the distance between them and on the amount of charge. In this and the next experiment you will examine a related effect: the force between *moving* charges—that is, between electric currents. You will investigate the effect of the magnitudes and the directions of the currents. Before starting the experiment you should have read the description of Oersted and Ampère's work (*Text* Sec. 14.11 and Sec. 14.12).

Fig. 14-3

The apparatus for these experiments (like that in Fig. 14-3) is similar in principle to the balance apparatus you used to measure electric forces. The current balance measures the force on a horizontal rod suspended so that it is free to move in a horizontal direction at right angles to its length. You can study the forces exerted by a magnetic field on a current by bringing a magnet up to this rod while there is a current in it. A force on the current-carrying rod causes it to swing away from its original position.

You can also pass a current through a fixed wire parallel to the pivoted rod. Any force exerted on the rod by the current in the fixed wire will again cause the pivoted rod to move. You can measure these forces simply by measuring the counter force needed to return the rod to its original position.

Adjusting the Current Balance

This instrument is more complicated than those most of you have worked with so far. Therefore it is worthwhile spending a little time getting to know how the instrument operates before you start taking readings.

1. You have three or four light metal rods bent into ⌴ or ⌐⌐ shapes. These are the movable "loops." Set up the balance with the longest loop clipped to the pivoted horizontal bar. Adjust the loop so that the horizontal part of the loop hangs level with the bundle of wires (the fixed coil) on the pegboard frame. Adjust the balance on the frame so that the loop and coil are parallel as you look down at them. They should be at least five centimeters apart. Make sure the loop swings freely.

2. Adjust the "counterweight" cylinder to balance the system so that the long pointer arm is approximately horizontal. Mount the ⊟ -shaped plate (zero-mark indicator) in a clamp and position the plate so that the zero line is opposite the horizontal pointer (Fig. 14-4). (If you are using the equipment for the first time, draw the zero-index line yourself.)

Fig. 14-4 Set the zero mark level with the pointer when there is current in the balance loop and no current in the fixed coil. (See large photo on *Handbook 4* cover.)

3. Now set the balance for maximum sensitivity. To do this, move the sensitivity clip up the vertical rod (Fig. 14-5) until the loop slowly swings back and forth. These oscillations may take as much as four or five seconds per swing. If the clip is raised too far, the balance may
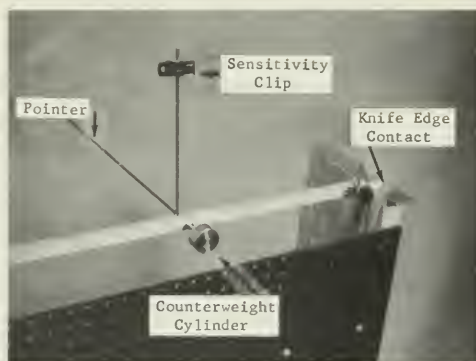
Fig. 14-5

become unstable and flop to either side without "righting" itself.

4. Connect a 6V/5 amp max power supply that can supply up to 5 amps through an ammeter to one of the flat horizontal plates on which the pivots rest. Connect the other plate to the other terminal of the power supply. (Fig. 14.6.)
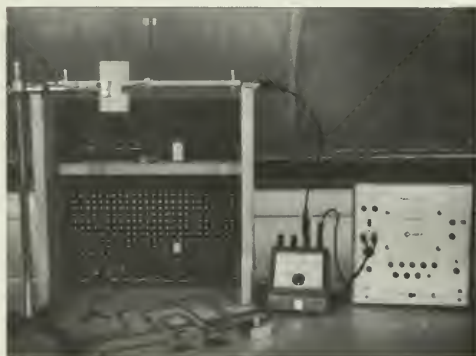
Fig. 14-6

To limit the current and keep it from tripping the circuit-breaker, it may be necessary to put one or two 1-ohm resisters in the circuit. (If your power supply does not have variable control, it should be connected to the plate through a rheostat.)

5. Set the variable control for minimum current, and turn on the power supply. If the ammeter deflects the wrong way, interchange the leads to it. Slowly increase the current up to about 4.5 amps.

6. Now bring a small magnet close to the pivoted conductor.

Q1 How must the magnet be placed to have the biggest effect on the rod? What determines the direction in which the rod swings?

You will make quantitative measurements of the forces between magnet and current in the next experiment, "Currents, Magnets, and Forces." The rest of this experiment is concerned with the interaction between two currents.

7. Connect a similar circuit—power supply, ammeter, and rheostat (if no variable control on the power supply)—to the fixed coil on the vertical pegboard—the bundle of ten wires, not the single wire. The two circuits (fixed coil and movable hook) must be independent. Your setup should now look like the one shown in Fig. 14.7. Only one meter is actually *required*, as you can move it from one circuit to the other as needed. It is, however, more convenient to work with two meters.
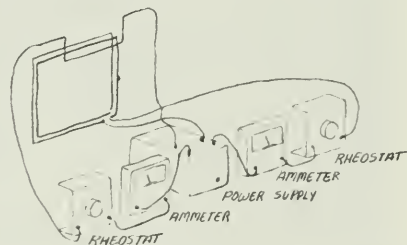
Fig. 14-7 Current balance connections using rheostats when variable power supply is not available.

8. Turn on the currents in both circuits and check to see which way the pointer rod on the balance swings. It should move *up*. If it does not, see if you can make the pointer swing *up* by changing something in your setup.

Q2 Do currents flowing in the same direction attract or repel each other? What about currents flowing in opposite directions?

9. Prepare some "weights" from the thin wire given to you. You will need a set that contains wire lengths of 1 cm, 2 cm, 5 cm, and 10 cm. You may want more than one of each but you can make more as needed during the experiment. Bend them into small S-shaped hooks so that they can hang from the notch on the

pointer or from each other. This notch is the same distance from the axis of the balance as the bottom of the loop so that when there is a force on the horizontal section of the loop, the total weight F hung at the notch will equal the magnetic force acting horizontally on the loop. (See Fig. 14-8.)
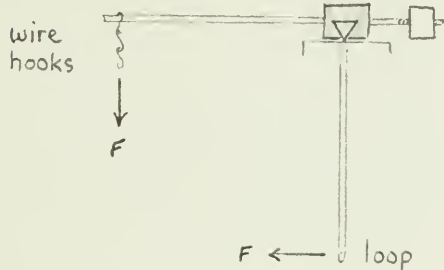
Fig. 14-8 Side view of a balanced loop. The distance from the pivot to the wire hook is the same as the distance to the horizontal section of the loop, so the weight of the additional wire hooks is equal in magnitude to the horizontal magnetic force on the loop.

These preliminary adjustments are common to all the investigations. But from here on there are separate instructions on three different experiments. Different members of the class will investigate how the force depends upon:

(a) the *current* in the wires,
(b) the *distance* between the wires, or
(c) the *length* of one of the wires.

When you have finished your experiment— (a), (b), or (c)—read the section "For class discussion."

(a) How Force Depends on Current in the Wires

By keeping a constant separation between the loop and the coil, you can investigate the effects of varying the currents. Set the balance on the frame so that, as you look down at them, the loop and the coil are parallel and about 1.0 cm apart.

Set the current in the balance loop to about 3 amps. Do not change this current throughout the experiment. With this current in the bal-

ance loop and no current in the fixed coil, set the zero-mark in line with the pointer rod.

Starting with a relatively small current in the fixed coil (about 1 amp), find how many centimeters of wire you must hang on the pointer notch until the pointer rod returns to the zero mark.

Record the current I_f in the fixed coil and the length of wire added to the pointer arm. The weight of wire is the balancing force F.

Increase I_f step by step, checking the current in the balance loop as you do so until you reach currents of about 5 amps in the fixed coil.
Q3 What is the relationship between the current in the fixed coil and the force on the balance loop? One way to discover this is to plot force F against current I_f. Another way is to find what happens to the balancing force when you double, then triple, the current I_f.
Q4 Suppose you had held I_f constant and measured F as you varied the current in the balance loop I_b. What relationship do you think you would have found between F and I_b? Check your answer experimentally (say, by doubling I_b) if you have time.
Q5 Can you write a symbolic expression for how F depends on *both* I_f and I_b? Check your answer experimentally (say by doubling both I_f and I_b), if you have time.
Q6 How do you convert the force, as measured in centimeters of wire hung on the pointer arm, into the conventional units for force in newtons?

(b) How Force Varies With the Distance Between Wires

To measure the distance between the two wires, you have to look down. Put a scale on the wooden shelf below the loop. Because there is a gap between the wires and the scale, the number you read on the scale changes as you move your head back and forth. This effect is called parallax, and it must be reduced if you are to get good measurements. If you look down into a mirror set on the shelf, you can tell when you are looking straight down because the wire and its image will line up. Try it. (Fig. 14-9.)
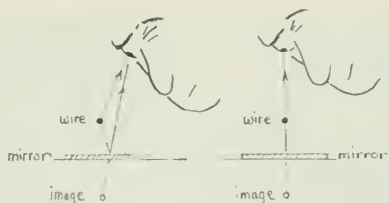
Fig. 14-9 Only when your eye is perpendicularly above the moving wire will it line up with its reflection in the mirror.

Stick a length of centimeter tape along the side of the mirror so that you can sight down and read off the distance between one edge of the fixed wire and the corresponding edge of the balance loop. Set the zero mark with a current I_b of about 4.5 amps in the balance loop and no current I_f in the fixed coil. Then adjust the distance to about 0.5 cm.

Begin the experiment by adjusting the current passing through the fixed coil to 4.5 amps. Hang weights on the notch in the pointer arm until the pointer is again at the zero position. Record the weight and distance carefully.

Repeat your measurements for four or five greater separations. Between each set of measurements make sure the loop and coil are still parallel; check the zero position, and see that the currents are still 4.5 amps.

Q7 What is the relationship between the force E on the balance loop and the distance d between the loop and the fixed coil? One way to discover this is to find some function of d (such as $1/d^2$, $1/d$, d^3, etc.) which gives a straight line when plotted against F. Another way is to find what happens to the balancing force F when you double, then triple, the distance d.

Q8 If the force on the balance loop is F, what is the force on the fixed coil?

Q9 Can you convert the force, as measured in centimeters of wire hung on the pointer arm, into force in newtons?

(c) How Force Varies With the Length of One of the Wires

By keeping constant currents I_f and I_b and a constant separation d, you can investigate the effects of the *length* of the wires. In the cur-

rent balance setup it is the bottom, horizontal section of the loop which interacts most strongly with the coil and loops with several different lengths of horizontal segment are provided.

To measure the distances between the two wires, you have to look down on them. Put a scale on the wooden shelf below the loop. Because there is a gap between the wires and the scale, what you read on the scale changes as you move your head back and forth. This effect is called parallax, and parallax must be reduced if you are to get good measurements. If you look down into a mirror set on the shelf, you can tell when you are looking straight down because the wire and its image will line up. Try it. (Fig. 14-9.)

Stick a length of centimeter tape along the side of the mirror. Then you can sight down and read off the distance between one edge of the fixed wire and the corresponding edge of the balance loop. Adjust the distance to about 0.5 cm. With a current I_b of about 4.5 amps in the balance loop and no current I_f in the fixed coil, set the pointer at the zero mark.

Begin the experiment by passing 4.5 amps through both the balance loop and the fixed coil. Hang weights on the notch in the pointer in the pointer arm until the pointer is again at the zero position.

Record the value of the currents, the distance between the two wires, and the weights added.

Turn off the currents, and carefully remove the balance loop by sliding it out of the holding clips. (Fig. 14-10.) Measure the length l of the horizontal segment of the loop.
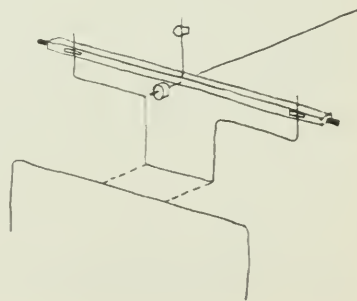
Fig. 14-10

Insert another loop. Adjust it so that it is level with the fixed coil and so that the distance between loop and coil is just the same as you had before. This is important. The loop must also be parallel to the fixed coil, both as you look down at the wires from above and as you look at them from the side. Also reset the clip on the balance for maximum sensitivity. Check the zero position, and see that the currents are still 4.5 amps.

Repeat your measurements for each balance loop.

Q10 What is the relationship between the length l of the loop and the force F on it? One way to discover this is to find some function of l (such as l, l^2, $1/l$, etc.) that gives a straight line when plotted against F. Another way is to find what happens to F when you double l.

Q11 Can you convert the force, as measured in centimeters of wire hung on the pointer arm, into force in newtons?

Q12 If the force on the balance loop is F, what is the force on the fixed coil?

For Class Discussion

Be prepared to report the results of your particular investigation to the rest of the class. As a class you will be able to combine the individual experiments into a single statement about how the force varies with current, with distance, and with length. In each part of this experiment, one factor was varied while the other two were kept constant. In combining the three separate findings into a single expression for force, you are assuming that the effects of the three factors are *independent*. For example, you are assuming doubling one current will *always* double the force—*regardless* of what constant values d and l have.

Q13 What reasons can you give for assuming such a simple independence of effects? What could you do experimentally to support the assumption?

Q14 To make this statement into an equation, what other facts do you need—that is, to be able to predict the force (in newtons) existing between the currents in two wires of given length and separation?

EXPERIMENT 37
CURRENTS, MAGNETS, AND FORCES

If you did the last experiment, "Forces on Currents," you found how the force between two wires depends on the current in them, their length, and the distance between them. You also know that a nearby magnet exerts a force on a current-carrying wire. In this experiment you will use the current balance to study further the interaction between a magnet and a current-carrying wire. You may need to refer back to the notes on Experiment 36 for details on the equipment.

In this experiment you will *not* use the fixed coil. The frame on which the coil is wound will serve merely as a convenient support for the balance and the magnets.

Attach the longest of the balance loops to the pivotal horizontal bar, and connect it through an ammeter to a variable source of current. Hang weights on the pointer notch until the pointer rod returns to the zero mark. (See Fig. 14-11.)
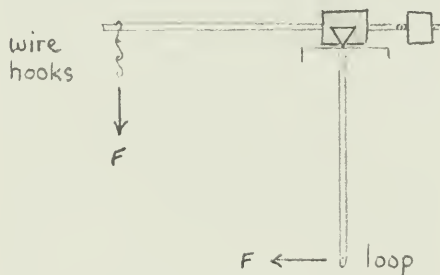
Fig. 14-11 Side view of a balanced loop. Since the distance from the pivot to the wire hooks is the same as the distance to the horizontal section of the loop, the weight of the additional wire hooks is equal to the horizontal magnetic force on the loop.

(a) How the Force Between Current and Magnet Depends On the Current

1. Place two small ceramic magnets on the inside of the iron yoke. Their orientation is important; they must be turned so that the two near faces attract each other when they are moved close together. (Careful: Ceramic magnets are brittle. They break if you drop them.) Place the yoke and magnet unit on the plat-

form so that the balance loop passes through the center of the region between the ceramic magnets. (Fig. 14-12.)
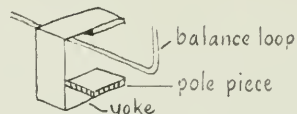
Fig. 14-12 Each magnet consists of a yoke and a pair of removable ceramic-magnet pole pieces.

2. Check whether the horizontal pointer moves *up* when you turn on the current. If it moves down, change something (the current? the magnets?) so that the pointer does swing up.

3. With the current off, mark the zero position of the pointer arm with the indicator. Adjust the current in the coil to about 1 amp. Hang wire weights in the notch of the balance arm until the pointer returns to the zero position.

Record the current and the total balancing weight. Repeat the measurements for at least four greater currents. Between each pair of readings check the zero position of the pointer arm.

Q1 What is the relationship between the current I_b and the resulting force F that the magnet exerts on the wire? (Try plotting a graph.)

Q2 If the magnet exerts a force on the current, do you think the current exerts a force on the magnet? How would you test this?

Q3 How would a stronger or a weaker magnet affect the force on the current? If you have time, try the experiment with different magnets or by doubling the number of pole pieces. Then plot F against I_b on the same graph as in *Q1* above. How do the plots compare?

(b) How the Force Between a Magnet and a Current Depends On the Length of the Region of Interaction

1. Place two small ceramic magnets on the inside of the iron yoke to act as pole pieces (Fig. 14-12). (Careful. Ceramic magnets are brittle. They break if you drop them.) Their orientation is important; they must be turned so that the two near faces attract each other when they are moved close together. Place

the yoke and magnet unit on the platform so that the balance loop passes through the center of the region between the ceramic magnets (Fig. 14-12).

Place the yoke so that the balance loop passes through the center of the magnet and the pointer moves *up* when you turn on the current. If the pointer moves down, change something (the current? the magnets?) so that the pointer does swing up.

With the current off, mark the zero position of the pointer with the indicator.

2. Hang ten or fifteen centimeters of wire on the notch in the balance rod, and adjust the current to return the pointer rod to its zero position. Record the current and the total length of wire, and set aside the magnet for later use.

3. Put a second yoke and pair of pole pieces in position, and see if the balance is restored. You have changed neither the current nor the length of wire hanging on the pointer. Therefore, if balance is restored, this magnet must be of the same strength as the first one. If it is not, try other combinations of pole pieces until you have two magnets of the same strength. If possible, try to get three matched magnets.

4. Now you are ready for the important test. Place two of the magnets on the platform at the same time (Fig. 14-13). To keep the magnets from affecting each other's field appreciably, they should be at least 10 cm apart. Of course each magnet must be positioned so the pointer is deflected upward. With the current just what it was before, hang wire weights in the notch until the balance is restored.
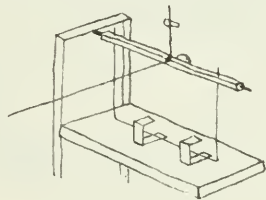
Fig. 14-13

If you have three magnet units, repeat the process using three units at a time. Again, keep the units well apart.

Interpreting Your Data

Your problem is to find a relationship between the length l of the region of interaction and the force F on the wire.

You may not know the exact length of the region of interaction between magnet and wire for a single unit. It certainly extends beyond the region between the two pole pieces. But the force decreases rapidly with distance from the magnets and so as long as the separate units are far from each other, neither will be influenced by the presence of the other. You can then assume that the total length of interaction with two units is double that for one unit.

Q4   How does F depend on l?

(c) A Study of the Interaction Between the Earth and an Electric Current

The magnetic field of the earth is much weaker than the field near one of the ceramic magnets, and the balance must be adjusted to its maximum sensitivity. The following sequence of detailed steps will make it easier for you to detect and measure the small forces on the loop.

1. Set the balance, with the longest loop, to maximum sensitivity by sliding the sensitivity clip to the top of the vertical rod. The sensitivity can be increased further by adding a second clip – but be careful not to make the balance top heavy so that it flops over and won't swing.

2. With no current in the balance loop, align the zero mark with the end of the pointer arm.

3. Turn on the current and adjust it to about 5 amps. Turn off the current and let the balance come to rest.

4. Turn on the current, and observe carefully: Does the balance move when you turn the current on? Since there is no current in the fixed oil, and there are no magnets nearby, any force acting on the current in the loop must be due to an interaction between it and the earth's magnetic field.

5. To make measurements of the force on the loop, you must set up the experiment so that the pointer swings up when you turn on the current. If the pointer moves down, try to find a way to make it go up. (If you have trouble, consult your teacher.) Turn off the

current, and bring the balance to rest. Mark the zero position with the indicator.

6. Turn on the current. Hang weights on the notch, and adjust the current to restore balance. Record the current and the length of wire on the notch. Repeat the measurement of the force needed to restore balance for several different values of current.

If you have time, repeat your measurements of force and current for a shorter loop.

Interpreting Your Data

Try to find the relationship between the current I_b in the balance loop and the force F on it. Make a plot of F against I_b.

Q5   How can you convert your weight unit (say, cm of wire) into newtons of force?

Q6   What force (in newtons) does the earth's magnetic field in your laboratory exert on a current I_b in the loop?

For Class Discussion

Different members of the class have investigated how force F between a current and a magnet varies with current I and with the length of the region of interaction with the current l. It should also be clear that in any statement that describes the force on a current due to a magnet, you must include another term that takes into account the "strength" of the magnet.

Be prepared to report to the class the results of your own investigations and to help formulate an expression that includes all the relevant factors investigated by different members of the class.

Q7   The strength of a magnetic field can be expressed in terms of the force exerted on a wire carrying 1 amp when the length of the wire interacting with the field is 1 meter. Try to express the strength of the magnetic field of your magnet yoke or of the earth's magnetic field in these units, newtons per ampere-meter. (That is, what force would the fields exert on a horizontal wire 1 meter long carrying a current of 1 amp?)

In using the current balance in this experiment, all measurements were made in the zero position—when the loop was at the very bottom of the swing. In this position a vertical force will not affect the balance. So you have measured only *horizontal* forces on the bottom of the loop.

But, since the force exerted on a current by a magnetic field is always at right angles to the field, you have therefore measured only the *vertical* component of the magnetic fields. From the symmetry of the magnet yoke, you might guess that the field is entirely vertical in the region directly between the pole pieces. But the earth's magnetic field is exactly vertical only at the magnetic poles. (See the drawing on page 68 of the *Text*.)

Q8   How would you have to change the experiment to measure the horizontal component of the earth's magnetic field?
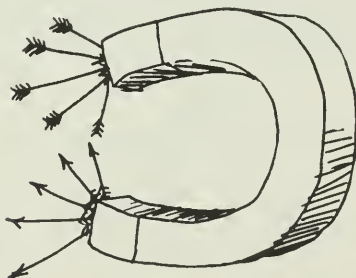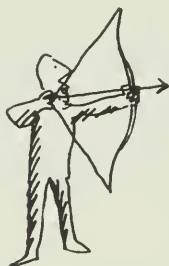
EXPERIMENT 38
ELECTRON BEAM TUBE

If you did the experiment "Electric Forces II — Coulomb's Law," you found that the force on a test charge, in the vicinity of a second charged body, decreases rapidly as the distance between the two charged bodies is increased. In other words, the *electric field* strength due to a single small charged body decreases with distance from the body. In many experiments it is useful to have a region where the field is uniform, that is, a region where the force on a test charge is the same at all points. The field between two closely spaced parallel, flat, oppositely charged plates is very nearly uniform (as is suggested by the behavior of fibers aligned in the electric field between two plates shown in Fig. 14-14).
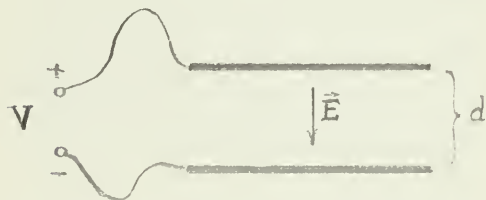
Fig. 14-14 The field between two parallel flat plates is uniform. $E = V/d$ where V is the potential difference (volts) between the two plates.

The nearly uniform magnitude E depends upon the potential difference between the plates and upon their separation d:

$$E = \frac{V}{d}$$

Besides electric forces on charged bodies, you found if you did either of the previous two experiments with the current balance, you found that there is a force on a current-carrying wire in a magnetic field.

Free Charges

In this experiment the charges will not be confined to a foam-plastic ball or to a metallic conductor. Instead they will be free charges — free to move through the field on their own in air at low pressure.

You will build a special tube for this experiment. The tube will contain a filament wire and a metal can with a small hole in one end. Electrons emitted from the heated filament are accelerated toward the positively charged can and some of them pass through the hole into the space beyond, forming a beam of electrons. It is quite easy to observe how the beam is affected by electric and magnetic fields.

When one of the air molecules remaining in the partially evacuated tube is struck by an electron, the molecule emits some light. Molecules of different gases emit light of different colors. (Neon gas, for example, glows red.) The bluish glow of the air left in the tube shows the path of the electron beam.

Building Your Electron Beam Tube

Full instructions on how to build the tube are included with the parts. Note that one of the plates is connected to the can. The other plate must not touch the can.

After you have assembled the filament and plates on the pins of the glass tube base, you can see how good the alignment is if you look in through the narrow glass tube. You should be able to see the filament across the center of the hole in the can. Don't seal the header in the tube until you have checked this alignment. Then leave the tube undisturbed overnight while the sealant hardens.
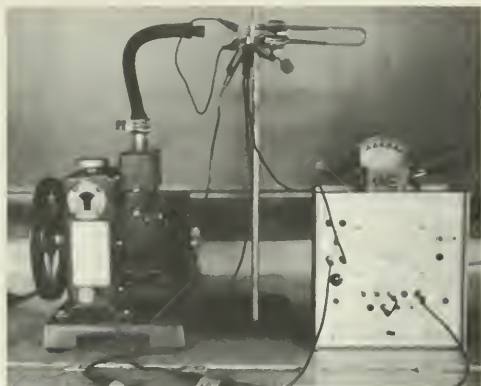
Fig. 14-15

Operating the Tube

With the power supply turned *OFF*, connect the tube as shown in Figs. 14-15 and 14-16. The low-voltage connection provides current to heat the filament and make it emit electrons. The ammeter in this circuit allows you to keep a close check on the current and avoid burning out the filament. Be sure the 0-6V control is turned down to 0.

The high-voltage connection provides the field that accelerates these electrons toward the can. Let the teacher check the circuits before you proceed further.
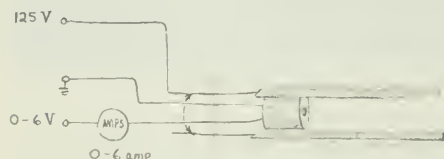
Fig. 14-16 The pins to the two plates are connected together, so that they will be at the same potential and there will be no electric field between them.

Turn on the vacuum pump and let it run for several minutes. If you have done a good job putting the tube together, and if the vacuum pump is in good condition, you should not have much difficulty getting a glow in the region where the electron beam comes through the hole in the can.

You should work with the faintest glow that you can see clearly. Even then, it is im-portant to keep a close watch on the brightness of the glow. There is an appreciable current from the filament wire to the can. As the residual gas gets hotter, it becomes a better conductor increasing the current. The increased current will cause further heating, and the process can build up – the back end of the tube will glow intensely blue-white and the can will become red hot. You must immediately reduce the current to prevent the gun from being destroyed. *If the glow in the back end of the tube begins to increase noticeably, turn down the filament current very quickly, or turn off the power supply altogether.*

Deflection by an Electric Field

When you get an electron beam, try to deflect it in an electric field by connecting the deflecting plate to the ground terminal (See Fig. 14-17), you will put a potential difference between the plates equal to the accelerating voltage. Other connections can be made to get other voltages, but check your ideas with your teacher before trying them.
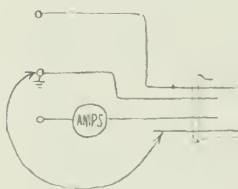
Fig. 14-17 Connecting one deflecting plate to ground will put a potential difference of 125 V between the plates.

Q1 Make a sketch showing the direction of the electric field and of the force on the charged beam. Does the deflection in the electric field confirm that the beam consists of negatively charged particles?

Deflection by a Magnetic Field

Now try to deflect the beam in a magnetic field, using the yoke and magnets from the current balance experiments.

Q2 Make a vector sketch showing the direction of the magnetic field, the velocity of the electrons, and the force on them.

Balancing the Electric and Magnetic Effects

Try to orient the magnets so as to cancel the effect of an electric field between the two plates, permitting the charges to travel straight through the tube.

Q3 Make a sketch showing the orientation of the magnetic yoke relative to the plates.

The Speed of the Charges

As explained in Chapter 14 of the *Text*, the magnitude of the magnetic force is qvB, where q is the electron charge, v is its speed, and B is the magnetic field strength. The magnitude of the electric force is qE, where E is the strength of the electric field. If you adjust the voltage on the plates until the electric force just balances the magnetic force, then $qvB = qE$ and therefore $v = B/E$.

Q4 Show that B/E will be in speed units if B is expressed in newtons/ampere-meter and E is expressed in newtons/coulomb. Hint: Remember that 1 ampere = 1 coulomb/sec.

If you knew the value of B and E, you could calculate the speed of the electron. The value of E is easy to find, since in a uniform field between parallel plates, $E = V/d$, where V is the potential difference between the plate (in volts) and d is the separation of the plates (in meters). (The unit volts/meter is equivalent to newtons/coulomb.)

A rough value for the strength of the magnetic field between the poles of the magnet-yoke can be obtained as described in the experiment, Currents, Magnets, and Forces.

Q5 What value do you get for E (in volts per meter)?

Q6 What value did you get for B (in newtons per ampere-meter)?

Q7 What value do you calculate for the speed of the electrons in the beam?

An Important Question

One of the questions facing physicists at the end of the nineteenth century was to decide on the nature of these "cathode rays" (so-called because they are emitted from the negative electrode or cathode). One group of scientists (mostly German) thought that cathode rays were a form of radiation, like light, while others (mostly English) thought they were streams of particles. J. J. Thomson at the Cavendish Laboratory in Cambridge, England did experiments much like the one described here that showed that the cathode rays behaved like particles: the particles now called electrons.

These experiments were of great importance in the early development of atomic physics. In Unit 5 you will do an experiment to determine the ratio of the charge of an electron to its mass.

In the following activities for Chapter 14, you will find some suggestions for building other kinds of electron tubes, similar to the ones used in radios before the invention of the transistor.

CHAPTER 14

ACTIVITIES

DETECTING ELECTRIC FIELDS

Many methods can be used to explore the shape of electric fields. Two very simple ones are described here.

Gilbert's Versorium

A sensitive electric "compass" is easily constructed from a toothpick, a needle, and a cork. An external electric field induces surface charges on the toothpick. The forces on these induced charges cause the toothpick to line up along the direction of the field.

To construct the versorium, first bend a flat toothpick into a slight arc. When it is mounted horizontally, the downward curve at the ends will give the toothpick stability by lowering its center of gravity below the pivot point of the toothpick. With a small nail, drill a hole at the balance point almost all the way through the pick. Balance the pick horizontally on the needle, being sure it is free to swing like a compass needle. Try bringing charged objects near it.

For details of Gilbert's and other experiments, see Holton and Roller, *Foundations of Modern Physical Science*, Chapter 26.

Charged Ball

A charged pithball (or conductor-coated plastic foam ball) suspended from a stick on a thin insulating thread, can be used as a rough indicator of fields around charged spheres, plates, and wires.

Use a point source of light to project a shadow of the thread and ball. The angle between the thread and the vertical gives a rough measure of the forces. Use the charged pithball to explore the nearly uniform field near a large charged plate suspended by tape strips, and the 1/r drop-off of the field near a long charged wire.

Plastic strips rubbed with cloth are adequate for charging well insulated spheres, plates, or wires. (To prevent leakage of charge from the pointed ends of a charged wire, fit the ends with small metal spheres. Even a smooth small blob of solder at the ends should help.)

VOLTAIC PILE

Cut twenty or more disks of each of two different metals. Copper and zinc make a good combination. (The round metal "slugs" from electrical outlet-box installations can be used for zinc disks because of their heavy zinc coating.) Pennies and nickels or dimes will work, but not as well. Cut pieces of filter paper or paper towel to fit in between each pair of two metals in contact. Make a pile of the metal disks and the salt-water soaked paper, as Volta did. Keep the pile in order; for example, copper-paper-zinc, copper-paper-zinc, etc. Connect copper wires to the top and bottom ends of the pile. Touch the free ends of wires with two fingers on one hand. What is the effect? Can you increase the effect by moistening your fingers? In what other ways can you increase the effect? How many disks do you need in order to light a flashlight bulb?

If you have metal fillings in your teeth, try biting a piece of aluminum foil. Can you explain the sensation? (Adapted from *History of Science Cases for High Schools*, Leo E. Klopfer, Science Research Associates, 1966.)

AN 11¢ BATTERY

Using a penny (95 percent copper) and a silver dime (90 percent silver) you can make an 11¢ battery. Cut a one-inch square of filter paper or paper towel, dip it in salt solution, and place it between the penny and the dime. Connect the penny and the dime to the terminals of a galvanometer with two lengths of copper wire. Does your meter indicate a current? Will the battery also produce a current with the penny and dime in direct dry contact?

MEASURING MAGNETIC FIELD INTENSITY

Many important devices used in physics experiments make use of a uniform magnetic field of known intensity. Cyclotrons, bubble chambers, and mass spectrometers are examples. Use the current balance described in Experiments 35 and 36. Measure the magnetic field intensity in the space between the pole faces of two ceramic disk magnets placed close together. Then when you are learning

about radioactivity in Unit 6 you can observe the deflection of beta particles as they pass through this space, and determine the average energy of the particles.

Bend two strips of thin sheet aluminum or copper (not iron), and tape them to two disk magnets as shown in the drawing below.
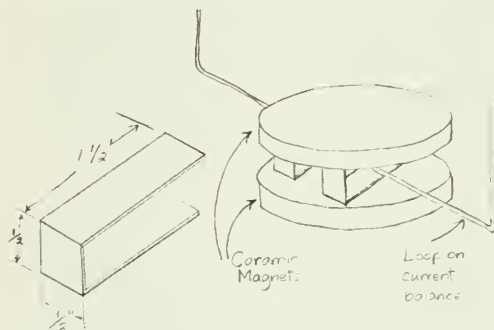
Be sure that the pole faces of the magnets are parallel and are attracting each other (unlike poles facing each other). Suspend the movable loop of the current balance midway between the pole faces. Determine the force needed to restore the balance to its initial position when a measured current is passed through the loop. You learned in Experiment 36 that there is a simple relationship between the magnetic field intensity, the length of the part of the loop which is in the field, and the current in the loop. It is $F = BIl$, where F is the force on the loop (in newtons), B is the magnetic field intensity (in newtons per ampere-meter), I is the current (in amperes), and l is the length (in meters) of that part of the current-carrying loop which is actually in the field. With your current balance, you can measure F, I, and l, and thus compute B.

For this activity, you make two simplifying assumptions which are not strictly true but which enable you to obtain reasonably good values for B: (a) the field is fairly uniform throughout the space between the poles, and (b) the field drops to zero outside this space. With these approximations you can use the diameter of the magnets as the quantity in the above expression.

Try the same experiment with two disk

magnets above and two below the loop. How does B change? Bend metal strips of different shapes so you can vary the distance between pole faces. How does this affect B?

An older unit of magnetic field intensity still often used is the *gauss*. To convert from one unit to the other, use the conversion factor, 1 newton /ampere-meter = 10 gauss.

Save your records from this activity so you can use the same magnets for measuring beta deflection in Unit 6.

MORE PERPETUAL MOTION MACHINES

The diagrams in Figs. 14-18 and 14-19 show two more of the perpetual motion machines discussed by R. Raymond Smedile in his book, *Perpetual Motion and Modern Research for Cheap Power*. (See also p. 206 of Unit 3 *Handbook*.) What is the weakness of the argument for each of them? (Also see "Perpetual Motion Machines," Stanley W. Angrist, *Scientific American*, January, 1968.)

In Fig. 14-18, *A* represents a stationary wheel around which is a larger, movable wheel, *E*. On stationary wheel *A* are placed three magnets marked *B* in the position shown in the drawing. On rotary wheel *E* are placed eight magnets marked *D*. They are attached to eight levers and are securely hinged to wheel
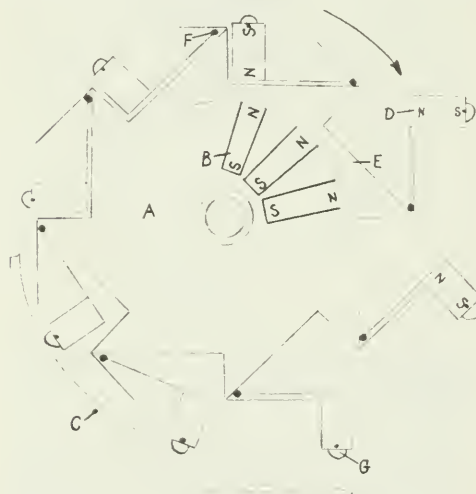
Fig. 14-18

E at the point marked *F*. Each magnet is also provided with a roller wheel, *G*, to prevent friction as it rolls on the guide marked *C*.

Guide *C* is supposed to push each magnet toward the hub of this mechanism as it is being carried upward on the left-hand side of the mechanism. As each magnet rolls over the top, the fixed magnets facing it cause the magnet on the wheel to fall over. This creates an overbalance of weight on the right of wheel *E* and thus perpetually rotates the wheel in a clockwise direction.

In Figure 14-19, *A* represents a wheel in which are placed eight hollow tubes marked *E*. In each of the tubes is inserted a magnet, *B*, so that it will slide back and forth. *D* represents a stationary rack in which are anchored five magnets as shown in the drawing. Each magnet is placed so that it will repel the magnets in wheel *A* as it rotates in a clockwise direction. Since the magnets in stationary rack *D* will repel those in rotary wheel *A*, this will cause a perpetual overbalance of magnet weight on the right side of wheel *A*.
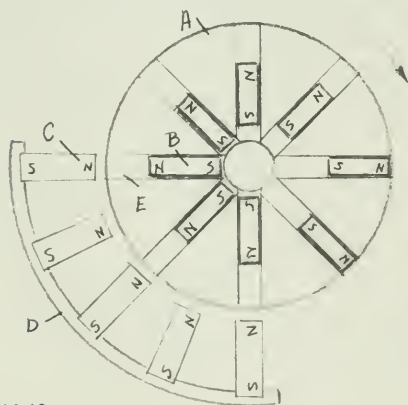
Fig. 14-19

ADDITIONAL ACTIVITIES USING THE ELECTRON BEAM TUBE

1. Focusing the Electron Beam

A current in a wire coiled around the electron tube will produce inside the coil a magnetic field parallel to the axis of the tube. (Ring-shaped magnets slipped over the tube will produce the same kind of field.) An electron moving directly along the axis will experience no force – its velocity is parallel to the magnetic field. But for an electron moving perpendicular to the axis, the field is perpendicular to its velocity – it will therefore experience a force ($F = qvB$) at right angles to both velocity and field. If the curved path of the electron remains in the uniform field, it will be a circle. The centripetal force $F = mv^2/R$ that keeps it in the circle is just the magnetic force qvB, so

$$qvB = \frac{mv^2}{R}$$

where R is the radius of the orbit. In this simple case, therefore,

$$R = \frac{mv}{qB}$$

Suppose the electron is moving down the tube only slightly off axis, in the presence of a field parallel to the axis (Fig. 14-20a). The electron's velocity can be thought of as made up of two components: an axial portion of v_a and a transverse portion (perpendicular to the axis) v_t (Fig. 14-20b). Consider these two com-

(a)   (b)   (c)   d

Fig. 14-20

ponents of the electron's velocity independently. You know that the axial component will be unaffected – the electron will continue to move down the tube with speed v_a (Fig. 14-20c). The transverse component, however, is perpendicular to the field, so the electron will also move in a circle (Fig. 14-20d). In this case,

$$R = \frac{mv_t}{qB}$$

The resultant motion—uniform speed down the axis plus circular motion perpendicular to the axis—is a helix, like the thread on a bolt (Fig. 14-20e).

In the absence of any field, electrons traveling off-axis would continue toward the edge of the tube. In the presence of an axial magnetic field, however, the electrons move down the tube in helixes—they have been focused into a beam. The radius of this beam depends on the field strength B and the transverse velocity v_t.

Wrap heavy-gauge copper wire, such as #18, around the electron beam tube (about two turns per centimeter) and connect the tube to a low-voltage (3-6 volts), high-current source to give a noticeable focusing effect. Observe the shape of the glow, using different coils and currents. (Alternatively, you can vary the number and spacing of ring magnets slipped over the tube to produce the axial field.)

2. Reflecting the Electron Beam

If the pole of a very strong magnet is brought near the tube (with great care being taken that it doesn't pull the iron mountings of the tube toward it), the beam glow will be seen to spiral more and more tightly as it enters stronger field regions. If the field lines diverge enough, the path of beam may start to spiral back. The reason for this is suggested in SG 14.32 in the *Text*.

This kind of reflection operates on particles in the radiation belt around the earth as the approach of the earth's magnetic poles. (See drawing at end of *Text* Chapter 14.) Such reflection is what makes it possible to hold tremendously energetic charged particles in magnetic "bottles." One kind of coil used to produce a "bottle" field appears in the Unit 5 *Text*.

3. Diode and Triode Characteristics

The construction and function of some electronic vacuum tubes is described in the next activity, "Inside a Radio Tube." In this section are suggestions for how you can explore some characteristics of such tubes with your electron beam tube materials.

These experiments are performed at ac-celerating voltages below those that cause ionization (a visible glow) in the electron beam tube.

(a) *Rectification*

Connect an ammeter between the can and high-voltage supply to show the direction of the current, and to show that there is a current only when the can is at a higher potential than the filament (Fig. 14.21).
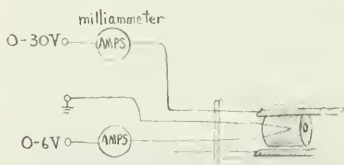
Fig. 14-21

Note that there is a measurable current at voltages far below those needed to give a visible glow in the tube. Then apply an alternating potential difference between the can and filament (for example, from a Variac). Use an oscilloscope to show that the can is alternately above and below filament potential. Then connect the oscilloscope across a resistor in the plate circuit to show that the current is only in one direction. (See Fig. 14-22.)
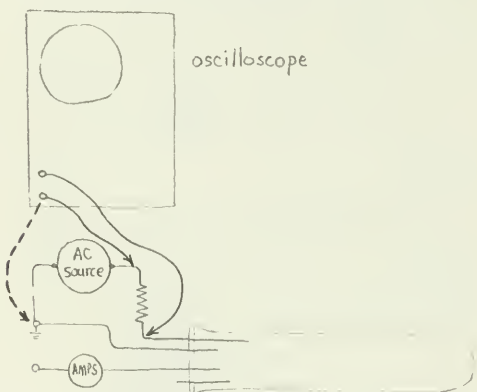
Fig. 14-22 The one-way-valve (rectification) action of a diode can be shown by substituting an AC voltage source for the DC accelerating voltage, and connecting a resistor (about 1000 ohms) in series with it. When an oscilloscope is connected as shown by the solid lines above, it will indicate the current in the can circuit. When the one wire is changed to the connection shown by the dashed arrow, the oscilloscope will indicate the voltage on the can.

(b) *Triode*

The "triode" in the photograph below was made with a thin aluminum sheet for the plate and nichrome wire for the grid. The filament is the original one from the electron beam tube kit, and thin aluminum tubing from a hobby shop was used for the connections to plate and grid. (For reasons lost in the history of vacuum tubes, the can is usually called the "plate." It is interesting to plot graphs of plate current versus filament heating current, and plate current versus voltage. Note that these characteristic curves apply only to voltages too low to produce ionization.) With such a triode,

Fig. 14-23

you can plot curves showing triode characteristics: plate current against grid voltage, plate current against plate voltage.
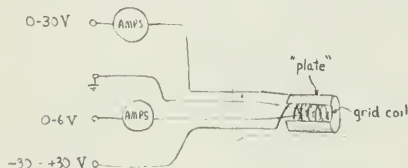
Fig. 14-24

You can also measure the voltage amplification factor, which describes how large a change in plate voltage is produced by a change in grid voltage. More precisely, the amplification factor,

$$\mu = \frac{-\Delta V_{\text{plate}}}{\Delta V_{\text{grid}}}$$

when the plate current is kept constant.

Change the grid voltage by a small amount, then adjust the plate voltage until you have regained the original plate current. The magnitude of the ratio of these two voltage changes is the amplification factor. (Commercial vacuum tubes commonly have amplification factors as high as 500.) The tube gave
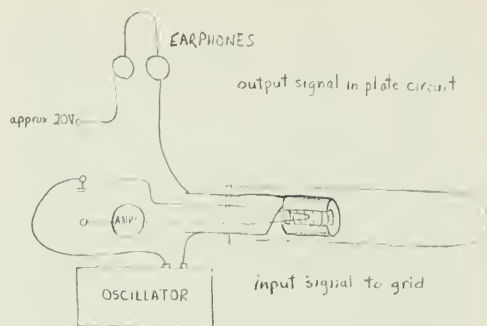
Fig. 14-25 An amplifying circuit

noticeable amplification in the circuit shown in Fig. 14-25 and Fig. 14-26.
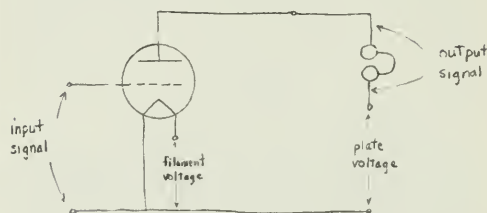
Fig. 14-26 Schematic diagram of amplifying circuit

TRANSISTOR AMPLIFIER

The function of a PNP or NPN transistor is very similar to that of a triode vacuum tube (although its operation is not so easily described). Fig. 14-27 shows a schematic transistor circuit that is analogous to the vacuum tube circuit shown in Fig. 14-26. In both cases, a small input signal controls a large output current.
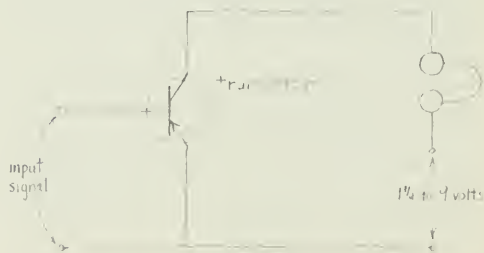
Fig. 14-27

Some inexpensive transistors can be bought at almost any radio supply store, and almost any PNP or NPN will do. Such stores also usually carry a variety of paper-back books that give simplified explanations of how transistors work and how you can use cheap components to build some simple electronic equipment.

INSIDE A RADIO TUBE

Receiving tubes, such as those found in radio and TV sets, contain many interesting parts that illustrates important physical and chemical principles.

Choose some discarded glass tubes at least two inches high. Your radio-TV serviceman will probably have some he can give you. Look up the tube numbers in a receiving tube manual and, if possible, find a triode. (The *RCA Vacuum Tube Manual* is available at most radio-TV supply stores for a couple of dollars.) WARNING: Do *not* attempt to open a TV picture tube!!! Even small TV picture tubes are very dangerous if they burst.

Examine the tube and notice how the internal parts are connected to the pins by wires located in the bottom of the tube. The glass-to-metal seal around the pins must maintain the high vacuum inside the tube. As the tube heats and cools, the pins and glass must expand together. The pins are made of an iron-nickel alloy whose coefficient of expansion is close to that of the glass. The pins are coated with red copper oxide to bond the metal to the glass.

The glass envelope was sealed to the glass base after the interior parts were assembled. Look at the base of the envelope and you can see where this seal was made. After assembly, air was drawn from the tube by a vacuum pump, and the tube was sealed. The sealing nib is at the top of miniature tubes and very old tubes, and is covered by the aligning pin at the bottom of octal-base tubes.

The silvery material spread over part of the inside of the tube is called the *getter*. This coating (usually barium or aluminum) was vaporized inside the tube after sealing to absorb some more of the gas remaining in the envelope after it was pumped out.

To open the tube, spread several layers of newspaper on a flat surface. Use goggles and gloves to prevent injury. With a triangular file, make a small scratch near the bottom. Wrap the tube with an old cloth, hold the tube with the scratch up on the table, and tap the tube with pliers or the file until it breaks. Unwrap the broken tube carefully, and examine the pieces. The getter film will begin to change as soon as it is exposed to air. In a few minutes it will be a white, powdery coating of barium or aluminum oxide.

Protruding from the bottom of the cage assembly are the wires to the pins. Identify the filament leads (there are 2 or 3) — very fine wires with a white ceramic coating. Cut the other wires with diagonal cutters, but leave the filament leads intact. Separate the cage from the base, and slide out the filament.

The tube components in the cage are held in alignment with each other by the mica washers at the top and bottom of the cage. The mica also holds the cage in place inside the envelope.
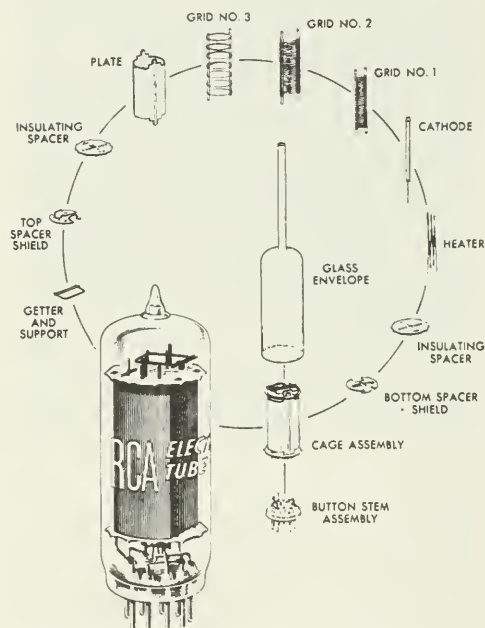
"Exploded" diagram of a 3-grid ("pentode") vacuum tube.

To separate the components. examine the ends that protrude through the mica washer, and decide what to do before the mica can be pulled off the ends. It may be necessary to twist, cut, or bend these parts in order to dis-assemble the cage. When you have completed this operation, place the components on a clean piece of paper. and examine them one at a time.

Mica was chosen as spacer material for its high strength. high electrical resistance, and the fact that it can withstand high tem-peratures. White mica consists of a complex compound of potassium. aluminum. silicon and oxygen in crystal form. Mica crystals have very weak bonds between the planes and so they can be split into thin sheets. Try it!

The small metal cylinder with a white coating is the *cathode*. It is heated from inside by the filament. At operating temperature, electrons are "boiled off."

The coating greatly increases the number of electrons emitted from the surface. When you wait for your radio or TV to warm up, you are waiting for the tube cathodes to warm up to an efficient emitting temperature.

The ladder-like arrangement of very fine wire is called the *grid*. The electrons that were boiled off the cathode must pass through this grid. Therefore the current in the tube is very sensitive to the electric field around the grid.

Small changes in the voltage of the grid can have a large effect on the flow of electrons through the tube. This controlling action is the basis for amplification and many other tube operations.

The dark cylinder that formed the outside

of the cage is the *plate*. In an actual circuit, the plate is given a positive voltage relative to the cathode in order to attract the electrons emitted by the cathode. The electrons strike the plate and most give up their kinetic energy to the plate, which gets very hot. The plate is a dark color in order to help dissipate this heat energy. Often. the coating is a layer of carbon, which can be rubbed off with your finger.

It is interesting to open different kinds of tubes and see how they differ. Some have more than one cage in the envelope, multiple grids, or beam-confining plates. The *RCA Tube Manual* is a good source for explanations of different tube types and their operation.

AN ISOLATED NORTH MAGNETIC POLE?

Magnets made of a rather soft rubber-like substance are available in some hardware stores. Typical magnets are flat pieces 20 mm × 25 mm and about 5 mm thick, with a mag-netic north pole on one 20 × 25 mm surface and south pole on the other. They may be cut with a sharp knife.

Suppose you cut six of these so that you have six square pieces 20 mm on the edge. Then level the edges on the S side of each piece so that the pieces can be fitted together to form a hollow cube with all the N sides facing outward. The pieces repel each other strongly and may be either glued (with rubber cement) or tied together with thread.

Do you now have an isolated north pole — that is, a north pole all over the outside (and south pole on the inside)?

Is there a magnetic field directed outward from all surfaces of the cube?

(Adapted from "Looking Inside a Vacuum Tube." *Chem-istry*. Sept. 1964.)

(Adapted from *The Physics Teacher*. March 1966.)

Chapter 15 Faraday and the Electrical Age

ACTIVITIES

FARADAY DISK DYNAMO

You can easily build a disk dynamo similar to the one shown at the bottom of page 80 in Unit 4 *Text*. Cut an 8-inch-diameter disk of sheet copper. Drill a hole in the center of the disk, and put a bolt through the hole. Run a nut up tight against the disk so the disk will not slip on the bolt. Insert the bolt in a hand drill and clamp the drill in a ringstand so the disk passes through the region between the poles of a large magnet. Connect one wire of a 100-microamp dc meter to the metal part of the drill that doesn't turn. Tape the other wire to the magnet so it brushes lightly against the copper disk as the disk is spun between the magnet poles.

Frantic cranking can create a 10-micro-amp current with the magnetron magnet shown above. If you use one of the metal yokes from the current balance, with three ceramic magnets on each side of the yoke, you may be able to get the needle to move from the zero position just noticeably.

The braking effect of currents induced in the disk can also be noticed. Remove the meter, wires, and magnet. Have one person crank while another brings the magnet up to a position such that the disk is spinning between the magnet poles. Compare the effort needed to turn the disk with and without the magnet over the disk.

If the disk will coast, compare the coasting times with and without the magnet in place. (If there is too much friction in the hand drill for the disk to coast, loosen the nut and spin the disk by hand on the bolt.)

GENERATOR JUMP ROPE

With a piece of wire about twice the length of a room, and a sensitive galvanometer, you can generate an electric current using only the earth's magnetic field. Connect the ends of the wire to the meter. Pull the wire out into a long loop and twirl half the loop like a jump rope. As the wire cuts across the earth's magnetic field, a voltage is generated. If you do not have a sensitive meter on hand, connect the input of one of the amplifiers, and connect the amplifier to a less sensitive meter.

How does the current generated when the axis of rotation is along a north-south line compare with that current generated with the same motion along an east-west line? What does this tell you about the earth's magnetic field? Is there any effect if the people stand on two landings and hang the wire (while swinging it) down a stairwell?

SIMPLE METERS AND MOTORS

You can make workable current meters and motors from very simple parts:

2 ceramic magnets ⎫
1 steel yoke   ⎬ (from current
1 no. 7 cork   ⎭   balance kit)

1 metal rod, about 2 mm in
  diameter and 12 cm long
  (a piece of bicycle spoke,
  coat hanger wire, or a
  large finishing nail
  will do)
1 block of wood, about 10 cm × 5 cm × 1 cm
About 3 yards of insulated no. 30 copper mag-
  net wire
2 thumb tacks
2 safety pins
2 carpet tacks or small nails ⎫
1 white card 4″ × 5″   ⎬ (for meter only)
Stiff black paper, for pointer ⎭
Electrical insulating tape (for
  motor only)

Meter

To build a meter, follow the steps below pay-
ing close attention to the diagrams. Push the
rod through the cork. Make the rotating coil
or *armature* by winding about 20 turns of
wire around the cork, keeping the turns par-
allel to the rod. Leave about a foot of wire at
both ends (Fig. 15-1).

Use nails or carpet tacks to fix two safety
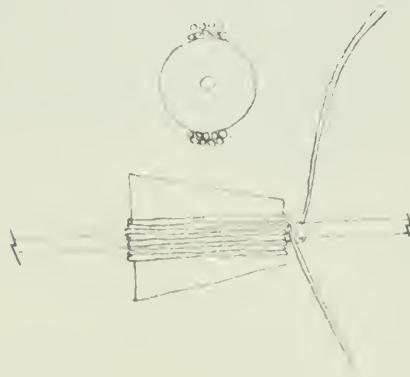
Fig. 15-2

pins firmly to the ends of the wooden-base
block (Fig. 15-2).

Make a pointer out of the black paper, and
push it onto the metal rod. Pin a piece of white
card to one end of the base. Suspend the arma-
ture between the two safety pins from the free
ends of wire into two loose coils, and attach
them to the base with thumb tacks. Put the
two ceramic magnets on the yoke (unlike poles
facing), and place the yoke around the arma-
ture (Fig. 15-3). Clean the insulation off the
ends of the leads, and you are ready to connect
your meter to a low-voltage dc source.

Calibrate a scale in volts on the white card
using a variety of known voltages from dry
cells or from a low-voltage power supply, and
your meter is complete. Minimize the parallax
problem by having your pointer as close to
the scale as possible.
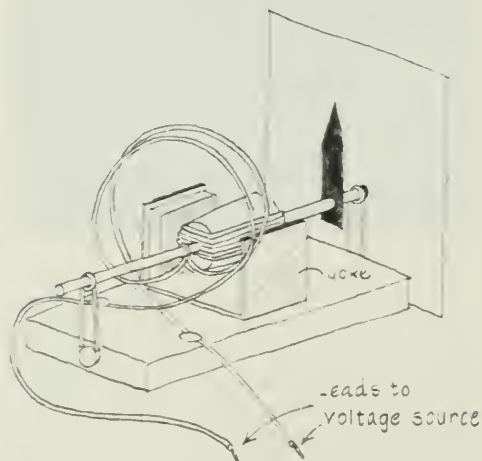
Fig. 15-1

Fig. 15-3

Motor

To make a motor, wind an armature as you did for the meter. Leave about 6 cm of wire at each end, from which you carefully scrape the insulation. Bend each into a loop and then twist into a tight pigtail. Tape the two pigtails along opposite sides of the metal rod (Fig. 15-4).
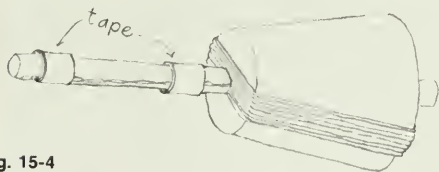
Fig. 15-4

Fix the two safety pins to the base as for the meter, and mount the coil between the safety pins.

The leads into the motor are made from two pieces of wire attached to the baseboard with thumb tacks at points X (Fig. 15-5).

Place the magnet yoke around the coil. The coil should spin freely (Fig. 15-6).

Connect a 1.5-volt battery to the leads. Start the motor by spinning it with your finger. If it does not start, check the contacts between leads and the contact wires on the rod. You may not have removed all the enamel from the wires. Try pressing lightly at points A (Fig. 15-5) to improve the contact. Also check to see that the two contacts touch the armature wires at the same time.

SIMPLE MOTOR-GENERATOR DEMONSTRATION

With two fairly strong U-magnets and two coils, which you wind yourself, you can prepare a simple demonstration showing the principles of a motor and generator. Wind two flat coils of magnet wire 100 turns each. The cardboard tube from a roll of paper towels makes a good form. Leave about $\frac{1}{2}$ meter of wire free at each end of the coil. Tape the coil so it doesn't unwind when you remove it from the cardboard tube.

No Contact

Contact   Contact

A   A
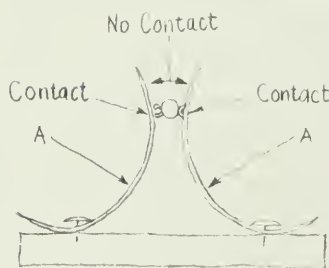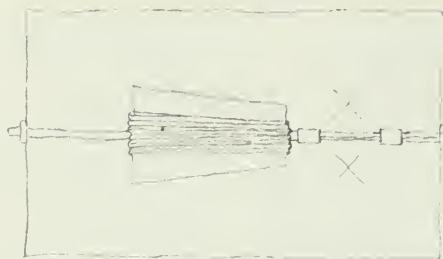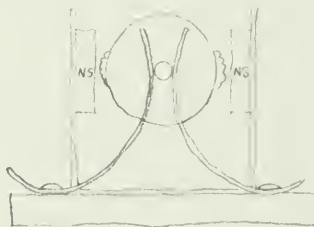
Fig. 15-5

Fig. 15-6

Hang the coils from two supports as shown below so the coils pass over the poles of two U-magnets set on the table about one meter apart. Connect the coils together. Pull one coil to one side and release it. What happens to the other coil? Why? Does the same thing happen if the coils are not connected to each other? What if the magnets are reversed?

Connectors

C
H
A
P
T
E
R
15

Try various other changes. such as turning one of the magnets over while both coils are swinging. or starting with both coils at rest and then sliding one of the magnets back and forth.
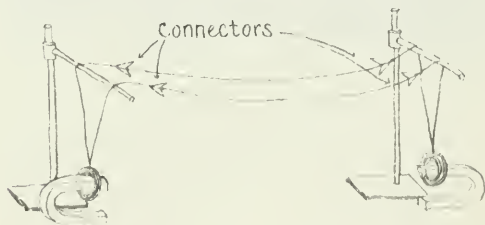
If you have a sensitive galvanometer, it is interesting to connect it between the two coils.

PHYSICS COLLAGE

Many of the words used in physics class enjoy wide usage in everyday language. Cut "physics words" out of magazines. newspapers. etc., and make your own collage. You may wish to take on a more challenging art problem by trying to give a visual representation of a physical concept, such as speed. light. or waves. The *Reader 1* article. "Representation of Movement." may give you some ideas.

BICYCLE GENERATOR

The generator on a bicycle operates on the same basic principle as that described in the *Text*. but with a different. and extremely simple. design. Take apart such a generator and see if you can explain how it works. Note: You may not be able to reassemble it.

LAPIS POLARIS, MAGNES

The etching (right) shows a philosopher in his study surrounded by the scientific equipment of his time. In the left foreground in a basin of water, a natural magnet or lodestone floating on a stick of wood orients itself north and south. Traders from the great Mediterranean port of Amalfi probably introduced the floating compass. having learned of it from Arab mariners. An Amalfi historian. Flavius Blondus. writing about 1450 A.D.. indicates the uncertain origin of the compass, but later historians in repeating this early reference warped it and gave credit for the discovery of the compass to Flavius.

Can you identify the various devices lying around the study? When do you think the etching was made? (If you have some background in art. you might consider whether your estimate on the basis of scientific clues is consistent with the style of the etching.)

LAPIS POLARIS, MAGNES.
Lapis reclusit iste Flauio abditum   Poli suum hunc amorem, at ipse nauitæ.
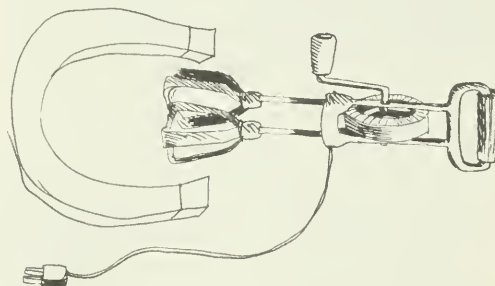
EXPERIMENT 39
WAVES AND COMMUNICATION

Having studied many kinds and characteristics of waves in Units 3 and 4 of the *Text*, you are now in a position to see how they are used in communications. Here are some suggestions for investigations with equipment that you have probably already seen demonstrated. The following notes assume that you understand how to use the equipment. If you do not, then do not go on until you consult your teacher for instructions. Although different groups of students may use different equipment, all the investigations are related to the same phenomena—how we can communicate with waves.

A. Turntable Oscillators

Turn on the oscillator with the pen attached to it. (See p. 310.) Turn on the chart recorder, but do not turn on the oscillator on which the recorder is mounted. The pen will trace out a sine curve as it goes back and forth over the moving paper. When you have recorded a few inches, turn off the oscillator and bring the pen to rest in the middle of the paper. Now turn on the second oscillator at the same rate that the first one was going. The pen will trace out a similar sine curve as the moving paper goes back and forth under it. The wavelengths of the two curves are probably very nearly, but not exactly, equal.

Q1   What do you predict will happen if you turn on *both* oscillators? Try it. Look carefully at the pattern that is traced out with both oscillators on and compare it to the curves

previously drawn by the two oscillators running alone.

Change the wavelength of one of the components slightly by putting weights on one of the platforms to slow it down a bit. Then make more traces from other pairs of sine curves. Each trace should consist, as in Fig. 16-1, of three parts: the sine curve from one oscillator; the sine curve from the other oscillator; and the composite curve from both oscillators.

Q2   According to a mathematical analysis of the addition of sine waves, the wavelength of the envelope (λ_e in Fig. 16-1) will *increase* as the wavelengths of the two components (λ_1, λ_2) become more nearly equal. Do your results confirm this?

Q3   If the two wavelengths λ_1 and λ_2 were exactly equal, what pattern would you get when both turntables were turned on; that is, when the two sine curves were superposed? What else would the pattern depend on, as well as λ_1 and λ_2?

As the difference between λ_1 and λ_2 gets smaller, λ_e gets bigger. You can thus detect a very small difference in the two wavelengths by examining the resultant wave for changes in amplitude that take place over a relatively long distance. This method, called the method of beats, provides a sensitive way of comparing two oscillators, and of adjusting one until it has the same frequency as the other.

This method of beats is also used for tuning musical instruments. If you play the same note on two instruments that are not quite in tune, you can hear the beats. And the more nearly in tune the two are, the lower
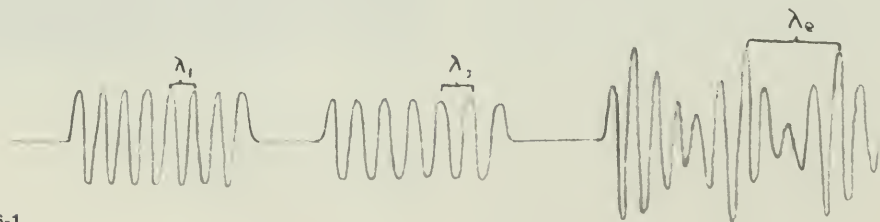
Fig. 16-1

the frequency of the beats. You might like to try this with two guitars or other musical instruments (or two strings on the same instrument).

In radio communication, a signal can be transmitted by using it to modulate a "carrier" wave of much higher frequency. (See part *E* for further explanation of modulation.) A snapshot of the modulated wave looks similar to the beats you have been producing, but it results from one wave being used to control the amplitude of the other, not from simply adding the waves together.

B. Resonant Circuits

You have probably seen a demonstration of how a signal can be transmitted from one tuned circuit to another. (If you have not seen the demonstration, you should set it up for yourself using the apparatus shown in Fig. 16.2.)
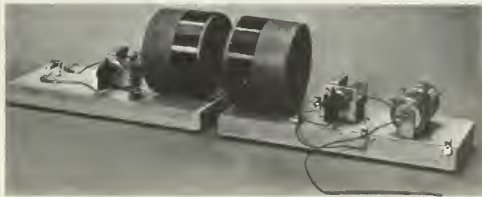
Fig. 16-2 Two resonant circuit units. Each includes a wire coil and a variable capacitor. The unit on the right has an electric cell and ratchet to produce pulses of oscillation in its circuit.

This setup is represented by the schematic drawing in Fig. 16-3.
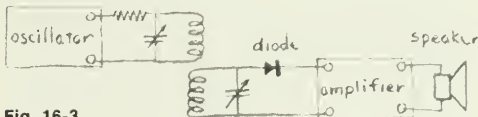
Fig. 16-3

The two coils have to be quite close to each other for the receiver circuit to pick up the signal from the transmitter.

Investigate the effect of changing the position of one of the coils. Try turning one of them around, moving it farther away, etc.

Q4 What happens when you put a sheet of metal, plastic, wood, cardboard, wet paper, or glass between the two coils?

Q5 Why does an automobile always have an outside antenna, but a home radio does not?

Q6 Why is it impossible to communicate with a submerged submarine by radio?

You have probably learned that to transmit a signal from one circuit to another the two circuits must be tuned to the same frequency. To investigate the range of frequencies obtainable with your resonant circuit, connect an antenna (length of wire) to the resonant receiving circuit, in order to increase its sensitivity, and replace the speaker by an oscilloscope (Fig. 16-4). Set the oscilloscope to "Internal Sync" and the sweep rate to about 100 kilocycles/sec.
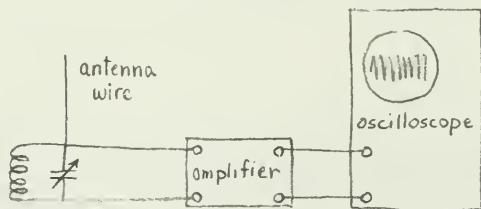
Fig. 16-4

Q7 Change the setting of the variable capacitor ( ) and see how the trace on the oscilloscope changes. Which setting of the capacitor gives the highest frequency? which setting the lowest? By how much can you change the frequency by adjusting the capacitor setting?

When you tune a radio you are usually, in the same way, changing the setting of a variable capacitor to tune the circuit to a different frequency.

The coil also plays a part in determining the resonant frequency of the circuit. If the coil has a different number of turns, a different setting of the capacitor would be needed to get the same frequency.

C. Elementary Properties of Microwaves

With a microwave generator, you can investigate some of the characteristics of short waves in the radio part of the electromagnetic spectrum. In Experiment 30, "Introduction to Waves" and Experiment 31, "Sound," you explored the behavior of several different kinds of waves. These earlier experiments

contain a number of ideas that will help you show that the energy emitted by your microwave generator is in the form of waves.

Refer to your notes on these experiments. Then, using the arrangements suggested there or ideas of your own, explore the transmission of microwaves through various materials as well as microwave reflection and refraction. Try to detect their diffraction around obstacles and through narrow openings in some material that is opaque to them. Finally, if you have two transmitters available or a metal horn attachment with two openings, see if you can measure the wavelength using the interference method of Experiment 31. Compare your results with students doing the following experiment (D) on the interference of reflected microwaves.

D. Interference of Reflected Microwaves

With microwaves it is easy to demonstrate interference between direct radiation from a source and radiation reflected from a flat surface, such as a metal sheet. At points where the direct and reflected waves arrive in phase, there will be maxima and at points where they arrive $\frac{1}{2}$-cycle out of phase, there will be minima. The maxima and minima are readily found by moving the detector along a line perpendicular to the reflector. (Fig. 16-5.) Q8 Can you state a rule with which you could predict the positions of maxima and minima?

By moving the detector back a ways and scanning again, etc., you can sketch out lines of maxima and minima.

Q9 How is the interference pattern similar to what you have observed for two-source radiation?
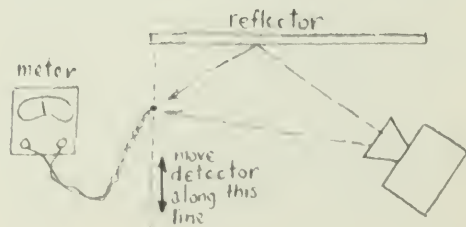
Fig. 16-5

Standing microwaves will be set up if the reflector is placed exactly perpendicular to the source. (As with other standing waves, the nodes are $\frac{1}{2}$ wavelength apart.) Locate several nodes by moving the detector along a line between the source and reflector, and from the node separation calculate the wavelength of the microwaves.

Q10 What is the wavelength of your microwaves?

Q11 Microwaves, like light, propagate at 3×10 m/sec. What is the frequency of your microwaves? Check your answer against the chart of the electromagnetic spectrum given on page 113 of *Text* Chapter 16.

The interference between direct and reflected radio waves has important practical consequences. There are layers of partly ionized (and therefore electrically conducting) air, collectively called the ionosphere, that surrounds the earth roughly 30 to 300 kilometers above its surface. One of the layers at about 300 km is a good reflector for radio waves, so it is used to bounce radio messages to points that, because of the curvature of the earth, are too far away to be reached in a straight line.

If the transmitting tower is 100 meters high, then, as shown roughly in Fig. 16-6, point A – the farthest point that the signal can reach directly in flat country – is 35 kilometers (about 20 miles) away. But by reflection from the ionosphere, a signal can reach around the corner to B and beyond.

Fig. 16-6

Sometimes both a direct and a reflected signal will arrive at the same place and interference occurs; if the two are out of phase and have identical amplitudes, the receiver will pick up nothing. Such destructive interference is responsible for radio fading. It is complicated by the fact that the height of the ionosphere and the intensity of reflection from it vary during the day with the amount of sunlight.

The setup in Fig. 16-7 is a model of this situation. Move the reflector (the "ionosphere") back and forth. What happens to the signal strength?
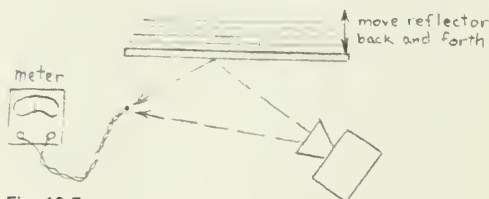
Fig. 16-7

There can also be multiple reflections – the radiation can bounce back and forth be-

tween earth and ionosphere several times on its way from, say, New York to Calcutta, India. Perhaps you can simulate this situation too with your microwave equipment.

E.   Signals and Microwaves

Thus far you have been learning about the behavior of microwaves of a single frequency and constant amplitude. A *signal* can be added to these waves by changing their amplitude at the transmitter. The most obvious way would be just to turn them on and off as represented in Fig. 16-8. Code messages can be transmitted in this primitive fashion. But

Fig. 16-8

the wave amplitude can be varied in a more elaborate way to carry music or voice signals. For example, a 1000 cycle/sec sine wave fed into part of the microwave transmitter will cause the amplitude of the microwave to vary smoothly at 1000 cyc/sec.

Controlling the amplitude of the transmitted wave like this is called *amplitude modulation*; Fig. 16-9A represents the unmodulated microwave, Fig. 16-9B represents a modulating signal, and Fig. 16-9C the modulated microwave. The Damon microwave oscillator has an input for a modulating signal. You can modulate the microwave output with a variety of signals, for example, with an audio-frequency oscillator or with a microphone and amplifier.

The microwave detector probe is a one-way device – it passes current in only one direction. If the microwave reaching the probe is represented in C, then the electric signal from the probe will be like in D.

You can see this on the oscilloscope by connecting it to the microwave probe (through an amplifier if necessary).

The detected modulated signal from the probe can be turned into sound by connecting an amplifier and loudspeaker to the probe. The
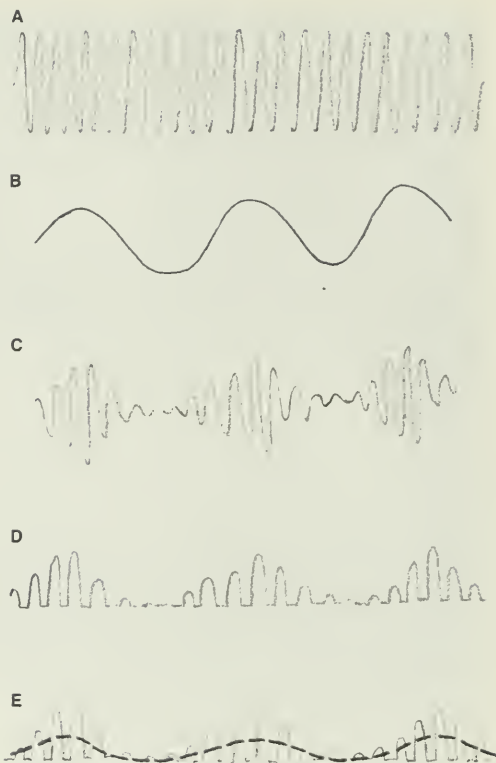
Fig. 16-9

speaker will not be able to respond to the 10^9 individual pulses per second of the "carrier" wave, but only to their averaged effect, represented by the dotted line in E. Consequently, the sound output of the speaker will correspond very nearly to the modulating signal.

Q12 Why must the carrier frequency be much greater than the signal frequency?

Q13 Why is a higher frequency needed to transmit television signals than radio signals? (The highest frequency necessary to convey radio sound information is about 12,000 cycles per second. The electron beam in a television tube completes one picture of 525 lines in 1/30 of a second, and the intensity of the beam should be able to vary several hundred times during a single line scan.)

ACTIVITIES

MICROWAVE TRANSMISSION SYSTEMS

Microwaves of about 6-cm wavelength are used to transmit telephone conversations over long distances. Because microwave radiation has a limited range (they are not reflected well by the ionosphere), a series of relay stations have been erected about 30 miles apart across the country. At each station the signal is detected and amplified before being retransmitted to the next one. If you have several microwave generators that can be amplitude modulated, see if you can put together a demonstration of how this system works. You will need an audio-frequency oscillator (or microphone), amplifier, microwave generator and power supply, detector, another amplifier, and a loudspeaker, another microwave generator, another detector, a third amplifier, and a loudspeaker.

SCIENCE AND THE ARTIST—THE STORY BEHIND A NEW SCIENCE STAMP

The sciences and the arts are sometimes thought of as two distinct cultures with a yawning gulf between them. Perhaps to help bridge that gulf, the Post Office Department held an unprecedented competition among five artists for the design of a postage stamp honoring the sciences.

U. S. POSTAGE　　　THE SCIENCES

5¢
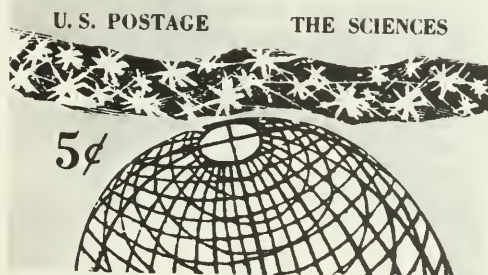
The winning design by Antonio Frasconi. The stamp was printed in light blue and black.

The winning stamp, issued on October 14, 1963, commemorates the 100th anniversary of the National Academy of Sciences (NAS). This agency was established during the Civil War with the objective that it "shall, whenever called upon by any department of government, investigate, experiment, and report upon any subject of science or of art."

To celebrate the NAS anniversary, the late President John F. Kennedy addressed the members of the academy and their distinguished guests from foreign scientific societies. After emphasizing present public recognition of the importance of pure science, the President pointed out how the discoveries of science are forcing the nations to cooperate:

"Every time you scientists make a major invention, we politicians have to invent a new institution to cope with it—and almost invariably these days it must be an international institution."

As examples of these international institutions, he cited the International Atomic Energy Agency, the treaty opening Antarctica to world scientific research, and the Intergovernmental Oceanographic Commission.

In the scientific sessions marking the NAS anniversary, the latest views of man and matter and their evolution were discussed, as well as the problem of financing future researches—the proper allocation of limited funds to space research and medicine, the biological and the physical sciences.

The stamp competition was initiated by the National Gallery of Art, Washington, D.C. A jury of three distinguished art specialists invited five American artists to submit designs. The artists were chosen for their "demonstrated appropriateness to work on the theme of science." They were Josef Albers, Herbert Bayer, Antonio Frasconi, Buckminster Fuller, and Bradbury Thompson.

Albers and Bayer both taught at the Bauhaus (Germany), a pioneering design center that welded modern industrial know-how to the insights of modern art. (The Bauhaus is probably best known for its development of tubular steel furniture.) Albers has recently published what promises to be the definitive work on color—*Interaction of Color* (Yale University Press). Bayer is an architect as well as an artist; he has designed several of the buildings for the Institute of Humanistic Studies in Aspen, Colorado. Buckminster Fuller, engineer, designer, writer, and in-

THE SCIENCES
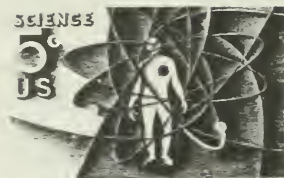
Albers

Bayer

Fuller
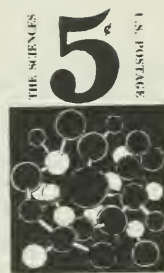
Frasconi

Thompson

ventor, is the creator of the geodesic dome, the Dymaxion three-wheeled car, and Dymaxion map projection. Frasconi, born in Uruguay, is particularly known for his woodcuts; he won the 1960 Grand Prix Award at the Venice Film Festival for his film, *The Neighboring Shore*. Bradbury Thompson is the designer for a number of publications including *Art News*.

Ten of the designs submitted by the artists are shown on the opposite page. The Citizen's Stamp Advisory Committee chose four of the designs from which former Postmaster General J. Edward Day chose the winner. The winning design by Frasconi, depicts a stylized representation of the world, above which is spread the sky luminescent with stars.

Which design do you feel most effectively represents the spirit and character of science, and why? If you are not enthusiastic about any of the stamps, design your own.

BELL TELEPHONE SCIENCE KITS

Bell Telephone Laboratories have produced several kits related to topics in Unit 4. Your local Bell Telephone office may be able to provide a limited number of them for you free. A brief description follows.

"Crystals and Light" includes materials to assemble a simple microscope, polarizing filters, sample crystals, a book of experiments, and a more comprehensive book about crystals.

"Energy from the Sun" contains raw materials and instructions for making your own solar cell, experiments for determining solar-cell characteristics, and details for building a light-powered pendulum, a light-commutated motor, and a radio receiver.

"Speech Synthesis" enables you to assemble a simple battery-powered circuit to artificially produce the vowel sounds. A booklet describes similarities between the circuit and human voice production, and discusses early attempts to create artificial voice machines.

"From Sun to Sound" contains a ready-made solar cell, a booklet, and materials for building a solar-powered radio.

Good Reading

Several good paperbacks in the science Study Series (Anchor Books, Doubleday and Co.) are appropriate for Unit 4, including *The Physics of Television*, by Donald G. Fink and David M. Lutyens; *Waves and Messages* by John R. Pierce; *Quantum Electronics* by John R. Pierce; *Electrons and Waves* by John R. Pierce; *Computers and the Human Mind*, by Donald G. Fink. See also "Telephone Switching," *Scientific American*, July, 1962, and the Project Physics *Reader 4*.
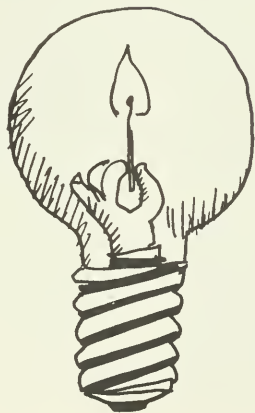
FILM LOOP

Standing waves are not confined to mechanical waves in strings or in gas. It is only necessary to reflect the wave at the proper distance from a source so that two oppositely moving waves superpose in just the right way. In this film, standing electromagnetic waves are generated by a radio transmitter.

The transmitter produces electromagnetic radiation at a frequency of 435×10^6 cycles/sec. Since all electromagnetic waves travel at the speed of light, the wavelength is $\lambda = c/f = 0.69$ m. The output of the transmitter oscillator (Fig. 16-10) passes through a power-indicating meter, then to an antenna of two rods each $\frac{1}{4} \lambda$ long.

Fig. 16-11

oscillator 435×10^6 cycles/sec Power Meter Transmitting Dipole Antenna Receiving Dipole Antenna
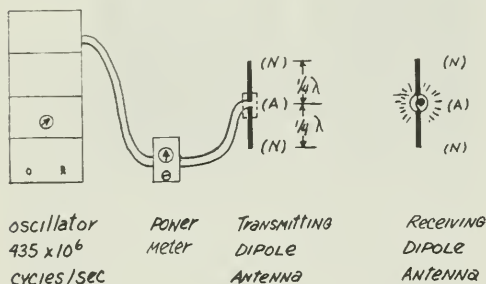
Fig. 16-10

The receiving antenna (Fig. 16-11) is also $\frac{1}{2} \lambda$ long. The receiver is a flashlight bulb connected between two stiff wires each $\frac{1}{4} \lambda$ long. If the electric field of the incoming wave is parallel to the receiving antenna, the force on the electrons in the wire drives them back and forth through the bulb. The brightness of the bulb indicates the intensity of the electromagnetic radiation at the antenna. A rectangular aluminum cavity, open toward the camera, confines the waves to provide sufficient intensity.

Initial scenes show how the intensity depends on the distance of the receiving antenna from the transmitting antenna. The radiated power is about 20 watts. Does the received intensity decrease as the distance increases? The radiation has vertical polarization, so the response falls to zero when the receiving antenna is rotated to the horizontal position.

Standing waves are set up when a metal reflector is placed at the right end of the cavity. The reflector can't be placed just anywhere; it must be at a node. The distance from source to reflector must be an integral number of half-wavelengths plus $\frac{1}{4}$ of a wavelength. The cavity length must be "tuned" to the wavelength. Nodes and antinodes are identified by moving a receiving antenna back and forth. Then a row of vertical receiving antennas is placed in the cavity, and the nodes and antinodes are shown by the pattern of brilliance of the lamp bulbs. How many nodes and antinodes can be seen in each trial?

Standing waves of different types can all have the same wavelength. In each case a source is required (tuning fork, loudspeaker, or dipole antenna). A reflector is also necessary (support for string, wooden piston, or sheet aluminum mirror). If the frequencies are 72 vib/sec for the string, 505 vib/sec for the gas, and 435×10^6 vib/sec for the electromagnetic waves and all have the same wavelength, what can you conclude about the speeds of these three kinds of waves? Discuss the similarities and differences between the three cases. What can you say about the "medium" in which the electromagnetic waves travel?

Sidney Rosen, University of Illinois, Urbana

John J. Rosenbaum, Livermore High School, Calif.

William Rosenfeld, Smith College, Northampton, Mass.

Arthur Rothman, State University of New York, Buffalo

Daniel Rufolo, Clairemont High School, San Diego, Calif.

Bernhard A. Sachs, Brooklyn Technical High School, N.Y.

Morton L. Schagrin, Denison University, Granville, Ohio

Rudolph Schiller, Valley High School, Las Vegas, Nev.

Myron O. Schneiderwent, Interlochen Arts Academy, Mich.

Guenter Schwarz, Florida State University, Tallahassee

Sherman D. Sheppard, Oak Ridge High School, Tenn.

William E. Shortall, Lansdowne High School, Baltimore, Md.

Devon Showley, Cypress Junior College, Calif.

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Sister M. Helen St. Paul, O.S.F., The Catholic High School of Baltimore, Md.

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Haven Whiteside, University of Maryland, College Park

R. Brady Williamson, Massachusetts Institute of Technology, Cambridge

Stephen S. Winter, State University of New York, Buffalo

INDEX/HANDBOOK SECTION

Answers to End-of-Section Questions

Chapter 13

Q1 No. Eventually diffraction begins to widen the beam.

Q2 Römer based his prediction on the extra time he had calculated it would require light to cross the orbit of the earth.

Q3 Römer showed that light does have a finite speed.

Q4 Experiments carried out by Foucault and Fizeau showed that light has a *lower* speed in water than in air, whereas the particle model required that light have a *higher* speed in water.

Q5 When light enters a more dense medium, its wavelength and speed decrease, but its frequency remains unchanged.

Q6 Young's experiments showed that light could be made to form an interference pattern, and such a pattern could be explained only by assuming a wave model for light.

Q7 It was diffraction that spread out the light beyond the two pinholes so that overlapping occurred and intereference took place between the two beams.

Q8 Poisson applied Fresnel's wave equations to the shadow of a circular obstacle and found that there should be a bright spot in the center of the shadow.

Q9 Newton passed a beam of white light through a prism and found that the white light was somehow replaced by a diverging beam of colored light. Further experiments proved that the colors could be recombined to form white light.

Q10 Newton cut a hole in the screen on which the spectrum was projected and allowed a single color to pass through the hole and through a second prism; he found that the light was again refracted but no further separation took place.

Q11 A shirt appears blue if it reflects mainly blue light and absorbs most of the other colors which make up white light.

Q12 The "nature philosophers" were apt to postulate unifying principles regardless of experimental evidence to the contrary, and were very unhappy with the idea that something they had regarded as unquestionably pure had many components.

Q13 The amount of scattering of light by tiny obstacles is greater for shorter wavelengths than for longer wavelengths.

Q14 The "sky" is sunlight scattered by the atmosphere. Light of short wavelength, the blue end of the spectrum, is scattered most. On the moon the sky looks dark because there is no atmosphere to scatter the light to the observer.

Q15 Hooke and Huygens had proposed that light waves are similar to sound waves: Newton objected to this view because the familiar straight-line propagation of light was so different from the behavior of sound. In addition, Newton realized that polarization phenomena could not be accounted for in terms of spherical pressure waves.

Q16 Reflection, refraction, diffraction, interference, polarization, color, finite speed and straight line

propagation (this last would be associated with plane waves).

Q17 No; only that light does exhibit many wave properties and that its speed in substances other than air does not agree with the predictions of a *simple* particle model.

Q18 Light had been shown to have wave properties, and all other known wave motions required a physical medium to transmit them, so it was assumed that an "ether" must exist to transmit light waves.

Q19 Because light is a transverse wave and propagates at such a high speed, the ether must be a very *stiff solid*.

Chapter 14

Q1 He showed that the earth and the lodestone affect a magnetized needle in similar ways.

Q2 Amber attracts many substances; lodestone only a few. Amber needs to be rubbed to attract; lodestone always attracts. Amber attracts towards its center; lodestone attracts towards either of its poles.

Q3 1. *Like charges* repel each other. A body that has a *net positive charge* repels any body that has a *net positive charge*. That is, two glass rods that have both been rubbed will tend to repel each other. A body that has a *net negative charge* repels any other body that has a *net negative charge*.

2. *Unlike charges* attract each other. A body that has a *net positive charge* attracts any body that has a *net negative charge* and vice versa.

Q4 A cork hung inside a charged silver can was not attracted to the sides of the can. (This implied that there was no net electric force on the cork—a result similar to that proved by Newton for gravitational force inside a hollow sphere.)

Q5 $F_{e1} \propto 1/R^2$ and $F_{e1} \propto q_A q_B$

Q6 F_{e1} will be one quarter as large.

Q7 No, the ampere is the unit of current.

Q8 Each point in a scalar field is given by a number only, whereas each point in a vector field is represented by a number and a direction. Examples of scalar fields: sound field near a horn, light intensity near a bulb, temperature near a heater. Examples of vector fields: gravitational field of earth, electric fields near charged bodies, magnetic fields near magnets.

Q9 To find the gravitational field at a point, place a known mass at the point, and measure both the direction and magnitude of the force on it. The direction of the force is the direction of the field; the ratio of the magnitude of force and the mass, is the magnitude of the field.

To find the electric field, place a known positive charge at the point, and measure the direction and magnitude of the force on the charge. The direction of the force is the direction of the electric field. The ratio of the magnitude of the charge, and the charge, is the magnitude of the field.

Note: to determine the force in either case one could observe the acceleration of a known mass or

determine what additional force must be introduced to balance the original force.

Q10 The corresponding forces would *also* be doubled and therefore the *ratios* of force to mass, and force to charge, would be unchanged.

Q11 The negative test body will experience a force *upward.*

Q12 If the droplets or spheres are charged *negatively,* they will experience an electric force in the direction opposite to the field direction.

Q13 Charge comes in basic units: the charge of the electron.

Q14 Franklin observed that unlike charges can cancel each other and he therefore proposed that negative charges are simply a deficiency of positive charges.

Q15 It produced a steady current for a long period of time.

Q16 The voltage between two points is the work done in moving a charge from one point to the other, divided by the magnitude of the charge.

Q17 No; the potential difference is independent of both the path taken and the magnitude of the charge moved.

Q18 An electron-volt is a unit of energy.

Q19 If the voltage is doubled the current is also doubled.

Q20 It means that when a voltage is applied to the ends of the resistor and a current flows through it, the ratio of voltage to current will be 5×10^6.

Q21 Apply several voltages to its ends, and measure the current produced in each case. Then find the ratios V/I for each case. If the ratios are the same, Ohm's Law applies.

Q22 The electrical energy is changed into heat energy and possibly light energy. (If the current is *changing,* additional energy transformations occur; this topic will be discussed in Chapter 16.)

Q23 Doubling the current results in four times the heat production (assuming the resistance is constant).

Q24 The charges must be moving relative to the magnet. (They must in fact be moving *across* the field of the magnet.)

Q25 It was found to be a "sideways" force!

Q26 Forces act on a magnetized (but uncharged) compass needle placed near the current. The magnetic field at any point near a straight conductor lies in a plane perpendicular to the wire and is tangent to a circle in that plane and having its center at the wire. The general shape of the magnetic field is circular.

Q27 Ampère suspected that two currents should exert forces on each other.

Q28 (b), (c), (d).

Q29 (b), (c), (e).

Q30 The magnetic force is not in the direction of motion of the particle—it is directed off to the side, at an angle of 90° to the direction of motion. It does NOT do any work on it, since it is always perpendicular to the direction of motion.

Q31 Gravity always acts toward the center of the earth, and is proportional to the mass (it is independent of the velocity).

The Electric Field acts in the direction of the field (or opposite to that direction for negative charges), is proportional to the charge on the object, and is independent of the velocity of the object.

The Magnetic Field acts perpendicularly to both the field direction and the direction of motion, is proportional to both the charge and the velocity, and depends on the direction in which the object is moving.

Chapter 15

Q1 The single magnetic pole is free to move and it follows a circular line of magnetic force around the current carrying wire.

Q2 Faraday is considered the discoverer of electromagnetic induction because he was the first to publish the discovery, and because he did a series of exhaustive experiments on it.

Q3 The production of a current by magnetism.

Q4 The loop is horizontal for maximum current, vertical for minimum. The reason is that the coil is cutting lines of force most rapidly when horizontal, and least rapidly when vertical.

Q5 It reverses the connection of the generator to the outside circuit at every half turn of the loop.

Q6 It comes from the mechanical device which is turning the coil in the magnetic field.

Q7 Use a battery to drive current through the coil.

Q8 Batteries were weak and expensive.

Q9 An unknown workman showed that Gramme's dynamo could run as a motor.

Q10 Too glaring, too expensive, too inconvenient.

Q11 An improved vacuum pump.

Q12 A small current will have a large heating effect if the resistance is high enough.

Q13 Cities became larger, since easy transportation from one part to another was now possible; buildings became taller, since elevators could carry people to upper floors; the hours available for work in factories, stores and offices became much longer.

Q14 There is less heating loss in the transmission wires.

Q15 A current is induced in the secondary coil only when there is a *changing* current in the primary coil.

Chapter 16

Q1 A magnetic field.

Q2 The small displacement of charges that accompanies a changing electric field.

Q3 The four principles are:
   (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.