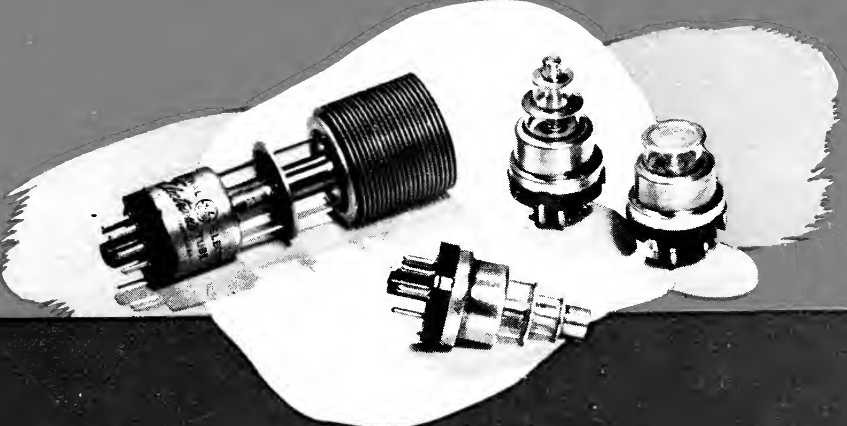
Electronics

WHAT EVERYONE SHOULD KNOW

Calvin N. Mooers
and
Charlotte Davis Mooers



This book tells where and how electronics works
r us behind the scenes of every day life in radio,

ELECTRONICS

What Everyone Should Know

In America today, in fact throughout the world, a word whose origin dates back many centuries has taken on a new and mighty meaning. It promises a future to eclipse the most fantastic scientific dream. We mean, of course, *Electronics.*

But what is electronics? What does it import to you as an individual?

Make a long-distance telephone call. Turn on your radio. Read a magazine. You are benefiting from the science of electronics, in its earliest and simplified forms.

The phone call and the radio are both dependent on electronics, and the magazine was probably manufactured or printed with the aid of electronic control.

Electronics is an art and an industry built around electronic devices and electronic tubes. These tubes and devices have special ways of putting electrons to work—electrons, those invisible particles existing in all matter, incredibly small, and capable of moving at unimaginable speeds.

Your home radio is an electronic device because it uses electronic tubes. These tubes can transform, control and amplify electronic energy. They can change a whisper into radio energy of many horsepower and send it out into space. They can dig infinitesimal voltages out of the air and fill your living room with music. They can

(*Continued on back flap*)

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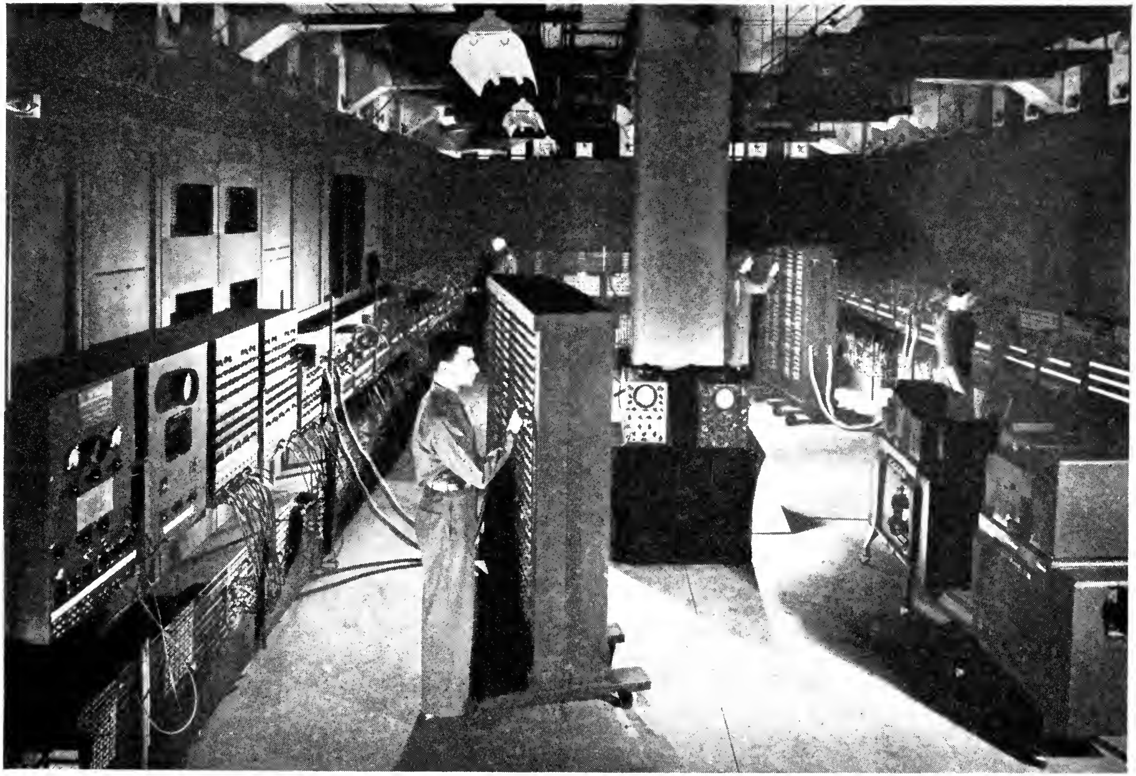
ELECTRONICS:
WHAT EVERYONE SHOULD KNOW

What Everyone Should Know

ASTRONOMY, BY JOHN S. ALLEN
AVIATION, BY DEVON FRANCIS
ELECTRONICS, BY CALVIN AND CHARLOTTE MOOERS
PLASTICS, BY BERNARD WOLFE



U. S. Army Photo

A preview of the future. This is the ENIAC, the electronic brain with 18,000 vacuum tubes, developed by the Army to solve intricate mathematical problems arising in the work at the Aberdeen Proving Grounds. Machines related to this one may eventually take over such diversified work as bookkeeping, chemical process control in factories, and flying airplanes.

ELECTRONICS

WHAT EVERYONE SHOULD KNOW

by

CALVIN and CHARLOTTE MOOERS

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DEDICATED TO

OUR PARENTS

Who listened in on crystal sets

THE authors gratefully acknowledge their indebtedness to those who had a part in the preparation of this book. Particularly they wish to mention the inspiration and encouragement of Watson Davis, the Director of Science Service, who not only set them an example by his long devotion to the cause of bringing scientific information to the public, but who also assisted immeasurably by placing at their disposal the library, files, and facilities of that organization. The drawings were prepared by Miss Christine S. Wilson, who also helped with the typing of the manuscript. Appreciation is given to the several companies who kindly furnished the photographs of electronic applications and equipment, and to whom credit is given under the individual pictures.

We are indebted to the following magazines for permission to use quotations: *Electrical Engineering; Television* for an excerpt by Mary Gannon; *Electronics* for a statement by Dr. L. A. Dubridge.

Finally, because our democracy requires its citizens to be well informed, on the technological as well as the political aspects of our world, the authors were glad to work with The Bobbs-Merrill Company in bringing out this book to explain the important subject of electronics to everyone.

CALVIN N. MOOERS
CHARLOTTE DAVIS MOOERS

Cambridge, Massachusetts, November 1946

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ELECTRONICS:
WHAT EVERYONE SHOULD KNOW

CHAPTER 1

WHAT IS ELECTRONICS?

To FIND the place of electronics in our civilization, look in on any American home—your home.

It is evening. The radio in the living room is playing softly, while out in the hall you are taking a long-distance telephone call. Opened on the floor where it fell is the evening paper. In it is a photograph taken in Paris the day before, a news article on the proposed erection of a television tower in your city, and in the bottom corner of the same page, an advertisement by an air line, telling about their new radio safety devices. When you finish your long-distance telephone conversation, you return to your easy chair and turn up the volume on the radio comic program. While listening you leaf through a magazine, looking at the colored pictures in the full-page advertisements. There are radios, photographs, radar, television, magnetrons, and FM receivers. It sometimes seems that every third page is devoted to some electronic device.

But what, you wonder, is so important about electronics? These are all nice gadgets certainly, but wouldn't life go on the same without them? Where, after all, does electronics affect your daily life?

Look around you: Electronics is at work behind the scenes in many ways.

Your radio uses at least four electronic vacuum tubes. The long-distance telephone call made use of dozens of vacuum tubes along the way to strengthen the distance-weakened voices. The current for your electric light may be distributed with the aid of electronic remote-control instruments which co-ordinate the many power-generating stations supplying your electricity. The Paris photograph in the news was sent electronically by wire and by radio. The colored inks for the pictures in the magazine were probably standardized by an electronic colorimeter. And finally the advertisements in your magazine were paid for by the electronics industry which before the war took in two percent of the national income and which during the war claimed many billions of dollars of the wartime expenditures. The postwar size of the electronics industry has yet to be estimated.

Electronics is the name of the science and industry built around the use of electronic tubes—such as the ordinary radio tube, the photoelectric eye, and the X-ray tube. Electronics is a young art, but it has already taken over many duties, and more are yet to come. Today, if all those electron tubes which are quietly assisting the operation of our civilization were to stop working, we would merely be seriously inconvenienced. But if this were to happen in as short a time as twenty years from now, after we have installed only the electronic equipment and devices now available, all our power stations, all our communications, all our rail, air, and ocean transport, and even many of our factories would have to stop. But don't be afraid; such a catastrophe could never occur. Instead, electronics will continue to take a more and more important place in our technology.

An electron tube can control the flow of electric current. Around this one fact is built the billion-dollar electronics industry. The electron tube is important not because it is the only device able to control electric currents, but because never before has there been any device so versatile and efficient in the handling of electricity.

In the home radio, electron tubes take the very small radio impulses from the air, and together with alternating current from the light socket, they produce music and speech. In the radio station they do just the opposite. There electron tubes cause the smallest whisper in the distant studio to control the transformation of many horsepower of electrical energy into radio waves that are sent out into space. Both of these applications involve exacting transformations of electric currents, and not until the electron tube was developed were they possible as we know them today.

Electron tubes, by means of their control of electric currents, are able to heat things from the inside out. This is called electronic heating, and is used in the gluing of plywood and in the heating of lumps of plastic before molding. In a hospital the same principles are used in diathermy machines for the deep-down heating of sore joints. Soon hot dogs may be electronically heated: coin-in-the-slot vending machines which deliver a toasted hot dog and bun have been announced.

When our metal-skinned aircraft are built, many of the plates are fastened together by welding. To make a perfect weld, a measured amount of current for a measured length of time must pass through the spot to be joined. Too little current and the metal will not stick. Too much and the metal will burn and lose its carefully developed strength. Electronic-welding timers now insure perfect welds by their consistently uniform currents and their split-second timing.

Electronic eyes have been used in so many places that they are no longer a novelty. The simplest kind, the phototube, makes talking movies possible, opens doors, counts oranges, and matches color—to name only a few of its uses.

A sharp-eyed cat can't see any better in dim light than can the newest electronic television camera tube that has just been introduced. Now instead of roasting the actors before a battery of powerful floodlights to televise a picture, the camera can pick up scenes from the light of a single candle. In the television receiver, another type of electron tube converts the electric impulses of the television program back into the picture of the scene.

Good as our five senses are, they can still use the ability of electron tubes to amplify effects which are extremely small or out of our sensory range altogether. Telephone messages coming from across the continent would be a million times too weak to hear if it were not for electronic amplification. Electronic devices in industry can feel and measure the roughness of even the smoothest of polished metal surfaces. In the laboratory, single cosmic rays coming in from the depths of interstellar space are detected and counted electronically. A new aircraft instrument senses the direction of north electronically without the use of a compass.

Electronics as an art, science, and industry is already too big to be described easily. It might be said that anything electrical which makes use of an electron tube is within the scope of electronics. But there is such a bewildering array of different types of electron tubes and specialized applications that this definition is of little help to the beginner in understanding what electronics is. Electronics' place in the world can best be illustrated by examples, and in this way this whole book is a definition of electronics.

CHAPTER 2

ELECTRICITY AND THE BEGINNINGS OF ELECTRONICS

THE history of electronics opens in the year 600 B.C. in the thriving commercial and seafaring city of Miletus. From this city at the mouth of the Maeander River on the shores of the Aegean Sea, in what is now called Turkey, trading vessels carried on a prosperous commerce with the Egyptians to the south and with the peoples around the Black Sea to the north. In the time of Thales, the first scientist to enter the story, this trade made Miletus the greatest city of early Greek civilization.

Thales probably was a trader by profession, for he traveled through most of the known world. At the same time, as a scientist, he met the priests and wise men of many distant countries. He learned much strange lore about eclipses from the Assyrian astronomers and geometry from the Egyptian priests. Somewhere in his busy life he ran across a curious little fact which he could not explain and which seemed to him only something to play with. A yellow substance, sometimes found on the seashore and called by the ancients "electron" (meaning golden), had the strange property of attracting bits of feathers, leaves, and straw when it had been rubbed with a woolen cloth. This was the first discovery in the long history of electricity.

Today with a plastic comb instead of a rare lump of amber (the modern name of the "electron" of old) we can again repeat Thales' experiment and make pieces of paper jump up off a table top.

Because none of his works have survived, we are indebted for a report of this discovery to the popular science writer Theophrastus who, at Athens in 321 B. C., wrote that the ancient wise man Thales had experimented with the attractive powers of "electron."

Ages passed. The Greek civilization was displaced by the Roman, and the Roman civilization in turn fell to the Vandals. In Turkey the Maeander River filled the harbor of Miletus with silt. The great city died and was forgotten. Today it is only a pile of ruins in a marsh in the wilderness.

A new civilization arose in Europe. The yellow jewel stone was now called amber and the ancient name "electron" was known only to scholars. In England, in the court of Queen Elizabeth, the handsome court physician Sir William Gilbert amused the ladies with the antics of amber and of a curious kind of iron ore called loadstone. He made bits of ordinary iron dance when the naturally magnetic loadstone was brought near, and he showed how a piece of amber rubbed with a cloth would pick up bits of paper. Gilbert, who had a scientific turn of mind, was greatly interested in these effects and he made a systematic study of them. He published his results in 1600, in a volume written in Latin. The book attracted wide attention. Here he first used the term electrica, derived from that Greek word "electron" for amber, to describe substances which were like amber in being able to attract light objects when rubbed. Soon this usage was generalized and the term electrical was applied to all related phenomena.

Following the publication of Gilbert's book, electrical experimentation became fashionable among scientists of the day and better ways of producing electricity were invented. The Mayor of Magdeburg, Otto von Guericke, developed one of the earliest electrical machines. In about 1650, laying aside for a time his experiments with air pumps and Magdeburg spheres, he mounted a large ball of sulphur, a very good insulator, on an axle which he turned with a crank. As he spun the ball he could excite it electrically by the friction of his hand held against it. With this device experimenters no longer needed to depend on small pieces of amber.

Benjamin Franklin in America was another of the many with inquiring minds interested in electricity. Desiring to demonstrate that frictional electricity and lightning are the same, he constructed a kite to fly up into a thundercloud to draw down electricity—a thoroughly dangerous experiment. The kite was made of silk to withstand the wet and violence of a storm. At the lower end of the kite string he tied a metal key and a silk ribbon to hold in his hand. Assisted by his son, he sent the kite into the first thunderstorm of the season in June 1752. The two experimenters stood inside a door to keep the silk ribbon from getting wet. At first Franklin despaired of any results, but after a while the fuzz on the string stood on end and the key sparked when he brought his knuckles near. Later when the string got wet from the pelting rain, more electricity came down the string and he was able to ignite an alcohol lamp and to perform other experiments which before had been impossible without an electrical machine.

The terms positive and negative in electrical usage come from Franklin. In his day there were many theories to explain electricity, and one of the most popular was that electricity consisted of two fluids. One, a "vitreous" fluid, was thought to be collected on the surface of glass when it was rubbed by wool. The other fluid, the "resinous," was supposed to be collected on the surface of amber or sealing wax when rubbed. Franklin disagreed and asserted that there was only one fluid and that the two kinds of electrical effects were due to either a surplus or a deficit of the electricity in the object. The charge which collected on glass he called positive because he believed glass attracted "electrical fire" when rubbed.*

In 1790 the only way of generating electricity at will was by some sort of electrical machine. Then machines were usually not much different in principle from the one invented by Von Guericke, although various improvements such as a glass disk rubbed by a leather pad had replaced the simple sulphur ball rubbed by the hand. With such a machine the next big discovery in electricity was made.

In the laboratory of Luigi Galvani, lecturer in anatomy at the University of Bologna, Italy, an assistant was playing with an electrical machine. At the next table Galvani was dissecting the nerves in a frog's legs. He noticed that when his dissecting scalpel was near the trunk nerve in one of the legs, the legs would twitch violently as each spark was produced by the machine. He wondered if atmospheric electricity would produce the same effect. To find out, he put up a lightning rod on top of his laboratory, dropped a wire into a deep well, ran wires from both to his bench, and waited for the next thunderstorm. At the approach of the storm he connected the ends of the two

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* By identifying the two kinds of electrical phenomena in this way Franklin started a confusion that inconveniences thinking in electronics to this day. We know that Franklin was correct when he said that there was only one kind of electricity and that the two effects were due to an excess and deficit of charge. But Franklin guessed wrong when he named the two states. It is now known that electrical effects result from the movement of electrons, and that friction between two objects transfers electrons from one to the other, the direction depending upon the material used. Friction between glass and wool produces a transfer of electricity; a positive charge accumulated on the glass according to Franklin, but it is actually the wool that collects negatively charged electrons. Then when the glass gives up its electricity, an electric current is said to flow from the glass to the wool, from positive to negative, even though the electrons are really traveling in the other direction. This mix-up confused no one during the early development and application of electricity. It was only with the development of electronics, where the devices must be explained by describing the movements of electrons, that the terms positive and negative caused trouble, and by then they were so firmly established that a change in nomenclature was impossible.

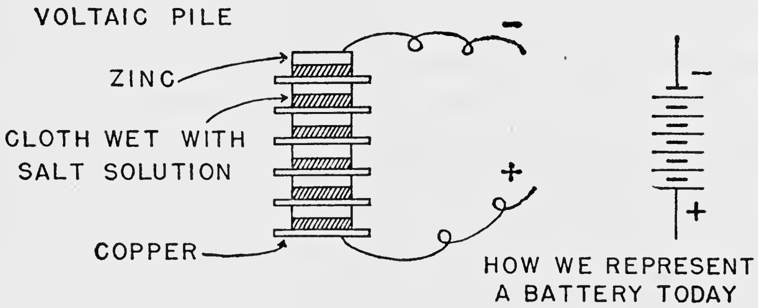
wires to a fresh frog's leg and waited. The legs twitched as the storm broke and the twitching was proportional to the violence of the electrical effects of the storm.

At this stage Galvani drew a wrong conclusion, but the end result was an advance in the knowledge of electricity. He concluded, for reasons best known to himself, that the twitching was not due to the electricity of the storm but was caused by the "animal electricity" in the frog's leg which was released by touching the leg with the metallic wires. Experimenting further, he found that when both a copper and an iron wire were applied to the nerve they would cause the muscular twitching, but only when the other ends of the wires touched together.

Alessandro Volta, a friend of Galvani and professor of physics at the University in Pavia, Italy, did not agree that the effect on the frog's legs was due to animal electricity. He thought it was due instead to some property of the two metals of the wires, and to prove his theory he began a long series of tests. In one of them he placed the end of a wire in his mouth while he placed the end of a second wire, connected to the first, on a moistened spot above his eye. By the strength of the metallic taste, and of the light sensations in his eye that this produced, he classified different pairs of metals according to their electric effects. Finally he took an equal number of copper and zinc disks and placed them in a pile, alternating the copper and the zinc. On top of every copper disk he placed a piece of cloth moistened in a salt solution. When he touched the top and bottom disks of this pile he felt an electric shock. It was weaker than that produced by the best electrical machine but it was continuous, something no machine had produced before.

Volta had invented the first battery, the famous "voltaic pile."

As soon as Volta's work was published in 1800, scientists in all parts of Europe began experimenting with the new voltaic cells. Humphry Davy made the first arc light by drawing sparks between pieces of carbon with the current from a large voltaic pile. The effect was spectacular, but we must go to Denmark for the next really important event in the history of electricity and electronics.

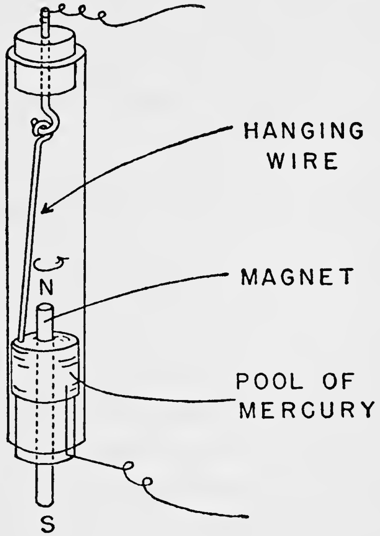


For two hundred years, ever since Gilbert first studied the electrical attractive forces of amber and the bafflingly similar magnetic attraction of loadstone, scientists had been trying to discover a relation between the two forces. But it was not until twenty years after Volta's discovery of the voltaic pile that Hans Christian Oersted at the University of Copenhagen discovered the relationship. Oersted found that if a wire connecting the two ends of a voltaic pile, and therefore carrying an electric current, is placed horizontally over a compass needle, the needle will swing from its north-south position and will try to place itself transversely to the wire, the magnitude of the effect depending on the distance between the wire and the needle.

This discovery was the key that the scientific world had been waiting for. Soon it was found that two parallel wires carrying electric currents in the same direction attracted each other, while if the currents were in opposite directions the wires were repelled. In other words, magnetic forces could be demonstrated without the use of a compass needle. It was also found that a small coil of wire with a current flowing through it would orient itself with its axis north and south just as a compass needle would.

The first electric motor was demonstrated within a year. It consisted of wire carrying a current and hanging loosely on a hook with its lower end dipped into a pool of mercury. The wire swung in circles round and round the end of a small magnet sticking up through the mercury. It was crude, it was a toy, but it worked.

THE FIRST ELECTRIC MOTOR



This electric motor was built by the young genius Michael Faraday, who as a youth began his first electrical experiments with homemade equipment in the back room of the bookbinding shop where he was apprenticed, and who educated himself by making it a point to read and master every scientific book that was brought into the shop for binding.

It was Faraday who forged the last link in the knowledge of basic electrical phenomena. Electric currents could cause wires and magnets to move. Why couldn't the inverse effect occur? Why couldn't the movement of a magnet near a wire cause an electric current in another near-by wire? Finally, with an iron ring wound with two coils of wire, each having many turns, he hit upon the trail that led to the answer. With the ring and wires—the world's first electric transformer—he found that a very small current appeared in the one coil just at the instant when the other coil was connected to or disconnected from a battery. Apparently the stopping and starting of the electric current in one coil caused the tiny pulse of current in the other.

With this initial success in August 1831, Faraday began a marathon of apparatus building and experimentation. He found that by moving a magnet up to a coil of wire he could make a small current appear in the coil. This was the sought-for inverse effect. By November he had discovered and stated all the basic laws governing the theory of electric generators and transformers, and he had made the model of the first dynamo. It is by the application of the laws resulting from Faraday's experiments that electric power is today generated and transported to our homes. The completeness of Faraday's work is amazing. Unlike Oersted, who after his initial finding seemed to let all the subsequent discoveries go to others by default, Faraday followed his discoveries through. By carefully building his equipment to demonstrate each part of his theory, and by searching his theory for all possible loopholes, he put together such a complete description of this branch of electrical phenomena that it stands today in essentially its original form.

In 1831 electronics was still nearly a hundred years away and the electron was yet to be discovered, but the building blocks of electrical knowledge were nearly all known. Batteries were well developed and were being used in laboratories for chemical processes and for arc lamps, in addition to their use in electrical experiments. Steel magnets could be produced at will with a coil of wire and a battery. Methods of measuring electric currents and voltages were being perfected.

With no more background in electricity than this, by hard work, genius, and the tools of mathematics, the Scottish physicist James Clerk Maxwell in 1864 predicted the existence of radio waves!

At that time radio waves were not only unknown, they were totally unexpected. No one had imagined that the observations of Oersted, Ampère, and Faraday concerning the electrical forces between current-carrying wires and magnets and coils contained the hidden knowledge of an electrical effect that was some day to leave the laboratory and circle the earth. Maxwell's predictions were so surprising, so far in advance, that it was not until nineteen years after his first announcement that the first radio waves were proved to exist!

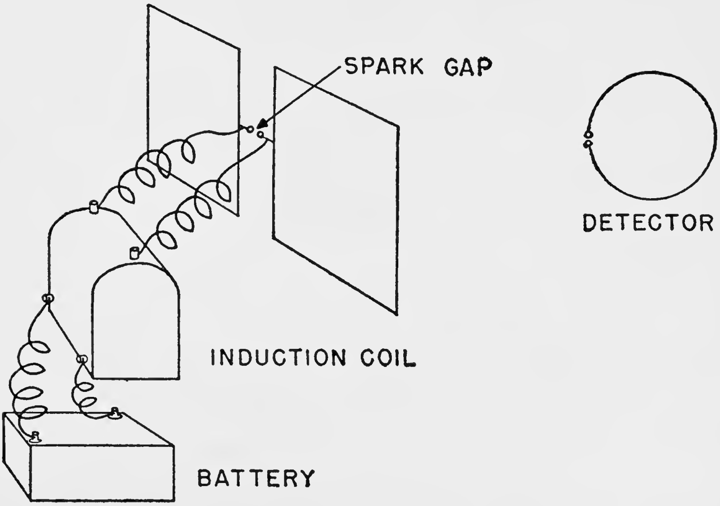
Maxwell's discovery was the result of his desire to reduce the many experimental results of Faraday into a mathematical pattern. He began with Faraday's idea that electromagnetic forces act something like imaginary elastic bands joining any two magnetic objects to pull and push the objects with the observed forces. Maxwell succeeded in explaining all electromagnetic actions between electricity, wires, and magnets on the basis of an "ether"—a hypothetical elastic jelly which filled all of space—and described these actions in higher mathematical formulae. The pulls and pushes on the wires and magnets were measured in terms of stresses and strains in this imaginary jelly. Here we must remember that an explanation of a principle of physics in those days was incomplete if it did not relate all forces and actions to some tangible mechanism. Thus, because there was no satisfactory way of describing electromagnetism with cogwheels, the ether was invented.

In the same way that a ripple can pass through a volume of jelly in a dish, Maxwell showed that ripples must be able to propagate through the ether. And such ripples in the ether must manifest themselves by electrical effects detectable at a distance. These effects are what we now know as radio waves.

While the world of physics seems to have been much impressed by Maxwell's work, the experimental scientists were remarkably slow in verifying the details. Fifteen years had passed after the first announcement by Maxwell, when the Berlin Academy of Sciences offered a prize problem to stimulate lagging research on the subject. The Academy asked for a demonstration of Maxwell's statement that an insulator develops a momentary magnetic field when an electric charge is applied to it. This problem came to the attention of a young German physicist, Heinrich Hertz, who had already done several fine pieces of electrical investigation. In two years of work Hertz took the prize with his excellent experimental demonstration. But he was only beginning: bigger things for him were ahead.

Experimentation in physics by Hertz's time had come far from the days of Galvani or Oersted. Useful discoveries happened less often by accident. In carrying on his electromagnetic investigation, Hertz had to build some carefully thought-out equipment. To set up the vibrations in the ether, which Maxwell's mathematics had predicted was possible, Hertz attached two square plates of zinc to the outer ends of two short rods, and to the inner ends he attached small polished metal spheres to form a spark gap.

Then with a battery and an induction coil or transformer to give a high voltage, he set up a series of sparks between the two metal spheres connected to the plates. That did it. To prove the existence of the "ether vibration" this produced, he used a detector, consisting of a wire loop broken by a similar spark gap between two metal spheres, and he was able to pick up enough electrical energy within several feet of the transmitter to cause little sparks to jump across the detector gap. These tiny sparks were the first radio signals received by man. The



HERTZ'S EXPERIMENT

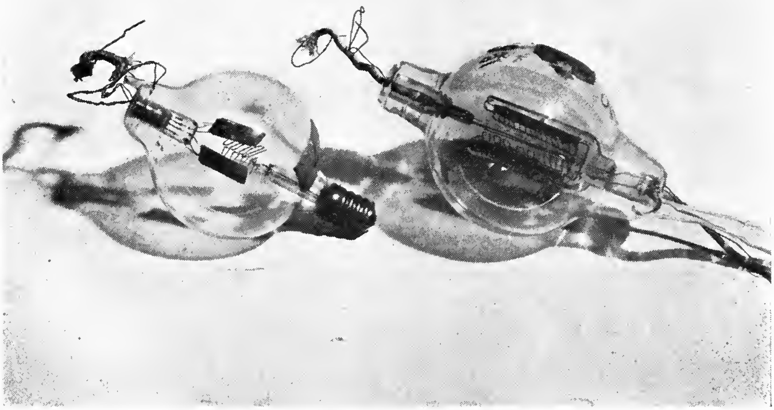
sparks showed that energy—the actual ability to do useful work—could be transported swiftly, silently, and invisibly across empty space with no apparent mechanism to guide or carry it.

The sparks could be seen only in the darkened laboratory with the gap adjusted to a very fine opening, but they were sufficient for Hertz to verify that the new waves behaved very much like light. They could be reflected by a metal plate mirror, they could be refracted or bent by a pitch prism, and they could be polarized by a panel of spaced, parallel wires.

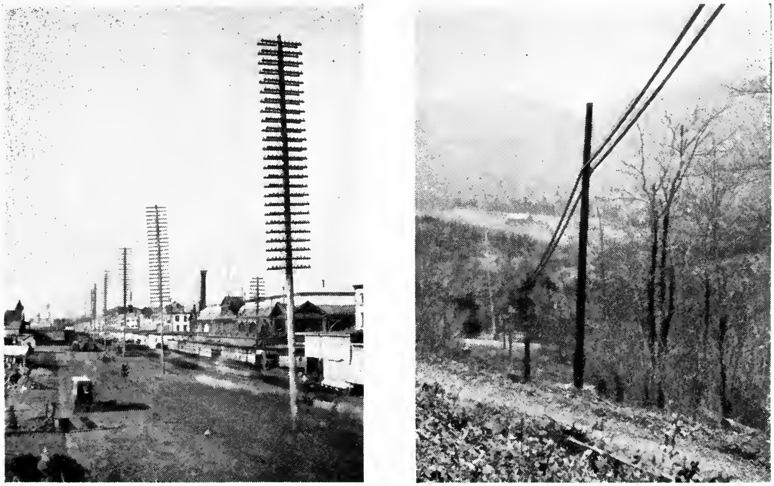
Hertz's radio apparatus, because of its simplicity, is an excellent illustration of Maxwell's electromagnetic theories. Maxwell had attempted to describe all the known electrical phenomena in terms of strains in the ether. Supposed to offer absolutely no resistance to the movement of material bodies, the ether could be observed only by its effect on electric charges. A positive electric charge was thought to exert some kind of a push in the ether, and a negative charge a pull. In Hertz's radio apparatus, the induction coil caused a large positive charge to build up on one plate and a negative on the other. When the voltage became high enough between the plates, there was a spark between the two spheres of the spark gap. The positive charge rushed over to the other plate, and piling up there, rushed back—and so back and forth, until in a few trips the process ran down and the spark went out, only to repeat at the next surge of voltage from the induction coil. As the positive charge rushed back and forth, the near-by ether was being jerked back and forth at the same time. This disturbance in the ether from the oscillating electric currents did not confine itself to the vicinity of the apparatus. Disturbance waves in the ether proceeded with the speed of light out in all directions, just as a disturbance in the surface of a pond sets up an ever-expanding ring of waves. Hertz, with his simple loop and spark-gap apparatus, then detected the disturbance waves. This he could do, according to Maxwell, because the changing strains in the ether reacted upon metallic conductors, such as his loop, to produce corresponding electric currents, just as a cork in a pond would bob around when a wave passed by.

Modern radio equipment sends its signals out into space, and receives them, in exactly the same way as Hertz did. The transmitter sets up a powerful back-and-forth surge of electric charges in the metallic antenna structure. These currents in turn set up a radio disturbance or wave in the vicinity of the antenna which speeds away at the velocity of light. The receiving antenna hundreds of miles away detects the passage of the wave by the small electric currents it sets up as it goes by. The receiver, by amplifying and converting these currents, reproduces the program.

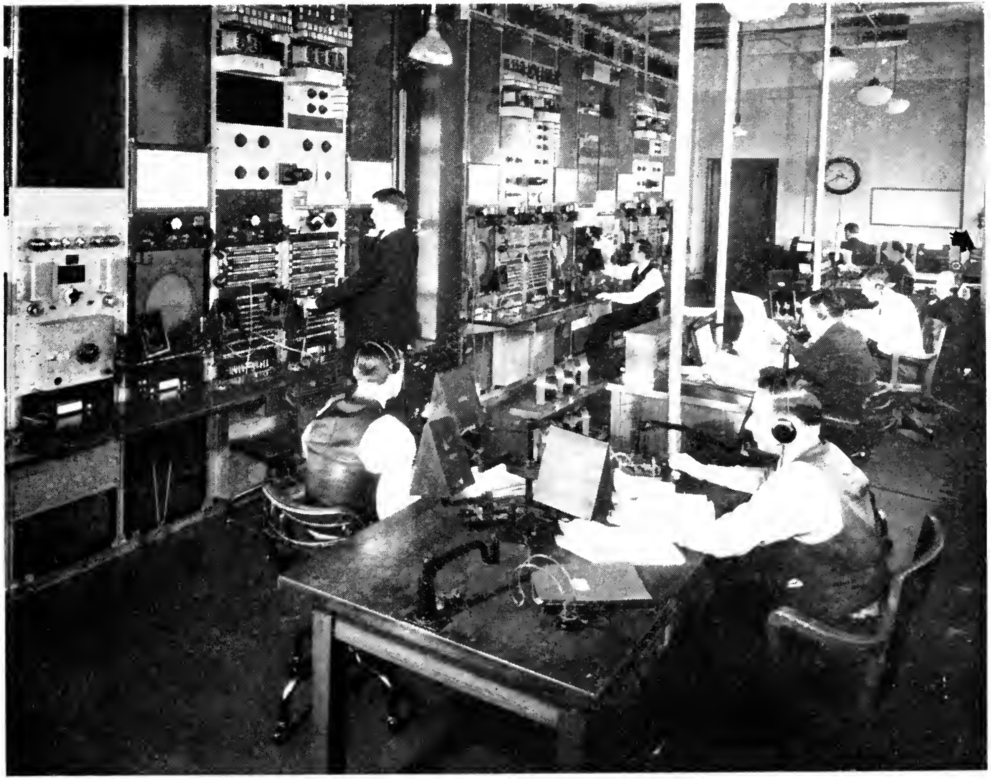
Seldom has the world witnessed such a stroke of genius. The usual course of physics has been to explain things only after



The beginning of modern electronics dates to 1913 when the DeForest audion, shown at the left, was improved by the engineers of the American Telephone and Telegraph Company to become the first high-vacuum triode amplifier tube. The tube at the right is one of the first high-vacuum tubes used as a repeater in the transcontinental telephone line in 1914. (Courtesy Bell Telephone Laboratories.)



Fifty years of progress: In 1890, enormous 90-foot poles with 25 cross-arms carried 250 wires, but transmitted only 125 conversations. Today, a single neat pair of lead-jacketed K carrier cables transmits eight times as many conversations. (Courtesy Bell Telephone Magazine.)



In this broadcasting network control room in a telephone central office, radio network programs are placed on long distance telephone wires for transmission to all parts of the country. By telephone and telegraph key, the operators are in touch with all parts of the system. Behind the scenes, they keep the programs flowing smoothly according to **schedule. (Courtesy Bell Telephone Magazine.)**

they have been discovered. Lasting fame has been accorded to those who have done nothing but observe a new effect as Oersted did, or to explain some action already known. By reversing this procedure, by describing and predicting an electrical effect which was not to be discovered in his lifetime, Maxwell secured a permanent place among the elite of physics—among those who by their genius have been able to make predictions far into the unknown. Two such men living today are Einstein, who in 1905 stated the law that predicted atomic energy, and Dirac, who predicted a new atomic particle, the positron, several years before its discovery in a cosmic ray measuring apparatus.

The ether, which furnished Maxwell the key to his predictions and his electromagnetic theory, is now no longer fashionable. Soon after Maxwell's paper, attempts of various sorts were made to detect its existence. For a time the results were the same as in the old theological attempts to prove or disprove the existence of the Deity. By definition the ether was imponderable; it could be neither seen nor felt, and it had no effects other than the transmission of electromagnetic forces. In an ingenious experiment designed to show the planetary movement of the earth through the ether, and thus through space, the two American physicists Michelson and Morley in 1887 found to their surprise that there was no detectable effect. Since then, scientists have decided the "ether" was more trouble than it was worth and that electromagnetic phenomena can be explained better without its help. Einstein, in attempting to reconcile the results of the Michelson-Morley experiment, hit upon his theory of relativity which became one of the first links in the history of atomic energy.

In spite of the Michelson-Morley findings, Maxwell's mathematics, conceived with the ether in mind, is still used by physicists. Maxwell builded better than he knew. His mathematical descriptions of electromagnetic phenomena have yet to be superseded and, strangely enough, his equations do not really require an ether at all.

After Hertz's successful demonstration of radio waves, announced in 1887, many experimenters tried to devise radio apparatus whose range would not be limited to one room. The biggest problem was the construction of a satisfactory detector for the weak electric currents found at a great distance from the sender. This was a problem that had plagued Hertz.

In 1896 a young Italian youth, not yet twenty-two years old, arrived in England to work for the British Post Office which has the monopoly of all wire communications in England. His name was Marconi. In spite of his youth he had already successfully experimented with the radio waves discovered by Hertz. Instead of the loop and tiny spark gap which Hertz had used as a detector, Marconi used a glass tube containing nickel and silver filings between two silver end plugs. It was called a coherer. The weak oscillating radio currents picked up by a receiving antenna and passed through the coherer would cause the filings suddenly to stick together—cohere—and allow a more powerful electric current from a battery to pass through and operate a telegraph sounder. The coherer was in effect a sensitive radio-operated switch, a detector. For the transmitter, he had modified Hertz's arrangement by connecting one plate to the ground and the other to a long elevated wire, the antenna. His receiver used a wire net suspended in the air to pick up the signal, and the tiny currents were detected as they flowed back and forth through the coherer between this antenna and the ground.

Less than a year after arriving in England, Marconi demonstrated radio transmission over a distance of four miles. Over water he sent signals for nine miles. Intervening hills seemed to have no serious effect in blocking the signals. The radio waves seemed to flow over the obstruction into the valley on the other side. His signals crossed the English Channel in

1899, and in the next year he began the ambitious enterprise of transmitting a radio signal across the Atlantic. On December 11, 1901, Marconi, shivering in a bitterly cold room at the top of a hill in Newfoundland, heard three faint clicks in the telephone held to his ear. It was the first transatlantic radio transmission. Radio signals had curved around the surface of the earth, traveling 1700 miles from the transmitter in Cornwall, England, to the wire suspended by a kite flown on the Newfoundland coast.

Marconi's radio detectors were marvelous for their sensitivity, and they had to be. Nevertheless attempts to devise a superior detector for radio signals went steadily on.

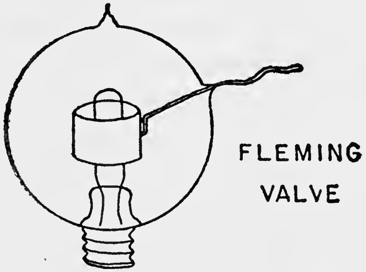
To continue our story, we must go back more than ten years to Menlo Park in the eighties, and look in on the laboratory of Thomas A. Edison, the great inventor. His newly invented incandescent lamp, which consisted of a carbonized filament in a bulb with all the air pumped out—a vacuum tube really—was subject to a troublesome blackening on the inside of the glass. As the lamp aged, the gathering black deposit meant an increasing loss of light and wastage of electricity. Edison was strictly an experimenter. He was willing to try anything, and usually did. The blackening had to be stopped. He and his assistants tried sealing a metal plate inside the bulb near the filament. The experiment was a failure, but something new was discovered. If the plate were connected to the positive side of a battery and the incandescent filament to the negative, a tiny current would flow through the space to the plate, but only so long as the filament was lighted. It was a curious effect, but Edison saw no practical use for it, and so forgot about it. Thus Edison dismissed the world's first electron tube.

Why was it an electron tube? Because the effect, the passage of current through the empty space inside the tube, depended on the flow of electrons.

The Edison effect was not to be forgotten by others, however.

Some of Edison's experimental lamp bulbs found their way to England and into the hands of J. A. Fleming, a young engineer, who repeated the experiment. Then he too laid the tubes with the Edison effect aside as being of no use.

Years passed. When in 1901 Marconi demonstrated transatlantic radio transmission, experimentation took on a hectic pace. Marconi was given competition from both sides of the Atlantic, and the cry was always for a more sensitive detector.



Fleming, remembering his early experiments with the Edison bulbs, realized that a new kind of detector could be made from such a tube. Thus in 1905, he patented the first electronic radio tube, the Fleming "valve," a detector, which was nothing more than an improved and practical version of the original experimental Edison tube. The patent was given to Fleming, because it was he who had found the use for the effect.

Detectors in a radio are necessary because the currents set up by signals arriving at the antenna oscillate or vibrate too rapidly to be heard in a telephone receiver. In fact the oscillations are so rapid that it is difficult to make *anything* sensitive to their presence. The Fleming valve can act as a radio detector because it can pass current when the plate is positive, but no current when it is negative. It changes the oscillating current into a current flowing in only one direction. Thus the Fleming valve's action is like that of the valves in a water pump, which convert the up-and-down motion of the pump handle into a steady flow of water. The one-directional flow of current coming out of the Fleming valve easily operates a telephone earpiece and makes the signal audible and understandable.

The superiority of the Fleming valve to the coherer was immediately recognized and soon the valve* was used widely. It, however, represented only the beginning of a rapid development in the use of electronics in communication.

In America a young radio experimenter named Lee De Forest was not satisfied with the Fleming invention, and with ideas of his own he went to a manufacturer of incandescent lamps to have some bulbs built to his prescription. Because Fleming held the patents on a tube consisting of a heated filament and a plate, De Forest, to get something new, had the glass blowers insert another wire in the bulb. The wire was bent into the zigzag shape of a gridiron, and was called the "grid."

The tubes were tried out. Some were found to be better detectors than any of the Fleming valves, while some didn't work at all. The tubes were prima donnas, and would stop working on no provocation. For a long time De Forest put the grid electrode on the opposite side of the filament from the plate—an ineffectual place as we know now. Later, having learned more about his invention, he placed the grid between the filament and the plate.

In this form, calling it the audion, De Forest announced his new invention in the world in 1906. As a detector it was better than the Fleming valve. Not only could it detect radio signals, but it showed an unexpected ability to amplify, or make stronger, the very weak signals. But at best the audion was a cranky little tube and took a lot of patience to use. It had few indications of greatness about it. De Forest himself did not know the true worth of his brain child. Little did he realize that by merely

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* Here we might note that the British speak of valves in their wireless apparatus when we would speak of tubes in our radio set.

placing a grid in one of Fleming's valves he had founded a new art, which twenty years later would be called "electronics," and which in forty years would be a billion-dollar industry.

De Forest, little dreaming of its fabulous future, continued to experiment with his tube, often with indifferent success. At about this time, the American Telephone and Telegraph Company was contemplating a transcontinental telephone line, to be ready in time for the San Francisco Panama-Pacific Exposition in 1915. An amplifier for the distance-weakened telephone signals was badly needed for the project. Knowing that his audion would amplify such signals, De Forest in 1912 demonstrated his tube to the officials of the company. From this demonstration they bought the audion patent for $50,000. It was worth easily a hundred times that.

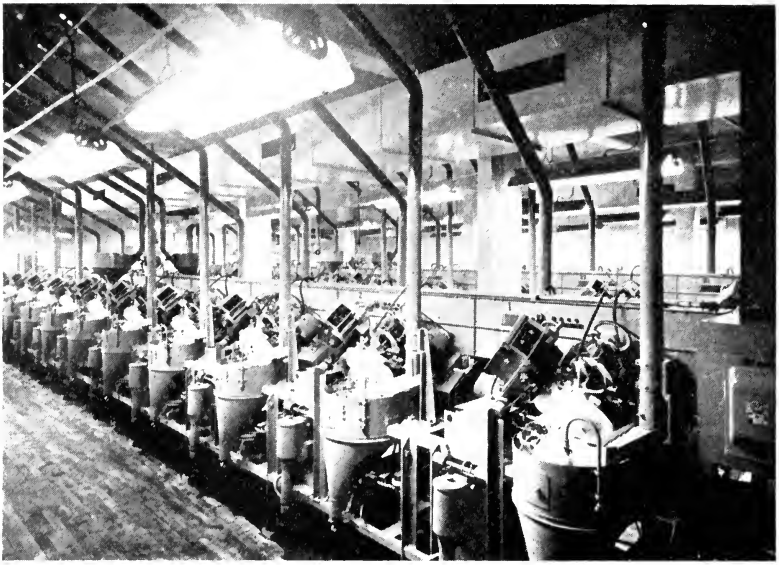
In the hands of the Bell Laboratories engineers, the audion was transformed. The blue glow that had appeared in the tube and had disrupted its action whenever the amplification of a loud telephone signal was attempted, was found to be caused by a poor vacuum. The electric lamp manufacturer simply had not removed all the air from the tube. Bell Laboratories physicists applied their knowledge of vacuum technique and the blue haze disappeared from the bulbs. The filament of tantalum was replaced by one that could emit more electrons. Improvements were made in the spacing and the structure of the internal elements. Finally, a somewhat different way of applying the voltages in using the tube was developed.

No longer was it the tricky and erratic audion. The improved tube, which could now be called by its modern name the triode, showed its worth and reliability by amplifying the words of the first coast-to-coast telephone conversation in the summer of 1914.

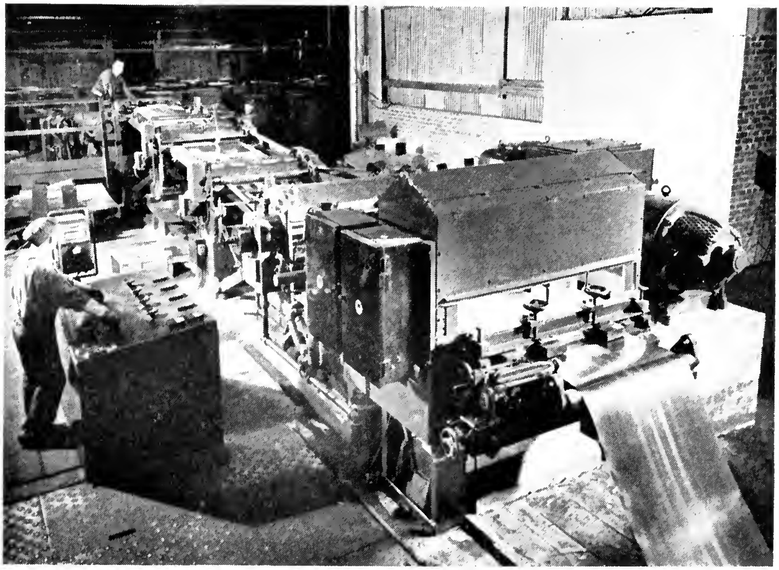
The triode tube had been born.

Our history of electricity and the beginnings of electronics is now nearly complete. The developments since are of recent

The two halves of this pressed steel droppable gasoline tank for a Lightning P-38 are welded together by an electronically-controlled resistance welder which makes a vibration-proof, gasoline-tight seam. Two wheels serve as electrodes, and the continuous seam is welded at a speed of 60 inches per minute. (Courtesy General Electric Company.)



Electronics now sorts and inspects foodstuffs. Here electronic eyes are sorting beans, picking out the dark or discolored ones. X-ray inspection of packaged food is another application of electronics. (Courtesy RCA Victor.)



Electric eyes spot pinholes in this strip of tin-plated steel as it races along to the shears at 1000 feet per minute. Under the hood is a bright light illuminating the whole width of the sheet. Pinholes as small as 1/64th of an inch across let enough light through to be detected by the memory. The triode tube went to war in 1918, but that war was won in the trenches, and it was chemistry and not electronics that held the stage. At the same time, the spark generators that Hertz used to produce radio waves were being replaced in transmitters by the triode tube which was a better generator of high-frequency currents. With the end of the war, radio blossomed, and experimenters all over the country began building or buying radio receivers. Broadcasting began in 1920, and by 1925 it had assumed the proportions of a fad. The home radio filled too many needs to remain a fad for long. Radio manufacturers soon dispensed with the troublesome batteries, until now a small box on your table top, plugged into a light socket, brings the world to your living room.

Electronics entered the factory to take over the welding of airplanes, the manufacture of plastics, and the automatic control of many processes. Battles in World War II were decided by the performance of electronic equipment. Now new and better electronic communication methods are appearing: FM, television, and radio relay. In such diverse fields as medicine, entertainment, and atom smashing, electronics is now indispensible. Yet as a servant of mankind it has only begun to take its place in the world.

Electronics is going places!

CHAPTER 3

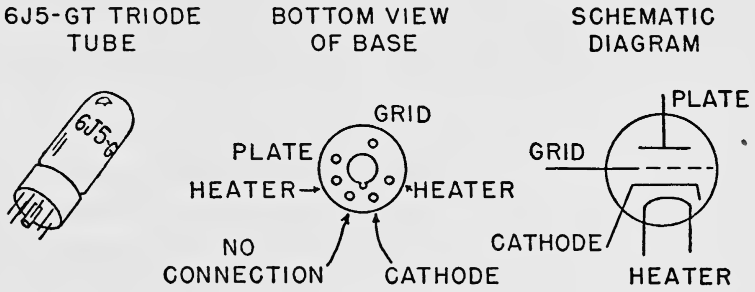
THE TRIODE TUBE AND HOW IT WORKS

ELECTRONICS is the science of using vacuum tubes to serve the needs and desires of our technological civilization. Electronics is not magic, in spite of the overenthusiastic publicity sometimes given to it. It is the careful putting together of the properties and capabilities of vacuum tubes to secure such useful results as music from a radio or the automatic opening of a door. The basic element is always the vacuum tube.

There are many kinds of vacuum tubes. One of the simplest and most important is that improved audion, the triode tube. Electronic engineering really began when the first triode tubes were used by the telephone engineers in coast-to-coast communication. From the triode tube there have been developed many new and more complicated types, but they still use very much the same principles of operation. And in spite of these newer types, the triode tube is still the most important single tube to the electronic engineer. Therefore by learning how and why a simple triode tube works, we can learn many of the fundamental principles of all kinds of electronic equipment.

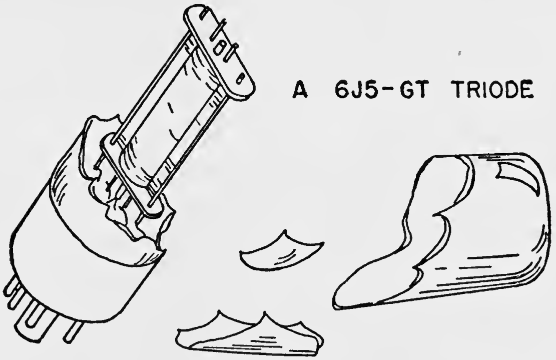
A triode tube can control the flow of electric current. This is the secret of the science of electronics. Other devices, such as the ordinary electric light switch or old-fashioned streetcar motorman's control crank, can also control the flow of electric current, but none of them can do what the triode tube does. A triode tube can control the flow of one electric current by means of another; what is more, the controlled current may be a hundred or a thousand times larger than the controlling current. A triode tube, with its control of electric current, performs the same kind of multiplication of power that occurs when a locomotive engineer, by a gentle push of the throttle, governs accurately and instantly the enormous pull of a 1000-horsepower locomotive.

The vacuum tube with the designation 6J5-GT is a triode tube often used by electronic designers in modern equipment. Taking this as a typical triode, we shall examine it, dissect its innards, discuss its method of operation, and finally demonstrate how it operates in an electronic circuit.



The 6J5-GT has a glass envelope or bulb mounted on a bakelite base. Inside the envelope are the active electrical elements of the tube. It is a vacuum tube because all the air has been pumped out from the inside of the glass bulb; air is removed to make it easier for electrons to move around. Sticking out of the base are six metal pins spaced around a bakelite centering pin. Connection to the internal elements of the tube is made by these pins. The plastic centering pin has a rib running lengthwise to make it easier to get the tube into the correct position in the socket. The internal connections to the various pins are called "heater," "cathode," "grid," and "plate."

The easiest way to find out what is inside the tube is to break open the glass and look at the inner structure. As the glass breaks, the air rushing into the evacuated interior of the bulb makes a loud pop.



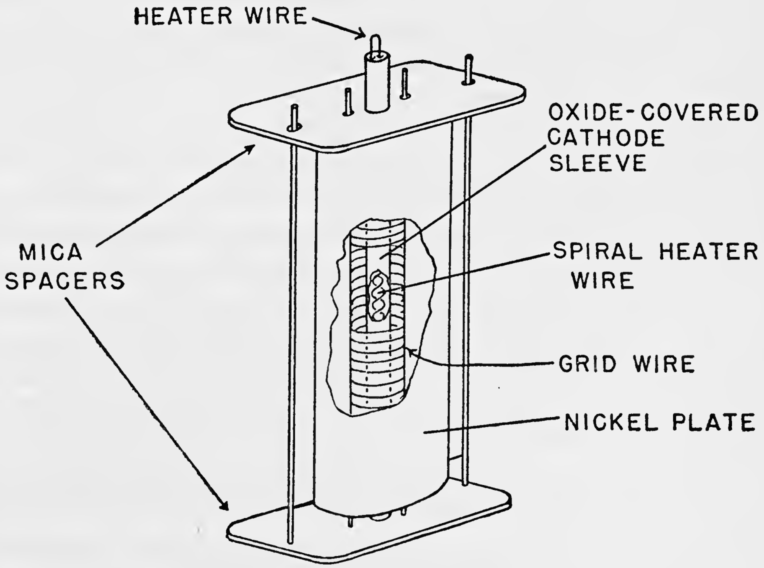
Inside, a thin sheet-nickel cylinder called the plate surrounds a spiral grid wire and a yet smaller tube down the center called the cathode. A mica spacer at both the top and bottom holds the plate, the grid, and the cathode in their proper positions. A cut-away view of the interior structure shows these details.

The cathode at the center is a seamless nickel sleeve coated with a thin layer of barium and strontium oxides. Inside this small sleeve the tiny heater wire winds spirally about itself from one end of the cathode to the other, and is insulated from itself and the cathode sleeve by a ceramic filler. Current passing through the wire causes it to become hot, and to heat the whole cathode sleeve to the operating temperature.

Surrounding the cathode, from one end to the other, is the fine, closely spaced, and spirally wound grid wire. The spiral grid is wound on two heavier vertical wires which hold it firmly in place. As we shall see later, the grid acts to control the flow of electrons as they boil off the heated cathode.

The plate enclosing the grid and cathode is simply a thin nickel tube covered with a powdered carbon coating.

To each of these internal elements, to the plate, to the grid, to the cathode, and to each end of the heater, a connection is made to the appropriate pin on the base. In this way voltages and currents from external batteries can be applied to the internal elements of the tube.



A CUT-AWAY VIEW OF THE INTERIOR OF THE 6J5-GT TRIODE TUBE

This is how a triode tube looks from the outside and from the inside. But before we can go on to learn why and how the triode tube works, we must review some basic facts about electrons, currents, and voltages.

Electrons are tiny particles of pure electricity, all alike, and all negatively charged. They are one of the important "building blocks" of every atom, and therefore of the entire universe. Electrons are the cause of all the effects that are called electric. An electric current is really nothing but a mass migration of electrons through a wire, and a battery is a chemical means to push them through. Electrons piled up in one place constitute an electric charge, and charges exert forces on one another. Electric charges on a piece of amber made feathers dance for Thales, and they make your hair stand up when you comb it in the wintertime.

A battery tries to push electrons out of its negative connecting terminal and to pull them in at the positive terminal. When a wire is connected to the terminals of a battery, a torrent of electrons—a heavy current—is pushed through the wire. They go in one end of the wire, while an equal number come out the other end. The electrical force that the battery exerts on the electrons is called a voltage, and it is measured in units that are called volts. The current, which is proportional to the number of electrons that pass through the wire in a second, is measured in units called amperes. A single electron is so tiny that more than a billion billion each second are required to cause a current of one ampere—enough to light an ordinary 100-watt electric light bulb.

The movement of electrons in wires—that is the science of electrical engineering.

But when the electrons leave the confines of the metallic conductors to fly by themselves like tiny electrical bullets through the artificially created vacuum of a tube and thereby accomplish a useful result—then the science is *Electronics.*

Only a beam of light travels faster than the tiny electron bullets in a vacuum tube. It is a slow electron indeed that pokes along at a mere 300 miles per second—in your radio electrons do better than 3000 miles per second! Being pure electricity, they have practically no weight, and for them such speeds are easy. Their weightlessness is their great advantage. Imagine an engine—or a typewriter—whose moving parts have no weight. There would be no limit to how fast it could operate. The tiniest force could cause the most rapid action. Electrons, by acting as weightless moving parts, give to radios and all other electronic devices this advantage of almost instantaneous electrical action.

Electrons bear a negative charge. Therefore they can be pushed around by electrical forces as they move through a vacuum tube. A positively charged object attracts them, while a negatively charged one repels them. The magnitude of the force is proportional to the amount of the attracting charge. Because electrons themselves are all negatively charged, they repel one another.

Wherever there is a current in a set of wires, there must be a voltage to cause the electron flow to take place. However, the same voltage or pressure will not always cause the same size of current. Electrons are able to flow through some materials easier than others: through copper easier than through iron, and hardly at all through glass, which is therefore a very good insulator. The descriptive term for the ability to impede the flow of current is resistance, and it is measured in ohms. The mathematical relation between a current and the voltage necessary to produce that current is given by Ohm's law, named after the German physicist Ohm.

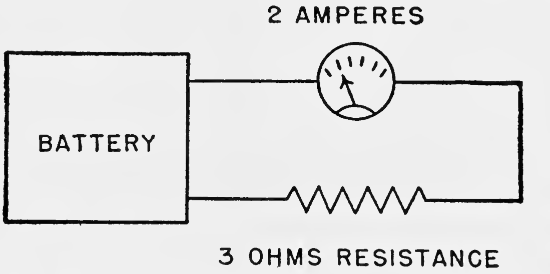
Ohm's law states that the voltage necessary to set up a current flow through a circuit is proportional to the resistance of the circuit, and proportional to the current flow. This is reasonable. A circuit containing a greater resistance to current should require a higher voltage to force through the same current. Also, a greater current flow should require a greater voltage pressure in the same circuit. Mathematically stated, Ohm's law reads:

$$\left\{\begin{matrix}\text{Number of volts needed to set}\\ \text{up current flow}\end{matrix}\right\} = \left\{\begin{matrix}\text{Ohms in}\\ \text{circuit}\end{matrix}\right\} \text{ x } \left\{\begin{matrix}\text{Current in}\\ \text{amperes}\end{matrix}\right\}$$

$$\text{or} \quad \text{volts} = \text{ohms} \text{ x } \text{amperes}$$

Ohm's law is fundamental to the understanding of electronics and all electrical circuits. Here are two examples of its use:

Find the battery voltage which forces 2 amperes through the 3-ohm resistor in the following circuit:

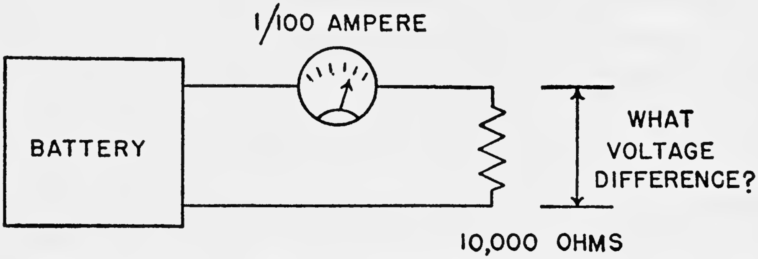


WHAT IS THE BATTERY VOLTAGE?

Volts = ohms x amperes
3 x 2 = 6 volts

Six volts from the battery are necessary to cause the current flow.

Find the voltage between the two ends of a 10,000-ohm resistor when a current of 1/100 ampere is flowing through it:



Volts = ohms x amperes
10,000 x 1/100 = 100 volts

Thus a current of 1/100 ampere develops a back pressure of 100 volts when forced through a 10,000-ohm resistor.

With this short review of the theory of electricity we can return to our investigation of the workings of the triode tube.

When the electron tube is in operation, electric current flowing through the heater wire inside the cathode sleeve heats the cathode with its surface of barium and strontium oxides to a dull red glow. At this temperature the oxide surface fairly boils with electrons trying to get away. They actually leap out from the oxide surface, only to be pushed back in again by the repulsive force of the cloud of electrons which have already got away, but which are still surrounding the cathode. This cloud of electrons is called a space charge.

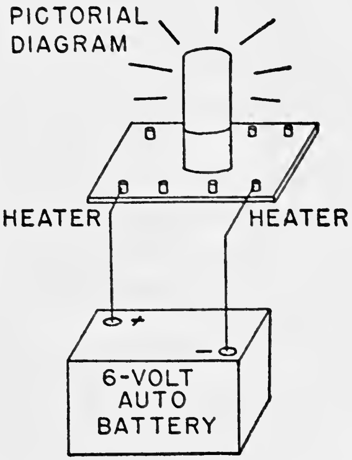
Close to the cathode are the spiral wires of the grid, and farther out beyond the grid is the plate. Batteries may be inserted between the cathode and the plate and between the cathode and the grid, to cause voltage differences between these elements inside the tube, and therefore to influence the motion of the electrons as they speed through the tube. By varying these voltages the engineer can make the electrons, and therefore the tube, behave the way he wants them to. For example, in our typical triode the 6J5-GT, if batteries supply a positive voltage of 100 volts to the plate and a negative 3 volts to the grid, a steady stream of electrons will flow from the cathode to the plate. This electron flow occurs because the effect of the positively charged plate penetrates between the wires of the negatively charged grid, attracting the electrons at the surface of the cathode and in the space charge and causing them to be pulled away toward the plate. Once they have left the cathode, they scoot between the negatively charged grid wires and then speed to the plate where they are collected as they strike the metal surface. This flow of electrons from the cathode to the plate is an electric current, and this current is pushed through the tube by the battery connected between the cathode and the plate. Without the battery there would be no current. Because the negative grid repels electrons, there is no current set up from the cathode to the grid.

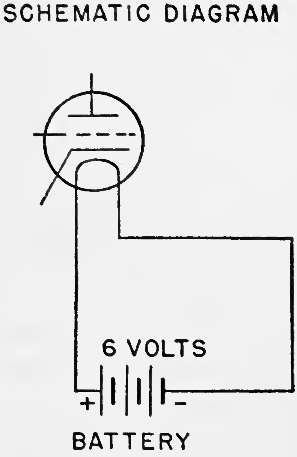
The electron flow from the cathode to the plate is determined by the voltage on both the plate and the grid. These two parts of the tube engage in a sort of tug of war over the electrons supplied by the cathode, with the plate pulling them away and the grid trying to push them back into the cathode. The positive plate voltage would exert a very strong pull on the electrons at the cathode, with a resulting large current, if its effect were not almost entirely blocked by the negatively charged, electron-repelling, spiral grid wire placed so much closer to the boiling electrons at the cathode. Because the negative grid is so close to the cathode, a small change in its voltage produces an increase in plate current many times larger than could be caused by a similar change in plate voltage. In fact, the amount of current flowing through the tube depends almost entirely on the voltage of the grid, and varies in proportion to the change in grid voltage.

This ability of the grid to control the current flow through the tube is the most important principle in electronics. Most electronic devices use this principle in one way or another. The electronic amplifier, a most important circuit, produces a magnified version of any electrical signal sent into it by way of the grid, and does so by this ability of the grid to control the current flowing through an electron tube, that is, the current applied to its cathode-to-plate circuit. Your home radio has many vacuum tube amplifiers, placed one after the other, to amplify the feeble voltages picked up by the antenna. Long-distance telephone would be impossible without vacuum tube amplifiers. In television, in radar, in scientific laboratories, and in innumerable other applications, electronic amplifiers are indispensable for magnifying small voltages.

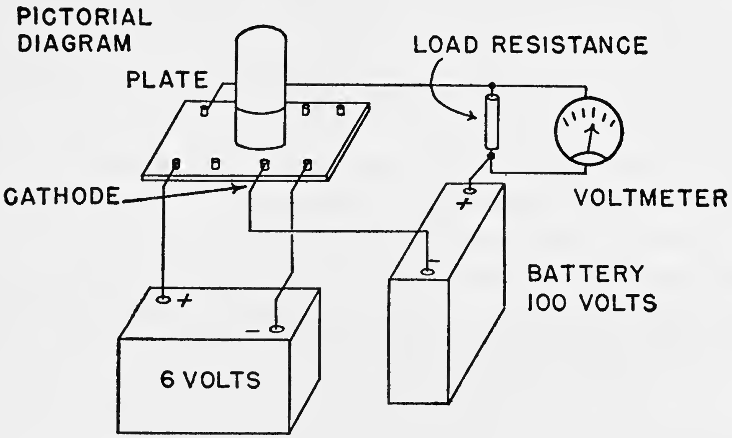
In a set of picture-experiments an electronic amplifier using a triode tube can be put together and operated. By "performing" these picture-experiments, we will learn many important principles of electronic engineering.

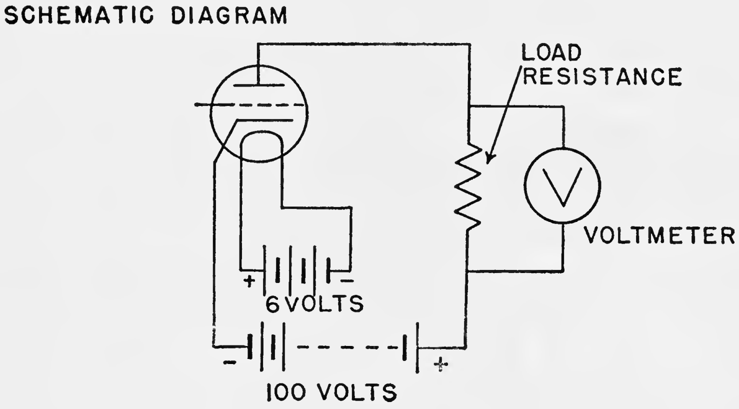
First we place the 6J5-GT tube in a laboratory-type socket. This socket is designed for experiments and allows easy connections to the pins of the tube. Next we attach an ordinary 6-volt automobile storage battery to the socket terminals connecting to the heater pins of the tube. This lights up the tube, and soon the whole cathode sleeve glows with a dull red color.





The triode tube can only control the flow of current. It cannot create the current. We need a high-voltage battery to supply the voltage necessary to push the electrons from the cathode to the plate and also to furnish these electrons which will flow through the tube. A battery of 100 volts will be used.





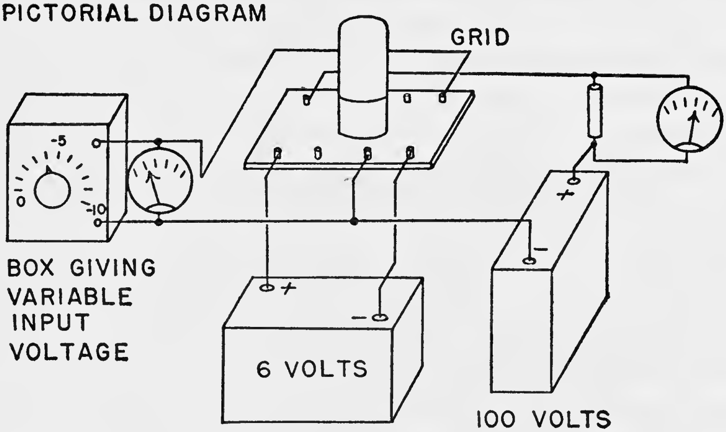
Even with a battery to supply the current, and an electron tube to control it, there is no point to this experiment if we do not use the current for something. We are building an amplifier which will magnify small voltages. From a small signal voltage put into the amplifier we want a magnified voltage output. Therefore the controlled current flow furnished by the tube and the battery must be converted into a proportional voltage. Ohm's law tells how this may be done. If the controlled current is sent through a resistor, a voltage proportional to the current will be developed across this resistor. In this experiment, we shall use a resistor of 100,000 ohms. It is called the load resistor.

The reason why the current produces this voltage is that the electrons, impeded in their flow by the high resistance, pile up at one end of the resistor. The piling-up causes a pressure difference between the two ends. In electrical terms this pressure difference is a voltage, and is measured by a voltmeter connected between the two ends of the resistor. The voltmeter shows the output voltage, or the voltage made available by the tube for doing useful work.

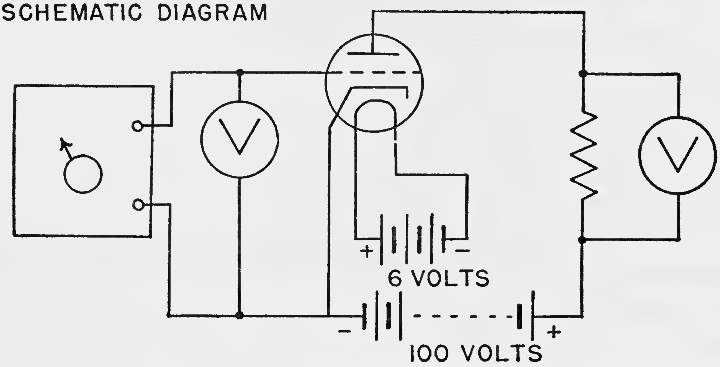
Now the plate circuit is complete. From the negative terminal of the 100-volt battery, the electrons travel by wire to the cathode, where they are boiled off and pulled through the vacuum to the plate. They collect at the plate and then pass through the resistor back to the positive terminal of the battery. The electrons travel in a closed circuit, round and round, pushed by the battery.

A control voltage must be supplied to the grid of the experimental amplifier tube. This control voltage will be the input to the amplifier, corresponding in actual use, for instance, to the feeble signal picked up through a microphone, or from a distant radio transmitter. We need to supply negative voltages in the range of 0 to —7 volts to perform the experiment, and we will do it with a box having batteries inside and a knob on the front which can be turned to give these different voltages. The voltage supplied by the box is connected between the grid and cathode of the triode, with the negative side to the grid. So that we will know what voltages are applied to the grid, we connect another voltmeter between the grid and the cathode.

PICTORIAL DIAGRAM



SCHEMATIC DIAGRAM



The circuit is now a triode-tube amplifier, complete and ready for testing. However, no veteran electronics engineer tests a circuit without first twisting the dials and playing with the apparatus. So let us turn the knob on the voltage input box and see what happens.

As we turn the knob back and forth, the grid voltmeter also swings back and forth, in step, from 0 volts to −7 volts. Not only does the grid voltmeter swing, but the voltmeter across the load resistor also swings, and it swings over a greater voltage range. The two voltmeters swing in general conformity: the more negative the voltage applied to the grid, the smaller will be the voltage measured across the resistor.

When a negative voltage of 6 volts or more is applied to the grid, the output meter reads 0. The reason for this is that the grid can totally cancel the plate's attraction for electrons at the cathode in this circuit when the grid is negative as much as 6 or more volts. No current from the cathode can flow, the tube is "cut off," and no voltage is developed across the resistor.

At the other extreme, when 0 volts are applied between grid and cathode, a maximum voltage of 75 volts is indicated by the voltmeter across the load resistor.

Between these extremes of 0 and −6 volts the voltage output is controlled smoothly by the knob on the voltage input box. As we turn the knob slowly, the output-voltmeter pointer moves slowly to the new voltage. A fast twist of the knob produces a rapid change on the output voltmeter. The output-voltmeter pointer seems to move always proportionally to the input-voltmeter pointer.

This proportionality deserves a more scientific study. By reading the output voltage each time the grid voltage is changed, in 1-volt steps from 0 to −7, we get this result:

Grid to Cathode Voltage	*Output Voltage*
0	75
−1	60
−2	45
−3	30
−4	15
−5	6
−6	0
−7	0

We see that from 0 to −4 volts, each 1-volt step in grid voltage causes 15-volts change across the load resistance. For voltages more negative than −4 volts, the uniform change does not occur, and so with the 6J5-GT triode these more negative voltages are not used.

This amplifier has a "voltage gain" of 15, which means that any voltage variation of the grid is magnified 15 times at the output of the amplifier. We notice that only voltage *changes* or variations are amplified. When the grid voltage changes by 1 volt, from −2 to −1, the output voltage increases from 45 to 60, a change of 15 volts. However, with a *steady* voltage of −2 volts on the grid, the output voltmeter reads a steady 45 volts, which is certainly not 15 times the −2 volts input. Only changes in the grid voltage are magnified by the amplifier.

The amplifier will magnify by 15 times even the tiniest voltage changes at the grid. A change of a thousandth of a volt at the grid will cause a fifteen-thousandth volt change at the output. It is this ability to amplify almost infinitesimal voltage changes that makes an electronic amplifier so valuable.

When amplifying very tiny voltage changes, an amplifier may not produce a large enough voltage-output variation to be usable. In this case the output from the amplifier may be used as the input signal for a second amplifier. Three or even four amplifiers are often used in series to secure large enough output voltages.

If each amplifier has a gain of 15, two amplifiers in series will produce a gain of 15 times 15 or 225 times the original signal. Three tubes in series give a gain of 3375, and four tubes a gain of 50,625. While these amplifications may seem enormous, an amplification of 50,000 is just about right to operate a loudspeaker from a microphone.

By adding one amplifier tube after the output of another, greater amplifications may be had, and smaller and smaller changes in input voltage may be amplified. But there is an end to this process. When signals of about one-millionth of a volt are amplified, the pointer of the output voltmeter no longer follows the variations of the input voltage. The pointer tosses and jumps, and its continuous erratic movement masks the signal that is being amplified. If you were to listen to the output of this amplifier, with either earphones or a loud-speaker, you would hear a continuous roar, sounding like a great jet of steam.

It is the fault of neither the amplifier nor of the signal. It is the roar of the billions of electrons jiggling around inside the wires of the input circuit at the grid of the first amplifier tube and of the individual electrons arriving at the plate from the cathode. The one-millionth-volt signal is so small that it begins to get mixed up with the primeval roaring confusion of the submicroscopic atomic world. Electronic amplification cannot go beyond this fundamental limit.

The oscillator is a special kind of amplifier that does not need an input signal to give a continually varying output voltage. As long as a steady battery voltage is supplied to the oscillator, but no input signal, the output voltage continuously varies up and down. The voltage variation is smooth and recurs at regular intervals, like this:

It is called an oscillating voltage, and is needed for many uses.

The secret of the operation of the oscillator circuit is that it is a triode amplifier circuit which amplifies a part of its own output signal. The output voltage from the plate is sent back to the grid in such a way that the same signal is amplified over and over again in the same tube. The oscillations cannot die out because they are always being renewed and strengthened in the amplifier.

The frequency of oscillation—that is, the number of voltage swings per second—is determined by what is known as a tuned circuit. A tuned circuit contains a coil and a condenser so set that they take the surging output voltage of the oscillator tube and force it into the pattern of a certain number of vibrations per second. This frequency of this tuned circuit is called the resonant frequency.

Operation of this circuit may be compared to striking a bell with a hammer. The hammer represents the surging current, and the bell, the tuned circuit. No matter how you strike the bell, it will vibrate always in the same manner, at the same frequency: the resonant frequency.

Such tuned circuits will be discussed more thoroughly in the next chapter on Radiobroadcasting.

The oscillator is therefore a triode amplifier with a tuned circuit in place of the load resistance, whose input signal is a part of the amplified voltage from its own output. It supplies its own input signal. It can amplify at only one frequency. As a result, voltage oscillations once started in the circuit will build up and continue as long as battery power is supplied to the tube. When the batteries are connected to an oscillator, the oscillations begin immediately. This is because even the slightest electronic disturbance is amplified over and over again by the tube, causing the oscillations to build up in an instant.

The oscillator is used primarily as a generator of high-frequency oscillating currents for use in radio transmitters. Where Hertz used two metal plates and a spark gap to generate the high-frequency electrical vibrations needed to produce radio waves, we now use triode oscillators. If your radio receiver is a superheterodyne, it has a small, low-power oscillator built in as a necessary part of the circuit. Other uses for oscillators are in hospital diathermy machines and industrial dielectric heaters used in gluing plywood. Next to the amplifier, the oscillator is the most useful electronic circuit.

The triode tube is not the only electronic tube that can control current by means of a small voltage applied to the grid. Many other vacuum tubes, such as screen-grid tubes, pentode tubes, beam power tubes, and pentagrid tubes have been developed from the triode by specialization and modification for certain applications. These tubes are really only triodes with additional grids placed between the regular grid and the plate. The original grid still dominates the flow of electrons to the plate. But in many cases, the additional grids give these tubes a superior performance that cannot be equaled by triodes. A television amplifier, for instance, built with triode tubes would require twice as many tubes as one built with pentodes, which have three grids.

We have now learned a little bit about what a triode is, why and how it works, and how it is used in a simple electronic amplifier and an oscillator. From the triode tube has been developed a diversity of many specialized tubes, each retaining certain of the characteristics of the parent triode, the most important of which is the ability of the grid to control the flow of the electrons to the plate. Therefore, knowing the triode, we also really know a few of the important principles of operation of these many other tubes and how they too can be used in electronic apparatus.

CHAPTER 4

RADIOBROADCASTING

Soap opera and news analysis, comic program and symphony—radio has moved in to become a part of the family circle. In twenty years the home radio has passed from a sprawling pile of tubes and messy batteries to a handy plastic package that children can carry from room to room to listen to their favorite five-o'clock adventure program.

Twenty years ago, it was a novelty to own a radio. A "wireless set" was something to show off to friends who were much impressed by the squeals and squawks and the occasional snatch of tinny-sounding music. Radio broadcasts were of local talent, cowboy balladeers, and ordinary photograph records. The sets were difficult to operate, having two or three tuning controls to adjust. They required heavy batteries which had to be recharged every so often, and which sometimes spilled corrosive acid on the floor. Long outside antennas, called aerials in those days, were required to get satisfactory reception. A set of tubes cost as much then as a whole radio does now. Radios were expensive luxuries, nifty newfangled gadgets, but they were of mighty little use.

Tonight, a radio program will fill part of the evening in most of the family circles in America. It may be a news roundup with on-the-spot commentators in London or Paris, a radio-theater program with stars from the New York stage, an address by the President of the United States, or a slapstick radio quiz. We may rebel at singing commercials, critics may deplore the time spent in advertising tooth pastes and laxatives, we may say that the neighbor's radio makes too much noise, but few of us would be without our own home radios.

Voice and sound contact with the whole world from our living rooms has caused a small revolution in the ways of our country. Democratic processes of government have been aided because elected and appointed officers can now make their appeals over the radio directly to the people. Political candidates are apt to be picked for their good radio voices. The musical treasures of the world, the operas and the symphonies, which not long ago could be enjoyed only by the wealthy concert-goers in the largest cities, have been "discovered" and are enjoyed by all of us. On many Saturdays, we can listen to a full-length opera presented by the Metropolitan Opera Company, or we can hear our favorite ball game.

Radio played an important part in making World War II the best reported war in history. By radio we were taken into battle and under fire, we heard from the lips of the conquered people their stories of horror, we followed the march of armies, and finally we attended the ceremonies ending hostilities. Radio gave us more than mere reporting. The emotional impact from hearing Winston Churchill defend the British Isles by little more than brave words in the crisis just after the retreat at Dunkerque will be long remembered by those who heard his "blood, sweat and tears" speech. Our men stationed in all parts of the globe were happier because of the radio broadcasts from the home networks.

On the lighter side, the evening comic programs are a relaxer for the tired businessman. During the day, the soap operas divert the housewife and take the place of over-the-fence gossip as she goes about her dusting and washing. Serials, trite as they are, are an escape from the monotony of housework. Johnny even tries to convince his parents that his school homework can be done just as well, or better, while he is listening to the radio.

Radiobroadcasting, which has become such a part of our lives, would be impossible without electronics. To see why, let us trace the electrical course of a radio program through the electron tubes, the wire circuits, and the ether as it travels from the performer to your living room.

The story might begin in New York or Hollywood, Washington or Pine Ridge. Where there is music, or song, or an important speech, there the broadcast will originate. While many programs begin on one of the special broadcasting stages, such as those in Radio City in New York, with all the advantages of special equipment and elaborate control, other network programs originate with no more equipment than a few microphones and a portable control panel mounted in a suitcase brought to a ballroom or banquet hall for the broadcast.

On the Terrace Garden in a large hotel, a dance band is playing for a nationwide audience. Many of the dancing couples are too preoccupied to notice that the program is being broadcast. They haven't observed the man sitting quietly in the corner behind the stage. He wears earphones and he quietly adjusts the controls on the front of a black box before him. Strategically placed among the players in the orchestra are several microphones. Up in front a blonde songstress is singing behind another microphone. From these the program is collected, and in less than one-twentieth of a second, but only after a surprising number of electrical transformations, the music they hear is presented in your living room.

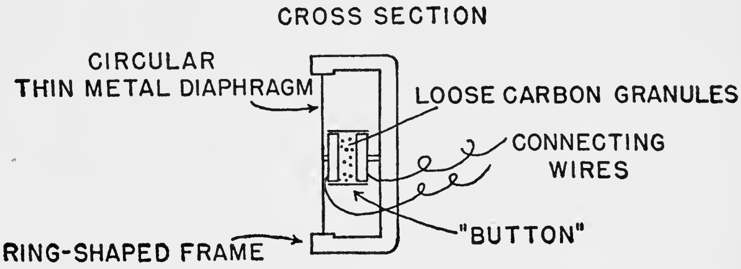
The microphone, at the first stage in the long journey of the sound, transforms the music it hears into electrical currents: it makes an electrical pattern of the sound coming to it.

But what is sound? We must know what sound is before we can understand how it can be heard by a microphone. Let's experiment. Hold a piece of cardboard or stiff paper to your lips. Talk at it. Say *o-o-o-o* and *a-a-a-ah*. Feel how the cardboard vibrates in your fingers and how its vibration tickles your lips. Do it again, change the pitch of your voice, and feel how the card vibrates more rapidly with the higher pitch. Sound consists of vibrations in the air. When you speak, your vocal cords and your mouth cavity generate these air vibrations, which then spread out in all directions. The experiment can be reversed, and instead of making the sound waves vibrate the paper, the paper may be vibrated to produce sound waves. Run the toothed edge of your comb across the edge of the card and you will hear a musical buzz caused by the resulting vibrations in the paper, which then vibrates the air to produce the sound. If the comb is moved faster, the more rapid impulses produce a higher-pitched sound.

These experiments show that sound is a vibration of the air, that this vibration will cause a card to vibrate in unison, that the vibration of a card will in turn generate sound, and finally that the pitch of a sound increases with more rapid vibrations.

Microphones which pick up sound take many forms, but they all have a light metal or paper diaphragm which vibrates in response to the sound and which by means of its movement generates a tiny electrical signal. This signal is an exact electrical duplicate of the complex sound waves striking the diaphragm. That there are many varieties of microphones is due to the numerous ways that the microscopic movement of the diaphragm can be transformed into an electrical signal.

The simplest microphone is the carbon-button microphone which is used in your telephone set, and which was once used in broadcast stations.


CROSS SECTION

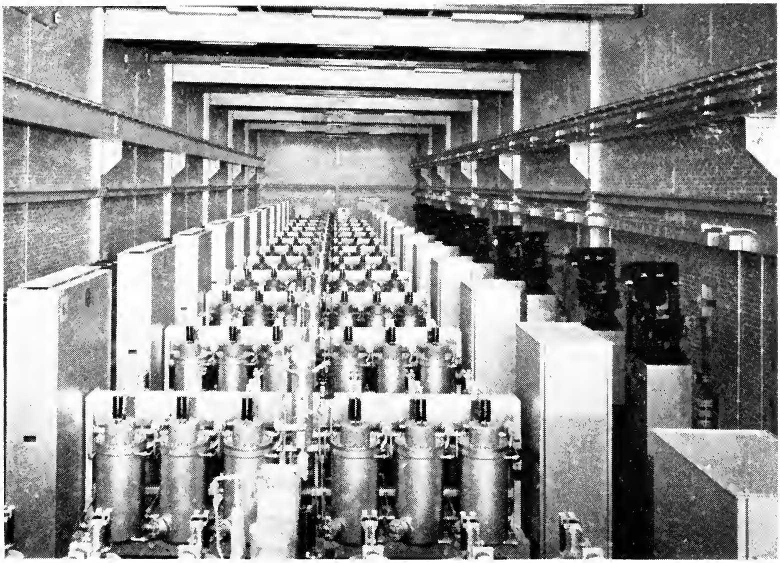
CARBON-BUTTON MICROPHONE

This microphone consists of a thin duralumin sheet stretched over a circular ring-shaped frame, with the "carbon button" fastened to the back of the diaphragm at the center. The button is a little flat box holding loose carbon granules between two metal disks. Because one of these disks is fastened to the flexible diaphragm and the other to the rigid frame, sound striking the diaphragm causes the disks to squeeze the carbon granules between them each time the diaphragm moves. Since an electric current from a battery can pass from disk to disk through the carbon granules easier when the granules are compressed than when they are not, the button converts the diaphragm vibrations into a varying electric current. This small varying current is an accurate replica of the sound vibrations that the microphone heard.

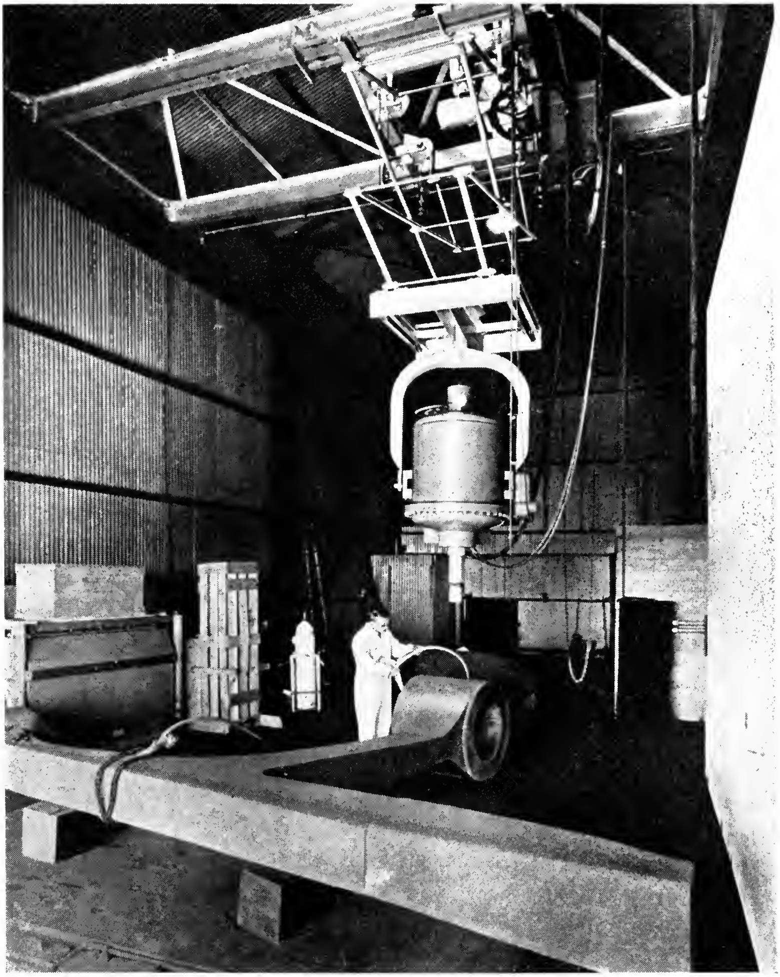
The carbon-button microphone has been largely displaced for radio use by several other types of microphones which give a more faithful sound reproduction. The most important of these are the dynamic microphone, the velocity microphone, and the crystal microphone. The dynamic and velocity microphones employ the same principles as are used in an electric generator to convert the vibration of the diaphragm into an electric current. In the dynamic microphone the diaphragm causes a small coil to move back and forth in a magnetic field. This movement produces a small electric current in the coil. The velocity microphone combines the moving coil and diaphragm into one. It uses just a single thin metallic ribbon whose vibration in a strong magnetic field generates the signal current. The velocity microphone is used when it is desirable to pick up sound coming from directly in front of the microphone. It is insensitive to sounds originating off to the sides and because of this effect of direction on its sensitivity, it is called a directional microphone. Other types of microphones can also be made directional by proper design.

The cream of tartar used in baking powder is a chemical cousin to the Rochelle salt used as the vibration-to-electricity

A push of the button, a shower of sparks, and four simultaneous electronically-controlled welds are completed. Precise regulation of welding temperature, attained by electronics, is essential for consistently strong welds in this thin metal strip. (Courtesy Westinghouse Electric Corporation.)



Cheaper and more efficient than the conventional rotating electrical equipment, ignitron rectifier installations, such as this, furnished direct current power for the majority of the wartime aluminum refining plants. Each ignitron shown here, in its cylindrical can, passes a current of 5000 amperes at 625 volts. (Courtesy General Electric Company.)



This million volt industrial X-ray tube can peer inside the large casting and give photographic proof that no hidden cracks or flaws exist. Here the operator measures the thickness of the steel section. From this information he will determine the length of exposure needed to penetrate the metal. (Courtesy General Electric Company.)

converter in the crystal microphone. Large crystals of Rochelle salt are laboratory-grown like rock candy. Tiny slabs, often about ¾ inch square and 1/16 inch thick are cut from them. On the two faces of these slabs tin-foil electrodes are cemented. In the microphone the crystal is arranged so that the moving diaphragm pushes on the corner, bending it by a microscopic amount. The Rochelle salt crystal responds to this bending by producing a voltage at the two faces. The voltage is picked up by the tin-foil plates and is the electrical version of the sound. This remarkable ability found in certain types of crystals is called the piezoelectric effect. The queer prefix was coined from the Greek word meaning "to press." Natural piezoelectric crystals of quartz have a very important use in radiobroadcasting transmitters, as we will see later.

After this detour into the theory of sound and the operation of microphones, we are ready to return to the Terrace Garden and look over the shoulder of the man with the earphones to see just what he is doing with that black box.

From each of the microphones, from the dynamic microphones among the members of the orchestra and from the directional velocity microphone before the singer at the edge of the stage, wires lead across the floor into the box. Here the man with the earphones, the broadcast engineer, proportions and combines into one carefully balanced result the signals from each of the microphones. In his earphones he hears the resulting program and by means of knobs on the box he can control the volume from each microphone until each instrument sounds in its place and the orchestra is held down to an even accompaniment for the voice of the singer.

Getting the music mixed in the right proportions is only part of the job. The engineer controls also the final volume or intensity of the broadcast radio signal. As we will see later, the radio station cannot handle too large a signal without destroying its perfect transmission. On the other hand, a broadcast signal weak signal will cause poor reception. On the engineer's control box is a meter whose pointer is dancing up and down with the beat of the orchestra and the inflection of the singer. The pointer tells how loud the signal is as it is sent to the transmitting station. As he watches the meter, the engineer sometimes turns the master control as he varies the loudness of the signal sent out. By it he holds down the volume of the loudest pieces and brings the softest passages up to a broadcast level. The job takes skill and training, since too much controlling will make all the music sound equally loud, while not controlling enough will result in poor program reception.

As if these duties were not enough, the man at the mixing panel must also be a clock watcher. By means of a telephone connection back to the main broadcasting studio, he gets the exact studio time so that just before the broadcast the announcer may synchronize his watch to the second.

The music is now translated into tiny varying electrical currents, the separate parts of the orchestra are balanced against the singer, the over-all volume is correct, but the tiny signals from the microphone must be amplified before they can be sent over the telephone lines to the broadcasting station. Here, in the engineer's black box, the first electronic amplifier is used. The small voltage from all the microphones enters the grid of the first tube and there controls the battery current flowing between the cathode and the plate. The weak current controls the stronger, and the signal is amplified. From the microphones, which gave a signal of about one-hundredth of a volt, the amplifier increases the signal to about one volt, which is large enough to send over the telephone line to the main studio.

Between the Terrace Garden and the main broadcasting studio, the music travels over regular telephone wires which have been hired by the broadcasting station from the telephone company for this broadcast. At the studio the telephone line connects to a complicated switch panel which handles all the incoming and outgoing programs. Before the Terrace Garden program is sent out over the air, or over the national network, it is checked again for quality and sound level by a studio program engineer. Then, after some further amplification to bring it again up to the proper telephone level, the program is sent out over leased telephone lines to the local station; and because it is a network program, out over the special leased long-distance network telephone lines to radio stations all over the country.

It may sound like a contradiction to use nationwide telephone networks to distribute radiobroadcast programs, but there is a very good reason for it. Radiobroadcasting stations can distribute their program over only a limited area. Beyond about fifty miles from the station, reception becomes unreliable. Coast-to-coast reception on a broadcast receiver is, and always will be, a stunt: something to try with an expensive set. But people from all over the country wish to hear programs originating in New York, Hollywood, or Chicago on their small inexpensive sets which are able to pick up only the local stations. A reliable means of carrying these programs was needed, and telephone connection was the answer. In the late twenties network broadcasts began, and soon the telephone companies provided special equipment and lines for broadcast-program transmission. Coast-to-coast chain broadcasting by means of special telephone lines has become a national institution, and few nights pass in which the coasts are not linked by programs going in both directions.

The Terrace Garden program which we are following begins its long telephone trip by first going from the studio through the central telephone office, and then out over long-distance lines to the various cities in which the program is to be broadcast. In each city the signal goes through the central telephone office, then to the local broadcast studio. On arrival at the studio the sound level is again checked and adjusted, and the program is finally sent by telephone wires out to the local transmitter.

The little fireproof house and the towering transmitting antennas of a radio broadcasting station are a familiar sight at the edge of most cities, but few people have ever been inside to see the equipment that sends the radio programs out over the air. There you might be reminded of a futuristic hospital with everyone out to lunch. The place is clean; there are gleaming floors and metal-paneled walls with glass windows through which are seen the transmitting tubes, each with its gleaming incandescent cathode. The house is nearly deserted: only an engineer and an assistant are on duty at the desk in the corner. With silent automatic power, the transmitter nearly runs itself. The Terrace Garden program, coming in over the telephone lines, controls at the transmitter the conversion into radio power of thousands of watts of electrical energy taken from the power lines. A typical large broadcasting station sends out into space from its antenna about 50 horsepower of program-carrying radio energy—more than enough power to propel an automobile. This energy departs invisibly, without a sound. We cannot detect it by any of our senses, yet it has a definite physical existence and is able to carry the program to thousands of listeners.

Before we examine the technical details of this radio station, it will help our understanding if we stop again to discuss what a radio signal is and how it carries speech and music. Just as in the early experiments by Hertz, modern radio signals are radiated from rapidly oscillating electric currents in the antenna. Hertz generated his electrical oscillations by causing a spark to jump across a spark gap connected between two large metal plates. Modern broadcasting equipment generates similar electrical vibrations, but it does so by means of electron tubes.

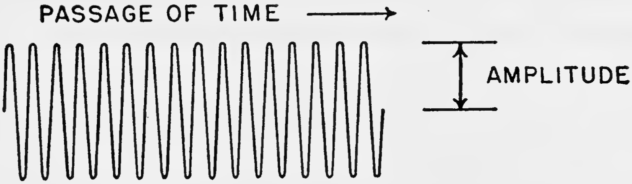
The frequency of oscillation of the generated radio current determines the position of the station on your radio-receiver dial. Because it is very important to have the frequencies properly spaced over the dial to give the best radio service, the frequency of each station is specified by the Federal Communications Commission. To retain its license, the station must at all times hold the broadcast frequency constant to within a very small limit. Radiobroadcasting in this country is done in the frequency band of from 550 kilocycles to 1500 kilocycles. "Kilo" means thousand. Therefore in the antenna of a station broadcasting on a frequency of 840 kilocycles, the circulating electric currents are surging back and forth 840,000 times a second! Your receiving antenna picks up the distant effects of these electrical vibrations and, if your set is tuned to 840, it selects that signal and rejects all the others at different frequencies.

There is more to broadcasting a radio signal than the generation of electrical vibrations of a specified frequency. The signal must also carry the "intelligence"—the speech or music making up the program. The intelligence is added to the radio frequency currents, the "carrier," by a process called "modulation."

Ten years ago there was only one accepted way of modulating the carrier for radio transmission. It was called "amplitude modulation." Since then several other basic types of modulation known as frequency modulation, phase modulation, and pulse modulation have been developed. For reasons that will be explained in the later chapter on the Electromagnetic Rainbow, only amplitude modulation can be used in the broadcast band. However, in the soon-to-be developed ultra-high-frequency broadcast bands, these newer types of modulation promise exceptionally fine, high-fidelity broadcast reception.

In an amplitude-modulated broadcast transmitter during a moment when no music or speech is being broadcast, the antenna sends out its radio signal at a constant intensity or amplitude. But any sound arriving at the studio microphone causes the strength of the oscillating currents in the antenna to vary in step with the air waves at the microphone. Consequently, the amplitude of the radio signal sent out follows accurately the movement of the microphone diaphragm. It is said that the amplitude of the radio carrier is "modulated" by the sound waves.

This process of amplitude modulation can best be explained by a set of diagrams. The basic electrical carrier vibrations sent out into space by a typical broadcast transmitter operating on a frequency of 840 kilocycles may be represented by:

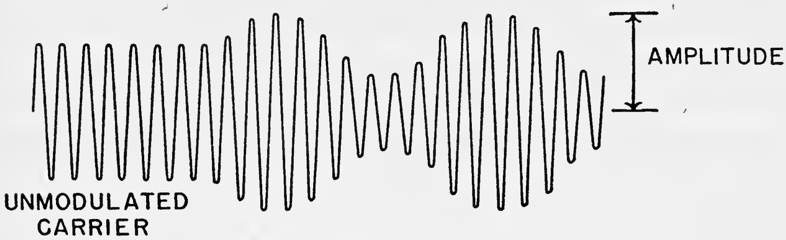


CARRIER: 840,000 VIBRATIONS PER SECOND

The zigzag line is a graph of the 840-kilocycle electrical vibrations. The vertical measurement of the zigzag line represents the strength or amplitude of the current oscillating at 840,000 times per second. The studio microphone, hearing sound vibrations, for instance the standard orchestra pitch "A" at 440 cycles per second, presents to the broadcast transmitter a varying voltage that looks like:

"A": 440 VIBRATIONS PER SECOND

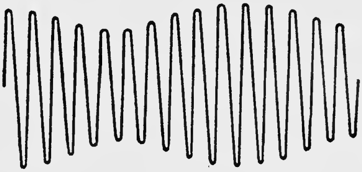
Notice that these vibrations are slower—the zigzag is much less compressed. The "modulator" in the transmitter puts these two signals together, and causes the amplitude of the 840-kilocycle carrier to vary up and down at the modulating frequency of 440 cycles:



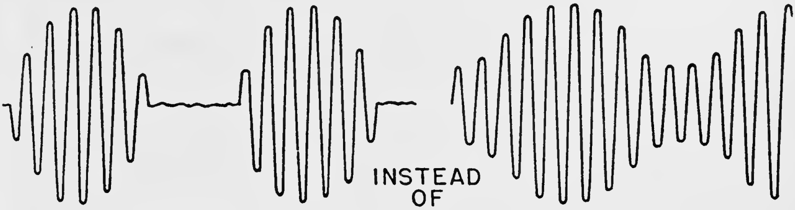
MODULATED CARRIER

The result is an amplitude-modulated radio signal that carries the program from the broadcasting transmitter to many receivers.

The sound level of the broadcast program sent to the transmitter must be carefully adjusted in order that the carrier be neither over nor undermodulated. A signal too weak will produce a modulated output looking like:

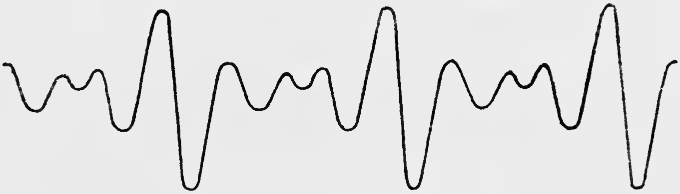


Such a signal sounds weak and wastes equipment. A signal too strong will overmodulate the carrier, giving:



An overmodulated signal is distorted and harsh and is very unpleasant to listen to.

The modulating signal, the program of the music, song, or speech, is called the "audio-frequency" signal to distinguish it from the radio-frequency carrier. The ear can hear these audio frequencies, and they are so named because they are audible. The range of the audio frequencies is from the very deepest rumble at about 30 cycles per second to the very highest peep at 16,000. The standard "A" is in the middle of this range. Voice and music are composed of a mixture of frequencies in the audio range. A typical audio-frequency signal, that of a violin, looks like:



and contains many harmonics or overtones of the bowed frequency.

It is the modulated carrier that carries the broadcast programs to your living room. These electrical carrier vibrations, swinging first with greater, then with smaller amplitude, but always at the same frequency, carry the program to the receiving antenna. Since your radio selects a station by means of the carrier frequency only, and not by the size of the radio signal, amplitude modulation has no effect on the tuning-in of the station.

With this understanding of modulation we shall return to the transmitting station to see how the Terrace Garden broadcast is sent out to the audience.

The electronic equipment in a broadcasting station performs four essential functions in the generation of a radio signal. The electrical energy from the commercial power lines is converted into high-voltage direct current for operating the transmitting tubes. The program coming in from the telephone wires is amplified until it is powerful enough for use in the transmitter. The radio-frequency energy for the carrier is generated at the assigned frequency. Finally, the amplified program and the carrier are combined in the modulator to give the signal which goes to the antenna and is sent out over the air.

A broadcast-transmitting station contains a great many tubes, each one of which requires electricity to heat the cathode and a high-voltage supply for the plate current. Of these two, the high voltage is the most critical. For some of the largest tubes, 10,000 to 20,000 volts are needed. Batteries would supply the right kind of current, but would be too expensive. Therefore power is taken from the regular commercial alternating-current power lines, and put through a transformer to raise its voltage to the necessary several thousand volts. But this current is alternating: it is changing its direction 120 times a second (60 cycles A.C.). If it were used in this form, the transmitted program would be totally obscured by a low-pitched buzz. To avoid this, the alternating current is "rectified," that is, it is put through an electron tube which allows the current to pass through in only one direction.

A typical rectifier tube is called a kenotron and is very much like a big triode tube without a grid. In operation, the alternating voltage is applied between the cathode and plate. Electron conduction takes place only when the plate is positive, giving pulses of current going in just this one direction. These pulses are then carefully smoothed out to give a steady flow before the current is sent to the transmitter.

The transmitter power supply is important because it supplies from the power lines all the electrical energy that is converted into the radio signal by the transmitting tubes. Electron tubes cannot generate their own energy; they can only control the flow of current furnished to them by the power supply.

The second important function performed by the station equipment is to amplify the program material coming in over the telephone lines until it is powerful enough to operate the modulator circuits in the transmitter. The transmitter amplifier consists of a sequence of one-tube amplifiers, placed end to end, the output of each amplifier feeding the grid of the one next in line. This part of the equipment must be very carefully designed, because any electrical distortion or marring of the program material by the amplifier would be sent out to all the listeners. Even the most expensive receivers cannot correct such a fault in the station equipment.

The carrier, those high-frequency oscillations that must be exactly on the licensed frequency, is generated in the third section of the transmitter. This part of the transmitter has a heart of stone, whose every beat times the surging radio-frequency currents throughout the whole transmitter.

This stone heart is a thin, precisely cut slab taken from a natural crystal of quartz. A quartz crystal is used for two reasons. The first is that quartz, like a Rochelle salt crystal, produces an electric voltage between the two parallel faces when the crystal is bent or deformed. The opposite effect also occurs; when a voltage is applied across the same faces, the crystal deforms.

The second reason for using quartz is that a carefully cut slab of it will vibrate mechanically at one frequency with greater exactness than any other known material.

These two properties of quartz are used together to control the frequency of a broadcasting station. The voltage developed across the vibrating crystal is amplified to be used in the transmitter. A little bit of this amplified signal is also fed back to the quartz to keep it vibrating at the carrier frequency. Thus we have what is called a quartz-crystal oscillator. Through this oscillator, controlled by the precisely timed vibrations of the crystal, the frequency of the whole transmitter is maintained. The oscillations are amplified by tube after tube, until at last in the largest tubes of the transmitter, kilowatts of electric power are being controlled and turned into radio-frequency currents for feeding into the antenna.

Like all powerful engines, the last power tubes in the transmitter are very large and they get very hot. Some of the largest tubes used are about as tall as a man. One end is glass with the wires coming out, the rest is a copper pipe enclosing the grid and the filament. The copper pipe is the plate. In fact the tube is wrapped up in the plate instead of in a glass envelope.

This construction is sensible because the plate gets very hot when it handles kilowatts of electric current by means of the electron flow to the plate. When the plate is on the outside, it can be water-cooled directly. The metal end of the tube is placed in a water jacket. Water is forced around the tube to carry away the heat, and there is a lot of it. For instance, a radiant electric heater, often used in bathrooms or chilly rooms, changes only one-half a kilowatt of electricity into heat. In comparison, a large transmitter cannot help but generate as much as 20 kilowatts of waste heat in its large power tubes. Therefore, there is no problem of winter heating in the transmitter house with so much free hot water available.

Modulation of the radio-frequency carrier by the audio-frequency broadcast program occurs in one of the tubes in the sequence of radio-frequency carrier amplifiers. On the grid of the tube is placed the amplified signal from the crystal at the carrier frequency. With a constant voltage supplied to the plate, the tube is just a plain amplifier giving a constant output signal. But if the plate supply voltage is made to vary in step with the audio-frequency program signal, the carrier output from the tube will also vary. The amplitude of the output will be in proportion to the program signal. The signals are not mixed: the audio signal merely determines the size of the radio signal. This is the method of amplitude modulation.

The broadcast signal is now completely assembled. The music from the Terrace Garden has been impressed by the modulator on the radio-frequency currents of the carrier, and these currents are readv to be sent out into space by the transmitting antenna.

There are many kinds of radio broadcasting antennas: single latticework metal towers, double or triple towers spaced apart from each other, or two high masts holding up a wire antenna between them. They all have one purpose, and if Maxwell's ether were still a respectable term, we could say this purpose is to get the best possible "grip" on the ether, so that the strongest possible electrical vibrations may be transmitted out to the many listeners. But whether we talk in terms of the ether or in terms of the higher mathematics used in its place today, the fact remains that the radio engineer in designing a transmitting antenna makes many careful decisions in order to give the listeners the best reception.

It is hard to realize that a radio-transmitting antenna, standing silent and motionless in the field beside the transmitter house, is sending many kilowatts of electrical energy out into space, never to return. Exactly how this happens can be explained completely only by higher mathematics. However, a simple description of what occurs is possible. The transmitter which is connected to the antenna causes a heavy current to surge back and forth from one end of the tower to the other at the transmitter frequency. The surging current varies in strength according to the output from the modulator. Because the current changes its direction so fast—a station at 840 kilocycles has 1,680,000 current reversals a second—some remarkable things happen. The magnetic effects resulting from the current in the antenna cannot move through space rapidly enough to keep up with such rapid oscillations. As a result, these magnetic influences are virtually thrown out into space by the currents in the transmitting antenna. Simultaneously the same thing occurs with respect to the electric effects from the rapid piling-up of electric charge first at one end, then at the other end of the antenna.

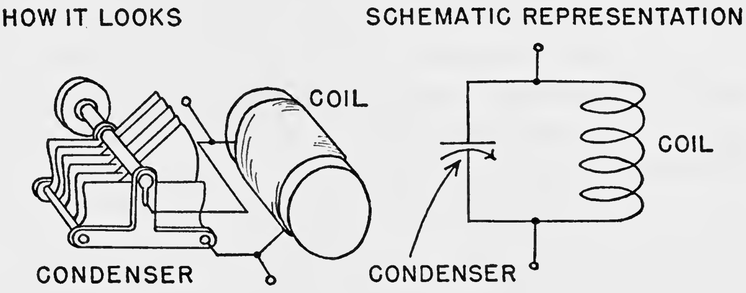
These two effects, the magnetic and the electric, combine and supplement each other to produce the radio wave that can travel tremendous distances. In somewhat the same way that water waves, as they move onward, are constantly changing from crest to trough, radio waves present a continual variation, the magnetic crests changing into electrical troughs and back again as the waves move outward. From the transmitting antenna the radio waves carrying the program move out in all directions at the speed of light. They travel fast enough to circle the globe at the equator seven times in one second. They permeate nearly everything. They fill the air, they go through houses, and they can even turn corners and drop down into valleys on the far sides of hills. However, they cannot go very far beneath the surface of the ground or penetrate into the sea.

A radio receiver has merely to catch one of these passing waves to reproduce a program. Actually the wave is not caught; it is the tiny electric current set up by the passage of the wave that is utilized in the receiver.

While older and less sensitive receivers required a receiving antenna wire placed high up on the roof to catch the elusive radio signals, modern receivers usually are sensitive enough to pick up the signal on a built-in antenna. This antenna is often in the form of a loop built into the back of the set. Such receivers depend on radio signals that penetrate houses.

The radio receiver, in one way or another, reverses many of the processes that went on in the transmitter—from the very tiny signal picked up, it produces a roomful of music. The precise frequency control of the transmitter enables the receiver to select its station. The signal is amplified to bring its strength up to usable values, then it is demodulated. Demodulation or detection is really the process of measuring the size of the oscillations which are received. While the transmitter impresses the audio signal on the carrier by varying its magnitude, the detector reverses this process to give the music and speech separated from the radio-frequency carrier. To perform all these functions, the receiver must have a source of power, and for that purpose it has a miniature edition of the large transmitter's transforming, rectifying and smoothing equipment.

The most important function in the receiver is the selection of the desired signal from the multitude picked up simultaneously by the receiving antenna. This is performed by tuned circuits, the same kind of device that the oscillator, described in the last chapter, made use of to hold its electrical vibrations at a constant frequency. In a radio receiver a tuned circuit consists of a spiral wire winding on a cylindrical insulating form with the two ends of the winding connecting to the alternate parallel thin metal plates of a variable condenser.



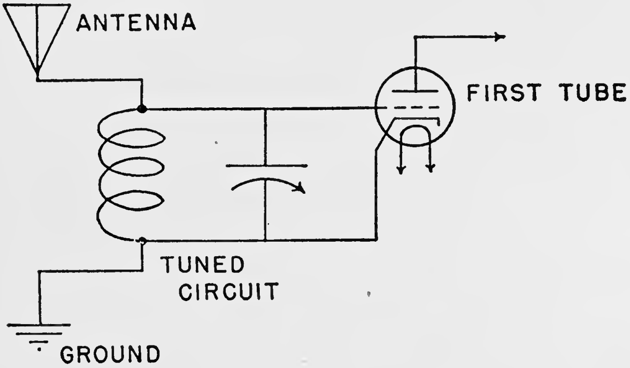
A TUNED CIRCUIT

A tuned circuit has the property of responding to electrical oscillations only at its resonant frequency. The resonant frequency is determined by the number and size of the turns on the coil, and by the number, the spacing, and the amount of intermeshing of the plates of the condenser. Turning the knob on the front of the radio rotates the shaft of the variable condenser and changes the amount that the plates intermesh. This changes the resonant frequency. A radio is tuned in this way.

An oscillating radio-frequency current applied to the terminals of a tuned circuit will develop a maximum voltage across the terminals if its frequency is the same as the resonant frequency. If the frequency is not the same, the current will develop only a very small voltage, almost as if the two terminals of the tuned circuit were connected or short-circuited.

A tuned circuit is used at the grid of the very first tube of a radio receiver. The wire from the antenna is connected to the grid of the first tube. A wire from the ground is connected to the cathode. Between is connected the tuned circuit.

The multitude of different radio signals caught by the antenna are brought in to the grid, and at the same time are applied across the tuned circuit. But because the tuned circuit is between the grid and the cathode of the tube, only those signals which have a frequency the same as the resonant frequency of the tuned circuit can cause a voltage at the grid. All other signals are shorted out by the tuned circuit and are not amplified in the first tube.



But this is merely the first tuned circuit in a radio receiver. The very smallest table-model superheterodyne-type receivers use five or six tuned circuits in conjunction with the other tubes of the set. Larger and more expensive receivers may use twice as many. Clearly, the more tuned circuits employed, the better the receiver can separate the wanted signals from the unwanted ones.

A receiver having as many as six separately adjustable tuned circuits would be very awkward to operate. Nevertheless, a good receiver requires at least that many in order to separate the crowded stations. The superheterodyne receiver, invented by Armstrong during the first World War, has solved this problem so well that is used almost universally today. In the superheterodyne, only two of the six or more tuned circuits need to be adjusted to pick up a given station, and both of these tuned circuits are controlled by a single knob.

The secret of the superheterodyne receiver is that the first few tubes and tuned circuits select the desired signal and change its frequency to one "intermediate frequency," the same for all stations. Then, with all the rest of the tuned circuits tuned to this one intermediate frequency, the necessary additional frequency-discriminating tuned circuits need not be made adjustable. Such nonadjustable tuned circuits are cheaper to make and give better performance.

Frequency changing is surprisingly easy. A small oscillator is built into the receiver, and its frequency is adjustable by the main tuning control. When a station at 840 kilocycles is being received, the local built-in oscillator furnishes a signal at 1305 kilocycles. This local signal is injected into the first tube of the radio along with the received signal at 840 kilocycles. The result of the mixing is a perfect modulated signal at a frequency equal to the difference between the two injected frequencies. The new signal at 465 kilocycles is the intermediate frequency and contains all the modulation of the original signal.

The signal with its frequency changed, after having been selected by the many tuned circuits and amplified by most of the tubes in the receiver, arrives finally at the detector tube. There the audio signal is re-created. The detector measures the amplitude of the modulated signal and produces a voltage output proportional to this amplitude. As the signal becomes stronger or weaker because of its program modulation, the detector gives a larger or smaller output voltage. Therefore the voltage produced by the detector is an accurate replica of the signal originally produced by the microphone in the Terrace Garden.

The loud-speaker requires more electrical energy to fill a large living room with the roar of a football crowd or the thundering climax of a symphony than the detector alone can furnish. This additional energy is supplied by a power-amplifier tube placed between the detector and the speaker. It is called a power tube because it is larger and can control the flow of a greater current than the other tubes in the set.

From the loud-speaker finally emerges the sound of the Terrace Garden music. For hundreds or thousands of miles and through innumerable transformations—through vacuum tubes, and telephone wires, and on the wings of speeding magnetic and electric fields—the signal has traveled. But all the way, between the first microphone and the loud-speaker in your home, the signal was not sound. Sound is an air-carried vibration that can be heard with the unaided ear; the Terrace Garden music was carried the whole distance by silent electric currents and electromagnetic waves.

The loud-speaker which re-creates the sound for the first time in this long journey does so by changing the surging electric currents from the power tube into vibrations of a cardboard cone. The cone, which is behind the front grill of the radio, in turn sets up the sound vibrations in the air. In operation, the varying electric current is sent through a small coil of wire wound on a cylindrical form attached to the cone. Because the coil is placed in a very strong magnetic field from a powerful electromagnet, there is an electromagnetic interaction between the coil and the magnet. The coil is pushed and pulled as the current changes, and it sets the sound-producing diaphragm into vibration with it. This useful electromagnetic effect is the same one that Oersted observed with his wire and compass needle.

Most radio sets use a "dynamic speaker," the kind that was just described. The similarity of its name to that of the dynamic microphone is not accidental, for the microphone is actually a small dynamic speaker worked in reverse. The basic electromagnetic interaction between wires and magnetic fields operates in two ways: a wire moving in a magnetic field generates a current, or a current in a wire placed in a magnetic field causes a movement of the wire. Electronics has many fortunate reciprocal relations such as this.

With the Terrace Garden program delivered to your living room, the job of the engineer, who made it possible, is done. That he has performed an astounding job is shown by the following computation of the total amplification of the signal in going from the microphone to the loud-speaker. Between the microphone and the telephone line, the signal was amplified to one thousand times its original size. In traveling the thousand miles by telephone, it was amplified a total of a million times to overcome the losses incurred in the telephone wires. At the transmitter the signal was amplified again about a thousand times before being sent out by the antenna. But in traveling through space the radio waves spread out and became weaker. When they reached the broadcast receiver the signals needed an amplification of about a million times before they could operate the loud-speaker. Combining these amplifications—a thousand; a million; a thousand; a million—we get a total amplification of a billion billion, or 1 followed by 18 zeros! Only by means of electronics are such enormous amplifications possible. Without electronics, broadcasting never could have been born, and could not exist today.

For the ordinary citizen, radiobroadcasting is the most important application of electronics. Until the war it was also the most important market for electronic equipment. Even now, in spite of television or radar or industrial electronics, the industry connected with furnishing radiobroadcast service to the public promises to remain a major division of the rapidly growing electronics industry.

CHAPTER 5

LONG-DISTANCE TELEPHONE

"LONG-DISTANCE, please"—with these three words there are at your command 10 million miles of long-distance wire and 25 million different telephone numbers in the United States alone. By radiotelephone, most of the telephones in the civilized world are at your disposal, and calls to Europe or Asia or to liners in mid-ocean may be placed with equal ease.

The telephone, from which we expect and get such reliable service that we have long since forgotten it as an exciting instrument, is not primarily an electronic device. There were thousands of telephones in use twenty years before the advent of the triode tube. With luck and good weather, calls between Boston and Omaha were made in 1906, the year the audion was invented. But modern long-distance telephone service came only with the development of two electronic tools: the vacuum-tube repeater to amplify the voice currents as they grow faint with miles of transmission, and the electronic carrier system which makes it possible for one pair of wires to carry simultaneously many high-quality voice channels.

Coast-to-coast telephone service was unknown at the end of the last century, but already the carbon-button transmitter and the magnetic receiver, now still in use, were standard equipment. Except for streamlining and improvements, such as the elimination of batteries and the addition of a manual dial, the instruments used then were not so very different from some in use today.

Each subscriber's instrument was connected to a central operator's switchboard by a pair of overhead wires. The operator at her switchboard would connect the two persons who wished to talk to each other. Voices were converted to electrical signals by the carbon-button microphone through which passed a current supplied by batteries. The voice vibrations at the microphone varied the flow of the current, and these variations were transmitted by a pair of wires to the listening subscriber, for whom the electrical currents were reproduced as sound by the telephone earpiece. The earpiece was like a small radio speaker. An electromagnet pulled on a thin steel diaphragm with a varying force which was in proportion to the changing voice currents in the wires. The result was an audible sound from the vibrated diaphragm which re-created the sound striking the distant transmitter.

Though the basic telephone equipment has remained the same since the nineties, the "hello girls" at the central switchboards have been largely replaced by automatic switching equipment that operates as you dial your number. The thousands of overhead telephone wires that at one time threatened to darken the sky have long since disappeared underground into lead-jacketed cables each holding thousands of wires compacted into a bundle the size of your wrist. Service has improved. Transmitted voices can be recognized. All these improvements were made without the help of electronics, and so far as is now expected, electronics is not soon to be used in ordinary calls within any one city.

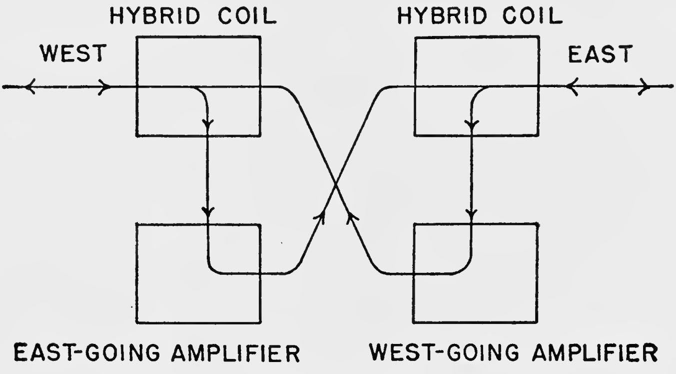
With long-distance calls the situation is different. Transcontinental telephone service first became possible in 1914 with the introduction of electronic amplifiers on the long New York to San Francisco wire circuit. Before that time, the very longest circuit that could be operated was from New York to Denver, or only two-thirds of the way across the continent. This circuit, which used all the available nonelectronic tricks of signal transmission, could give a whisper at Denver from a shout in New York. The distance was almost too great for any transmission at all. The electric currents, never too strong to begin with, nearly died out in the 2000-mile wire path. For transcontinental transmission, the signals surely required a boost or an amplification somewhere on the way if they were ever to get to San Francisco loud enough for use. Telephone engineers, realizing the importance of the problem, worked intensely for several years to find a good telephone relay or amplifier. Several mechanical and electrical devices were built and tested, but their performance was far from ideal. Something entirely new was needed; all the old ideas had been tried.

The audion, announced to the radio world by De Forest in 1906, was the answer. But not until De Forest's demonstration in 1912 did the engineers of the American Telephone and Telegraph Company think of using it for the telephone. Then, realizing its value for repeater amplifiers, they bought the patent rights and went to work.

Not content with its performance, the engineers redesigned the audion, pumped out the gas that caused a troublesome blue glow, rearranged its internal structure, put in a good electron emitter for the filament, and learned for the first time how to use it efficiently in an amplifier. First with three, then with six of the new vacuum-tube repeater stations, spaced over the 3359-mile circuit between New York and San Francisco, the transcontinental telephone line went into operation on July 29, 1914. The "Hello, Frisco!" era began, with numerous demonstrations and wide public interest.

Each repeater station in a long-distance line must amplify both the east-going and west-going messages. Until you think about it, this doesn't sound so hard. Actually, it is one of the difficult tricks in telephone engineering because any repeater amplifier inserted in a telephone circuit can become an oscillator. If it does, it will squeal and howl with earsplitting malicious glee—and make conversation on the line utterly impossible. The effect is the same as that produced by a poorly operated public-address system in an auditorium or dance floor when the microphone is too close to the loud-speaker or when the "gain" is turned up too high. Any amplifier will howl if the amplified signal can return to the input to be reamplified—whether the "feedback" occurs between the east-going and west-going telephone messages or from loud-speaker to microphone in the public-address system.

In the repeater station electrical devices called hybrid coils prevent these unwanted oscillations by separating the signals traveling in the two directions before the signals go to the repeater amplifiers. If the signals passing through the repeater station follow the arrows on the diagram



ONE REPEATER-AMPLIFIER STATION

all is well. But if things go wrong and the signals are able to "feed back" by making a wrong turn at the hybrid coils, the repeater will "sing" as the signal is amplified and reamplified round and round through the two amplifiers, and a squeal will go out on the line in both directions.

Needless to say, the problem of the "singing repeater" was licked in time for the building of the first transcontinental line. But it was a problem that did not stay solved nor will it ever remain completely solved. Each new kind of amplifier or method of sending telephone signals, whether by carrier circuits or by radio links, brings in new ways for repeaters to sing.

Without repeaters, the first transcontinental signal would have dropped to one-millionth of its original magnitude at the far end. With repeaters in the line, the signal dropped to only one-hundredth—which was almost as strong as some signals originating in the same city. If a higher gain had been used—that is, if the repeater gain had been turned up to where there was no transmission loss—the system probably would have sung in spite of the best hybrid coils.

The early long-distance telephone lines were quite simple compared with modern practice. Each conversation was carried by two ⅙-inch diameter copper wires supported by glass or porcelain insulators on the crossarms of telephone poles.

Additional long-distance channels were accommodated by adding more pairs of wires, but the extra wire was expensive and each new pair of wires required another set of repeaters.

The utility and rapidly growing popularity of long-distance telephone service soon required more and more wire circuits between cities. To meet this demand economically, methods of "duplexing" and "multiplexing" several voice circuits on each pair of wires began to be devised. The earliest methods made use of the versatile hybrid coils to place an extra "phantom" talking circuit on top of every two regular circuits. But this wire saving was not enough, and besides it was difficult to make repeaters work well on the phantom circuits.

Electronically operated "carrier-system transmission," invented in the twenties, solved the problem of how to put many conversations on only one pair of wires. Long-distance wire circuits now carry 4, 16, or with the amazing new coaxial cable as many as 480 separate conversations on each pair of wires. Parallel progress in repeater design has resulted in repeaters each of which can handle the many carrier conversations on each wire pair. This double saving of both wire and number of repeaters per conversation makes modern low-cost long-distance telephone service possible.

Carrier transmission of telephone signals is very closely related to radio transmission. It actually is a sort of "wired radio," with each pair of telephone wires carrying the signals of a number of "radio stations." The "program" of each "radio station" is a complete telephone conversation. Thus each pair of telephone wires can carry many conversations at once. While there are many signals on each wire, they do not get mixed up. Just as a radio receiver picks out of the air the one station that is wanted from among those that are not wanted, so carrier equipment separates the various telephone messages on each pair of wires. The only difference between radio and carrier is that with carrier the messages travel by wire all the way.

The enormous savings in wire and station equipment resulting from the use of carrier-system transmission has led to its consistent use on all circuits longer than about 50 miles. For such circuits, the electronic terminal equipment necessitated by carrier is cheaper than additional wires and repeaters otherwise needed for each additional conversation.

A typical telephone carrier system is the "K carrier system," which is one of the newest. At the telephone central office, where the long-distance intercity lines terminate, the local voice signal modulates a high-frequency carrier signal assigned to the particular call. The voice is actually turned into a modulated radio-type signal, which, instead of being sent out over the air, is transmitted over one of the 88 pairs of tiny wires bunched in the special K-carrier-type lead-sheathed cable two inches in diameter. On this same pair of wires in the K system there can be 11 other similar carrier voices, each at a different frequency, and each independent of the others. At the receiving end the 12 carrier signals on each wire are separated from one another. After conversion back to voice frequencies again, they go to the switchboard over the usual 12 different wire pairs. The separation of carrier channels and conversion to voice frequency requires the equivalent of an individual radio receiver for each carrier channel. If all 88 wire pairs in a single K carrier cable were utilized to the full, the one cable would transmit 1056 carrier voices.

Usually in modern carrier-system transmission, the one voice going out and its answer coming back travel over separate wires. In the K carrier system, wire pairs in two separate cables are used. All messages from the east are carried in one lead-sheathed cable and the answering voices from the west arrive in another similar cable. By this trick of separating the two directions, singing repeaters are much easier to prevent and transmission is clearer.

Besides the K carrier, there are several other carrier systems in general use, each developed for some definite need and each using a different type of wire connection. These systems form a historical sequence of successive improvement.

One of the earliest applications of carrier transmission was to the open-wire cross-country lines that were originally built to transmit nothing but the voice frequencies. By "open wire" is meant a line of bare wires supported on poles, crossarms, and glass insulators. By using simple carrier techniques, it was early found possible to add three additional talking circuits to each pair of wires.

The transmission engineers were not satisfied. They reasoned that if three additional channels could be added by carrier to a wire system that was not designed for carrier use, many more could be added if the wire system was really designed for the job.

Experimentation showed that this was the case, and the modern J carrier system using accurately strung open-wire lines places a total of 16 simultaneous conversations in both directions on each pair of wires. The J system is used extensively in the

West where great distances have to be covered and the anticipated telephone traffic load is too light to justify the K system with its expensive lead cable.

In general, where the number of long-distance circuits desired is larger than can be conveniently provided by open-wire systems or where sleet and windstorms are prevalent, the double lead-covered cables and the K carrier system are used. The two cables are hung on poles, placed in clay ducts or tunnels under the streets of a city, or, in the country, plowed right into the ground to a depth of 30 inches or more.

The coaxial cable and its associated carrier system are the latest and most spectacular method of providing wire-communication channels in large quantities over long distances. In the place of a wire pair, the signal is sent over a coaxial unit which consists of a copper tube, a little larger than a lead pencil, through the center of which runs a smaller wire centered in position by tiny insulating buttons. The metal tube and the inner conductor take the place of the two wires of a conventional circuit.

One coaxial unit can transmit as many as 480 carrier telephone voices in one direction, while another unit placed in the same lead cable is used to transmit the 480 answering signals. A typical lead-sheathed coaxial cable contains 6 units. A most important application of "coax" is for long-distance wire transmission of television signals. A single television picture or "video" channel requires as much "room" as 480 voice channels, and so uses the full capabilities of one coaxial unit.

The difference between the transmission ability of a K-carrier wire pair and a coaxial unit is about the same as the difference between the reception of a standard broadcast receiver and an all-wave set able to tune to both the broadcast and short-wave bands. The radio able to tune to both bands can hear more stations: it covers a wider frequency range. Similarly, K-carrier can handle frequencies up to only about 60,000 cycles before transmission becomes too difficult, allowing but 12 carrier channels. Coaxial units operate up to 3,500,000 cycles and can therefore transmit a correspondingly greater number of channels. The upper frequency for a coaxial system is limited by the difficulty in designing repeaters able to amplify an extremely wide range of frequencies. The present coaxial repeater required the development of a special tube to make the 3,500,000-cycle performance possible.

The coaxial repeaters, spaced at 5 to 8-mile intervals, each handle 480 channels at once. The open-wire J carrier system requires repeaters every 50 miles, but each repeater handles only 12 carrier channels. The K system using the lead cable needs repeaters every 17 miles for its 12 channels. Thus in spite of the close repeater spacing, the coaxial line can carry many more channels with fewer repeaters than either the J or K carrier systems.

In virtue of the remarkable performance of coaxial cable for both telephone and television picture transmission, the Bell System has begun a five-year installation program which will finally provide a national coaxial network connecting coast to coast and North to South. Already television programs are being transmitted over the coaxial line in operation between New York and Washington.

When confronted with a water obstacle, wire circuits have to give way to radio, since telephone transmission by submarine cable is not satisfactory for any long distance. Radio links have proved their worth for both short and long hauls.

At Norfolk, Virginia, an ultra-high-frequency—UHF—radio link bridges the Chesapeake Bay to Cape Charles, a distance of about 25 miles, and thereby saves carrying telephone wires 400 miles around by land. Because ultra-high-frequency radio is used on this crossing, it is possible to broadcast with one transmitter the whole 12-channel K carrier signal intact, exactly as it is in the cable. Thus the expense of separating the carrier channels and of operating 12 different radio links instead of one is avoided. At the other end, the receiver feeds the one signal (containing the 12 carrier channels) directly into a K carrier cable.

A similar link from the tip of the hook on Cape Cod connects Provincetown to the mainland, and during the 1938 New England hurricane it provided the only telephonic route to the Cape. Newer and even more spectacular uses of UHF radio links resulted from the war, are now being developed, and they will be discussed in a later chapter.

Have you ever wanted to telephone from your car? You may now do just this under a program to establish two-way voice communication by radiotelephone for trucks, cars, boats, and barges within metropolitan areas and on intercity highways. A telephone and a small transmitter-receiver on these vehicles connects by radio into the general telephone system, so that a subscriber to this two-way mobile service may talk from his car or boat to any telephone number in the city system. Likewise, the mobile unit can be called from any city telephone. By means of mobile radiotelephone, trucking concerns may render faster and more complete service to their customers, contact may be made with doctors while on calls, or tugs and harbor and river craft may be reached by telephone from the company office.

In one city where the two-way mobile service has recently been installed for dispatching taxicabs, the cruising drivers have discovered several fires and have turned in the first alarm by radio-telephone—an unexpected dividend from the service. An extension of the service for use along major highways is being set up and will benefit trucking companies, intercity bus lines, and even boats operating in any near-by navigable waters.

Radiotelephone links to every country in the world having 75,000 telephones or more have been established. Powerful transoceanic transmitters in New York connect with London, Moscow, Paris, and Berne; transmitters in Miami connect with our South American neighbors, with Rio de Janeiro and with Buenos Aires; and from San Francisco the whole Pacific area is covered: Sydney, Manila, and Chungking. Beam antennas squirt the radio energy from the transmitter to the distant receiver over global great-circle paths. Unfortunately these long-distance radio links are expensive to use, primarily because only two, or at most three voices may be carried over one transmitter. Moreover, it does not seem possible, for technical reasons, to send any more voices. Cheaper and better mass handling of transoceanic telephone messages, comparable to coaxial carrier-system transmission, is a development yet to come.

The telephone system presents an amazing picture of change and technical progress. Now while the first coaxial transmission lines are just being put into use, the Bell Laboratories of the telephone company are experimenting with new means of transmission that may make even coaxial cable obsolete. UHF radio links and microwave guides are two possibilities being tested. Electronic engineering of a high order is being continuously expended to examine such ideas and to develop them into reliable and economical systems of communication.

CHAPTER 6

RECORDED MUSIC AND ACOUSTICS

It's in the groove! Captured for your convenience on a plastic phonograph record, hot jazz, or austere symphony may be yours for the playing when you want to hear them. This is the gift of the modern electronic phonograph, the one musical instrument that anyone can play.

The electronic phonograph ranks next to the radio as the most popular source of musical enjoyment. Over a hundred million record disks a year feed the juke boxes and the home record players. Radio manufacturers, taking advantage of the demand, have brought out large and small combination radio-phonograph sets. Record manufacturers compete for the market with new record materials, outstanding artists, and gorgeous picture covers on the record albums.

Home recording machines, built into the radiophonograph, have been introduced and may become as popular for preserving family voices as home movies have been for visual record. An added attraction is their ability to record radio programs, so that you may build up your own library of recorded music as you hear it.

Having almost completely dominated the recording field for many years, the conventional disk-type shellac phonograph record is about to meet some competition. New recording methods and new recording mediums have been used in the war and are now being developed for civilian use. Magnetizable wire, embossed cellulose film strip, and magnetizable coatings on paper or cellulose tape are the newest recording mediums. The cellulose-covered disk, long used in radio stations for transcription work, is already in use in the few prewar home recording machines. Noiseless plastic phonograph disks now on the market have done away with the objectionable needle scratch so familiar with conventional abrasive-filled shellac records.

Electronic amplification applied to phonograph recording and reproduction was the most important improvement made on the phonograph since its invention by Edison in 1876. No more is it necessary for the orchestral performers to huddle before a large horn to make the recordings. Nor does the tiny wiggly groove have to furnish directly the energy for the reproduced sound when records are played with electronic amplification and pickup. Brilliant, full-bodied reproduction of music, nearly as good as hearing the original performance by the artist, is obtained with electronically recorded and reproduced phonograph records.

Phonograph recordings are made in a studio with the same kind of microphone and amplifier used in radiobroadcasting. The amplified electrical replica of the sound is used to vibrate the stylus of a recording cutter which carves the sound groove in the surface of the rotating wax original. By a process of electroplating, chromium-faced molds or matrices are made from the wax disk. These molds are then used to press out the final shellac records.

Sound may be recorded in a groove in either of two ways. In the "lateral" recording method the needle moves from side to side, tracing the music in the groove as the record revolves, while in the "hill and dale" method the needle moves up and down in the groove. The phonograph records that we are all familiar with are lateral recordings. Hill-and-dale recording was the original method invented by Edison, and it is still used in the Ediphone and Dictaphone dictating machines used in business offices.

Ten and 12-inch disks are standard for home phonographs and they are turned at a speed of 78 revolutions per minute.

High-quality, long-playing commercial transcription records for broadcasting use either hill-and-dale or lateral recording on 16-inch disks turning at 33⅓ revolutions per minute. The slower speed and greater number of grooves in the large records allow much more to be recorded on each one, but good slow-speed turntables are too expensive for general home use.

When records are played, the music is taken from the groove by a steel needle or a sapphire stylus at the end of the tone arm. The wiggly groove vibrates the stylus which in turn actuates a Rochelle salt crystal, or a magnetic, or some other kind of electromechanical transducer to produce an electrical signal. The action is exactly like a microphone, with the moving stylus taking the place of the diaphragm. One phonograph pickup utilizes a beam of light reflected from a tiny mirror on the stylus into a phototube to generate the electrical signal. The tiny voltages from the pickup are electronically amplified until they are powerful enough to operate a loud-speaker. Except for the complaints of neighbors, the loudest symphony could be reproduced full-strength electronically from records in your living room. The tiny replica of the music in the sound groove furnishes the pattern for the music; electronics adds the power.

Steel needles, thorn needles, jeweled needles—have you ever wondered why there are so many conflicting claims? First, why do steel needles have to be renewed after each playing of a record? The answer goes back into the history of phonograph reproduction. Before electronic amplification of records was widespread—which was not many years ago—the needle had to be held down into the groove with enough pressure for vibrational energy obtained from the groove to drive directly the sound-producing diaphragm. In this type of reproduction loud passages require a vigorous diaphragm movement, and correspondingly large lateral forces at the tip of the needle. When, at the beginning of a record, a new needle is inserted in the tone arm, the needle point does not fit the groove exactly because the microscopic cross section of the record grooves differs. At the infinitesimal areas of contact, enormous pressures are developed. The few ounces' weight of the tone arm, when concentrated at the needle point for the first few turns of the record, produce pressures of 25 to 50 tons per square inch—enough to destroy the impressions recorded in the shellac surface. To prevent this, an abrasive is incorporated in the shellac of the record; and this abrasive, during the first few turns of the disk, grinds the point of the needle into conformity with the cross section of the groove. The needle, "broken in," then plays through the record with a minimum of wear on the disk, though the abrasive continues to wear the point of the needle while it plays. If this worn needle is then used on a new record, the point does not fit the new groove. The sharp chisel edges of the needle's worn point will wear down the new record rapidly, and even worse, the blunt worn-down point of the needle will require many more revolutions of the record before the abrasive can reshape the point again. This is why the record companies caution you to use most steel needles for only one playing.

To make a long story short: lack of electronic amplification requires heavy tone-arm pressure, which in turn requires the inclusion of an abrasive in the composition of the record.

With electronic amplification the record groove and needle do not have to supply directly the sound energy, and lighter needle pressures may be used. Then because the pressure at the point of the needle is low, the needle will not ruin the record if it does not fit the groove exactly, and there is no need for the needle to wear. Harder materials can be used for the point of the needle—hard tungsten alloys, or sapphire jewels—which wear very slowly in spite of the action of the abrasive. This is the theory behind the "permanent" needles. However, a permanent needle can be used safely only with a light-weight electric tone arm. If the tone arm is not sufficiently light, the hard point will soon ruin the records.

The abrasive in the records also causes the hissing noise or needle scratch that is especially noticeable in the soft passages of music. The full musical brilliance of a recording can be heard only if the tone control of the reproducer is set to give the treble notes their natural prominence. At the same time, the needle scratch due to the abrasive in the record appears at its loudest. Little can really be done about this in records containing an abrasive. The high frequencies carrying the musical color and overtones cannot ever be completely separated from the scratch. Cactus-thorn needles are sometimes used, and they produce a mellow, scratchless tone—but the high frequencies are lost in the process. More complicated metallic needles, employing a thin resilient section near the point, attempt to eliminate scratch by the same expedient.

Scratchless reproduction of records containing the full orchestral brilliance requires a record without an abrasive. Such disks, pressed from pure, flexible, translucent vinyl plastic have recently appeared on the market, and in a high-quality record player they should give superior performance.

There are other types of disk records besides those pressed from shellac or plastic. Home recording outfits, the new Sound-Scriber office dictating machine, and broadcast-transcription machines all record by cutting the sound groove into the same surface that will be used later for playing. For this purpose record disks are made with a plastic coating over an aluminum, paper, or glass base, or, in some cases, disks of a soft metal such as aluminum with no coating at all are used. The sound track is made either by cutting into the record surface and removing a thin shaving of material, or by pressing a permanent groove into the surface with the recording stylus but removing no material. The two methods are known as record cutting and embossing.

The newer methods of sound recording, some of which are being groomed for use in home recorders and others which are being perfected for commercial applications, use a variety of materials. Magnetizable wire, magnetizable coated tape, and a continuous strip of cellulose with an embossed track are used in several recorders under development or already perfected. Unlike the disk records, the success of these newer methods depends entirely on electronics.

Sound recording on magnetizable steel wire or tape was perfected and produced commercially during the war. The basic idea is very old. Magnetic recording was invented by Valdemar Poulsen in the nineties for sound recording and was used later for recording high-speed radio signals.

The modern device, which both records and reproduces, employs a steel wire no thicker than a human hair. One spool of the wire can hold up to 66 minutes of continuous recording. The wire carries the sound record, and as it reels from one spool to the other it passes over a combination magnetic pickup and recorder. The wire carries the sound patterns in the form of small magnetized regions, the amount of magnetization duplicating exactly the vibrations heard by the recording microphone.

To record, the wire is drawn at a speed of 16 inches per second through the magnetic recording head, which impresses the electrical signal from the microphone magnetically on the wire.

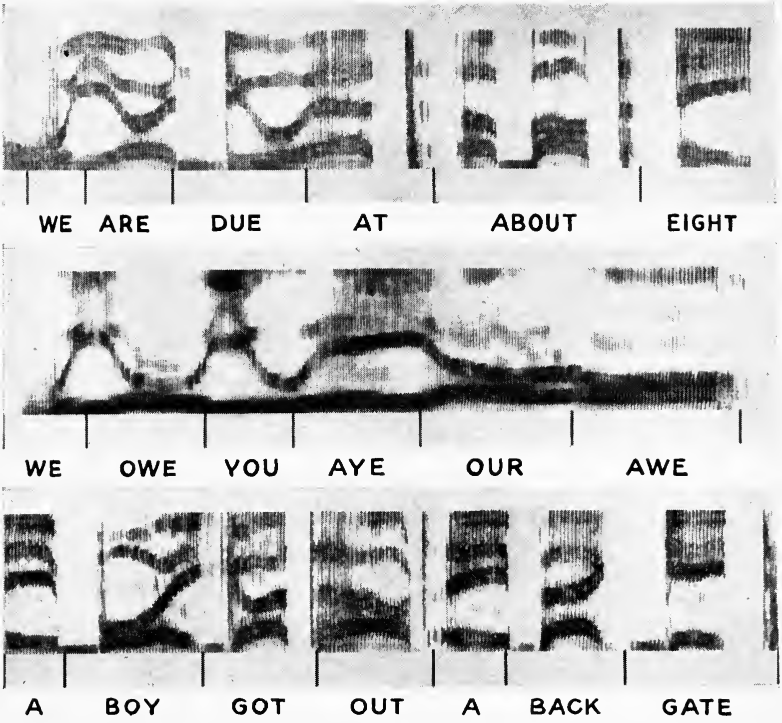
To play back the recorded signal, the wire is first rewound, and then is run through the pickup in the original direction. The current induced by the passing magnetic pattern is converted to sound through an amplifier and loud-speaker. The magnetic record may be played over repeatedly with no deterioration. When the record is no longer wanted, the sound may be magnetically wiped off the wire, and the wire may be used again for a new recording. Any part of the wire record may be magnetically erased without harm to the sound recorded on adjacent parts.

One version of the device, for recording only, is a battery-operated unit in a plastic case of a size that allows it to be carried in the pocket. It uses a lapel or hand microphone. Up to an hour of sound record may be made. It would be useful for dictation or for making a permanent record of interviews and special events.

Paper tape or plastic ribbons containing powdered magnetic material are under development for use in magnetic recorders, and will operate in much the same fashion as the metallic wires and tapes. The method was invented in Germany before the war. One possible advantage of tape for records is that sections can be cut out, or spliced in, by pasting. The paper tape may also be more uniform and cheaper to manufacture than the wire.

The Recordograph, a 50-pound portable instrument, embosses a lateral sound track on a cellulose tape which looks much like clear movie film. It can record several hours continuously on one reel of recording film, and can play back immediately. It operated under fire to record the Normandy and Pacific invasions for later broadcast to the world. The Recordograph film is in one continuous strip, 50 feet long, rolled into a loose skein. The skein is supported by, and rotates loosely over, four pegs as the film is pulled from the inside of the skein to the recording stylus and is then wound back onto the outside of the skein. By this trick, a continuous track, round and round, may be recorded as the stylus embosses the grooves, beginning at one edge of the film and slowly embossing tracks to the other side. Immediately after recording, the sound may be played off. Film speeds of 20, 40, or 60 feet a minute are used, the higher speeds giving higher-fidelity reproduction, while the lower speeds give a longer recording time. Up to 115 sound tracks may be embossed side by side on one film. The Recordograph was designed particularly for government, broadcast, educational, and industrial use.

The movies have long used electronics to give a voice to their



Try saying a few of these sentences transcribed as visible speech, and you will find that the patterns begin to make sense. As you say "boy," notice the seeming rise in inflection on the "ee" part of "boh-ee." Then look for the rising dark line in the latter half of the word "boy," transcribed in the last sentence. The letter "T" comes out as a fuzzy vertical line. Steady vowel sounds appear as horizontal bands, the very lowest giving the pitch of the voice, while the higher bands give descriptions of the overtones formed by the oral and nasal cavities. Look for vowel patterns, such as the "aa" sound in eight, aye, and gate. (Courtesy Bell Telephone Laboratories.)

Modern Hospital X-ray equipment is efficient and versatile. This unit can direct its beam horizontally, as shown, or can be rotated to direct its beam downward through the examination table. When all is ready, the nurse steps into an X-ray proof cubicle and triggers the exposure by remote control. (Courtesy Westinghouse Electric Corporation.)

pictures, first with the music on large 16-inch phonograph disks, and now with a photographic process called "sound on film." By this method a variable slit is formed between two movable vanes of metal which are actuated by the amplified electric currents from the microphone. A beam of light passing through the slit is modulated either in intensity or in width of the beam in accord with the sound. The modulated light beam is photographically recorded along the edge of the movie film, at the side of the picture, and the recorded image is called the sound track. Two types of sound track are produced. One is a thick black line with a saw-tooth edge depicting the sound vibrations, the other is a series of crosswise markings of lighter or darker shading. Both may be played back with the same equipment. When the film is projected at the movie house, a beam of light shines through the sound track as the film moves smoothly through that part of the projector. A photocell senses the variations in intensity of the light beam and produces a voltage. The voltage is in turn amplified and fed to loudspeakers to give the sound. Sound on film is a very high-quality, though expensive, method of sound recording.

Good sound reproduction on the record, or in the electronic circuit, does not insure correct reproduction at your ear. Have you ever noticed the increased brilliance of music when you are sitting directly across the room from a radio? Have you observed that some rooms make music sound better than others? The science of acoustics deals with just such problems of airborne sound.

Acoustics is of deep concern to the electronics engineer, because he knows that his most careful designs can come to nothing if in the end the sound waves fail to convey an accurate musical message to the listener. A loud-speaker system in an auditorium is of little help if there is a bad echo from the rear wall. Acoustical science, in its studies of sound and musical instruments, is dependent in turn upon electronic instrumentation.

Here are some hints for the best acoustical performance of your radio or electronic phonograph. First the instrument: A big box or cabinet is more than mere looks. It really makes a difference because only with a big box or enclosure is the loud-speaker able to reproduce the deep bass notes. A large, powerful loud-speaker is required to re-create the loud passages of a symphony without rattles and distortion. Some of the very best reproducers use two loud-speakers, a large "woofer" for the very low frequencies of the bass, and a small "tweeter" for the treble notes.

The room and the placing of the radio or phonograph in the room have a considerable effect on the reproduction of high-quality music. A large room is better than a small room. The loud-speaker cabinet should be located with a thought to where the listeners will be sitting when music is played. The higher frequencies, which carry the brilliance, squirt out from the speaker in a straight line and are absorbed as they strike the furnishings of a room. The middle and lower frequencies on the other hand tend to diffuse and spread throughout the room. Therefore in most living rooms the best solution is to place the speaker unit at the far side, preferably in a corner, and as far away as possible with an unobstructed sound path to the listener. A room bare of furnishings would be too reverberant for good musical reproduction—room echoes would cause notes to "hang on" after they were sounded. A living room, furnished in the usual manner, will not have this difficulty, and in fact may instead be somewhat "dead" as the sound is absorbed a little more rapidly than optimum listening would require.

"Fidelity" is the term describing the accuracy of the tonal and musical reproduction of a radio or phonograph. If reproduced music contains musical sounds of both the highest and lowest pitches that the ear is sensitive to, if these sounds are in the same proportions that existed in the original music, and if in the reproduction process no extraneous sounds have been added, then it is said that the instrument has high fidelity. Most sets, because they do not reproduce the extreme high and low frequencies, are of medium fidelity.

Manual variation of the tone controls on a set has a further influence on its fidelity in proportion to the amount by which the controls are able to accentuate or diminish the treble or the bass. If the natural brilliance due to the treble frequencies is cut out by the tone control, the reproduction becomes "mellow." Many people like this, even though it is not an accurate reproduction of the music. While purists of the tone control insist upon the full natural sound to the best capabilities of the instrument, careful tests of musical preference have shown that even some concert musicians like their music mellow. Be that as it may, if you have a good radio or phonograph, it is your privilege to be your own orchestral conductor, and to balance as you wish the crash of the bass drums with the piping of the piccolos.

Cheap instruments often demonstrate a defective reproduction. "Booming" bass which emphasizes a single pitch whenever the orchestra strikes it is common. Poor speaker design is the cause. Only a few of the very best electronic reproducers of sound can actually reproduce the very loudest passages without distortion evidenced by an unpleasant rawness and blurring of the music when the volume is turned up. Though it makes for an expensive instrument, good design can give pure, clear music at the loudest volume levels—and such sets are a revelation to hear.

There are actually only a few good sources of high-fidelity music available. While the sensitivity of the ear extends to about 16,000 cycles per second, phonographs cut off around 5,000 cycles where scratch becomes oppressive. Ordinary broadcast reception is usually only a little better. On the other hand, FM broadcasting, which will be discussed more completely in a later chapter, will transmit up to 15,000 cycles. But whether this high-quality, high-fidelity music survives its trip through the electronic channels of a radio or amplifier and through the air to the ear is a matter of electronic design and acoustics.

Have you ever indulged in the popular American pastime of singing in the bath, being secretly proud of your vocal ability, only to find when you emerged and tried it again in any other room not so reverberant that your ability has disappeared? Instrumental musicians and concert singers are affected in the same way by different rooms, and they prefer to perform in a small highly reverberant one in which they are able to hear themselves easily. In a large concert hall or auditorium the musician cannot hear himself, and the result is the full list of the artist's woes: he finds it's harder to hold pitch, he is tense and unable to relax, he feels a low vocal efficiency, and he forces his voice. He does not doubt his ability. It is merely that the acoustics of a large auditorium make a musical performance difficult.

A most interesting electronic solution to this acoustical dilemma was invented by the singer Paul Robeson and has been used experimentally in the theater and concert hall. A small microphone in the footlights picks up the singer's voice, which is amplified and projected out to the performing artist from a loud-speaker located about 50 feet away, off in the wings of the stage. The volume is held low, and only the artist can hear it. The effect on the artist of this small electronic echo is remarkable. He can hear himself as in a small room again, and he sings with ease and sureness. The audience, which never hears the echo speaker, is treated to a better performance than would otherwise be possible. Artists who have been persuaded to try the experimental technique have been most enthusiastic. Usually when they first try it out they won't go home, saying, "I could sing all night!"

Even more spectacular effects for the theater have been demonstrated by Harold Burris-Meyer, of the Stevens Institute of Technology, who perfected the Robeson technique. Subsonic sound—sound of such a low frequency it cannot be heard but only felt—has been used to set up a feeling of tension in an audience. A subsonic drumbeat in *The Emperor Jones* kept the audience unknowingly on edge while Jones was running through the voodoo forest. Voices have been remade electronically to give other inhuman vocal effects. In one demonstration, three witches in *Macbeth* were given the following startling voices: one higher-pitched than a soprano, one with a quality somewhere between the sound of a rock crusher and a whisky baritone, and the third lower than a basso.

Leopold Stokowski has sometimes worn earphones while directing, and listened to the sound of his orchestra as it was picked up by microphones. Then at his podium he has had gain controls for the different mikes so he could adjust them to produce the best tonal balance for the orchestra as a whole, an artistic task that is otherwise left to the broadcast technician.

Other tricks with electronics and acoustics have come from the Disney Studios in Hollywood. *Fantasia* presented one of the most elaborate demonstrations of three-dimensional sounds—sounds with a "depth" which seemed to come from all directions—for those fortunate enough to hear it with all the acoustic tricks installed. In *Make Mine Music* a whale sang simultaneously the several parts of an opera—each part with Nelson Eddy's voice electronically recast and transposed. At the finale there was a grand chorus of 400 Nelson Eddy voices!

Acoustics and electronics have only begun their development in the field of music and entertainment. Sound-recording and reproducing devices of all kinds are undergoing rapid change and development. The possibilities of electronic musical instruments such as the Hammond Organ and the Novachord have barely been touched.

The theater and concert hall, as they install electronic aids, should benefit increasingly. As for us, we can look forward to more and better acoustical values in our entertainment.

CHAPTER 7

ELECTRONICS IN INDUSTRY

STEP into a factory and watch the electrons at work: In a steel mill a wide strip of shining tin plate destined to become tin cans is racing a thousand feet a minute to the "flying shears" where it is cut into sheets and stacked. See that hood bridging the shining strip with the bright light showing out from under? Inside are electron tubes at work finding pinholes and marking them so the defective sheets may be rejected. A welding machine in an aircraft factory is stitching together difficult-to-weld sheets of stainless steel. Electron tubes in the black cabinet standing behind the machine control the current and time the welds to a fraction of a second, to insure strong, uniform welds without danger of weakening the metal by excess heat. At an aluminum plant, tens of thousands of kilowatts of electric power, enough for a small city, arrive over a special high-tension line direct from the near-by hydroelectric station. Inside the electric substation of the plant, where the power is received, row on row of steel tanks convert the power from alternating to direct current for use in the electrolytic extraction process for aluminum. Electrons at work inside those steel shells are performing the conversion.

In industry, electronic devices inspect materials, measure quantities such as colors and temperatures, control machines, and convert electric power from one form to another. Already the diversity of applications is too wide to catalogue, though the full potential use of electronics in industry has only begun to be explored. New processes and new industrial problems present opportunities for electronic assistance. Old ways of doing things can often be improved.

The devices of industrial electronics consist of a number of electronic building blocks assembled to perform specific functions. The combinations are endless, but the blocks are comparatively few. Once we have mastered functions of the blocks, the solutions to industrial problems, in some cases, come automatically.

Take for example three electronic building blocks, a triode tube, a photoelectric cell, and a relay. A photocell and a relay can open doors for you as you cross a beam of light. Nearly the same device will ring a gong in the boiler room to tell the fireman that his furnace is producing too much smoke, while a photocell and a triode-tube amplifier can convert the modulated light beam from the movie sound track into an electrical signal suitable for a loud-speaker.

Electron tubes deal only with electrical voltages and currents. In order to control a machine or process electronically some measurement of what is happening must be converted into an electrical quantity. Measuring instruments of this kind are the first type of electronic building blocks.

The most important is the photoelectric cell, or the "electric eye," which converts variations in light intensity into an electric signal, just as a microphone converts sound. Within the clear

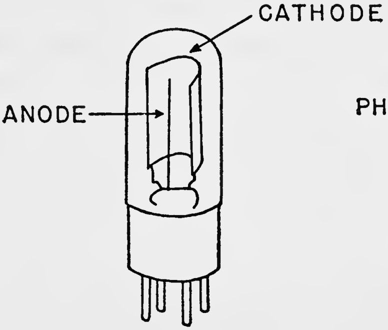
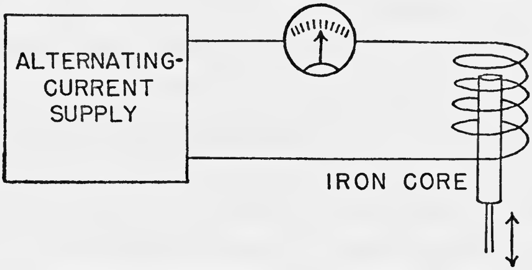


PHOTO CELL

glass bulb are two electrodes: a curved metal sheet and a wire in front of it. Light falling on the photosensitive sheet releases electrons. If a positive voltage is applied to the wire a current will flow, in proportion to the amount of light, producing an electrical measurement of the light and any variations in it.

There are other devices which also give "senses" to an electronic instrument. An iron core moving into a coil of wire will vary the amount of alternating current that can flow through the coil. The position of the core can be determined by the reading of the meter measuring the current. If the movable core is attached to a flexible diaphragm the combination will measure liquid pressure. Again, because the electrical resistance of wires increases as the temperature goes up, thin platinum wires in "resistance" thermometers are used to measure high temperatures. Similarly, when a thin wire is stretched, it becomes longer and thinner and its electrical resistance increases. From a tiny wire of this kind cemented onto the surface of an engine mounting or on a spar in an airplane, electronic instruments can measure and record the tiny variations in the resistance of the wire as the part underneath stretches in operation and stretches the tiny wire with it. The B-29 Superfortress would have been



impossible without data on strains and stresses collected by such electrical strain gauges.

Microphone-type measuring instruments are used to measure noise and vibration. The microscopic roughness—or smoothness—of finished surfaces is measured with something very like a phonograph pickup which produces a voltage proportional to the roughness when pulled across the surface.

These are but a few of the very many ingenious devices used to make electronic instruments aware of their surroundings; we will come across more later.

A phototube or other measuring device usually furnishes only a tiny electrical signal, too small to be used directly for any control purposes. Amplification is therefore needed before equipment can be operated. Two kinds of amplifiers are available. The triode vacuum-tube amplifier is the most important and is one with which we are already familiar. As we have seen, it acts as a throttle to control a heavy flow of current through its cathode-to-plate circuit in accord with the voltage at the grid. The amount of current that it allows to flow varies in proportion to the change in grid voltage.

The thyratron relay, which is the other kind of electronic amplifier, acts differently. The thyratron tube is very much like a triode tube—it has a heater, cathode, grid, and plate—and it is connected to the batteries and circuit in the same way that a triode is. Its one difference is that the bulb does not contain a high vacuum. It is a gas tube and it contains a little argon or neon gas at a low pressure. The presence of the gas causes the thyratron to behave very differently from the triode. While the triode controls the current passing through the tube with a smooth valvelike action, the thyratron acts like a switch. It is either all on or all off. The explanation goes like this: When the grid of the thyratron is many volts negative, no electrons can leave the cathode. When the voltage on the grid becomes less negative, a small electron current from the cathode begins to flow until a point is reached where the tube "triggers." Then full current flows and the interior of the tube lights up with a glow.

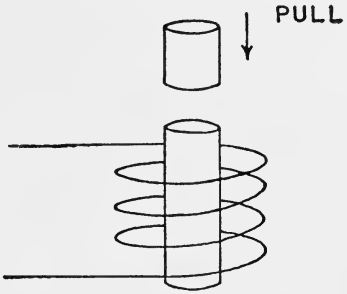
Triggering of a thyratron occurs when electrons leaving the cathode are able to pass through the grid in large enough numbers to "ionize" the gas in the tube. Ionization, which is essential to the operation, is the same thing as the "blue glow" that caused trouble in the early audions when too much voltage was put on the tube. When a speeding electron strikes a gas atom hard enough, it will knock one of the electrons out of the electron shell surrounding the atom. There are then two negatively charged electrons and one positively charged atom fragment, called an ion. In the thyratron tube the two electrons now speed off toward the positive, attracting plate; while the oppositely charged ion migrates more slowly toward the negative cathode which is attracting it. Each of the two irresponsible electrons soon collides with another gas atom, creating additional electrons and ions. It is a cascade process which in an instant fills the interior region of the thyratron with a cloud of ions and electrons.

The negative electrons moving in the one direction and the ions in the other can carry a heavy current through the tube, usually many times greater than if the same tube were used as a high-vacuum tube. But to offset this advantage is the difficulty that, once the tube is triggered, the grid has no further control. Unlike the triode, making the grid negative now has no effect on the current. To cut off the current the voltage supply for the plate must be removed. An easy way to make the tube go out is to use a pulsating on-and-off voltage on the plate; then the tube will go out almost immediately whenever the grid is again made negative.

To have the choice of these two different kinds of amplifiers is the electronic engineer's good fortune. In most industrial applications one of them is usually definitely superior to the other. When a phototube is used to read the flickering light from the passing sound track of a movie film, proportional amplification is required to preserve for reproduction the exact sound-pressure variations heard by the microphone. But when a phototube is used to count boxes passing on a conveyer as they block a beam of light, an on-off response is needed and the thyratron-relay type of amplifier is better.

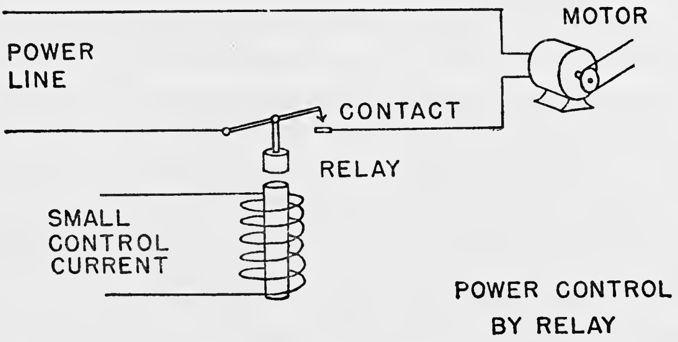
The electronic controller needs muscles. The relatively small electric currents from the amplifier—vacuum triode or thyratron—must be converted to physical action. Electric motors must be turned off or on; levers must be actuated.

The electromagnet is the simplest kind of muscle. It is a coil of wire wound on an iron core, part of which is movable. When a current flows through the coil, the two pieces of iron core become temporarily magnetized by the influence of the current and attract each other.



Sometimes the force and movement of such a solenoid is enough to do a control job such as turning on the water in a photocell-actuated drinking fountain.

If bigger "muscles" are needed, the electromagnet can close a contact and thereby furnish electric current to a powerful motor.



This is an electric relay, a valuable tool for the industrial engineer. The thyratron-type amplifier is often called a thyratron relay because it has this same "all on or off" response as the electric relay. Electric relays are also amplifiers, since large currents through the contacts are controlled by small currents in the winding. In some special cases phototubes or other measuring devices are able to furnish directly enough current to operate an electric relay; then no electronic amplification is needed.

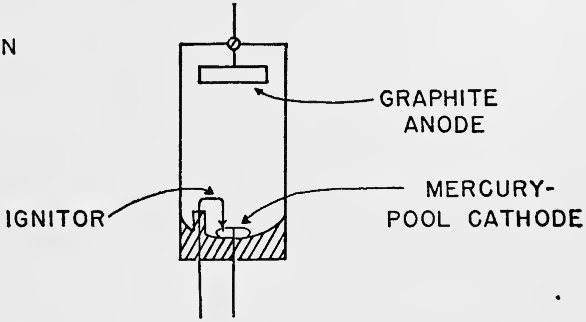
The engineer combines all of these electronic building blocks into an almost infinite number of combinations in order to perform specific tasks of industrial measurement and control.

A photocell placed at the receiving end of a beam of light can open doors or count boxes on a conveyer. In a Michigan plant one hundred photoelectric units are sorting 80,000 pounds of beans each day. Beans are picked up by suction from tiny holes in the circumference of a rotating drum. As the drum rotates, it carries the beans up to the sorting eye for inspection. When a white bean acceptable for market passes, it is allowed to go on. When a dark or discolored bean comes up, the phototube causes a metal finger to flip it into the reject chute.

Full-color pictures in magazines and books are made by printing four or more colors exactly on top of one another. If the colors are out of position by more than a few thousandths of an inch, the picture is spoiled. Electronic-control equipment is used to adjust the presses so that the different colors "register" in spite of differing paper tension, humidity, and temperature, or speed of the press. A tiny mark is printed on the edge of the sheet in the first color used. Then as the continuous strip of paper passes through the press, a phototube at the next printing cylinder checks the position of the mark. If the mark arrives too early or too late the phototube and a thyratron relay energize a small reversible motor which makes a correction. Identical control equipment is used to register each of the following colors.

The ignitron is a heavy-duty electronic switch of many uses. It can change alternating current into direct current and back again. It controls the heavy currents used in electric resistance-welding machines. It is the heart of an important type of motor-speed regulator.

IGNITRON
TUBE



Inside the steel can enclosing the ignitron there is a mercury pool at the bottom with a pointed ignitor electrode of boron carbide dipping down into it. At the top of the can is a disk of graphite for the anode.

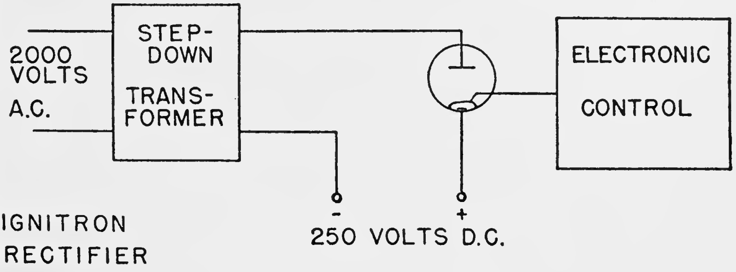
An electric arc or spark between the mercury pool cathode and the anode conducts the current through the tube. The mercury vapor present ionizes and assists the conduction. No heated cathode is needed to supply electrons in the ignitron, because the "cathode spot" formed on the mercury pool at the one end of the arc is among the best electron emitters known.

The ignitron is started by applying a rapid positive pulse of voltage to the ignitor electrode. A tiny spark forms, and if the anode is also positive, the tube "fires" and many amperes can be passed. The current through an ignitron is a torrent compared with the small fraction of an ampere that a high-vacuum tube the same size can pass. As in the thyratron, conduction continues until the voltage is removed from the anode.

Electric power is most easily generated and transmitted in the form of alternating current. Alternating-current generators are simple and efficient, and A.C. voltages are easily stepped up or down by transformers for transmission. But for many chemical processes, such as the electrolytic refining of aluminum, direct current power is essential and the alternating current must be converted to direct current. This can be done with an A.C. motor driving a D.C. generator. However, since its commercial introduction in 1937, the ignitron has become the preferred power-conversion device. In contrast to rotating machinery, the ignitron has no moving parts, is more reliable, has less vibration and noise, and has greater efficiency at light loads and higher voltages.

The expansion of aluminum refining during the war required an immediate installation of new converters capable of changing 2,000,000 kilowatts from alternating current to direct current. The use of rotating machinery was ruled out by material shortages and urgency. In this gap, electronic converters and predominantly the ignitron gave a rapid and efficient solution. An estimated 20,000 tons of steel and 4,000,000 pounds of copper were saved by their use, since the electronic converters contain so much less of these metals than do motors of equivalent capacity.

The ignitron produces direct current from alternating current by a process called rectification. A transformer first changes the A.C. voltage to the desired level, say from 2000 volts down to 250 volts. The 250-volt current induced in the secondary winding of the transformer is alternating or changing direction like the original current; but with an ignitron switch inserted in the circuit, the tube ignites only when the current is surging in the one direction, it blocks off any reverse flow, and the current is rectified. The electronic control fires the tube at the proper instant just as the current begins to flow in the desired direction. When the current changes direction, the tube goes out. By using two tubes in a slightly more complicated circuit "full-wave" rectification occurs and use is made of both directions of current flow.



As an "inverter," the ignitron can do the reverse of rectification. Several ignitrons, acting as versatile switches under electronic timing control, can take current from a D.C. line, and by switching back and forth at a specified frequency, can convert it to alternating current. Ignitron inverters are especially useful for passing electric power from one A.C. system to another at a different frequency. Steel mills, generating their own power at 25 cycles A.C., can obtain additional capacity by tying in with the 60-cycle public-utility power system. The 60-cycle power is first rectified by ignitrons, and the D.C. output is fed to a set of ignitron inverters operating at 25 cycles. One great advantage of the method is that the two power systems need not be exactly in step, as they would have to be with rotary converters.

No single kind of industrial electronic equipment contributed more to the nation's war output than electronic-controlled resistance welding. The method speeded up the making of liquid-tight and gas-tight metal joints by 400 or 500 percent. The welding of the new aluminum alloys and stainless steels would have been impossible without the precise timing and heat control made possible by electronics.

Resistance welding unites metals by the application of pressure and heat. Electrodes clamp the two sheets at the point where the weld is to be made, and the passage of a controlled amount of current between the electrodes momentarily melts the metal sheets at their point of contact. When the current stops, the metal "freezes" and the weld is made. Too little current will give a weak weld, while too much will heat too big an area and spoil the strength of the carefully heat-treated alloy. With rollers instead of pointed electrodes, continuous seam welds are made in which the metal is joined in almost the same way that fabrics are stitched on a sewing machine. Seam welds would be utterly impossible without electronic control.

No weight is added to the material by resistance welding and fewer handling operations are required than with other methods of metal fabrication. Speed and consistent quality are other advantages. The use of ignitron tubes to switch the momentary heavy welding currents makes possible the necessary split-second electronic timing of the duration of the welding cycle. With ignitron tubes, no moving parts or heavy-current contactors are needed. There is less maintenance of equipment than when mechanical switches are used. But most of all, the exact electronic control of current improves the quality of the weld.

The perfect adjustable-speed electric motor for operation on alternating current has yet to be invented. Engineers for years have been trying to duplicate in A.C. machines the ease of speed regulation inherent in the D.C. motor, with varying success.

A flexible solution to the problem of a variable-speed A.C.-powered motor has been found in the electronic adjustable-speed drive. This method combines an electronically controlled thyratron rectifier and a D.C. motor, and now gives a better and more convenient motor control than was ever possible with straight direct-current equipment. The motor speed depends on the voltage. Through control of the instant in the alternating-current cycle that each thyratron fires, the amount of current passed in the swing is regulated. This measured amount of rectified electric power drives the motor at the desired speed. Starting, acceleration, and speed are all controlled by a set of buttons and a knob on a small control panel at the side of the machine with which the motor is used.

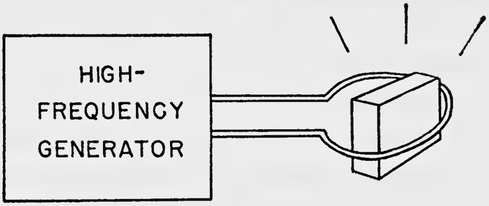
Motor speed is controllable over a 100-to-1 range, with stepless control, whereas alternating-current motors can be built only with speed adjustments at certain fixed intervals, an expensive and unsatisfactory process. In electronic adjustable-speed drive the full torque or turning power is available at low speed; protection is given against overload, short circuit, and low supply voltage. The electron tubes last about five years in ordinary use before replacement is needed.

Electronic drives have been mostly used to turn lathes, drill presses, precision grinders, and automatic screw machines, but it is certain that they will find an important place in every industry where adjustable-speed drives can be used to an advantage.

An object can be heated more rapidly by electronic high-frequency heating than by any other practical means. A 2-inch bar of steel can be brought to the melting point at its surface in half a second—so rapidly that the inside is still cold. An 8-inch stack of oak boards piled up in a gluing press can easily be brought to the 300° F. glue-setting temperature in five minutes. For the same job, hot plates at the top and bottom of the stock heated to the charring temperature of the wood require 20 hours to bring the center up to temperature. Electronic high-frequency heating is now performing tasks in industry that would be impossible with other methods of heating, and on other jobs it has speeded up production rates or provided savings in cost, time, and floor space.

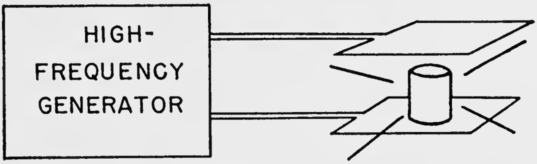
Heat is generated *inside* an object by electronic high-frequency heating. Energy from the electric lines is electronically converted into radio-frequency power which is then transferred directly into the object being heated. The radio-frequency waves instantly penetrate to all parts of the object; the circulation and absorption of the radio power inside the object produces the heat. The speed of heating does not depend on the slow conduction of heat from the surface as in all other methods of heating because the heat develops inside. Neither is the surface of the work exposed to damage from excessive heat or hot corrosive gases from a flame. Heating speeds hitherto impossible are the result.

Two methods are used to transfer the kilowatts of radio-frequency heating power from the vacuum-tube oscillator to the material to be heated. Metals and other electrically conducting materials are heated by *induction* heating. Several turns of copper tubing (with cooling water flowing inside) are wrapped loosely around the work. Radio-frequency currents from the oscillator sent through the copper tubing cause corresponding heavy currents to circulate in the object being heated. These circulating currents produce the heating, which is greatest near the surface.



H.F. INDUCTION HEATING

Dielectric heating is used with electrical nonconductors such as plywood, plastics, textiles, and foods. Power from the oscillator is fed to two parallel plates with the material in between. The intense radio-frequency voltage between the plates permeates all through the interior of the material and shakes the molecules into vibration. Internal molecular friction converts the vibrational energy to heat throughout the whole volume of the work. Before the advent of dielectric heating, there was no really satisfactory method of quickly and safely heating these materials, especially because they are often fairly good thermal insulators.



H.F. DIELECTRIC HEATING

The applications of electronic heating are as varied as the industrial uses of heat. One of the earliest uses of induction heating was to heat the interior metal structure of a vacuum tube during manufacture while the last traces of gas were being pumped out. Any other method would have melted the glass instead of heating the interior.

The tin scarcity during the war compelled the use of the thinnest possible tin coating on tin cans. In the rolling mill where the tin-coated iron was made in continuous strips, an electrolytic plating process provided the requisite thinness. However, the surface was neither bright nor continuous enough to be corrosion-proof. An electronic heating unit furnishing 1200 kilowatts of power (and that's a lot!) at 200,000 cycles per second was used to heat the long sheet as it came speeding through the plant at 11 miles per hour. The heat caused the tin to flow into a bright corrosion-resistant surface and the problem was solved.

Casehardening is a process applied to metal machine parts to make the outer part or case much harder than the core. In gears, for instance, it is very desirable to have the surface layer on the teeth, where the wear comes, just as hard as possible. But for strength the core should be tough instead of hard and brittle. Induction heating, because of its phenomenal heating speed, makes possible the "self-quenching" technique for surface hardening. Using a million-cycle frequency and a very heavy current in a single loop around the gear, the casehardening equipment applies power for just an instant and then turns it off. The surface heats up to the casehardening temperature, and then rapidly chills and hardens as the heat flows into the cold interior. With the right power concentrations and timing, it can produce a perfect case, doing away with the usual cold water or oil quenching bath.

Soldering, brazing, and localized annealing are easily done by the concentration of heat from an induction heating coil. Because electronic regulators and timers are a part of the equipment, the quality is more uniform than when it depends on the skill of the man with the torch. By the use of fixtures to position the part in the heating coil, operation can be almost automatic. Only one unskilled operator is needed to load and unload the pieces as they go to the coil. In one instance it was found that an inexperienced operator using electronic heating brazed the alloy tips onto several cutting tools in the same time that a skilled workman formerly took to produce one by torch.

Dielectric heating is particularly useful for the heating of thick pieces of nonconducting material. The manufacture of the new waterproof plywood used in the hulls of the wartime PT boats is an example. Previously the wood laminations had been fastened with animal glue and then pressed together between steam-heated platens for two to four hours to dry. Because the heat was conducted to the center so very slowly, only a 3 or 4-inch stack of laminations was practical. The development of waterproof thermosetting plastic adhesives made waterproof plywood possible, but the new plastics required a more uniform heating and curing to realize their full strength and durability. Engineers brought in a 300-kilowatt dielectric heating unit. Using the top and bottom plates of the press as electrodes, it produced a controlled uniform heating throughout the whole thickness of the stack and reached the curing temperature in from 12 to 15 minutes. Dielectric heating increased plywood production tenfold, and produced a superior product.

Laminated wood spars and airplane propellers are fabricated in a similar fashion by dielectric heating. High-quality furniture, moisture-resistant and durable, can be made with electronic heating to cure the thermosetting resin joints. Sewing machines to stitch plastic fabrics by dielectric heating are in use. "Compreg" wood, with the strength of steel, is produced by saturating wood laminations in a plastic resin, compressing the stock of laminations to half its former thickness and then curing by electronic heating.

Lumps of plastic to be used in a plastic molding machine must be heated before using so the material will be soft enough to flow into all of the crevices of the mold. By using dielectric heating, the time required for some parts has been reduced from 30 minutes to 2 minutes. Dielectric heating has reduced the molding pressures, improved the quality of the product, and increased the machine production. These advantages give it supremacy in this field.

There has been considerable popular interest in the electronic cooking of foods, but it is certain that the gas range in the home is in little danger of obsolescence from this competitor since a small 1-kilowatt electronic heating unit would cost about $1500.

Large metal castings are difficult to make, and distressingly often they contain interior cracks and blowholes that seriously weaken them and make them dangerous to use. Without X-ray examination of their interiors there is no guarantee of their strength. Cutting the casting open will disclose the defect, but such destructive examination is as useless as striking a match to see if it is a good one.

Similarly, when manufacturers changed from riveting to welding for the fabrication of high-pressure boilers, they adopted the X ray to examine completed welds. Radiography will disclose such defects as entrapped slag, porosity, and cracks.

The X-ray tube is really one of the oldest electronic devices. Because the earliest and most extensive use of X rays has been in medicine, the description of how an X-ray tube works will be postponed to the next chapter, "Electronics in Medicine."

Both radiographic and fluoroscopic methods of X-ray examination are used in industry. Radiography, which records the X-ray shadows on a photographic film, is used when a permanent record is desired or when a thick casting or weld is examined by very-high-voltage X rays. The fluoroscopic method dispenses with film. The X-ray shadows are examined directly with a fluoroscopic screen. Fluoroscopy can be used in the examination of aluminum or magnesium aircraft castings, or in the inspection of foods packed in cartons ready for shipment.

During the war a number of million-volt X-ray equipments were put in use. One unit, built by General Electric, is completely enclosed in a steel tank 5 feet high and 3 feet in diameter, which weighs about 1500 pounds. The radiation supplied by this unit is equivalent to that produced by 8½ pounds of radium, and up to a few years ago, radium at $30,000 a gram was the only source of such penetrating radiation.

In the Philadelphia Navy Yard, engineers placed 20 castings in a circle around the target of a million-volt unit, and radiographed them simultaneously with a single two-minute exposure. Gamma rays from a practicable amount of radium would have required four hours.

To inspect loaded 155-mm. shells for the uniformity of the TNT filling at the Milan, Tennessee, Ordnance Center, the shells and a photographic film were loaded on a merry-go-round that continually circled a million-volt tube. Workers standing behind a thick protective wall loaded and unloaded the shells while on the other side of the wall the X-ray exposures were being made. An average of two shells a minute were inspected.

Fluoroscopic X-ray inspection has found the widest use in the food industries where it is most important that any foreign material be detected and removed. The products to be inspected are usually carried on a conveyer belt past the X-ray tube and under the fluoroscopic screen. The operator sitting in a darkened booth sees on the screen the image of the material on the conveyer belt. Foreign materials, which are usually denser than the food, are easily recognized by their dark shadows. In addition the operator can often detect shortages in filling the containers.

CHAPTER 8

ELECTRONICS IN MEDICINE

THE deaf may hear, and the blind may see; the interior of a disease-racked body may be seen and treated without the knife; the throbbing of the heart and the working of the brain write their messages of health or woe—such is the work of electronics in the service of medicine and mankind.

X rays, discovered fifty years ago, began the procession of electronic aids to medicine. The vacuum tube, borrowed from the radio engineer, has made it possible to measure the tiny voltages produced by body processes, the workings of the heart, the nerves, the brain. Radio-frequency heating, called diathermy in medicine, was perfected for the baking of aching joints from the inside out with no burning of the surface. Hearing aids for the partially deaf, as indispensable to them as spectacles are to many of us, are a miracle of tiny electronic-amplifier construction. For the first time, by means of electronic visible speech, the totally deaf can really "hear by sight" with patterns of light on a moving screen. Photoelectric cells measure the colors of serums and assay the results of biological tests. With a newly developed electronic cane, the blind may find their way, with a photoelectric light-beam system that tells them the distance to objects and reports by a set of musical tones in an earphone. Optical microscopes have been outdistanced in the seeing of the invisibly small by electron miscroscopes which employ the new science of electron optics to focus and use electron beams instead of visible light. In medicine, as in all other aspects of our lives, electronics has already become an indispensable tool and servant.

Foremost of the electronic contributions to medicine is the

X ray. While new advances in medicine such as the antibiotic agents penicillin and streptomycin, sulfa drugs, and the use of blood plasma might seem to dwarf the tremendous importance of the discovery of X rays, this fifty-year-old development is one of the most valuable weapons for medical care.

X rays were discovered in 1895 quite by accident. The German physicist W. K. Roentgen was experimenting with the passage of electricity through a Crookes tube, a highly evacuated glass bulb with a metal disk electrode sealed inside at each end. When the voltage applied between the electrodes of such a tube was sufficiently high, in the order of tens of thousands of volts, the glass walls of the tube were known to glow with a strange greenish-yellow light. Roentgen had for some reason enclosed his tube in a tightly fitting black cardboard box. Working in a completely darkened room, he noticed with astonishment that a paper screen lying near by, which was coated with some barium and platinum chemical compounds, lighted up brilliantly with a fluorescent glow.

But why? How could the paper screen light up when there was no light in the room, and when there was no light from the Crookes tube falling on it? Could the Crookes tube be generating some new mysterious kind of radiation that was capable of penetrating the opaque cardboard jacket?

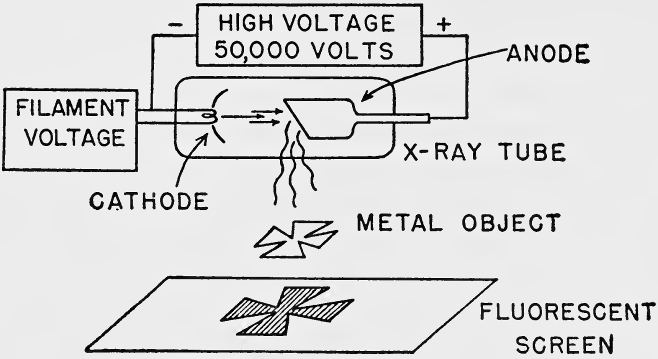
Investigation soon confirmed this suspicion. Some sort of radiation was coming from the Crookes tube, and while it was strongest near the glowing part of the glass bulb, it could still be detected up to six feet away by the faint glow of the chemically coated paper screen. It passed with almost undiminished strength through the black opaque cardboard cover. Metal objects were found to be almost opaque to the radiation, and they cast sharp shadows on the fluorescing screen. Wood and cardboard were nearly transparent. The rays were only slightly absorbed by the flesh of the hand, but the bones, being denser, cast shadows, and every joint stood out with clarity.

It was a surgeon's dream come true, for here was a means to see into and to watch the activity of the living body, to diagnose pathological conditions, or to locate foreign objects. These possibilities were not missed by Roentgen, and within three months the new radiation was being used in surgery by a Viennese hospital.

Early experiments showed that the new radiation could not be reflected by any material acting as a mirror, nor could it be refracted or bent in its path by any sort of prism. It passed in a straight line through substances, and the only change in the radiation was the absorption that it suffered in passing through the denser materials. Such behavior was unlike either of the two kinds of radiation—light or Hertzian radio waves—which were known at that time. Roentgen first thought that the radiation either consisted of some kind of particles or that it was a new kind of etheric vibration different in character from the Hertzian electromagnetic vibrations. Because of his uncertainty as to the nature of the new radiation, Roentgen called it X ray after the mathematical unknown *x*.

In the fifty years since their discovery, scientists have learned much about X rays. Contrary to Roentgen's first surmise, X rays are closely related to both light and radio waves and they are but one of the many different kinds of radiation in the large family of electromagnetic radiations. They are most closely related to the ultraviolet rays that can cause sun tan or sunburn, but their wave length is very much shorter and they are vastly more powerful and penetrating. X rays are also akin to deadly and penetrating radiations given off by the explosion of an atomic bomb.

X rays are generated whenever electrons speeding under the impulse of thousands or millions of volts strike a solid object. The sudden jar of the stopping causes the tiny charged electron to send out a parcel of electromagnetic radiation, an X ray, much as when a stone strikes a hard wall it sends out a sound wave.



The higher the voltage and the denser the metal of the target, the more abrupt is the stop and the greater is the energy of the radiation and the deeper its penetration. The earliest X-ray tubes were as difficult to operate as the De Forest audion triodes, and for the same reason. They both contained a small amount of residual gas which was essential for their working. Use caused the gas pressure to vary, and so the tube seldom behaved in the same way twice. Most modern tubes now employ a heated tungsten filament to emit the necessary electrons, and the tube is evacuated to a very high vacuum. Such tubes, often called Coolidge tubes after their inventor, are very easy to control.

In ordinary circumstances X rays are invisible and a specially prepared fluorescent screen or a photographic film is necessary for their detection. Yet the ability of the eye to see X rays directly is a method for diagnosing a certain type of blindness!

After a normal eye has been adapted to total darkness for thirty minutes, it can see a faint fluorescence produced by the rays acting directly on the retina. Small lead objects placed in the beam can then be seen as they cast their X-ray shadow on the retina. Eyes open or closed, it makes little difference—the rays travel through the lids unhindered. Thus in cases of blindness due to an opaque lens (cataract) or an opaque cornea, the eye specialist can use X rays to determine whether or not the patient has an intact retina and optical nerve. If the patient can "see" by X rays, the retina and optical nerve are still functioning, and eye surgery may be able to give the patient use of his eye.

X rays are made visible for diagnostic purposes either by a fluoroscopic screen or by a photographic film. The professional fluoroscopic screen is made by coating a surface of paper or glass with zinc sulphide, which glows with a yellow-green light when struck by the X rays. The patient to be examined is interposed between the X-ray tube and the screen, the shadows cast on the screen indicating to the radiologist or X-ray specialist the internal conditions. To protect the operator from the action of the rays, a heavy plate of X-ray-absorbing lead glass is placed between him and the sensitive screen. Fluoroscopy, by being able to show bodily movements, can often give a valuable three-dimensional impression to the operator.

Roentgenography or X-ray photography is used when finer details are to be observed or when a permanent record is desired. The photographic film is placed in intimate contact with a fluorescent calcium tungstate screen. The screen produces a light image, which the photographic film retains. This particular chemical was chosen because it fluoresces with a violet light under the action of the X rays, and violet is a color to which film is especially sensitive. The direct action of X rays on photographic film is similar to that of light rays, though the effect is weaker. Roentgenograms can be made in this way without the fluorescent screen when the greatest detail is necessary, but exposures five to ten times longer are required. After exposure, the film is developed and viewed as a photographic negative. Because roentgenograms require a film the full size of the part to be examined, and are therefore expensive, a photofluorographic method has been developed in which a fluoroscopic image is photographed by a regular camera using a lens and a much smaller film. This latter method has had wide use in mass examinations for lung tuberculosis. Needless to say, the film magazine of the camera must be adequately shielded from the direct action of the X rays.

Because X rays are stopped in proportion to the density of the material they traverse, bones or metal objects cast dense shadows that may be easily recorded on photographic film. Interior organs of the body may be seen if they differ in density from their surroundings. Thus the heart, because it is surrounded by the air-filled lungs, is easily visible in chest films, but it would not be visible if nature had surrounded it by the liver which is of approximately the same density.

Special X-ray techniques allow the examination of organs and parts of the body that would ordinarily cast no shadows because of their similarity to their surroundings. A "dinner" of white powdered barium sulphate in water causes an X-ray shadow that can be followed as it courses through the alimentary canal. Gastric or duodenal ulcers are but one of the conditions that may be so diagnosed. The visibility of the liver and the spleen may be enhanced by intravenous injection of thorotrast, a drug which has the property of depositing itself in these organs. A certain iodine compound when swallowed causes the bile to become temporarily opaque, and the gall bladder filled with this material allows the only method of diagnosis for a type of X-ray-transparent gallstone. The brain, which normally casts no distinguishing shadow, may be examined by performing spinal puncture (in the lower part of the back) and by allowing an air bubble to pass up into the cerebrospinal pathways around, between, and in the various lobes of the brain. Various types of brain injury, brain disease, and tumors may be detected by a specialist who observes the movement of the bubble. The air is absorbed by natural process and replaced by normal fluid within a few days. Opaque iodized oil injected in the spinal canal allows X-ray examination of the spinal cord. The patient is tilted back and forth on a rocking table which causes the "lake" of opaque oil to traverse the canal and to reveal indentations and defects by the way it moves.

If X rays had made no other contribution to medicine than the ability to study the shadows cast by the lungs in living individuals, they would have performed a tremendous service. Mass surveys of hundreds of thousands of people have been made for tuberculosis. While the best method of examination requires a 14-by-17-inch film for a full-size exposure of the chest, a currently popular and less expensive method involves the photofluorographic method with a camera using the smaller 35-mm. film. Built-in photoelectric cells to time the exposures appear in some of the newest machines. The prime object in such surveys is to detect cases of open pulmonary tuberculosis who have lesions from which they cough bacilli, and innocently infect their neighbors.

The X-ray specialist has many tricks at his command. Triangulation, and X-ray photography in two perpendicular planes, are sometimes used to locate the exact position and depth of foreign objects. The action of the heart can be photographed through a slit in an X-ray-opaque lead plate. As the slit is slowly moved to scan the heart region, contractions cause the edge of the heart to photograph as a jagged line. The distance from peak to valley of this line can be measured and used to compute the stroke output of the heart. Body-section roentgenography can give pictures of interior organs free from shadows of over or underlying structures. The X-ray tube above and the film below the patient are removed simultaneously but in opposite directions during the exposure about a fulcrum in the plane of the intended picture. The shadows of all parts not in this plane move during the exposure and blur to invisibility. The shadows of the organs in the plane of the fulcrum do not move, and leave a sharp image.

X rays can be dangerous. The earliest workers found that excessive exposure to the radiation causes severe burns. Some lost fingers, while a few unfortunate scientists died as a result of overexposure. The effect of excessive X-ray radiation is something like sunburn except that the penetrating rays are not limited to the surface, and cause damage to all tissues traversed by them. It may require three or four weeks for the characteristic redness of an X-ray burn to develop, followed by tanning that may last for months. Larger doses cause a faster response and are correspondingly more severe.

One early experimenter, Elihu Thomson,* reported in 1896: "I had read a few times that certain people had been burned by Roentgen rays. I did not believe it. These rays went through tissues so easily that their action could not amount to anything, but it was certainly worth while investigating so as to know. . . . I put my finger up pretty close to the tube, and after half an hour I thought that perhaps it was not long enough. . . . I shut down the tube and went away. Five, six, seven, eight days passed and nothing happened, and I felt that people had been mistaken about the effect of the rays. But on the ninth day the finger began to redden; on the twelfth day there was a blister, and a very sore blister. On the thirteenth or fourteenth day after exposure, the blister . . . had gone around the finger almost to the other side." The skin came away, and he continues: "I had to go through the painful process of having a raw sore there and the epidermis growing in from the side and gradually closing up . . . the skin is yet very tender, and nature does not appear to have found out how to make a good skin over that finger."

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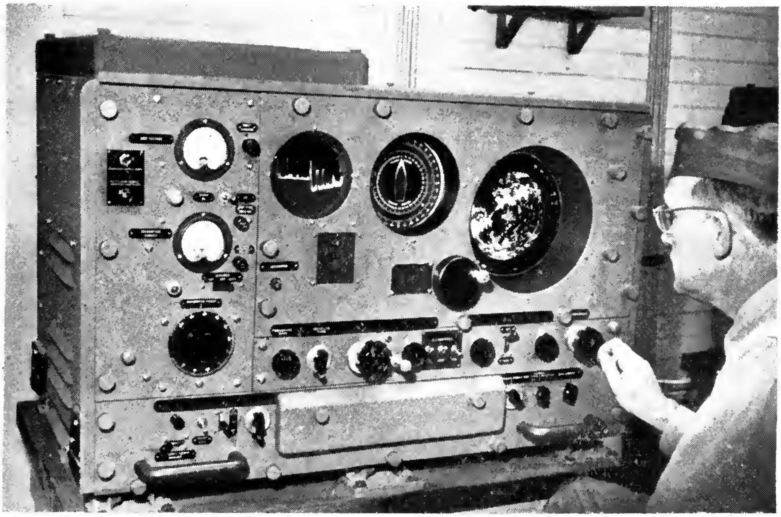
* "X Rays, an Early Institute Topic," *Electrical Engineering* 64:435-436, Dec. 1946.

These rays which burn are invaluable for healing when given therapeutically in small doses by a highly trained expert. This is because their destructive action is slightly greater on certain unhealthy tissues than on the normal healthy body; or in other cases their beneficial action is due to the "sunburn" caused in that tissue. Diseases ranging from simple ringworm of the scalp to serious processes such as cancer may be treated by X-ray therapy. However, the physician performing the therapy must be as careful in measuring the dose as a pharmacist measuring drugs, and he must be as accurate in directing the rays as a surgeon in applying his knife. Doses too small or too large may be either ineffective or dangerous, while misdirected radiation could be as bad as a slip with the knife.

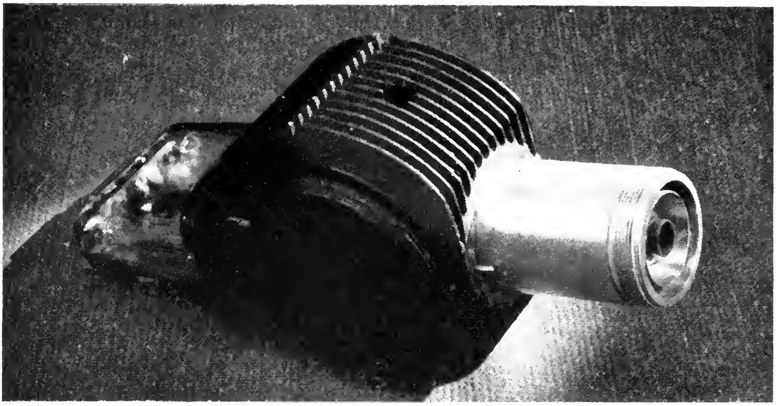
The therapist employs a wide variety of equipment and techniques. Low-voltage tubes (40,000 to 100,000 volts) giving "soft" radiation of low penetration are used in treating the skin. Medium and high-voltage tubes (120,000 to 220,000 volts) are used to treat deep-seated lesions, while tubes using up to a million volts are employed for selected conditions and biological research. The voltage determines the penetration. The radiation from a tube is not all of one kind, and the soft radiation produced along with the harder radiation must often be removed by passing the rays through thin aluminum or copper absorbing screens or filters. Otherwise the skin would receive an undesirably large dose of radiation from both the hard and soft rays, while the internal organ under treatment would receive only the effect of the hard, penetrating radiation.

Doses are calculated in roentgens, the unit measuring the action of radiation. Small therapeutic doses range from 10 to 100 roentgens to be repeated at weekly or monthly intervals. For example, the skin condition called acne would require weekly doses of 100 roentgens over a period of three months. A small localized cancer might require 6000 roentgens in one or several sessions. In comparison, a simple X-ray examination

This is Cape Cod seen by radar eye from a high-flying airplane. The large bright patch at the top is Boston. Similar radar instruments can find and track the center of storms because the radar waves are reflected from the clouds and raindrops. (Courtesy Bell Telephone Laboratories.)



This shipboard search radar gives much information. On the screen at the right is a complete PPI map of the surroundings, with the position of the ship in the center. The distance to any suspicious object can be measured with precision on the A-scope at the left. The center indicator with the outline of a ship assists the operator to keep track of the target direction, the direction of his ship, and the compass direction. (Courtesy Raytheon Manufacturing Company.)



The cavity magnetron is the heart of a microwave radar transmitter. Fins like those on the cylinders of an aircraft engine carry away the large amount of heat generated during operation. Radio energy emerges through the system of concentric tubes at the right. A powerful magnet, essential to the operation of the magnetron, is placed with its pole faces against the flat front and back surfaces of the tube. (Courtesy Bell Telephone Laboratories.)

This is a similar magnetron, skillfully cut away to show the interior. Compare its size with the one-inch cube at the bottom. The keyhole shaped slots, or cavity resonators, cut in the block of solid copper, pick up their radio energy from the electron tornado whirling around the white oxide-coated cathode in the center. A limited amount of tuning is possible by means of the gear mechanism. The "hairpin" in the cavity at the lower left is a small loop antenna which picks up the radio power inside the tube and conveys it outside through the connector. (Courtesy Bell Telephone Laboratories.)

would give a dose of only a few roentgens, while an extended fluoroscopic examination would give up to 100 roentgens. Therefore a simple ordinary X-ray examination would have neither therapeutic nor harmful effect. For continuous exposure to X rays, day after day, the maximum dose is set by safety rules at 1/10 roentgen per day. This is the reason for the elaborate precautions and heavy lead shielding used to protect all workers with X rays.

Conditions that respond to X-ray therapy are inflammatory diseases of the skin and adjacent tissues, certain types of warts and moles, disturbed function of such glands as the salivary and thyroid, and many benign and malignant tumors.

Radio waves have an important use in medicine. Electrically powered short-wave diathermy machines are used to produce internal heating of tissues. A cabinet on wheels, the size of a tea wagon, containing a small powerful high-frequency oscillator, supplies radio-frequency currents to a few turns of heavily insulated conductor coiled over the part to be treated. The radio energy, absorbed in the interior of the body, causes a deep beneficial heating of the body tissues, with no danger of burning the surface. Because it can produce the heat at the approximate spot desired, the diathermy machine is superior to heat lamps, hot-water bottles, or electric pads. Medical diathermy and HF heating in industry employ the very same principles, but the doctors were using the machines first!

Many claims have been made concerning germicidal and other actions of the high-frequency currents thus introduced in the body, but experts generally agree that the only demonstrable effects of short-wave diathermy are the production of heat in the tissue. Though the temperature may not be raised high enough by short-wave diathermy to exert a bacteriocidal effect, the resulting increased supply of blood bringing more leucocytes or white blood cells and antibodies to the site of infection best accounts for the beneficial results obtained in the treatment of infections. Pleurisy, neuritis, and many other complaints respond to this method of treatment.

If the high-frequency current from a diathermy machine is supplied to a needle in a convenient insulated handle, and a return path for the current is furnished by a large electrode fastened to some part of the patient's body, the result is a high-frequency surgical knife. At the very point of the needle the high temperatures produced cut the tissue by a sort of burning that takes place along such a sharp line it is almost like cutting with a knife. The method simultaneously seals by heat any of the small blood vessels at the edge of the cut so that bleeding is greatly reduced. For certain operations, such as brain surgery, the "radio knife" is often preferred.

All living cells in the body exhibit an electrical activity which is a most sensitive index of their health and state of activity. These voltages are an essential part of the living machine and enable it to function. The electrocardiograph which measures and records the voltages generated by the beat of the heart is one of the most important tools possessed by physicians concerned with the diseases of the heart. Voltages from the heartbeat are picked up by electrodes placed externally on various pairs of the extremities. These voltages are fed to an extremely sensitive electronic amplifier which in turn actuates a magnetically operated pen, writing on a moving paper strip. This record drawn on the strips show the rhythmic variation in voltage produced by the heart action. The record is called an electrocardiogram. Thanks to studies with the electrocardiograph, physicians know the intimate details by which the heart beat is created and its pumping action sustained. In diagnosis of heart conditions, benign irregularities can be differentiated from the serious ones. "Injury currents" detectable by the electrocardiograph show the progress of degenerative diseases of the heart. The magnitude of strains on the heart or the seriousness of a diseased condition can be estimated from the recorded voltages.

The nerve cells which make up the brain also depend on electricity to do their job. Nervous messages are carried throughout the body by an electrochemical reaction which travels at airplane speed down the long nerve fibers. The brain, filled with 10 billion nerve cells intricately interconnected in the world's most marvelous telephone central, is a center of electrical activity.

Metal electrodes stuck on the outside of the scalp can pick up the tiny stray voltages resulting from this brain activity. These voltages also may be amplified and recorded on a paper strip to picture these "brain waves." The instrument in this case is called an electroencephalograph.

The brain waves exist when the subject is at rest, and they are disrupted by activity. The main rhythm, called the alpha wave, is most pronounced when the subject is sitting relaxed in the dark. Light, mental effort, and mild emotion disrupt it. Experiments with animals confirm that the brain itself has a spontaneous electrical beat, analogous to the automatic mechanical beat of the heart.

Each person's brain wave is as unique as his handwriting. Tracings made months apart are easily matched, and identical twins have identical brain waves. As yet there seems no possibility that thoughts may be read by brain waves, although attempts to correlate the patterns with intelligence, emotional structure, and character are a lure to further study.

To the neuropsychiatrist, brain waves are an important index of abnormality. Several types of insanity give characteristic patterns by which the course of the disease or the success of treatment may be measured. Epilepsy is diagnosed by the characteristic brain-wave patterns produced. By brain waves pre-epileptic problem children are differentiated from those who are merely badly raised. Brain tumors, abscesses, and concussions are recognized and located by the kind of brain wave and its point of origin on the scalp.

One out of every 78 men and one of every 85 women in the United States have hearing which is impaired at least to the extent of making listening at the theater or in a church difficult. For these people the modern vacuum-tube hearing aid has meant a new freedom from handicap and an increased enjoyment of life. In a small plastic container little larger than a package of cigarettes, an electronic hearing aid contains a microphone, two tiny tubes each the size of the end of one's finger, and all the associated wiring. Batteries may be contained either in another small package to fit in a pocket, or, in the latest models, within the amplifier case. Earpieces tailored to the special convolutions of the user's ear, and carefully prescribed accentuation of those frequencies of greatest hearing loss, contribute to the superior performance of these hearing aids. In the long history of devices designed to aid hearing, the vacuum-tube aid is the first one to be so convenient and satisfactory that people in the earliest stages of deafness have come to use it. For them the earlier hearing aids had been worse than the impairment.

Visible speech is a method of electronically translating the spoken word into a legible pattern of light and shadow. The equipment and method were recently demonstrated by engineers of the Bell Telephone Laboratories. Visible speech holds great potential value for teaching the totally deaf how to talk. Since they have never heard the human voice, and are unable to hear their own voices, learning to talk is so very difficult that few ever accomplish it. Those who do usually speak in a monotone with a voice that is distinctly unpleasant and very hard to understand. This is a serious social handicap.

Visible speech provides a promising means of overcoming these difficulties. With the equipment a deaf person can watch the speech patterns made by his instructor, which he then compares with his own as he tries to duplicate the sounds.

In operation the visible speech translator picks up the voice by microphone and analyzes it into twelve different pitches. Twelve lamps, each turning on or off depending on the presence or absence of the pitch it represents, record the sound in patterns of light on a moving phosphorescent belt. Adequate demonstration that the patterns can be learned and used in speech is furnished by the several young women of normal hearing who have been trained to converse by means of the translator. One of them insists she can distinguish a Jersey from a Brooklyn accent by the patterns!

Besides its use in teaching the 20,000 deaf children in this country, the machine should be valuable for language studies, and may be the basis of a new phonetic symbolism that could be printed in books along with the text to give the exact dialect pronunciation.

The electronic "cane" for the blind, to be carried like a lunch box, which scans the path up to 30 feet ahead with a light beam is under development. The work is being done by the Army Signal Corps at the request of the Surgeon General. The little nine-pound device projects a beam of light which is reflected by near-by objects. The reflected beam is picked up by a photoelectric cell which in turn creates a coded tone signal in an earphone, the tone indicating the distance to an obstruction. To make the instrument responsive only to the light sent out by its own little beam, in spite of daylight or flashing street lights, the outgoing beam is turned off and on 500 times per second, and the pickup amplifier is sensitive only to light modulated at this frequency.

The optical microscope, long the familiar tool of the research worker in medicine or biology, is now completely outclassed by the electron microscope for seeing the invisibly small. It has been known for years that magnifications greater than 2000 are impossible with any optical microscope. This limitation is set by the properties of light itself, and not by the design of the microscope. The modern optical microscope is a pretty nearly perfect device. Finer lenses could not much improve its performance so long as visible light is used for seeing.

The wave length of visible light is just too long to permit smaller objects to be seen, or to allow greater magnifications. To see objects much smaller would mean attempting to see things which are smaller in linear dimension than the wave length of light. The difficulty of this is apparent if you will recall the action of water waves at the lake shore. Small pilings and posts cast no shadows in the waves going by. Boats and larger objects do, because they are many water wave lengths long. Because seeing in a microscope is limited by the ability of the object to cast shadows, and the wave length of visible light is fixed, there is a natural limit in seeing the very small beyond which the ordinary microscope cannot go. Further enlargement of the image is as futile as trying to get additional detail by enlarging a newspaper half tone—all that results is a blur.

To see smaller details, radiation of a shorter wave length is necessary. Ultraviolet light has a shorter wave length than visible light, but it can raise magnifications only from 2000 to 3000, and the black light image must be studied photographically. X rays, which have an exceedingly short wave length, are out because there is no known way to refract them by any lens—they go right on through! Electrons, though they are usually thought of as particles, cast shadows and otherwise behave as though they were a form of optical radiation having a very short wave length. A microscope requires lenses. Electrons are easily focused by magnetic or electrostatic lenses. Therefore electrons can be used instead of light in a new kind of microscope.

The electron microscope as perfected and sold commercially can see things fifty times smaller than can the best optical microscopes. Viruses of influenza and polio which were never seen before have been studied. A whole new submicroscopic world has been opened. Single large chemical molecules become visible. By a technique of evaporating a coating of metallic atoms on a biological specimen, the surface structure of organisms such as typhoid or staphylococcus is shown with such detail that the classic quotation:

"So naturalists observe the flea
Has smaller fleas that on him prey,
And these have smaller fleas to bite 'em
And this goes on ad infinitum,"

is an illustration of scientific study. The "fleas" in this case are the mysterious viruslike bacteriophage organisms that prey on the larger disease cells.

CHAPTER 9

THE ELECTROMAGNETIC RAINBOW

If you watch a compass needle in the vicinity of a large dynamo as the machine is brought up to speed and as its hundreds of amperes are switched into its circuit, you will notice that the deflection of the needle changes at each change in electric or magnetic adjustment of the machine. If you had a more delicate instrument than the compass needle, you could recognize smaller electric or magnetic changes at greater distances. A radio is that kind of a delicate instrument, and it can detect in some cases a current of only 10 amperes flowing in a transmitting antenna at the other side of the globe! The tiny electron, hurrying through a vacuum under the impulse of 100,000 volts, makes an even greater disturbance as it strikes the tungsten target of the X-ray tube: its electromagnetic report of what happened goes through flesh and bones, lead and steel!

In a distant star a thousand years ago, an atom was jostled. One of the atom's attendant electrons shifted to absorb the blow and then fell back to its normal position with the emission of a parcel of light to report its annoyance. Tonight, if you go out and look at the stars, you will see such reports coming in. They have all come a long way. Few have been traveling for less than 10 years, though they have all been racing at 186,000 miles per second—5 trillion miles a year—ever since they started.

These reports of the electric and magnetic happenings in the universe are called electromagnetic radiations. They appear whenever some electrical or magnetic change occurs. Some can travel a great distance, others are soon dissipated in their surroundings. Radio waves, light, X rays, and some cosmic rays—

they all belong to the same family. James Clerk Maxwell in 1864 described mathematically the way electromagnetic radiation traveled and how it was reflected and refracted, and his description stands today.

The complicated mathematics that Maxwell used had a simple story to tell. Electromagnetic radiation is a form of energy. It occurs in a manner best described by "waves" which travel at the velocity of light, 186,000 miles per second. The wave is both electric and magnetic in character—these two aspects are inextricably bound together and are both required for the wave to exist. At the end of its travel the wave gives up its energy, perhaps to make your radio play or to give you a sunburn, depending on the kind of radiation.

Since Maxwell, only one really important addition to the description of electromagnetic radiation has appeared. Max Planck found that radiation comes only in standard-sized lumps of energy and that for a given wave length there is only one size of lump. Moreover he found that as the wave length of the radiation became shorter, the unit lump of radiation contained a greater amount of energy. Since then, these lumps have been named "photons" and they have come to form an important part of modern quantum theory. For us, we may reckon the energy of a single photon to be too small to consider separately except for light, X rays, or cosmic rays, where its effect can be detected. Radio waves are seldom thought of in terms of photons; the blur of the billions of tiny photons required by radio makes a smooth stream of radiation of the kind imagined by Maxwell.

An electronic oscillator which sets up currents in an antenna causes a steady stream of electromagnetic radiation to leave the antenna at a speed of 186,000 miles per second. If the frequency of the oscillator were to be set at exactly 186,000 cycles per second, then the electromagnetic reports of what was happening at the antenna could travel only one mile before the oscillator had repeated the original flow of current at the antenna and thereby caused a duplicate report to be emitted. The spacing of duplicate reports, one mile in this case, is called the wave length. If the oscillator frequency is raised, more duplicate reports are sent out each second, and therefore the spacing or wave length must be shorter. Mathematically:

$$\left\{\begin{matrix}\text{Spacing in}\\ \text{miles}\end{matrix}\right\} \text{ x } \left\{\begin{matrix}\text{number per}\\ \text{second}\end{matrix}\right\} = \left\{\begin{matrix}\text{velocity of radiation}\\ \text{in miles per second}\end{matrix}\right\}$$

or

$$\text{wave length} \quad \text{x} \quad \text{frequency} \quad = \quad \text{velocity of light}$$

because the velocity of all electromagnetic radiation is the same and is equal to the velocity of light.

In radio engineering and in scientific work, the metric units of measure are used in the formula. Wave length is measured in meters (about 39 inches) and the velocity of light is 300,000,000 meters per second. As an example, a regular broadcasting station operating on an assigned frequency of 1500 kilocycles (1,500,000 cycles per second) has a wave length of 200 meters, as the computation below proves:

$$\begin{array}{ccccc}(200) & \text{x} & (1{,}500{,}000) & = & (300{,}000{,}000)\\ \text{wave length} & & \text{cycles} & & \text{velocity in}\\ \text{in meters} & & \text{per second} & & \text{meters per}\\ & & & & \text{second}\end{array}$$

A station on a frequency of 3000 kilocycles (used for airways communication) has a wave length of 100 meters. As the frequency increases, the wave length decreases, since their product in this equation must always be 300,000,000.

This is why the radio engineer can speak of "higher frequencies" or of "shorter waves" and still mean the same thing. Each of the two methods of describing radio waves has its special uses for which it is the most convenient. For example, transmitting antennas are often adjusted to be exactly ½ wave length long for whatever the transmitter frequency may be—though the ½ wave length may be 325 feet for a broadcast transmitter (1500 kilocycles) or 1 inch for a radar transmitter (6 billion cycles). Wave length is generally useful whenever physical size of equipment is under discussion.

Frequency is important in all discussions about how close together stations may be crowded on the tuning dial before their programs overlap and cannot be separated. The overcrowded radio bands, and the unsatisfied requests for station permits, testify to the importance of this problem.

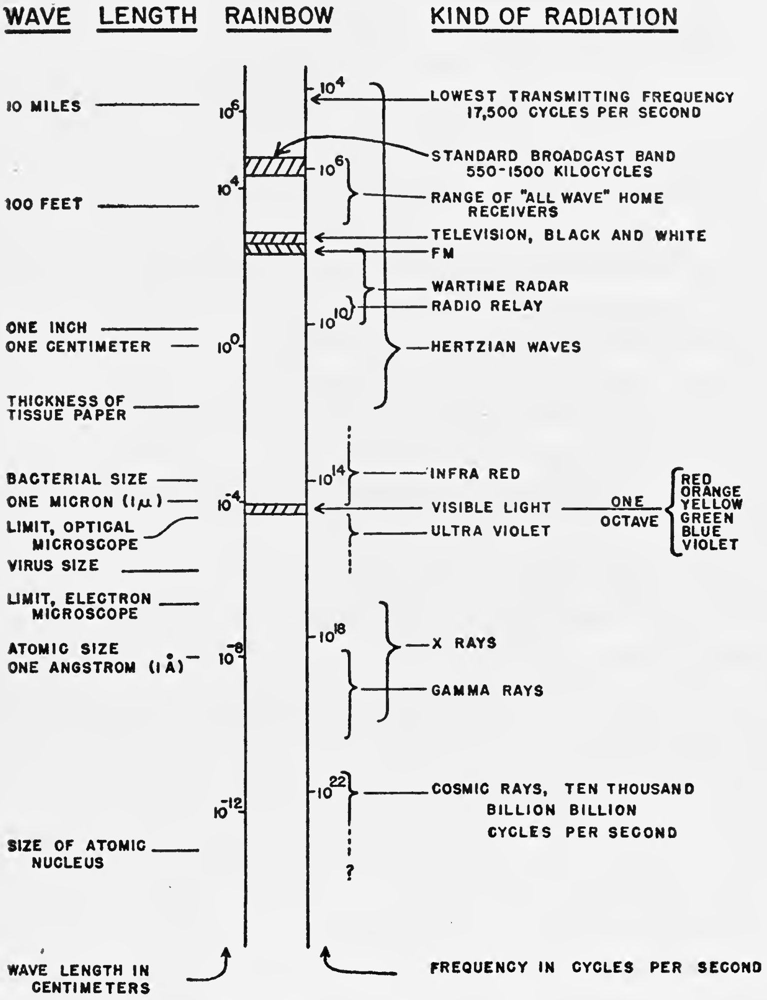
All electromagnetic radiations—whether they be visible light, radar waves, or cosmic rays—may be described both in terms of frequency and in terms of wave length. By either description, all the different kinds of electromagnetic radiation fall into a natural order, just as an optical prism separates white light into the different colors and projects them in the natural order of the rainbow.

The whole rainbow or spectrum of visible light, from the deepest red to the farthest violet, covers just about one octave. That means that the frequency of the violet light is almost double the frequency of the red light. This is like the octave on a piano keyboard where the higher note has exactly twice the frequency of the lower one.

The whole electromagnetic rainbow, from the lowest frequencies used in radio to the mysterious cosmic rays that come in from the stars, covers a range of 60 octaves. In this spectrum, each kind of electromagnetic radiation has its place, just as the colors of the rainbow are each in its own place. To show this, the electromagnetic rainbow has been put into a diagram that is like the keyboard of an immense electromagnetic piano, with each of the 60 octaves given a uniform spacing.

The different radiations in this rainbow are best described by

THE ELECTROMAGNETIC RAINBOW



their wave lengths instead of by their frequencies. Frequency, while useful in radio, carries little information for the ordinary person in the rest of the electromagnetic rainbow because the numbers are too large to comprehend. Orange light, for instance, has a frequency of 500 million million cycles per second. Wave length is more descriptive because it is closely related to the "optical" properties of the radiation and determines the size of the smallest object which may be "seen" by means of the radiation. A radar apparatus using radiation of a 5-inch wave length can "see" flying birds; a microscope using orange light can form an image of a microbe; and a diffraction camera using X-rays can "see" atom arrangements in crystals. These are the limits on "seeing" for the three kinds of radiation, since in each case the object cannot be very much smaller and still be visible by that kind of radiation.

At the top of the chart are the useful radio waves, beginning at wave lengths of 10 miles for the radiation from the long-range low-frequency transmitters, and extending down to wave lengths of ½ inch for the shortest radar waves. These useful radio waves cover 20 octaves of the electromagnetic rainbow. Experimental radio waves, produced in the laboratory, extend the range down to where the wave length is comparable to the thickness of tissue paper. With these included, the collection of all the radio waves is called "Hertzian waves."

At the center of the band of useful radio radiation is the standard broadcast band, employing radio waves several hundred feet long. The broadcast band is about 1½ octaves wide. Prewar "all-wave" receivers could also pick up shorter waves, down to wave lengths of about 50 feet. This gave them a wider coverage of about 6 octaves. However, these sets cannot tune to the new television or FM bands which have a wave length of less than 30 feet.

Air-borne radar sets use radiation of nearly the shortest wave length that has been found practical; its wave length is a little greater than 1 inch. Radiation of wave length shorter than ½ inch is absorbed by the atmosphere and therefore cannot be used in radio.

Visible light occupies about an octave in the middle of the electromagnetic rainbow. The different colors range themselves in order, with the red at the long wave length and the blue-violet at the short wave length end. Blue light, with its shorter wave, is sometimes used in attempts to see the smallest possible detail with a microscope. Blue light sets the limit of seeing for the optical microscope. Bacteria can be seen by visible light, but viruses cannot, for they are too small compared with the wave length of visible light.

At the two ends of the visible octave are the infrared and the ultraviolet radiations which cannot be seen. Infrared may be sensed as radiant heat. Infrared spectroscopes which can separate and measure the intensities of the different "colors" or wave lengths of the radiation are an important new tool for the industrial chemist. Between the longest infrared radiation and the shortest radar waves is a region that has been difficult to explore and for which there has been found no use.

The effects of ultraviolet radiation are familiar to anyone who has been sunburned after a day at the beach. Their action is much like that of X rays, which is not surprising because they are next to X rays in the electromagnetic spectrum. Ultraviolet radiation is powerful, so it is fortunate that it is mostly absorbed by the atmosphere as it comes from the sun.

X rays, gamma rays, and cosmic rays seem to form a family like the radio waves at the other end of the rainbow. These radiations are penetrating, and in large quantities are dangerous. The radiations with the shorter wave lengths are more penetrating and the energies locked into individual photons become relatively enormous.

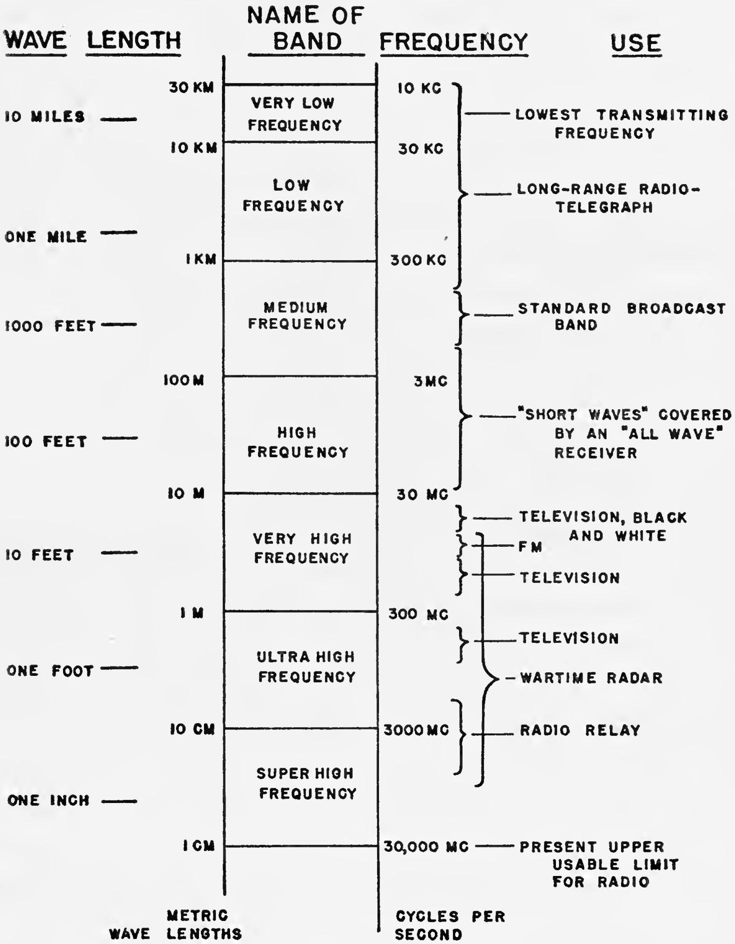
These radiations are differentiated according to their origin.

X rays are generated by speeding electrons through a vacuum with tens of thousands of volts and causing them to crash into a tungsten or some other metallic target. Gamma rays originate in nuclear fission. Radium gives a dangerous number of gamma rays as its nuclei, one by one, blow up. The atom bomb releases an enormous blast of gamma radiation as pounds of uranium or plutonium explode in an instant. This gamma radiation was the cause of the delayed deaths from "radiation sickness" among the Japanese victims as described in the newspapers. Little is known about the part of cosmic rays due to electromagnetic radiation. They seem to originate somewhere out in space and they carry a tremendous amount of energy locked in each of their photons. A cosmic-ray photon, striking an atom, can cause this atom to blow up with such force that the pieces in turn tear other atoms apart! While life on this planet has become accustomed to the relatively small numbers of cosmic rays that come through the atmosphere, it is thought by some that spontaneous genetic mutation of species may be due to cosmic-ray-induced rearrangements of the heredity-carrying genes. Cosmic-ray relatives, the X rays, have actually been used for that purpose in certain breeding experiments.

The most interesting part of the electromagnetic spectrum for the electronics engineer is the part containing the radio waves. Because these electromagnetic radiations have their greatest use in communication, where crowding between stations is a problem, it will be appropriate to switch to the frequency description of the spectrum instead of the wave-length description. Radio frequencies involve big numbers, so it is sometimes handy to use the abbreviations, kc or kilocycle for thousands of cycles per second, and Mc or megacycle for millions of cycles per second.

The usable radio spectrum extends from 10 kc to 30,000 Mc, that is, from 10,000 cycles to 30 billion cycles per second. It is a frequency range that contains radiations of enormously differ-

THE RADIO-FREQUENCY PART OF THE SPECTRUM



ent properties. For convenience in talking about the radiations, engineers have arbitrarily divided the spectrum into seven regions and have given these regions names ranging from "very low frequencies" to "super high frequencies." This division is illustrated in the diagram called "The Radio Frequency Part of the Spectrum." The diagram is really a magnified version of the top part of the electromagnetic rainbow. Marked out in the various frequency regions are some of the radio services for which they are used. For instance, the ordinary broadcast band is in the medium-frequency band, while television and FM are in the very-high-frequency region.

The radio-transmission characteristics of each of these bands is quite different and consequently each band is particularly fitted for some certain class of service.

Radio waves, if left to themselves, travel in straight lines. But we live on the surface of a spherical earth covered in part by land and in part by water, the whole wrapped in a layer of atmosphere 200 miles thick. All these factors influence the propagation of radio waves, and the manner and the amount of the influence depends on the frequency of the radiation. For this reason there are large differences in the transmission characteristics of the different frequency regions. If it were not for this interaction between the radio waves and their environment, round-the-world radio communication would be impossible.

Although the early experiments with radio by Hertz in 1887 were conducted with radiation in the very-high-frequency part of the spectrum, the transmitters used by Marconi and the other pioneers operated in the low-frequency regions of the spectrum. At first, little attention was paid to the frequencies used, but it was soon found that the lower the frequency the better the signal was transmitted over long distances. Powerful radiotelegraph stations operating on very low frequencies around 15 kilocycles were built and they consistently sent their signals for hundreds or a thousand miles. By 1912 the "ether" was jammed with government and commercial stations and with the signals of a great many amateur experimenters who had built and were operating their own radio stations for the fun of it. Regulation was needed and federal laws, licenses, and regulations appeared.

The lowest frequencies were thought to be the most desirable, while the medium frequencies around 1500 kilocycles and above were considered to be absolutely worthless for any distance transmission. Accordingly the commercial and governmental interests saw to it that the bothersome experimenters were assigned to the useless frequencies in the neighborhood of 1500 kilocycles and above. The amateurs, believing the best engineering advice of the day, stuck to the lowest frequencies in their assignment. Therefore in the whole radio-frequency spectrum from 1500 kilocycles on up there was a vast radio silence with the ether undisturbed by any transmission.

To the surprise of the radio engineers, amateurs soon began to make contacts with stations, first 1000 miles, then 2000 miles away while using the "worthless" 1500-kilocycle band. Still transatlantic communication eluded them. But the engineers who had said that the 1500-kilocycle region was no good for distance transmission had been disproved by the 1000-mile amateur transmissions. Having been wrong once, they might be wrong again, and the irrepressible amateurs who would try anything began experimenting in 1922 and 1923 with transmissions on first 2300 and then on 3300 kilocycles. As the frequency went up, the results were better!

Armed with this information, amateurs in November 1923 succeeded in communicating back and forth across the Atlantic with low power on 2700 kilocycles. Such performance was unheard of—hitherto only the very-low-frequency stations using enormous power could make a transoceanic contact! Other amateurs tried the new high frequencies, and found that they too could communicate with amateurs in Europe.

A wild rush began, and by 1924 dozens of commercial stations had moved in to take advantage of the new discovery. A chaos of overcrowded frequency bands and conflicting interests threatened until a radio conference in 1924 allocated the new high-frequency territory. The amateurs who had once before been moved up into the "worthless" part of the spectrum above 1500 kilocycles were now again shoved out and the proved trans-oceanic frequency of 2700 kilocycles was of course assigned to commercial use. Representatives from the amateurs' organization, the American Radio Relay League, obtained for their members a frequency allocation at 3500 kilocycles, this being the nearest frequency to 2700 they could get. But also, with a vision born of experience, they asked for and got slices of the spectrum at 7000, 14,000, 28,000, and 56,000 kilocycles—a batch of frequencies with unknown characteristics which no one then wanted.

Frequencies are no longer "grabbed" by competing services and companies as they were in the earliest days. In this country we now have a very hard-working and efficient regulatory agency, the Federal Communications Commission, which assigns the available radio spectrum space on the basis of need and utility and which supervises the uses to which radio is put. For instance, the FCC decides the frequencies and operating hours of broadcasting stations, but beyond encouraging the greatest utility to the public, it does not censor or regulate the content of the broadcasts. In co-operation with similar agencies from other countries, the FCC and the Department of State also help set up international standards of radio service and frequency allocation. Moreover, it has recognized the value of amateur experimentation for pioneering work in radio and as a valuable source of skilled radio operators for wartime and other emergencies, and has therefore awarded the amateurs a very desirable set of frequencies for their use.

The amazing story of the discovery of the high-frequency spectrum continues. The amateurs found that their new 3500-

kilocycle assignment was better for distance than the old 2700-kilocycle band. The 7-megacycle band (7000 kilocycles) was tried, and soon New Zealand, South Africa—the whole world—could be reached at night with amateur low-power equipment. The new band at 14 megacycles was a surprise. It permitted low-power round-the-world communication during the daylight hours, while the band went "dead" at night. Behavior of this kind was unprecedented, all lower frequencies consistently gave better distance performance during the nighttime hours while reception faded out during the day.

The remarkable transmission characteristics of these high-frequency radiations is due to something that was unexpected. There exists a "radio mirror" of ionized or electrically active particles in the upper atmosphere which reflects the radiation back to the earth. Beginning at 30 to 50 miles above the surface, this "ionosphere" extends up to the top of the atmosphere. It is thought that ultraviolet radiation from the sun causes the ionization. During the day the ionization is greater and the bottom of the ionosphere drops closer to the surface of the earth.

The ionosphere mirror affects the various frequencies differently and is largely the cause of the differing properties of the various frequency regions. In the two lowest, used in worldwide radiotelegraphy service, the reflecting ionosphere and the earth below act as two spherical concentric mirrors channeling the signals around the world. Some radiation is absorbed by imperfect reflections. These losses are small for the very low frequencies and increase as the frequency becomes higher. The early radio engineers made the mistake of presuming that this trend continued steadily into the higher frequencies.

In the standard broadcast band, located in the medium-frequency region, the ionosphere strongly absorbs all radiation that reaches it during the day. The only radiation usable to the listener then is that which stays close to the ground.

Even this part is absorbed by the ground after about 50 miles' travel. At night, when the ionosphere has lifted to nighttime altitudes it becomes reflecting to these frequencies, and broadcast signals from across the continent can sometimes be heard, the signal arriving by a series of long leaps and reflections, bouncing between the earth's surface and the ionosphere. This difference between daytime and nighttime propagation explains why many stations are required to reduce their power at sundown and why some of the smaller ones are required to go off the air entirely. With about 1100 operating broadcast stations in the country doubled up and crowded onto only 96 available broadcast channels, such arrangements are necessary to prevent serious interference between distant stations in the same channel.

With still higher frequencies, the radiation that hugs the ground becomes less important, until in the high-frequency region of the spectrum the "sky wave" which arrives only after one or more reflections from the ionosphere is the most useful. A new effect enters: The radiation at the high-frequency end of this region begins to go on through the ionosphere mirror out into space, never to return. The effect is most pronounced at night when the ionosphere is high and thin, while during the day the denser ionization at the lower levels is often able to reflect the signals down again. On the other hand, the dense daytime ionization absorbs the sky-wave signals at the lower or 3-megacycle end of the region, and here long-distance transmission occurs only at night. Therefore by choosing a transmitting frequency appropriate to the expected condition of the ionosphere between the two message points, satisfactory world-wide point-to-point transmission during most of the 24 hours of the day is possible. Because of their remarkable long-distance characteristics, frequencies in the 3-to-30-megacycles range are among the most valuable in the whole radio spectrum, and are consequently the most crowded.

Above 30 megacycles, the radio waves are reflected back to the earth only under unusual conditions of the ionosphere. The radiation travels in straight lines; beyond the "line-of-sight" horizon it cannot be picked up. Therein lies one of the advantages of these frequencies. Because stations beyond the horizon cannot interfere with local stations, each locality can have more broadcasting stations with no crowding of the radio spectrum. There is no nighttime sky-wave bugaboo.

The other advantage possessed by the frequencies above 30 magacycles is that "signal-squirting" transmitting antennas and directional receiving antennas become small enough to be practical. With such an antenna, the transmitter can aim its radiation in the desired direction instead of broadcasting it in all directions. Similarly, when used with a receiver, the same antenna will greatly enhance the reception of stations lying in the direction the antenna is pointing. The two effects are analagous to the action of a searchlight and of a telescope with light radiation. Because the linear dimensions of a signal squirter must be at least several wave lengths, such antennas are only practicable for high-frequency radiation having a very short wave length. Radar, which makes the greatest use of a sharply directed beam of radio energy, employs radiation with a wave length of only a few feet—or inches.

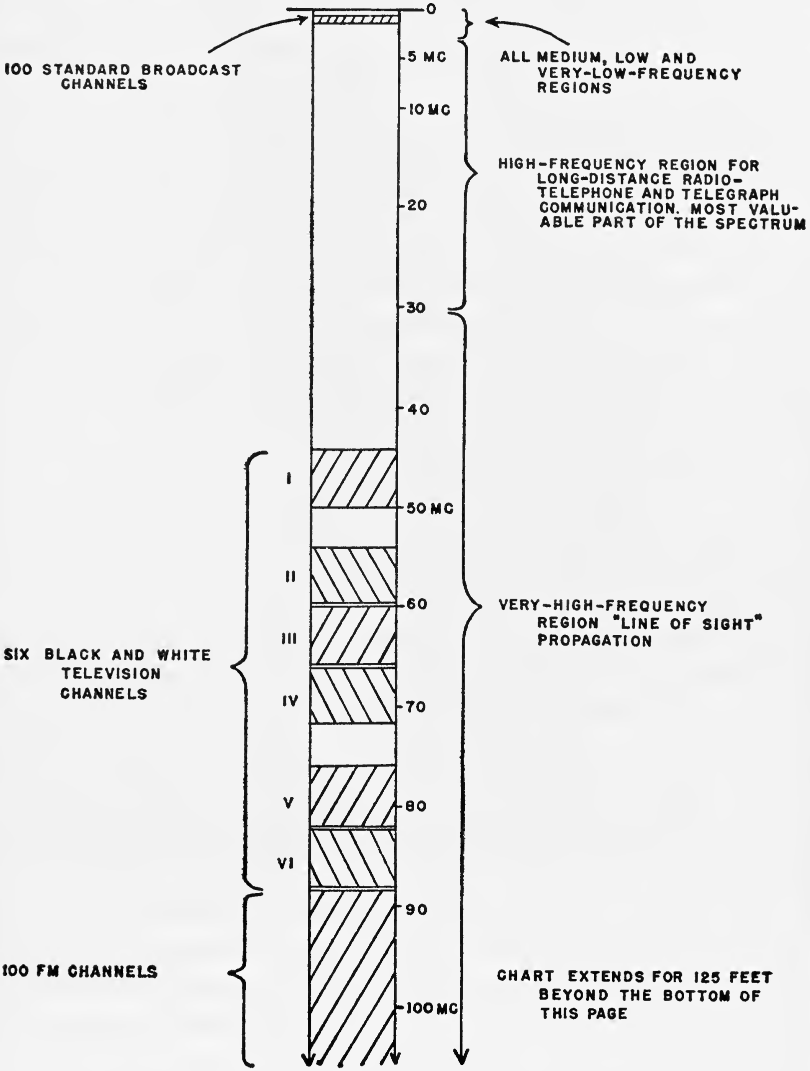
Straight-line propagation and easy directability are characteristic of both the ultra-high and super-high-frequency regions. In these regions a new factor enters which is still under experimental study. It is the refraction or bending of the waves by layers of air of differing humidity and temperature near the ground. For certain of the highest frequencies, around 30,000 megacycles, there is also a selective absorption by raindrops and some of the gaseous constituents of the air.

A radio transmission, that is, the signal from a radio transmitter, occupies space on the dial just as definitely as a physical object occupies space. The space a radio transmission occupies depends on what is being sent. A conventional broadcast transmitter sending out a musical program will transmit all sound vibrations up to about 5000 cycles per second, the full range of the piano keyboard. Such a transmitter is said to have an audio band width of 5000 cycles and it will occupy a space on the dial extending for 5000 cycles or 5 kilocycles on either side of the assigned carrier frequency, 10 kilocycles in all. Ten kilocycles or 10,000 cycles is therefore the width of the transmitted signal, and represents the space in the spectrum that such a musical program requires for its transmission. No matter where in the radio spectrum the carrier frequency is located, the program will always require a chunk 10,000 cycles wide. The carrier frequency of a similar transmitter must be no nearer than 10 kilocycles if the "side bands" of the two stations are not to overlap and cause the one program to interfere with the other.

Television picture programs will never be transmitted in the standard broadcast band—the band simply is not wide enough! Six complete broadcast bands put end to end would be required to transmit the radiations of one single modern television transmitter. One television program must have a space 6,000,000 cycles wide to transmit its picture. It therefore occupies as much room in the electromagnetic spectrum as almost 600 standard broadcast programs. An FM transmitter, sending out a musical program, is not nearly so bad; it takes only as much room as 20 regular broadcast stations. Where to put these two services in the frequency spectrum was a problem. Its solution shows the enormous utility of the highest-frequency parts of the radio spectrum.

If we look at the radio-frequency spectrum from the standpoint of "program space" instead of octaves, we get a new diagram in which the megacycle-frequency markers are evenly spaced. Then because each megacycle can hold the same number of stations, whether the frequency be high or low, this diagram gives a fair representation of the amount of program space in each part of the radio spectrum. On this diagram a television

PROGRAM SPACE IN THE RADIO SPECTRUM



transmitter, whose picture program requires 6,000,000 cycles of spectrum, will take up just as big a chunk of the spectrum wherever it is put. Thus we can see directly from the diagram that if television channel No. 1 were moved up to the broadcast region, it would indeed be six times as wide as the whole 100-channel broadcast band!

The radio-frequency spectrum presented in this way is a revelation. The whole radio spectrum lower in frequency than the broadcast band—that is from 550 kilocycles on your radio dial to the very end of the radio spectrum—has less actual space for transmission than the broadcast band which seemed to be so narrow on the octave diagram.

The immensely valuable high-frequency region which furnishes round-the-world radiotelegraph and radiophone service has room for thousands of voice and code stations. Even so, it is immensely overcrowded and requests for frequencies in this region are rigorously scrutinized by the Federal Communications Commission. A television-sized chunk big enough for a single picture channel would displace too many valuable services to be practical. Furthermore, there are certain technical limitations at these frequencies that would make television impractical here.

The "very-high-frequency" region does have enough room for television. Its line-of-sight propagation removes the competition from the other long-distance radio services. The FM band can also be placed in this region and for the same reasons.

The diagram of program space is left uncompleted at the bottom of the page—and for a good reason. The very-high-frequency region extends for another ten inches that are not shown. But if the enormous program space of the ultra-high and super-high-frequency regions were shown on the same chart, the chart would extend 125 feet beyond the bottom of the page!

Strangely enough, while it would seem that there was enough program space for all at these higher frequencies, the demands of a multitude of new services have already filled up this part of the spectrum with staked-out claims, each for one or more slices of the spectrum: police radio, mobile radiotelephone, handy-talky radios for the ordinary person, amateur radio, television, radio relay, aircraft radar, ship radar, aircraft-to-ground communication, FM broadcasting—and more. All have legitimate demands that the FCC has recognized by assigning them program space.

With this, we have covered the whole usable radio spectrum. These characteristics of the different types of radio radiation are highly important tools for the radio engineer. Whether he is building a military radar set or a standard broadcast transmitter, the tubes and wires and parts he assembles have no other purpose than to make use of certain of the propagation characteristics of some frequency in this radio spectrum. For you, a knowledge of it will make many things clearer as the future brings the new electronic devices using radio waves.

Radio for the ordinary person is about to leave the confines of the regular broadcast receiver dial. This chapter is a road map to the future of the wide-open megacycles.

CHAPTER 10

RADAR

RADAR was by far the most important new technical weapon of the war. Battles were won or lost through the use of radar alone. We disregarded our own radar warning and suffered the Pearl Harbor disaster. Later in the war, German industry was bombed to ruins through the clouds because we had the superior radar equipment.

More than any development since the airplane, radar has changed the face of warfare. Darkness, smoke, rain, nor clouds can stop the radio beam of the radar set. Farther than the unaided eye can see, radar eyes can detect an enemy plane or surface vessel and report its exact position. One of the greatest weapons of warfare is the surprise attack. It is usually achieved by concealment until the last moment in darkness, fog, or the glare of the sun. With radar on the watch, such concealment and surprise simply cannot occur.

Radar was first developed for defense against aircraft. By the end of the war radar was performing a multitude of services and all military and naval operations depended heavily on its help. Aircraft early warning radar sets detected hostile planes 100 or 150 miles away. As the planes came nearer, to within the range of our guns, antiaircraft fire-control radars took over and directed the gunfire, whether the sky were cloudy or clear. Naval guns took their firing-range data from radar equipment, observation of the distant fall of the shells was done by radar, and precise corrections were made for firing the next round. Vessels, guided by radar maps of the surroundings, steamed at cruising speed in the dark of night through twisting, reef-filled, uncharted waters to bombard the island strongholds of the Japanese. The factories and cities of the Continent were bombed through the clouds by the help of radar, day after day in what would otherwise have been impossible bombing weather. German buzz-bombs were shot down with automatic radar gun-pointing equipment which left the crew little more to do than to load the guns. Planes with marvelously small and light air-borne radars stopped the German submarine warfare in the Atlantic by spotting the subs when they were surfaced at night and then attacking them. Our bombers were directed home and "talked down" to a safe landing in poor flying weather by operators at radars on the landing field.

Whole new industries for the manufacture of radar equipment came into being during the war, and the production of radars became one of the nation's major war efforts. Up to July 1945 radar equipment worth nearly three billion dollars was delivered to the Army and Navy, and an additional amount was delivered to the British. In comparison, the widely publicized atomic-bomb project cost two billion dollars.

The design and development of the new radars employed many of the best physicists and electronic engineers in the country. On the campus of the Massachusetts Institute of Technology, the famed Radiation Laboratory was set up in 1940. By 1941 the Radiation Lab had 4000 of the best men that could be found, hard at work developing microwave radars employing the new cavity magnetron—the radars that were decisively superior to the equipment of the Germans and the Japanese. The Radar Section of the Naval Research Laboratory in Washington, D. C., increased in size to 600. The Evans Signal Laboratory of the Army at Belmar, New Jersey, employed a peak of 3000 technicians. Besides these government-sponsored labs, a host of industrial concerns aided in the development of the equipment while at the same time they were delivering a torrent of manufactured gear. Their performance was notable, considering the frequent rush requests for the production of equipment, often while the design was still barely out of the laboratory "breadboard" stage.

Radar is not the name of any single device—it is a coined word that describes a method of using special electronic equipment and very high frequency radio waves to detect and locate distant objects with radio echoes. Radar is contracted from *Ra*dio *D*etection *a*nd *R*anging—a phrase that describes its earliest and most important applications.

There were nearly a hundred different kinds of radar sets developed for the use of our armed forces during the war. In size they ranged from a small hundred-pound outfit, the shape of a small bomb, which was mounted under the wing of a plane, to a sprawling array of shacks and trucks full of equipment, with a telephone central and a company of soldiers to run it. Battleships and cruisers carried tons of radar equipment with large radar antenna "topside" on the masts and turrets. The lowly landing craft had radar, the set consisting of several watertight boxes on deck and a small antenna on the mast.

Whatever their size or shape, all radar sets operate on the same principle—that radio waves behave like a beam of light and that they travel at a measurable velocity.

As in a searchlight, radio waves are focused into an intense beam by the radar antenna. The beam of radio energy, if it strikes a distant plane, ship, or shore line, scatters, and a small part reflects back to the sending point. The radar antenna "sees" this returning radiation and thereby locates the distant object. The process is similar to the way an automobile headlight at night illuminates the highway far ahead of the car. If there is another car, a road sign, or an obstruction ahead, it reflects a little of the headlight beam back. We can see that there is something ahead although we may not be able to make out the exact shape. But when we drive over the top of a hill, where the headlight shines out into space, there is nothing to reflect the light back, and we see nothing.

The returning radar echo comes as fast as light. But that is still not too fast for an electronic clock to measure the time of flight and from that time to find out how far the echo has traveled. The echo speeds at 186,000 miles per hour—7 times around the world in 1 second—but a clock in a radar set that splits the second into 6 million parts can accurately time this echo and measure the distance it has traveled to within 80 feet, though the reflecting object may be miles away.

The radar transmitter, which is the source of the radio energy, produces its signal in short, powerful bursts of radiation. These bursts are about a millionth of a second in duration and are repeated several hundred or several thousand times a second. Bursts of radio energy are used instead of a steady signal so that the echo time—the time required for the radiation to go to the object and bounce back again—may be measured most easily. As anyone knows who has played with an echo, a quick shout or a handclap gives the best demonstration of the echo delay, and of the period of silence between the shout and the echo. The radar set uses this principle. On the other hand, a steady sound would drown out the weak returning echo and nothing could be heard.

Most effective radar operation requires enormous transmitter powers at very high frequencies. Usable radar echoes from small ships or aircraft a hundred miles away require that the radar transmitter put out during each "burst" several times the power of a conventional radiobroadcasting station. With the greater power of our radars, we could spot Jap planes long before their radars had "seen" us. Then we had time to put our planes up to give them a warm reception miles ahead of our battle fleet. Super-high radar transmitter frequencies won for us the "Battle of Radar" with Germany. Our planes bombed targets by radar through the clouds while on the ground the German "Wurzburg" antiaircraft radars, operating at lower frequencies, were hopelessly jammed by our radar countermeasures. Moreover, only the extremely high frequencies made practicable the small compact antennas suitable for air-borne radars—the radars which licked the submarine menace.

Dishpan, bathtub, mattress—such are the descriptive names of radar antenna systems. But whatever their shape or similarity to household equipment, the radar system is designed to focus and direct the radio energy into a tight searchlight beam which can be directed to any point in the sky or on the horizon by rotating the whole antenna. Because the radar set hears only a returning echo, a wide beam covering a large territory will give poor information as to exact direction of the distant target. Such an antenna can be rotated back and forth over a limited range and the echo will still return. On the other hand, the antenna of a narrow beam radar set must be carefully pointed at the target to give any echo at all. The directional information from such a narrow-beam radar is so accurate that large antiaircraft guns are now aimed almost exclusively by their control.

To produce a sharp, narrow radio beam requires either a very large antenna or very high radio frequencies. At the beginning of the war there were no good generators of high-frequency radio energy and the antennas had to be embarrassingly large. The best generators would not give much power above 200 megacycles, but at this frequency the length of the radio wave is 1½ meters or about 5 feet. Because an effective beam antenna must be several wave lengths across to secure any satisfactory beam, radar at these frequencies was clearly impossible except for large fixed ground installations. For instance, a directive antenna at 200 megacycles which was 4 or 5 wave lengths across would have a minimum dimension of 20 or 25 feet—as big as the front of a house—and still it would not give a very sharp beam. At the beginning of the war the English coast was protected with a ring of radar stations operating at these low frequencies, and their antennas were strung between large towers. But the pressing need for radar sets small enough to be carried in an airplane, where large antennas were impossible, demanded higher frequencies than any available prewar oscillator was able to furnish. Luckily, the cavity magnetron was discovered in 1940, and it operated with ease at frequencies of around three billion cycles per second—or a wave length of 1/10 meter. It brought the size of the beam antenna structure down to a width of only a few feet.

A radar set uses a single antenna for both transmitting and receiving. During the microsecond-long transmitting pulse, thousands of watts of radio energy pour out from the antenna and are directed at the distant target. Then an ingenious electronic tube, called a T-R tube (for transmit-receive), instantly switches the antenna over and connects it to the receiver to wait for returning echoes. The same radar antenna then acts as a highly efficient collector of radio waves coming back in from the direction of the transmitted beam. Directional radio antennas all have this very useful property of acting both as a "searchlight" when transmitting and as a "telescope" when receiving: the advantage for detection of small and distant targets is enormous.

Radar receivers are among the most sensitive pieces of electronic equipment built—and they must be to squeeze out the last few miles of ultimate range of detection. They usually employ a modification of the superheterodyne circuit, the circuit used by practically all standard broadcast receivers. The old-fashioned cat's-whisker and galena detector of the early days of broadcasting has been revived in a modern form for radar receivers, and is preferred over an electron tube at the super-high frequencies. Upon the efficient performance of the T-R tube depends the safety of the receiver, since malfunction of

Soon after the Marines landed on bloody Okinawa, they had their radars set up and ready to detect approaching enemy planes. (Courtesy Western Electric Company.)

Official U. S. Navy Photograph

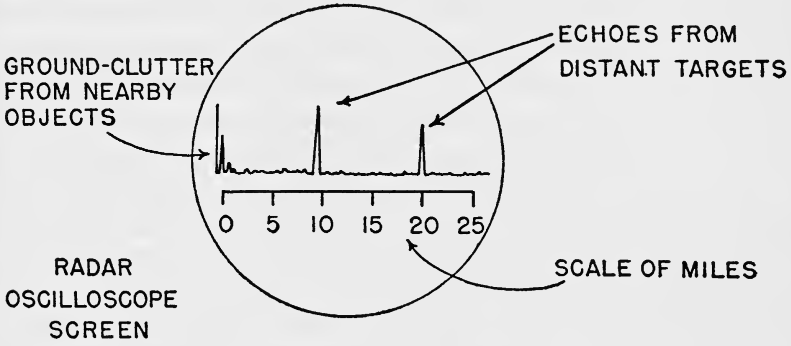
That isn't a bomb on the wingtip, but a complete aircraft radar —transmitter, antenna, and all. Putting the equivalent of several tons of battleship radar equipment into such a small, hundred-pound package was one of the great achievements of the war.

A radio beam replaces the wires of a conventional telephone circuit in this radio relay installation. One bowl antenna of each pair beams the radio wave out to the distant relay station while the other picks up the answering messages. In this experimental installation, each pair of reflectors can handle eight simultaneous two-way conversations. (Courtesy Bell Telephone Laboratories.)

Television and FM broadcasting may be done by transmitters carried in giant planes flying in slow circles in the stratosphere if tests of the "Stratovision" system, proposed by Westinghouse Electric Corporation and Glenn L. Martin Company, continue to prove successful. Programs radioed up from the ground will be rebroadcast by the plane to listeners within a radius of several hundred miles. (Courtesy Westinghouse Electric Corporation.)

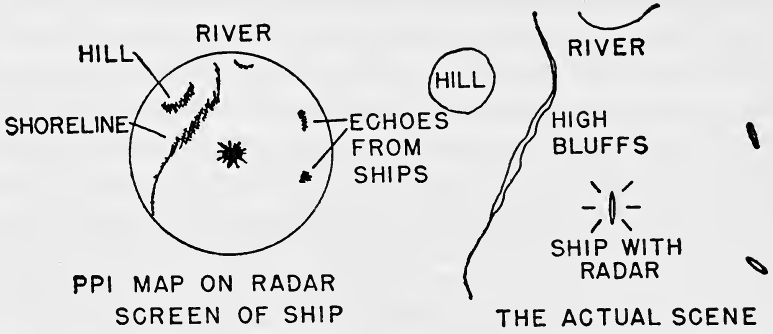
that tube would allow some of the enormous energy of the transmitter to reach and burn out the delicate circuits of the receiver. Because of the similarity of design problems, prewar experience with television gave our radar engineers a good start in the development of ultrasensitive radar receivers. After amplifying the initially very weak radar signals several million times, the receiver passes them to the "display" or "indicator" for presentation to the radar operator.

Here on the glowing screen of a cathode-ray tube, very similar to a television-picture tube, the operator sees the radar echoes. In the "A scope" presentation, the echoes appear as vertical "pips" of the luminous line traced by an electron beam on the darkened screen of the tube.



At the instant the transmitter sends out its burst of radiation, the deflecting coils cause the electron beam inside the indicator tube to begin its sweep across the screen from left to right, at a uniform rate, leaving a bright fluorescent trace behind it. Immediately the echoes begin coming in, first from near-by buildings or ships, then later from targets at greater and greater distances. As each echo is received the deflection coils cause a jog in the path of the electron beam, giving a pip on the indicator screen. The pips, by their position, tell how long it has taken this echo radiation to make the round trip from the radar set to the target and back, and consequently, by their position, they show the distance to the target in miles. One thousand microseconds after the initial transmitted pulse, the echoes from targets 90 miles away will just be arriving—and causing their pips. The distance to the target as shown in the "A scope" and the direction in which the radar antenna is pointing locate exactly the distant target. To search for an attacking enemy, who may approach from any point on the horizon, the antenna of a radar using an "A scope" is slowly rotated. Then its beam is cast successively in all directions, and a pip appears when the beam shines on an object. If there are many ships or aircraft in the vicinity it becomes increasingly difficult to keep track of them with the A scope, and then the PPI presentation is used.

The PPI—Plan Position Indicator—draws an actual map of the surroundings as seen by radar. The PPI combines and presents on the screen of a single scope all the echo information obtained by the radar for a complete rotation of the antenna. The electron beam in the PPI scope starts at the center of the screen when the pulse is sent and moves radially outward at a uniform rate in a direction corresponding to that in which the antenna is pointing. When the radar echoes arrive the electron beam momentarily becomes very intense and leaves bright spots on the fluorescent screen. At the next pulse from the transmitter, the antenna will have rotated a tiny bit, and the PPI scope will draw another line close by, but at a new angle. By the time the antenna has completed a full revolution, the PPI will have drawn a complete radar map with hundreds of bright lines written electronically on the fluorescent screen, and with the center of the map corresponding to the position of the radar antenna.



PPI MAP ON RADAR SCREEN OF SHIP

THE ACTUAL SCENE

Special long-persistent fluorescent screens, which give an afterglow for many seconds, are used with PPI because the complete map may take many seconds to draw while the search antenna slowly rotates. Ships are represented as blobs of light. While they do not have the actual shape of ships because they are only a representation of an echo, they are easily interpreted by a trained operator. Shore lines and hills beyond stand out. Buoys and navigational aids in harbors can be seen, as can any rocks or reefs extending above the surface of the water.

A major peacetime use of radar will be for the navigation of ships and passenger liners. The potentialities of radar navigation are illustrated by the following story taken from the official government document, "Radar, A Report on Science at War":

"A formation of cruisers was ordered to steam into an archipelago in the Solomon group to bombard some enemy shore installations. The time chosen was on the blackest of black nights, and the waters had been charted only sketchily, yet the formation set out, relying on their radar to bring them through. They took column formation, steaming at 25 knots, and kept formation perfectly. They cruised confidently through the intricacies of the unfamiliar archipelago to the point to be bombarded. Reaching that point, they successfully evaded several minesweepers engaged in sweeping operations in the immediate vicinity. They found their objective and carried out their assigned bombardment. Still at 25 knots, they turned and countermarched in the narrow waters and steamed back out. And on their arrival back at base, they were able to report that one of the reefs on their crude charts was in error by about six miles. All this was done in zero visibility."

The air-borne PPI radar called "Mickey," designed for use by bombers, showed the terrain below with sufficient accuracy and clarity to carry out high-altitude bombing of targets hidden by clouds. Lakes, rivers, fields, cities and individual buildings showed in the screen due to their different scattering and reflecting effects on the radar radiation. Each Mickey-equipped pathfinder plane led and directed the bombing of 60 other planes through weather so thick that only for a few days of any month could visual bombing have been practiced over the Continent. During the most important winter (1943-44) of the European strategic bombings, no more than 12 planes equipped with Mickey led the world's biggest heavy-bomber formations while they dropped 24,000 tons of bombs in one month. Visual sighting of the target was preferred, but because an opening in the clouds over the target was too often only a fortunate accident, the radar man at his PPI scope and the bombardier at his Norden bombsight usually worked together to take advantage of the smallest break in the clouds. Mickey was used to guide the plane into position for the bombing run, and the radar operator continued his control as if he were going to do the whole job. The optical bombardier lined up his sight from the radar information, so that if any break occurred in the clouds the telescope of his Norden bombsight was already pointed right at the aiming point below. A single sight to the ground enabled him to take over the run and drop the bombs optically. If not, the radar operator dropped them according to the information provided by Mickey.

Our enemies also had radar. The German radar equipment was particularly efficient and deadly. Because they knew in advance that they were heading for war, their radar research had a head start. The Italians never got very far with radar—the Germans furnished their protection. The Japanese had some equipment, often poor copies of early Allied radars, but it was enough to be dangerous.

For every weapon there is a countermeasure, and radar was no exception. The history of the race between our scientists and those of the enemy, and of the pitting of countermeasure against radar system was one of the thrilling technical stories of the war. For us to have lost this battle could well have meant our total defeat.

At the beginning of our strategic bombing, Europe was protected against air attack by thousands of antiaircraft guns aimed by the highly accurate German "Wurzburg" radar. This radar could point a gun at a plane flying in the dark or behind clouds with as little error as though an optical gun-director system had the plane across its sights in daylight.

As soon as our heavy bombers received fighter protection against intercepter planes, the Germans' only defense against our radar bombing through clouds was their Wurzburg-controlled antiaircraft fire. Then we used "Window." Each bomber dropped thousands of thin strips of aluminum foil which spread out like locusts as they slowly settled to earth. The Wurzburg operators below were unable to distinguish the clouds of Window from our bombers. Their defenses were disrupted and our losses immediately dropped. Mickey, which operated with microwaves instead of the longer Wurzburg wave lengths, could see through the Window unhindered, and our bombing through the clouds went on.

Soon Window was supplemented by "Carpet." This countermeasure employed a radio transmitter carried in each plane. It operated on the frequency of the enemy radar and sent out such a hash of spurious signals and noise that any faint radar echoes from the planes were drowned out and confused by the louder signals from Carpet.

The combination of Window and Carpet made the Wurzburg radars an actual liability. They furnished no protection. And in an attempt to salvage their billion-dollar investment in the 4000 nearly worthless radars, the Germans at one time tied up 90 percent of their best electronic scientists for work on this futile job. Microwaves could have cut through the Window, but their technicians were too busy patching up a system that had been built to win a short war.

We had other tricks besides Window and Carpet for use wherever our forces encountered enemy radar. By the use of radar search receivers tuned to the enemy radar frequencies, we could hear the probing radar signals of an approaching foe long before he could pick up the faintest echo from us. Moreover, by tracing the signal to the source with one of our planes, we could often locate and destroy the enemy.

With radar all ships and airplanes look much alike. Radar "eyes" are not sharp enough to distinguish shapes. However, with IFF—Identification Friend or Foe—our radars separated friend from enemy. Our ships and planes were each equipped with an IFF responder box that replied with a radar signal "password" whenever our radars looked their way. If the password were correct for that day we didn't shoot. The Japanese, who did not have an IFF system, many times fired on their own ships in the midst of radar-controlled gun battles at night.

Both the Japs and the Germans, suffering under the impact of our countermeasures, belatedly tried the same thing against us. They were too late. It can be said that we had radar, and got the most out of it; the Axis also had radar, but because of our countermeasures got very little out of it.

A third of a million watts at three billion cycles per second—sounds impressive, doesn't it? Such is the peak power during a burst of radiation in a typical radar transmitter, seven times more powerful than the largest standard broadcasting transmitter. Our wartime supremacy in radar was due to just such superior power and performance of our equipment. Electronics engineers in 1940 would have ridiculed as utter fantasy the generation of such enormous powers at frequencies anywhere near this frequency. With the special laboratory-model tubes then available, the production of only a few hundredths of a watt at three billion cycles was an achievement. Even at less than a tenth of this frequency, the outputs of the best tubes that could be built were only a few watts. But in the face of this, radar engineers, both here and in England, knew in 1940 that to exploit fully the radar idea, transmitter frequencies must be increased, 'way beyond the 100 to 200 megacycles used by the radars then. Power output could not be reduced in the process, but preferably should be increased. The problem of a high-frequency generator seemed almost impossible.

To the British scientists at the University of Birmingham goes the credit for the development of the cavity magnetron—which did the impossible and more. When exhibited in this country in August 1940 by the British Technical Mission, its performance at microwave frequencies amazed our scientists. Within three weeks a hurried copy was built. Co-operative arrangements with the British were set up whereby we were to develop radars using the new tube for both countries. A microwave laboratory on the grounds of the Massachusetts Institute of Technology was organized, and within a year 4100 scientists were working at full tilt. The first microwave radar operated in 1941. By 1943 the avalanche of the new microwave radars coming from our production lines was beginning to be felt by the enemy.

The cavity magnetron generates its radio energy by whirling a dense cloud of electrons through a magnetic field. At the center of the tube is a large, cylindrical coated cathode, the source of the electrons. There is no grid. Spaced from the cathode and surrounding it is the heavy copper anode with keyhole-shaped slots cut into it. These are the cavities. Placed outside the tube are the pole faces of a powerful magnet which sets up the strong magnetic field parallel to the axis of the cathode. Electrons leaving the cathode cannot fly straight to the positive, attracting anode. They are forced by the magnetic field to whirl in tight loops in the space between the cathode and the anode. As the electrons sweep by the slots in the anode they give up some of their energy, and produce the super-high-frequency electrical oscillations within the cavities.

The radio energy is conveyed from the cavities of the magnetron to the antenna through the interior of a hollow metal pipe, the wave guide. There are no wires! Radio energy at microwave frequencies will not follow along a pair of wires as it will at lower frequencies. It would evaporate off and be lost long before it could reach the antenna to be directed at the target. Coaxial cables can be used in very short sections, but general use of them in the set would absorb too much of the precious radio energy.

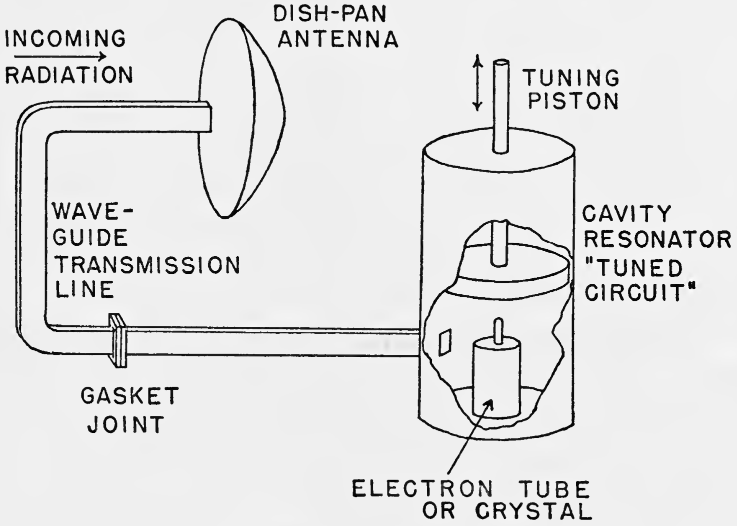
Microwave plumbing—the wave-guide technique—is the only efficient way of handling these frequencies. Within the rectangular or circular metal wave guide, which looks remarkably like a rain-water downspout, the radio waves are sent bouncing along, from one reflecting wall to the other, through the tube. Holes or leaks cannot be tolerated, for they would allow the energy to escape, and would disrupt the smooth pattern of internal reflections necessary for efficient transmission. One of the cross-sectional dimensions of the wave guide must be slightly greater than the wave length of the transmitted radio energy. A wave guide for a 3-cm. magnetron such as used in Mickey (10,000 megacycles) would have a rectangular cross section of about 1½ inches by ½ inch. Lower frequencies and longer waves require larger guides. Fortunately, at those lower frequencies at which the wave guides are too large for convenience, coaxial cables have regained their efficiency.

An interesting sidelight is that wire-communication companies intend to use wave-guide high-frequency transmission for future development and expansion, if tests show that radio relay links do not give the anticipated reliability and satisfaction. Coaxial cable telephone and television transmission, while far superior to anything now in general use, is thus only a transition method. Coaxial methods are now perfected, and a nationwide network is being established to carry the immediately anticipated load. Meanwhile, in their laboratories engineers and scientists have been looking ahead to better ways of conveying information.

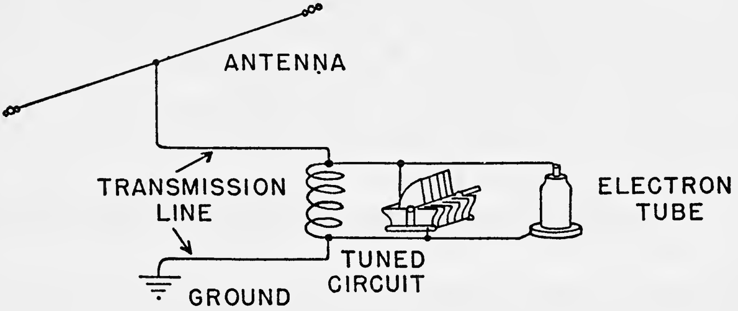
A flaring mouth at an open end of a wave guide makes of it a horn for directing the radio energy efficiently out into space. Operated in reverse, the same configuration is an "ear trumpet" for collecting and "listening to" weak incoming radiation. Sharper radio beams than those furnished by a horn alone are obtained by supplementing it with a "dishpan" or "bathtub" reflector.

Cavity resonators for tuning radar transmitters and receivers is another new trick at microwave frequencies. A metallic hollow box, rectangular or circular, replaces the familiar coil and variable condenser of the tuned circuit. Tuning is accomplished by varying the position of the movable end plug or piston. The box responds to electrical oscillations of only one frequency for the same reason that a bottle or jug whistles at a single frequency when you blow into it. Radio energy is brought to the cavity resonator through a wave guide. If the grid of an amplifying tube is to be connected to this new kind of electrical tuned circuit, the whole tube is usually built right into the hollow resonator.

Using radar plumbing in a microwave receiver, the antenna system, the tuning element, and the associated first vacuum tube are assembled in this fashion:



The metal reflector catches the radiation and directs it into the horn and thence through the hollow silver-plated wave guide to the resonator and vacuum tube. Where joints occur, ingenious gaskets and connectors are inserted to keep the radiation from leaking out. At ordinary frequencies, the equivalent radios are composed of wired circuits.

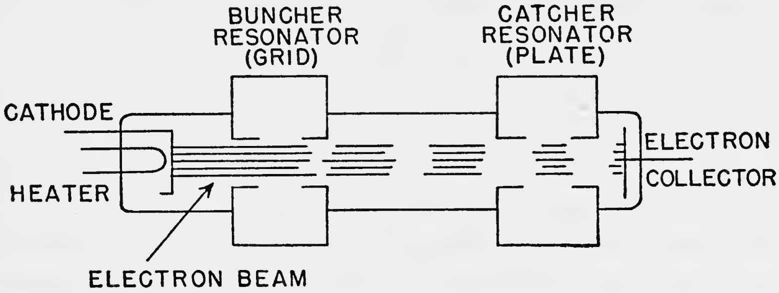


The essential difference between the two methods is that at ordinary radio frequencies, the radio energy passing the wire antenna is converted to tiny oscillating electric *currents* which can be carried through the circuit by wire connections. At microwave frequencies, however, it is most efficient not to convert the radio waves to electric currents, but instead to "pipe" the *radio waves themselves* through the apparatus.

High-pressure wartime research and development produced and perfected a variety of useful new electronic tube types. In an emergency it is not safe to put all reliance on only one line of development. Thus, while the magnetron held great promise when first demonstrated, development continued on such tubes as klystron and resnatron signal generators—and happily, too, for each was soon found to have an indispensable application.

Electrons do not travel fast enough to allow ordinary tubes to operate at the radar frequencies. At ordinary frequencies, when the grid swings toward positive, the electrons flash by from cathode to plate. Not so in microwave operation. Then the voltage fluctuation applied to the grid is so rapid that an electron released from the cathode on a positive grid swing is repelled back again by the following negative grid swing before it is able to pass the grid wires. The "transit time" of the electron is too great. In the new "lighthouse" tubes transit-time effects are mitigated by moving the grid to within a few thousandths of an inch from the cathode. These tubes are designed to be built right into a cavity resonator, and the internal structure becomes an integral part of the cavity. Their name "lighthouse" comes from their ingenious construction in which cylinders of glass space the metal disks which support the internal elements. Metal-to-glass welding, essential to such construction, was developed to a high state during the war.

Transit time, the bane of the triode in the microwave part of the spectrum, provides the operating mechanism of the klystron tube. The klystron, often used in radar receivers, is a "velocity-modulated" tube. In it, unlike usual electronic usage, the speed of the electrons is modulated. An electron beam from the cathode is shot axially through the center of the klystron. Two microwave cavity resonators are built right into the tube and the electron beam passes through them. The first resonator box functions as a grid, the second as the plate of a triode. As the cathode beam passes through the first cavity resonator, called the "buncher," the radio energy contained in the box causes the beam to speed up or slow down in accord with the radio oscillations. Then, while the beam drifts along to the next cavity —at a mere 9000 miles a second—the speedy electrons overtake those ahead, the slower crowd those behind. By the time the beam reaches the second cavity, the electrons are traveling in tight bunches. These parcels of electricity, zipping like beads through the second cavity, induce there a powerful radio oscillation, an amplified replica of the weak oscillation inserted in the first cavity.



KLYSTRON

Operating with microwave oscillations, the klystron is able to amplify and oscillate in much the same way as the triode tube.

The resnatron, also a velocity-modulation tube, was the most powerful radar tube used during the war. Used in the installation called "Tuba," it threw a blast of radar noise from England across the Channel and over the continent into the faces and radars of the German night-fighter pilots chasing the British bombers home. Within the month of initial operation, the Germans were forced to drop the use of their "Lichtenstein" airborne radars and to use a radically different type. The resnatron develops about 50 kilowatts continuously—as much as a high-powered standard broadcasting station—at 100 to 500 megacycles. Thus it is expected to be useful in television and FM transmitters which operate in this frequency band, though its full power is much too great for economical use.

Writing of the future of radar in the January 1946 *Electronics,* Dr. L. A. DuBridge, wartime director of the Radiation Laboratory, said, "Radar will have two important fields of application—navigation of ships, and navigation and traffic control for aircraft. Techniques developed during the war for radar will find use throughout the field of electronics and radio. These electronic and high-frequency results may, indeed, be the most important peacetime result of the radar war research."

Later in his article he said, "With a suitable radar set, a ship may sail safely in the thickest weather or the darkest night through congested harbors, narrow waters, and iceberg-infested seas."

Airplane navigation and traffic control present a series of complicated problems that are solvable by means of radar techniques. Flying on schedule, in spite of any inclement weather, is a first requirement of a really successful system of air transportation. Operations which are now possible are: radar navigation of airplanes, blind landing by radar control or by microwave glide-path beams, and the central position plotting and control, by the airport dispatcher, of incoming and outgoing planes in the neighborhood of the airport. Weather, in the form of violent storms, appears on radar screens. Information and instructions may be relayed from powerful ground radar stations to the pilots so they avoid the storms.

A war-developed system of guiding pilots in to a landing through clouds and fog is now being applied in a limited fashion at some of the commercial airfields of the country. The system is called GCA—Ground Controlled Approach—and makes use of a radar on the ground to measure the exact location of the plane over the field as it comes in for the landing. The operator on the ground, viewing his radar screen, talks by radio to the pilot and tells him to fly right or left, up or down—he "talks" the pilot down to the ground. No more than a radio receiver in the plane is required for the system. GCA has disadvantages but it served during the war, and now, until equipment better-suited for commercial use is developed, it will serve in peacetime emergencies.

A series of 28 technical books soon to be published will probably be among the greatest peacetime contributions of our wartime radar research. These books, written by the now disbanded staff of the Radiation Laboratory, contain a full report of the new electronic knowledge and developments gained from five years' work in radar and allied fields by 4100 of the country's outstanding physicists and radio engineers. The long-time impact of this and other information from radar engineering on industry and communication can now only be guessed, but it will certainly be to the benefit of communication and of industry in innumerable applications.

CHAPTER 11

TELEVISION

TELEVISION has been "just around the corner" for the last ten years—a victim of war, economics, and its own technological improvements. Even today, the biggest question in television—when will it come?—still has no answer. Television sets could have come onto the market in quantity in 1946 if buyers would have been content with high-quality black-and-white pictures, if there had been no problem about obsolescence of receivers when color television emerges on a practical basis within the next few years, and if sponsors able to pay for expensive "motion-picture-quality" television programs could have been found. But the expected deluge of sets did not appear. When television will finally be released is anybody's guess. On the basis of technical accomplishments, television is here now. A few thousand sets in New York and Pittsburgh have been receiving television programs all through the war. The television boom could begin within a year. But due to other factors, the general introduction of television may yet be five years away.

When television comes it will have some surprises in store for you. Have you ever seen a television set in operation? Probably not if you are an average American. When you see your first program you may be surprised to learn how much television is like a talking movie shown on a reduced scale in your living room. Television has added attraction in that you see the action instantaneously, as it is happening in the distant studio. Television is so unlike radio, there is little comparison. True, both transmit the program by radio waves and electronics and both transmit voice or music, but the similarity ends there.

Because television is so new and different, it has some remarkable advantages, and at the same time it has certain inevitable limitations.

Television presents a moving picture. In doing so it appeals to our most highly developed sense—the visual. The moving television image gives an emotional impact, a feeling of being at the scene as events are actually happening. Actually to *see* the sports event and the contestants, to see the actions and mannerisms of foreign representatives at international conferences, or to see the play of emotion across the faces of actors in dramatic performances is your privilege with television, and one that radio cannot equal.

Accompanying the picture is sound, transmitted with the high-fidelity perfection of FM. But the sound is secondary. To follow the program you must watch the screen. Unlike radio, television will not allow you to split your attention between the program and a newspaper. The radio sports commentator at a boxing match describes the scene blow by blow. The television commentator lets you watch the blows, and once in a while he will pass on a bit of information about the form the fighters are exhibiting.

As at a movie, you sit facing the screen and, with the smaller screens, not too far away. Moreover, the quality of the picture is enhanced if it is viewed in dimmed light or a darkened room. When you watch a television program you can do little else.

The programs, in order to attract a wide audience, will be good—good enough to compete with such other attractions in the home as reading, work, card playing, or gossip. People don't go to any movie, good or bad, simply because it is a movie. Neither will they watch just any television program after the novelty has worn off. But the problem of producing enough high-quality programs to fill several hours each night has not been solved, and it is one of the factors that is holding back the commercial arrival of television. When it is solved—and it must be solved before television can be fully successful—the fine visual entertainment in our homes will include new movies and Broadway plays. They rate high in audience-preference surveys. Sports events, news, and on-the-spot broadcasts will fill in.

The technical problem in television is one of converting a moving picture into an electrical signal suitable for transmission from an antenna, and then putting the signal back together into a picture at the receiver.

A picture is no more than a pattern of light and shadow. A square array of hundreds of light bulbs on the face of a panel, with each light capable of being turned on or off separately, could create such a pattern. Certain elaborate display signs do in fact use this principle to present news headlines or simple animated cartoons. It was the method of television-picture transmission proposed in 1880 by two English engineers. A camera focused an image on an array of light-sensitive cells. Each cell was connected by wire to a corresponding electric light bulb on the distant picture panel. The light bulbs were light or dark depending on the light pattern falling on the light-sensitive cells. The array of lights would then recreate the distant picture.

Television by this method has the disadvantage of requiring a stupendous number of separate wire circuits to make a recognizable picture. The crude picture that could be drawn by blacking in the squares on a checkerboard would require 64 expensive wire circuits—and it would be completely impractical. The fine picture detail of the present television sets would require a quarter million connecting wires and lamps!

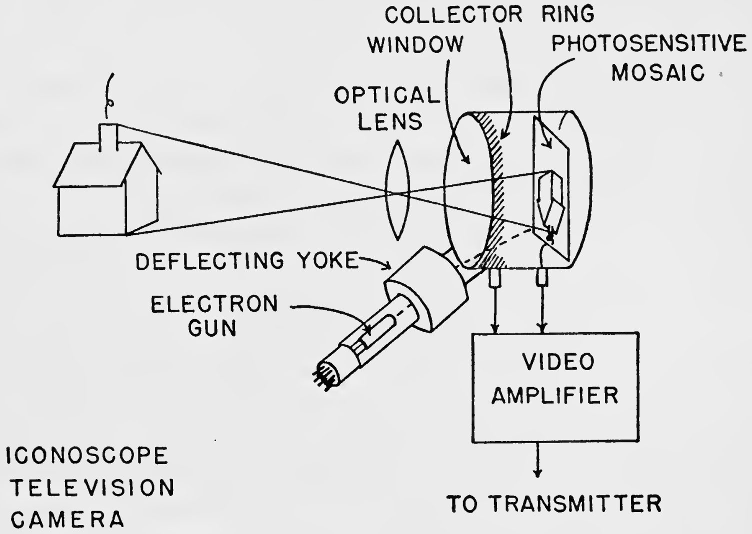
The transmission method used now is based on the way your eye reads the printed page. You do not read the page all at once. You start at the top line and read across, then you begin the next line and read across it, and so on to the bottom. You "scan" the page, absorbing the whole by systematically looking at one small spot at a time. Scanning is necessary because your mind and eyes are "one-track" and can take in only one word at a time. Then in your mind the parts are fitted together to give a meaning to the writing on the whole page.

Television employs scanning for the same reason. The television-camera tube reads across the picture as if it were a printed page, line by line, from top to bottom. Only one tiny part of the picture is being looked at by the camera tube at any one time. The light or shade at this single spot is electronically converted into a voltage signal which may then be sent out over a wire to the transmitter. Scanning is the only practical method of converting a picture with its hundreds of thousands of tiny details into a form suitable for transmission. Each scanning from top to bottom transmits one complete picture. After sending one picture, the tube begins at the top all over again.

Rapidly repeated scannings of a changing scene allow television to present to the eye a series of pictures which convey the illusion of movement—the same trick which is used by the moving pictures. Television pictures change 30 times per second, movies change 24 times, but the eye is fooled with as few as 16.

Television-camera tubes, which electronically scan an optical image and convert it to an electrical signal, bear such names as "iconoscope," "orthicon," "image dissector," and "image orthicon." Their differing characteristics fit one or the other for a particular application. The most sensational performer is the new image orthicon which can see and televise scenes by the light of a single candle! With this tube, for the first time, indoor events can be televised with no more than the usual lighting. This is in sharp contrast to the intense lighting that earlier tubes required. The image dissector is especially useful in color-television cameras. The iconoscope, invented by V. K. Zworykin of RCA, was the first really practicable camera tube, and in spite of competition from the newer types it still dominates the field.

The iconoscope is an odd-shaped vacuum tube about 12 inches long. Inside, facing the clear glass window, and at the back of the bulb, is a very thin mica plate about 3 by 4 inches in size with a photosensitive front surface. This light-sensitive surface corresponds to the sensitive emulsion used in a regular camera. Brown and velvety-looking, the surface is made up of millions of microscopic globules of silver and cesium evaporated onto the face of the mica sheet. The back of the mica sheet is covered with a layer of tin foil, and from this the television-picture signal voltage, the "video signal," is taken.



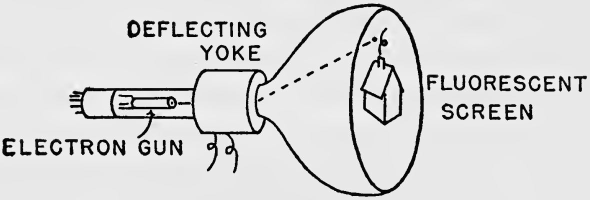
Sticking out from the bottom of the window in the iconoscope tube is a long neck containing the electron gun. From the gun a beam of electrons shoots up at the photosensitive surface. The point at which the beam strikes is the point at which the iconoscope "sees" at any instant in the scanning sequence.

The deflecting yoke slipped over the neck of the tube contains two sets of electromagnetic windings. Current in one controls the horizontal point of impact of the electron beam; current in the other controls the vertical. By proper variation of the currents in the deflecting coils, the electron beam can be made to scan systematically the whole photosensitive surface.

In operation, light from the picture image falling on the silver and cesium photosensitive surface "kicks out" electrons, which fly away from the screen and are gathered by the collector ring. Where bright light falls on the screen, there is created a deficiency of electrons. In this way the photosensitive surface translates the picture image of light and shadow into a pattern of electrical charges spread over the surface of the plate. But the video-picture signal has not yet been generated. This is done with the help of the electron beam. The beam, directed by the deflection yoke, scans the pattern of charges on the screen, line by line, tracing out 525 lines from top to bottom 30 times each second. As the tiny point of impact of the electron scanning beam crosses a spot deficient in electrons, the missing electrons are replaced and a video-signal voltage appears in the tin-foil back plate. This voltage is proportional to the brightness of the optical image at the point where the scanning beam falls. The tiny scanning beam passes over the whole picture screen, and a complete electrical description of the picture is generated each 1/30 of a second. The small voltage impulses appearing on the tin foil are the picture signal.

They constitute the video voltage, which, after amplification, amplitude-modulates the carrier of the television transmitter. In order to keep the complicated scanning sequence and timing of both the transmitter and the receiver exactly in step, extra synchronization pulses are transmitted to mark the time when the electron beam is returning to read the next line.

At the receiver the video signal is reconstructed into a picture by a kinescope tube, which also depends on an electron beam for its operation. Because an electron beam is called a "cathode ray," coming as it does from the cathode, kinescopes are sometimes called cathode-ray tubes.



KINESCOPE

The electron beam is again furnished by an electron gun in the neck of the tube. In passing through the deflecting yoke, the beam is deflected so that it will scan the inside surface of the large flat front end of the kinescope in synchronism with the scanning sequence at the television-camera tube. The inside surface of the kinescope is covered with a thin coating of crystals which fluoresce or glow when they are struck by the electron beam, and the picture appears on this fluorescent screen.

The electron gun controls the number of electrons in the beam according to the signal received from the transmitter. Thus at the instant the scanning beam of the camera crosses a bright spot of the iconoscope screen, the electron gun of the receiver kinescope sends out many electrons and causes a bright spot on the fluorescent screen. Few or no electrons cause a dark spot. Because the scanning beams of both the camera tube in the studio and the receiver in the home operate in exact synchronism, a picture is built up, point by point, in the home receiver. Of course it is built up so fast that it appears instantaneously to the human eye.

The audio part of the television program is sent by FM from a separate transmitter and is picked up by a separate circuit in the television receiver, though the set uses only one tuning knob for both.

Color television is more complicated than black-and-white because the images have to be separated into three component colors for transmission, and then recombined at the receiver. The process is very much like the one used in color printing. Synchronized color wheels, divided into sectors of green, blue, and red, rotate in front of the camera tube and in front of the receiving kinescope.

First one complete green picture is transmitted and received, then a blue, then a red picture. Three sets of images, one in each color, are presented to the eye every 1/40 of a second. The rapid succession of colored pictures blend in the eye, and the result is a full-colored, moving image. A feature of color television is that the audio signal goes over the same transmitter and receiver as the video, in contrast to the double receiving equipment used with black-and-white.

Color television is still experimental, and several crucial technical details need a great deal of study and development work. Yet it is close enough to practicability to give the television industry doubt as to the advisability of immediate widespread introduction of black-and-white television.

Large bright television images are highly desirable and many schemes to produce them have been tried. Kinescopes can be made larger, but they become more and more expensive. Besides, tubes with a 10 or 12-inch-diameter screen are so long that they are difficult to mount in a console of reasonable size. Larger images are obtained by optical projection to a translucent screen. For this a kinescope giving a very bright image is required, and the arrangement operates in much the same fashion as a movie projector. Projection images 18 by 24 inches in home console receivers, or 11 by 15 feet for theater television, have been demonstrated.

The transmitting frequencies for television lie in the very-high-frequency region of the radio spectrum, around 50 megacycles for black-and-white television and at a yet higher frequency for color. Radio waves in this region travel only as far as the horizon, the line-of-sight distance. By raising the antenna, the range of the transmitter can be increased. Therefore, high transmitting towers are used, and hills near metropolitan areas are much in demand for television-transmitter sites.

Good television reception will require a special antenna on the roof. Color television may be especially critical in this respect. Aiming the antenna at the television station may be necessary in built-up areas among skyscrapers, where ghost images can be produced by radar type echoes from the sides of buildings.

Network distribution of television programs is planned. However, a television signal simply cannot be transmitted over ordinary telephone-wire circuits as can radio programs. It would die out before it had gone a mile. Special facilities, such as the new coaxial cable, are needed. One such coaxial transmission line is already in operation and is used to exchange television programs between Washington, D. C., and New York. A nationwide network of similar lines is being rushed to completion so that within two or three years television programs may be sent by wire from coast to coast. Besides coax, experiments are being made with the radio-relay type of transmission.

"Stratovision" is an ingenious system proposed for transmitting television and FM programs from a plane slowly circling in the stratosphere. Because of the increased height of the transmitting antenna, it promises to extend the transmitter service range from its present 35 to 50 miles to something over 400 miles. Acording to this plan, as stated by Westinghouse Electric Corporation and Glenn L. Martin Company engineers, a chain of aircraft at intervals across the continent, each cruising over a fixed spot, would simultaneously transmit 5 FM and 4 television programs to listeners on the ground 30,000 feet below. They estimate that with 14 planes they may furnish television service to 78 percent of the country's population. In operation, a ground FM or television studio would beam the original program up to the plane, which would then retransmit it back to the ground audience. Because adjacent planes of the cross-country chain would be in radio contact, programs could be relayed from plane to plane throughout the chain and across the continent. The cost of providing nationwide television service would be tremendously reduced, since it is estimated that a single plane costing perhaps $500,000 could give a coverage that would cost $100,000,000 to duplicate by coaxial cable and local television transmitters.

Television-program production presents new problems and a great deal more work to the studio than radio. Many more rehearsals are required. The scene is set not so much with sound effects as with backdrops, costumes, furniture, and all other kinds of "props." Mary Gannon, one of the few experts in television programing, writes in the trade journal *Television* about these settings.

"Breaking 28 hours a week of programing into such segments as fifteen-minute, half-hour, or even one-hour shows is going to call for a lot of variety in formats presented. And that same degree of variety must also be reflected in the settings and background of each telecast. The lunch counter in Joe's Diner looks very familiar to the televiewer if it appears as a soda fountain the next night and repeats itself as a bar in Kelly's saloon the night after. Not that all these items have to be stocked! A coat of paint, some molding, and a lot of imagination can turn a disreputable bar into an altar rail—and on very short notice too!"

Many televised programs will be obtained from outside the local studio. Portable equipment in suitcase-sized units, using the new image orthicon camera (which can almost see in the dark) make television reporting of indoor and outdoor events an attractive source of program material. In New York City, sessions of the United Nations and sporting events, such as horse shows and boxing, have been telecast. A considerable percentage of all programs will be canned on movie film for presentation at a convenient hour. At the moment, color television is completely dependent on a movie-film intermediary. Direct televising of color scenes still suffers from technical difficulties.

Local schools are a fertile source of television programs, and the arrangement provides the students with an actual workshop in television techniques. Schools in both New York and Chicago have embarked on regular series and have completed several dozen telecasts. "There Ought to Be a Law" features informal extemporaneous debate on a topic such as "compulsory military training," or "the tragedies of youth." "The World We Live In" combines educational film and discussions by students. "Juke Box Jamboree" is a high school jam session at the Teen Canteen.

According to one school of thought, commercial advertising must eventually support television. In the New York area commercial programs have been tried out on the limited audience of 5200 set owners. Pan American World Airways presented a series of film-reproduced travelogues on distant picturesque lands that can be reached by airways. Chef Boy-Ar-Dee Quality Foods took the audience into the kitchen for demonstration of good preparation; and the Sanforized Division of Cluett, Peabody & Company produced a fashion show entitled "Fashions—Coming and Becoming."

There are others in the television industry who believe that the cost of supplying high-quality television programs will be so great—it will certainly be many times that of a comparable radio program—that only by selling television service to set owners can television be a success. An evening television program, to win a wide audience, must compare favorably in entertainment value with a feature moving picture. But feature pictures cost on the average $370,000 per hour showing time. At this rate the total yearly radio budget, if applied to television programs, could supply only a hundred hours of movie-quality television programs in the year.

Television has an insatiable appetite for programs. A piece of music may be enjoyed repeatedly, but few want to see a movie the second time. Visual entertainment will not bear repetition. Therefore each television station must be prepared to present a continuous stream of new program material for several hours a day, each day in the year. Multiply this by the four or five television stations expected eventually in each community, and it is evident that the cost of producing enough different program material will be immense.

Methods for the audience to pay for the programs they actually see are under discussion. The principle is the same as a movie admission fee. According to one proposal, the picture would be scrambled so it could not be received by ordinary sets, and an unscrambler would be furnished to the subscription television audience. This unscrambler, like an electric meter, would record the use of the set each month, and the subscriber would be billed only for those pictures he actually saw. And, of course, by turning the unscrambler off he could also see whatever free television programs were being transmitted.

The problems of paying for the television programs is not the only thing that is retarding the advent of television. It is plagued by technological improvements. In broadcast radio, a 25-year-old cat's-whisker and galena crystal receiver can still receive the finest of modern broadcast transmissions. It is not so with television. Any improvement in the method of transmission of the television picture has invariably meant the junking of all earlier receiving equipment. It is not a matter of inferior performance on the improved transmissions—it is a matter of no performance at all! Attempting television reception on the wrong kind of receiver is as bad as trying to run a 16-mm. movie film through an 8-mm. projector.

Improvements in television have usually come through the introduction of new and better methods of scanning. Before the war, scanning with 441 lines across the picture was standard. During the war, the standard was changed to 525 lines to give a clearer picture and more detail. Color television, in addition, scans the picture separately for each of the three colors. Scanning is a complicated process, and if the picture is not put back together exactly right, it is unrecognizable.

The history of television in the last ten years illustrates what a serious problem these technological improvements are. As early as 1936 several research laboratories were exhibiting high-quality pictures with experimental apparatus. It was generally conceded that a year or two of intensive developmental engineering would have perfected the equipment for general use. Most of the present engineering knowledge was available, and two camera tubes, the iconoscope and the image dissector, were in use then as now.

Television did not appear on the market because these experimental sets, before they had left the laboratory bench, were already threatened with obsolescence. New ideas and inventions demanded a trial. Engineers wanted to make the pictures sharper with an increased number of scanning lines. Newly invented tubes such as the orthicon showed great promise. If sets had been built and marketed, the next major improvement would have left them worthless.

By 1941 the developmental engineers in television had nearly caught up with the research engineers. The current laboratory models contained many improvements and their pictures were good. It seemed that the time had come to stop making changes and start building sets. The public had been kept waiting for television long enough—some people had been "sold" on television since the early demonstrations with the first primitive equipment in 1927. Then, with the attack on Pearl Harbor, television went to war.

At the end of the war, new sets were brought out and demonstrated. The cream of the ideas from five years of wartime development had been incorporated into their improved 525-line black-and-white scanning systems. The receivers were good

—the bigger sets gave large brilliant images with a detail comparable to the best home movies. Sets costing $150 to $200 with 4½-by-7-inch screens were slated for quantity production by midsummer of 1946, with larger console models retailing at about $500 to be available later. Broadcasters rushed to file applications for operation in one of the six television channels. Television-transmitter sites were chosen and local citizens' groups began to express concern about the proximity of transmitting towers several hundred feet high. Television in black and white seemed to be on its way!—or so the industry thought.

Then, glamorous full-color television was demonstrated to engineers and to the public by the Columbia Broadcasting System in December 1945. Color television was advertised as being only a few months or a year from perfection. Prospective set owners naturally wanted the full color if it was to be available in so short a time. However, many experts in the industry gave their opinion that it would be more like five years before color television was ready to be released. But when it should be, color would make any black-and-white sets obsolete. It is that way with every major improvement.

The ensuing color *versus* black-and-white controversy confused the industry. Some timid broadcasters withdrew their station applications. Set manufacturers, already beset with strikes and material shortages, built only a few demonstration models and waited to see what would happen. The 1946 boom for black-and-white television had subsided.

Television is a brilliant technical accomplishment. The vast fortunes that have been spent in its development over many years have produced a black-and-white system that is little short of perfection. But television is an entirely new medium of entertainment and it has its own new set of problems. Programs must be good to hold an audience. A way of paying for expensive programs must be found. At some point a compromise with progress must be made and a halt called to the upsetting introduction of improvements. The television industry must know where it is going and how before sets can be brought out in quantity. A mistake, a widespread premature presentation to the public, could cause a boomerang, the effects of which television might never overcome.

Television is here now—but how soon you may have a set depends on policies yet to be decided by the industry.

CHAPTER 12

FM BROADCASTING

A REVOLUTION in radiobroadcasting is on its way. Frequency-modulation broadcasting, or FM, first demonstrated to astonished radio engineers by Major Edwin H. Armstrong in 1935, will soon change our whole pattern of broadcast listening. The change will be drastic. FM is a new method of transmitting voice and music by radio. New transmitters are required to operate in the very-high-frequency FM band. Listeners must buy special FM receivers and use roof-top antennas to take advantage of the new method. Yet the change promises to be well worth the price. Leading broadcasters predict that, except in a few rural areas, FM is destined within the next three to ten years to replace completely standard broadcasting methods.

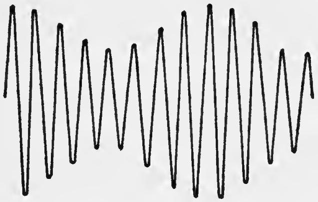
Why? Because the staticless, high-fidelity reproduction of FM is a revelation and a dream come true to listeners of conventional amplitude-modulated (AM) broadcasts. For the first time in radiobroadcasting, the full audible tonal range is to be transmitted. With a fine, large console receiver, you will be able to hear the deepest throbbing note of an organ pipe or the most piercing whistle of the piccolo in their true strength and brilliance. But what is most striking to the new listener is the absolute quiet when there is no music. Over an FM receiver, you may hear a pin drop. Quiet musical passages and dramatic scenes need no longer be marred by the hissing background noises, the crashes of static, the garbled voices from distant stations, that are often annoying in an AM receiver. Additional anticipated results of FM broadcasting are many more local stations in each community, more variety and better programs, and a higher standard of service to the listener.

The FM revolution is well under way. Fifty-three pioneer FM stations were in operation when the wartime freeze stopped construction. Hundreds of FM stations now proposed or under construction should be in operation within a year. Eventually, thousands of stations, large and small, are expected to cover the nation. While this change-over to FM from AM is going on, the best protection for a sizable investment in a new postwar receiver is one of the new FM-AM combination sets now being manufactured.

Major Armstrong, who developed FM, has had a brilliant radio career. His interest in radio began in high school, and while an undergraduate student in electrical engineering at Columbia University, he discovered that a De Forest audion tube could be made to operate as a regenerative detector and as an oscillator—two of the most valuable discoveries in the history of radio. Five years later he invented the superheterodyne, the basic circuit used today in nearly all radio receivers.

At an early date he began working on one of the most challenging problems of radio reception: the elimination of static. Engineers and inventors had long worked on this problem, and the patent files are full of their methods for filtering out the noise from the radio signal. None was very successful. In order for the noise and the radio signal to be separated, there must be some essential difference between them that a radio filter can recognize. Armstrong decided that the amplitude-modulated radio signal had too much in common with noise and static ever to allow their separation.

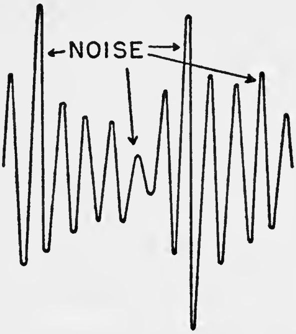
As we have seen, the conventional AM receiver measures the size of the electrical oscillations as they come to it, and their variations in size determine the movement of the paper cone in the loud-speaker. Therein lies the difficulty with AM. When music is received, and there is no static, the incoming radio signal and the outgoing music look like this:



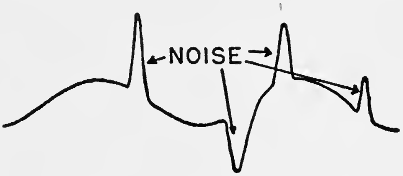
RADIO SIGNAL WITHOUT NOISE

MUSIC

However, atmospheric conditions and thunderstorms produce very intense electrical disturbances—static—which behave like radio waves and travel great distances to be picked up by the receiver. The sharp bursts of static disrupt the rhythmic musical variation in amplitude of the incoming radio signal, and the loud-speaker of the AM receiver responds with agonized cracks, crashes, and roars.

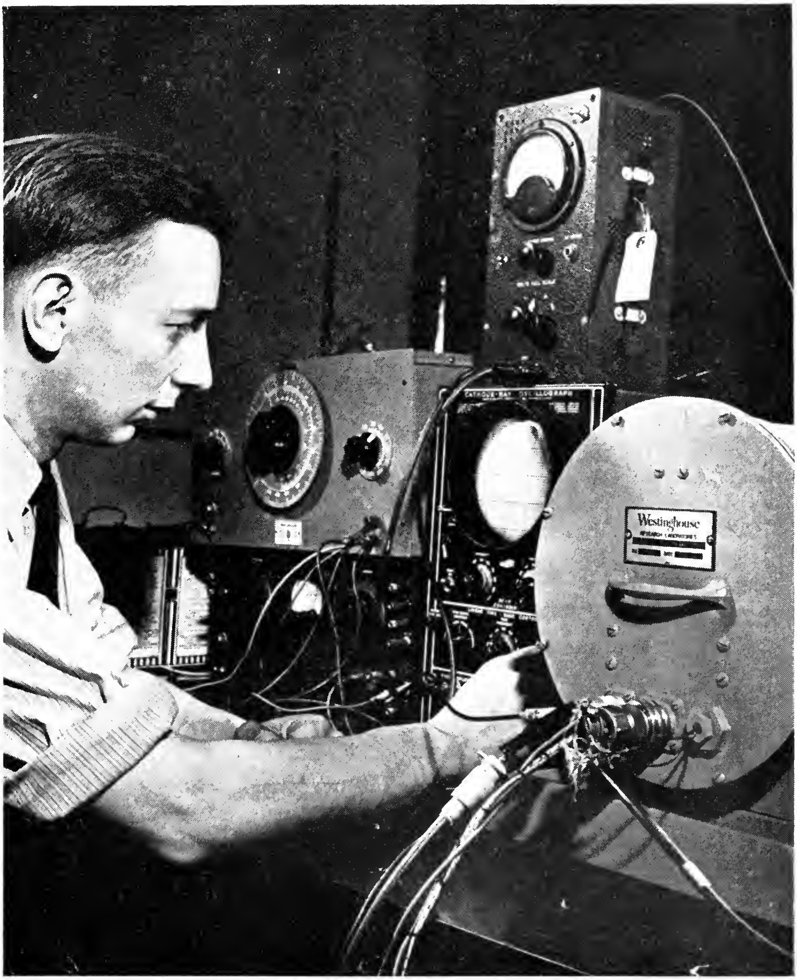


NOISY RADIO SIGNAL



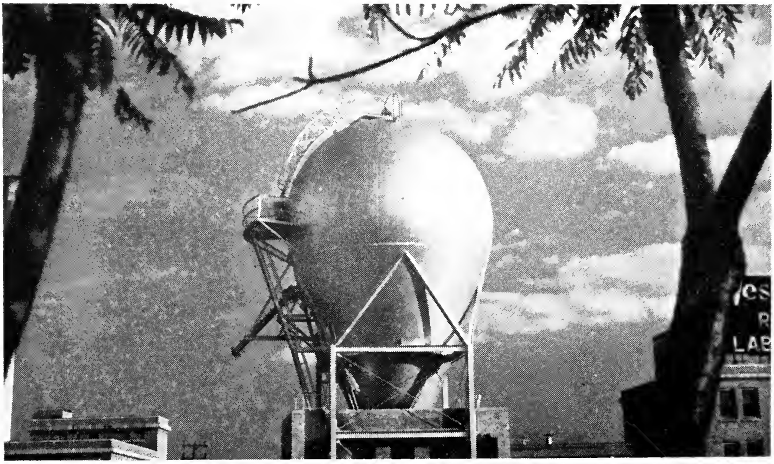
RESULTING NOISE AND MUSIC

To the AM receiver which measures only the size of the electrical oscillations, there is no difference between the bursts of static and the music, so both go through. No separation is possible with AM.



Here is an electronic engineer at work. Inside the circular can is a new electronic circuit under development. To determine its characteristics, the engineer sends into it electrical signals generated by the oscillator in the light colored box at the left, while he observes its electrical performance on the screen of the cathode ray tube before him. (Courtesy Westinghouse Electric Corporation.)

The nearest approach to the stupendous particle energies found in the mysterious cosmic rays is obtained from this betatron or induction accelerator. Electrons within the light-colored doughnut in the center are whirled by the huge magnet above and below it until they acquire the enormous energy of 100 million electron volts. (Courtesy General Electric Company.)

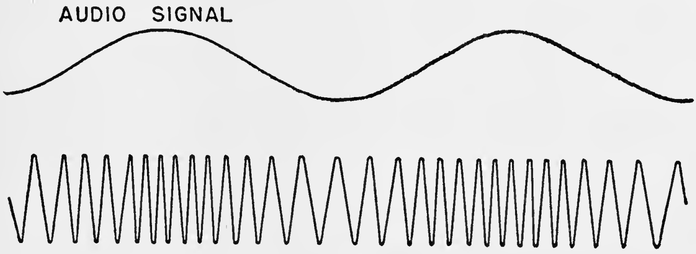


Van de Graaff type atom smashers, such as this one, produce atomic bullets of several million volts energy. While they are no longer the most powerful, they are indispensable for nuclear research because of the uniformity of particle energy and their ease of control. (Courtesy Westinghouse Electric Corporation.)

Armstrong reasoned that a method of radio transmission that did not depend on the size of the electrical oscillations might be freed of static. He remembered from his engineering classes at Columbia that amplitude modulation was not the only method of conveying the audio program on the radio-frequency carrier. There was also a method known as frequency modulation, in which the frequency of the oscillations instead of the amplitude was varied. But early in the history of radio, frequency modulation had been discarded and forgotten, because it had been shown by a mathematical study that an FM transmission would occupy much more space in the radio spectrum than an AM transmission. Space in the radio spectrum even then in the early days of broadcasting was altogether too precious to be used for FM transmission.

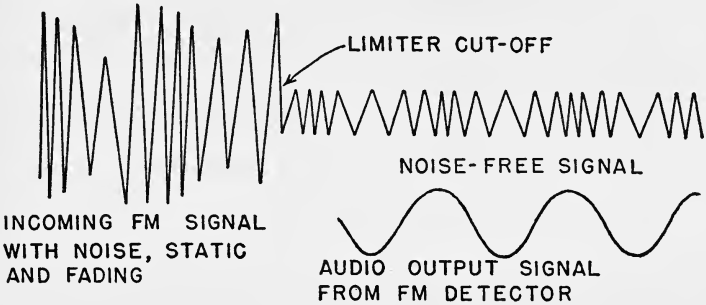
When the very-high-frequency region of the radio spectrum was opened up by radio experiments about 1930, Armstrong saw the opportunity. The VHF band, with 270 times as much radio "room" as the standard broadcasting band, could certainly accommodate FM transmitters. Years of experimental work began, filled with technical difficulties and a notable lack of cooperation or encouragement from the radio profession. Finally in November 1935, after working night and day with a friend to ready a transmitter, he gave a dramatic demonstration of FM before a meeting of the Institute of Radio Engineers. When the radio voice was heard announcing that the transmission was at a frequency of 110 megacycles, a surprised hush fell over the audience. The transmission was clearer than that produced by the average broadcast station—at a frequency so high it had hitherto been considered worthless!

An FM transmission conveys the audio signal by varying the frequency of the transmitter carrier in step with the voltage from the audio signal. When the diaphragm of the studio microphone moves back and forth under the impulse of the sound it hears, the radio carrier frequency goes up and down by a small amount in proportion. The amplitude is held constant.



This modulation of the carrier is equivalent to a tiny back-and-forth movement of the station on the tuning dial. The FM receiver senses this small change in frequency and converts it to audible sound. On the same signal, an AM set could hear little or nothing.

Noise, interference due to other stations, and fading are conquered in FM by a process called limiting. The incoming FM signal picked up by the receiver should be of constant amplitude —any variations in amplitude are due to unwanted noise. The limiter electronically slices off these undesired variations in amplitude which would mar the transmission, leaving a noise-free constant-amplitude FM signal. From this the detector re-creates the audio-signal voltage to be fed to the loud-speaker.



Noise or other extraneous disturbances do not affect the frequency of the incoming wave. Only the amplitude is affected. Therefore limiting, if it cuts the signal down deeply enough, can eliminate almost all the AM noise. Slow changes of signal strength or fading are also eliminated by the limiter. A remarkable property of FM due to limiting is that you can never hear two stations at the same time on the same frequency. Only the stronger station is heard, with no interference from the other.

The secret of FM is this ingenious combination of impressing the audio message on the frequency of the carrier, and then at the receiver of using a limiter to cut out all the noise which appears as amplitude variations.

An ordinary radio receiver cannot receive the FM broadcasts. It can neither tune to the 88-to-108-megacycle FM band nor, if it could, would it be able to take advantage of the signals it picked up. Therefore, the really major advance in radiobroadcasting made possible by FM has its price—the cost of a new FM receiver or FM-AM combination. Less expensive converters may be brought out, but since they would operate through the loud-speaker of the old set, the performance would be only slightly better than standard broadcast reception. This is because the FM broadcasters transmit the complete audible range of sound frequencies, from 50 to 15,000 cycles—which is a range three times as wide as any ordinary set and speaker can reproduce!

For the same acoustical reasons that a bass drum cannot be made smaller, a table-model FM receiver cannot perform to the full capabilities of FM reception. The loud-speaker must be in a large console-sized cabinet in order to reproduce the low-frequency musical vibrations in the air of the room. With the same speaker in a small cabinet, such notes just will not be heard. In addition, higher-quality—and therefore more expensive—electronic equipment is required in a good FM receiver if the advantage of 50-to-15,000-cycle transmission is not to be lost. In performance and price—$300 or $400—a good console FM receiver must be classed as a fine musical instrument.

Nevertheless, smaller-sized FM sets will retain the advantages of static and interference-free FM reception and will give a better reception than AM sets in the same price range. These less expensive sets can give the listener access to the wide selection of program material that is expected on the FM bands.

For the very best high-fidelity FM performance, room acoustics and the relative placement of the radio and the furniture will be important. The high frequencies, containing the brilliance of the sound, move in a straight line out from the loud-speakers. Furniture or hangings absorb these sounds instead of reflecting them. One good way to make sure they arrive at your ear is to arrange the chairs for listening at the far side of the room from the radio, and in line with the speakers. The room should contain enough furnishings to eliminate echoes and reverberations, though this is not likely to be a problem in an American living room.

The scrap of wire or the built-in antenna of the AM receiver will not serve in the FM band. Best reception—or sometimes any reception at all—will require an FM antenna in the clear on the roof. This will mean that an FM set cannot be moved from room to room and merely plugged into any light socket to operate, like the little plastic AM sets so popular now.

At the frequencies used in FM, radio waves travel in almost straight lines. Over the horizon or behind a very large hill, the FM station cannot be heard. "Line-of-sight" transmission, instead of being a disadvantage, is one of the fortunate properties of these high frequencies. Ordinary broadcast stations give adequate listening service up to about 50 miles away, while farther away the waves are too weak for adequate reception, but can still seriously interfere with any other transmitter in the same channel. Beyond the 30-to-60-mile radio horizon of an FM station, there can be no interference. The signal is never heard again at ground level. Each of the 100 FM channels may be assigned to many geographically separated stations. With nearly the same number of available channels as in the crowded standard AM broadcast band which is jammed with 1100 stations, the new FM band has room for thousands of FM stations, each giving a high-quality local service. When compared to AM, up to twice as many local FM stations can be assigned in each of the larger cities, and thousands of small community stations will dot the country. FM will bring an era of abundance in broadcasting channels.

For sparsely populated rural areas, too far from a community with an FM transmitter for reception, powerful AM transmitters are contemplated by the FCC. A few such transmitters with extra power and clear channel assignments could cover the country with network programs. In the cities these stations would have few listeners because of the advantages of local FM reception.

The higher the FM transmitting antenna the greater will be the range and the less the power required for adequate coverage. Skyscrapers and mountaintops will be at a premium. A pioneer FM station belonging to the New England Yankee Network is at the top of 6300-foot Mount Washington in New Hampshire, where the winds often sweep at 180 miles per hour and the temperatures drop to 40 below. The Empire State Building in New York, originally equipped at the top for mooring dirigibles, is now used for FM and television broadcasts. Hilltop locations and towers several hundred feet high will be used at other stations.

Stratovision planes have been suggested as an alternative to towers and mountaintops for greater FM coverage. It is estimated that 20 stratovision planes, flying at 30,000 feet with a line-of-sight horizon of over 400 miles each, could supply FM network programs to 90 per cent of this country's population. The same nationwide coverage would require a network of 200

FM ground stations, aided by a few strategically located very high-power AM stations to cover the few rural areas that would not be within the range of an FM transmitter.

FM should result in higher-quality programs and greater listener service. The many available FM channels in each community will give station ownership to a diversity of interests. AM stations want to double in FM; newspapers and publishers intend to enter broadcasting via FM; labor unions are looking for an FM voice, as are politicians; metropolitan school systems, farmer co-operatives, and moving picture producers have all applied for FM licenses. This diversity is aided by the low cost of a small FM station—from $15,000 to $25,000 for the complete electronic equipment, exclusive of real estate and buildings. Competition for listeners should produce programs of definitely higher standards in the FM bands than in the current AM bands, but to make doubly sure, the FCC intends to check promises against performance at the yearly hearings for license renewal, with a view to reallocating any channel not being employed in the public interest.

FM is on the way. There is no fear of obsolescence through improvement holding it back. Unlike television, whose pictures can always be improved for the eye, FM presents the ultimate to the ear—all the ear is capable of hearing from 50 to 15,000 cycles. Hundreds of new FM transmitters are being built. FM receivers are being bought as fast as they can be manufactured. The rush to FM has begun.

CHAPTER 13

RADIO RELAY

Early on the third morning of the Normandy coast invasion, trucks loaded down with a new kind of radio gear rolled ashore and climbed to the top of the bluffs overlooking the English Channel. Towers to support special signal-squirting antennas were put up, and the antennas were carefully aimed at the Isle of Wight, just over the horizon. There, a relay station with similar equipment was already in radio connection with the English coast. By noon the radio-relay telephone bridge across the Channel was complete. Generals in their headquarters in Normandy were calling by field telephone straight through to the invasion bases in southern England. Not one, but four, telephone conversations were handled at once by each equipment. When needed, each voice connection was replaced by a facsimile circuit to transmit photographs and maps, or by several high-speed teletype circuits.

Telephone lines with searchlight-beamed radio waves instead of wires—that's radio relay. At 30-mile intervals along the route of transmission, a radio relay station picks up the oncoming UHF radio beam with a highly directional antenna at the top of a tower, amplifies the radio signal, and then beams it on to the next relay point. Radio beams replace wires, and relay stations and towers replace the telephone poles and repeater stations.

Radio relay is one of the most promising new methods of overland communication. In 1936 RCA installed a three-hop radio relay connection between Philadelphia and New York for two-way multiplexed telegraph printer and facsimile service.

In approximately five years of service, this relay connection, with its two automatic unattended relay stations, provided communication more reliable than had been obtained by wire circuits over the same route!

The war gave radio relay its baptism of fire. In a crude form, radio relay began its service in Africa, where the rapid movements and great distances covered made it impractical for wire circuits to follow the advance. In the Sicilian campaign, a three-hop radio relay covered 243 miles over water between Sidi-Bon-Saïd and Malta. The Normandy beachhead cross-channel relay was a sensation, and its use for facsimile transmission of targets marked on aerial photographs was most valuable. With the airfields in England supplying bomber support for the ground forces, battles and lives depended on accurate and speedy transmission of pictorial information. By VE day there were enough radio relay sets in use to supply seventy-four 100-mile point-to-point systems. Radio relay was valuable in the Pacific, where often short radio jumps through mountainous and impassable jungle terrain furnished the quickest form of communication. General MacArthur after landing on Leyte made his famous "I have returned speech" over a radio relay set beamed to the powerful transmitters in one of the ships offshore for rebroadcast to the Phillipines.

For communication with a rapidly moving front line, radio relay went into operation faster with less equipment and fewer men than wire lines. Forty-four men could install 100 miles of radio relay in two days: with wire 1800 men with "clear the road" priority for bringing up their wires and poles required 10 days to provide equivalent service. Moreover, once installed, every foot of the wire line was vulnerable to bombing, sabotage, and trucks. Even buried cables were cut by bulldozers and graders. However, wire lines were usually established as soon as possible after each advance to guard against radio interception. Then, as a matter of routine procedure, all important communications channels were paralleled by radio relay to guard against interruptions in the wire service. To supply the immense volume of communication necessary in the rear areas, radio relay took the load off the inadquate and damaged French communications lines. From Paris there were links to Cherbourg, to Deauville, to London, to Namur, and to Vittel. The Air Force had a 410-mile eight-relay link, the longest in Europe, between Chantilly and Bad Kissingen, Germany. The last vehicle to enter encircled Bastogne, in the Battle of the Bulge, was a radio relay truck and trailer which provided telephone and teletype communication past the German lines until the division was relieved.

Now with the war over, the rush to apply radio relay communication methods has begun. Five companies already have obtained authorization from the Federal Communications Commission to construct experimental installations.

The American Telephone and Telegraph Company and its associated Bell System have plans under way to link Boston with New York by seven relay stations, and Milwaukee with Chicago by three. The Western Union Telegraph Company has announced plans eventually to replace much of their 2300 miles of wire channels by radio relay. The Radio Corporation of America, a pioneer in the radio relay field, is licensing Western Union to use their radio relay equipment. Flight tests by Westinghouse Electric Corporation have begun to test their Stratovision system—a form of radio relay employing stratosphere planes instead of tall masts to support the relay antennas. International Telephone and Telegraph Corporation have demonstrated their version of a system over an experimental 80-mile loop.

There are many variations on the radio relay idea, but all the systems fit the same pattern. They all operate in the ultra-high or super-high-frequency regions, usually from about 2000 megacycles up to about 7000. At these frequencies radio waves can be focused by curved dishlike reflectors or metal grillwork lenses into tight beams, just as light is concentrated into a beam by a searchlight. Reflectors a few feet in diameter can give a sharp beam at 5000 megacycles—while a reflector 10 times as large would be required to give the same kind of beam at 500 megacycles. This is one of the reasons why these high frequencies are preferred. At the receiving end, the incoming signal is collected by a similar arrangement. The efficiency of such a transmission system is many times greater than it would be if the radio signals were radiated in all directions or if the receiving antenna were not carefully aimed toward the incoming beam. As a consequence, only a watt or a fraction of a watt of transmitter power is needed to give consistent reception at the distant relay point. The principle is the same as that employed in a lighthouse. There, a lens and a reflector system concentrate the light from a lamp no larger than that used in your living room and throw it into a narrow beam that can be seen many miles out to sea.

Line-of-sight propagation prevails at radio relay frequencies. The waves do not bend over the horizon or behind hills. Radio relay antennas like television antennas are therefore mounted on towers or at the tops of hills to make the station-to-station jumps as great as possible. In Germany, with a mountaintop for a relay site, a 106-mile line-of-sight span was successfully operated, but 20-to-30-mile paths are more usual. As in FM broadcasting, line-of-sight characteristics have a great advantage for radio relay because there is no interfering with other similar services beyond the horizon.

Intermediate relay stations are used to connect stations not in line-of-sight distance of each other. A relay station consists of a combination receiver and transmitter and a set of antennas at the top of a tower. The relay station picks up the beam from the distant transmitter, amplifies it and sends it out again to the next relay point. The station simultaneously handles messages traveling in both directions. Because there may be many relay stations in a long radio circuit, the relay equipment must be very carefully designed so that it does not cause undesirable distortions of the signal—for such effects would accumulate in passage through each relay station until the transmission became worthless. This is an important problem in use of radio relay for transcontinental communication, where over 100 relay stations in series may be required.

A wider and a less expensively transmitted band width is the great promise of ultra-high-frequency radio relay systems. Present-day black-and-white 525-line television with its band width of around 3½ megacycles is already crowding the carrying capabilities of the coaxial cable now used for intercity transmission. Color television requires a 10-megacycle band width, and the coming theater projection of television may require more. At such band widths, the losses in coaxial cable become prohibitive while at the same time the required repeater amplifiers lose their gain. The limitations on band width for UHF radio relay are not known, but it is already clear that a properly designed radio relay system for the transmission of color-television signals will require less amplification for a given distance than when coaxial cable is used. Television aside, each megacycle of transmitted band width can carry 250 separate telephone conversations by using a modification of standard carrier techniques. Ten megacycles, which is a reasonable band width for radio relay, could carry 2500 telephone circuits. Alternatively, there may be inserted, in place of each telephone conversation, a facsimile circuit, or several teletypewriter circuits.

All radio relay systems make use of some type of radio transmission which eliminates static, noise, and fading. It is true that there is very little natural radio noise in the UHF part of the spectrum, so half the job is done to begin with. Noise-free frequency modulation is used in some systems, with the same satisfactory results as in broadcast FM.

Pulse-position modulation—PPM—is a new and promising method of transmission. PPM, like FM, is able to discriminate against noise. It had an advantage over FM in that it is easier to design repeaters for PPM which can relay the signal a great many times with no distortion.

The PPM transmitter sends out its constant-frequency signal in short bursts—the pulses—which are precisely timed and spaced. Each pulse may be only a millionth of a second long, but the pulses are repeated thousands of times each second. The audio signal causes some of the pulses to be sent out ahead or behind schedule, with reference to a fixed marker pulse, the delay depending on the instantaneous audio voltage. Therefore the name "pulse-position modulation." The pulses are all sent out with the same size, so an FM-type limiter is used at the receiver to slice off any noise. Several different telephone conversations or audio channels may be transmitted with PPM by assigning the first, second, and third conversations to pulses coming first, second, and third, etc., after the marker pulse. A radio relay system under development by the International Telephone and Telegraph Company obtains 24 different channels in this way. As a method of putting several messages over the same transmitter, it is basically different from the "carrier technique" used with coaxial cable and also the other relay systems. It is called "time-division multiplex" and has been used for years in "duplexing" many teletypewriters on the same wire.

Wire circuits for mass overland long-distance communication may be on the way out, with radio relay taking over. If portents from the communications industry are to be believed, the change will surely come. If so, the history of overland communication shows a consistent pattern. First, only one message was sent per pair of wires. Carrier transmission, which is really a modified radio technique, sent first three, then a dozen messages over a single pair of open telephone wires. By using coaxial cable and carrier frequencies extending up to the radio high-frequency region, 480 telephone conversations were put on one conductor. In the cable, these radio frequencies were guided to their destination through the hollow coaxial pipe with the wire in the center. Radio relay is merely one step farther. The radio waves, at a much higher frequency, are carefully beamed from one reflector to another between the distant relay points. Moreover, these higher frequencies, with their greater transmitted band width, can carry an even greater number of telephone messages—or better television pictures.

CHAPTER 14

ELECTRONICS AND THE FUTURE

The science of electronics is only a little more than thirty years old, yet its present accomplishments are already outrunning the imagination. No longer is it a matter for prediction that some day there will be winged aircraft flashing through the upper atmosphere guided by electronic mechanisms, or that some day electronic brains will take part of the load of thinking away from busy humans. These things and many more have already been done. If the experience of the last few years is any guide, we may be sure that electronics is destined to occupy an ever more important place in the material operation of our civilization. Never before has there been such a versatile genie to assist the muscles and the mind of man.

By collecting hints from research laboratories we may forecast a few of the important electronic developments that are on the way. In the field of communications, electronics will continue to reign supreme, with ever better methods of transmission of intelligence. In the intricate control of aircraft and of industrial machines and processes, electronics will take over a large part of the work. Electronic robot brains will appear in increasing numbers to assume onerous jobs of mathematical computation and bookkeeping. New dimensions of measurement and inspection, and of seeing the invisibly small, possible only with electronic methods, will further supplement our limited human senses. The probing of the secrets of the atom and the unlocking of the immense energies of the nucleus will depend on electronically powered atom smashers and on electronic instruments for measuring results. The conversion, control, and transmission of electrical energy will make great use of electronic devices.

Electronics is primarily a servant. Its place is behind the scenes where it does the controlling, thinking, measuring, amplifying, or converting. When electronics is at work, you may see big machinery or spectacular equipment performing some operation, but the electronic tubes will seldom be seen. They will be tucked away unobtrusively in small boxes from which they quietly control the larger operations. But whether the job is controlling the processes in a giant chemical plant, or guiding a fateful atom-bomb rocket to the destruction of a city, the part to be played by electronic equipment will be crucial.

In a peaceful world, what can the future of electronics promise? What are some of the unsolved problems within the scope of present or soon-to-come electronic technology? What marvelous devices are still in the laboratories, not yet ready to emerge?

The possibilities in the field of communication—by wire and radio—have only begun to be exploited. For instance, telephone service within continental limits has reached a high state of perfection, and tens of thousands of long-distance calls are handled quickly and surely each day. In sharp contrast is the limited service available over transoceanic and international communication circuits. One hundred simultaneous outgoing telephone calls could easily swamp all available transoceanic radiotelephone transmitters. There are simply not enough channels. Between any two points at opposite sides of the globe, radio communication is dependent upon the state of the ionosphere, the stratospheric radio mirror. Because of this, at certain times of the day communication between these points is impossible. Transmission of a modern television program from London to New York is also impossible. Furthermore, as was explained in the chapter on the Electromagnetic Rainbow, it would be difficult to spare for television many precious megacycles in the much used high-frequency region. There are too many stations and there is too little room in the part of the radio spectrum good for world-wide communication. Submarine cable circuits, while reliable, can only transmit high-speed telegraph messages. Voice messages, and especially television video signals, would be completely absorbed and lost a fraction of the way across.

World-wide telephone and picture communication which is cheap and which can handle a large volume of messages requires new technical developments.

Several proposals have been made. Before the war, a vacuum-tube repeater was under design which would have an expected service life of about fifty years before tube failure. One of these repeaters would be inserted at intervals in a short enlargement of the submarine cable, and it would lie on the bottom for the life of the cable, amplifying the messages going through. One or several telephone channels could be accommodated, depending on the details, or each telephone channel could carry many teletype circuits. Television transmission was not contemplated.

Radar to the moon experiments furnish the basis of a proposal for world-wide radio transmission advanced by Federal Telephone and Radio Corporation engineers. Powerful microwave transmissions beamed at the moon would be scattered and reflected at the lunar surface, and part of the signal would find its way back to the earth. The return signal presumably could be received over the whole hemisphere where the moon was visible. Transmitters of enormous power would be needed, and there are many difficult technical and economic problems to be solved before it would be feasible.

The German V-2 rocket suggests another solution. A rocket whose final velocity was only three times greater than a V-2 could be made to rise above the stratosphere and establish itself in a stable orbit rotating about the earth like a tiny moon by the time the fuel ran out. If the radius of the orbit were carefully set, the period of revolution of the dead rocket could be made exactly 24 hours, and it would remain apparently motionless over a given point on the revolving earth's equator. Such a nearby artificial moon would be an excellent reflector-scatterer of microwave transmissions. Several rocket moons and intermediate ground radio-relay stations could provide round-the-world multichannel telephone, facsimile, and television-picture transmission. Since the dead rocket would scatter only the energy beamed up at it, there would be no batteries to wear out.

Transatlantic radio relay by four or five Stratovision planes is a less visionary solution. If cross-country Stratovision radio relay proves feasible, transoceanic relay should not be much more difficult.

The future expansion of radio communication must be in the line-of-sight frequency regions, whether for long-distance radio relay systems or for short-range broadcast. Nowhere else in the radio spectrum is there room for the multitude of new services clamoring for radio space. Moreover, beyond the horizon the same frequency channel can be used again without interference. At microwaves, there are advantageous tricks in transmission methods such as FM, radio beaming, and pulse-time modulation which are impossible or difficult at lower frequencies. A color-television transmitter, for instance, would be technically impractical at frequencies lower than the very high region of the radio spectrum.

Which services are clamoring for space in the ultra-high-frequency spectrum? Better ask which are not! Ocean vessels want radar; planes and airport ground stations do, too. Personal "handy-talkie" radios for citizens already have a frequency allocation. The postwar expansion of flying, with the use of all sorts of radio flying aids and communication, will take up radio space. Railroads want UHF radio service to talk from engine to caboose. Service is now being established to provide radiotelephone communication to trucks on intercity highways. Radio relay services, FM broadcasting, and plain and fancy television transmissions take their bite of the spectrum. For their valiant service as radio operators in two wars, the ubiquitous radio amateurs also have been given generous assignments.

The newspaper of the future may be printed in your own home with one of the facsimile printers which are now perfected. Pictures and diagrams are reproduced along with the printing. Facsimile operates by scanning the original page, like a television camera. The signal is transmitted, and in the home facsimile receiver the picture is reassembled in a permanent form on a sheet of special paper. Foreign telegraph companies, long plagued by the problem of multiple alphabets, have shown considerable interest in the use of facsimile for restoration of their war-wrecked equipment. By facsimile, an exact copy of the original message is created at the receiving end—pictures or Chinese characters transmit as easily as Roman letters.

It now costs no more to fly to your destination than to go by Pullman, and flying is at least three times as fast. Yet businessmen and others who must keep appointments in distant cities still travel by train. They cannot afford to take chances with the weather which might ground their plane at the last moment before planned departure, or en route.

The present inability of air lines to furnish reliable all-weather flying is the biggest obstacle in the development of really successful air transport. The planes are sturdy enough to fly in rough, rainy weather. Anti-icing equipment can protect them from the danger of ice, the pilots are skilled and brave, radio blind-landing equipment and methods are available, but still bad weather holds the planes down.

When the weather is thick, the planes are grounded primarily because of the danger of collision aloft! With the regular volume of traffic, an airport may have up to a dozen planes circling and waiting to land. In poor visibility, neither the ground dispatcher nor the pilot knows exactly where the other planes are, so clumsy methods of "stacking" incoming planes are resorted to. Each plane is put at a different level a thousand feet apart. Collisions cannot occur then, but neither can the traffic be handled nearly fast enough. Between airports the collision problem arises from the narrowness of the radio beams along which the planes fly. In many places the beam is less than a mile wide and the planes fly the center of the path. Here the dispatcher must follow on a plotting board the position of all planes on a given beam, and then "leapfrog" them to different altitudes when he thinks they are nearing each other. It can be done with a few planes; but with many planes, some with different speeds, and with mountains below and icing conditions above, the job soon becomes impossible without exact information of each plane's position. That information is not now available.

Radar and television, working in combination, may provide a solution. The "Teleran" method proposed by RCA engineers uses several PPI-type radar screens to plot the positions of all aircraft within the range of a ground radar station. By an ingenious trick, the aircraft at widely different levels appear on different screens. A transparent map of the region placed over the radar screen locates the planes with respect to ground landmarks. By television, this radar map is transmitted from the ground station to a special television receiver screen mounted on the instrument board of the plane. The pilot then has an accurate map showing his position by a small comet of light to represent the plane and its speed and direction, and with the terrain below and the airport clearly delineated. Other planes in the same altitude level appear as similar small comets of light and may easily be avoided by flying according to the map. Planes not equipped with Teleran are also visible on the plot and can be avoided.

When the plane is ready to land, a different equipment takes over. It presents to the pilot, by means of another kind of picture, detailed instructions for following a preset radar glide path down to the field.

Auxiliary Teleran sets between cities can provide continuous information to the pilot. Planes would no longer be restricted to the single-lane radio-beam aerial highway. Parallel paths could be set and flown, and collision would be impossible while the pilot had his Teleran gear working.

Why the complication of both radar and television? Simply because weight in an airplane is money lost. A complicated air-borne radar set able to equal the ground radar performance would be many times heavier than the simple television receiver. Moreover, maps of the ground would be difficult to incorporate in the picture with the air-borne set. Weather maps, easily transmitted by Teleran, would be unavailable in the plane.

"Navar" and "Navaglide" are two similar proposals under development by Federal Telephone and Radio Corporation to accomplish the same navigation and blind-landing functions. Certainly, by these methods, the last serious problem in the way of all-weather flying is nearing a solution.

The modern airplane is becoming almost too complicated for a human being to fly. It took two men besides the pilot to watch the instruments during take-off of our B-17 and B-24 bombers. Another man navigated, and a fifth kept the radio going. Before the plane could roll down the runway, the pilot had to go through a check list of about 100 items to make sure that controls were working and that all was in order. He had to check for bomb-bay flaps closed, hydraulic pressure up, all four engines performing, radios working, engine generators on, wing flaps set and locked, propellers set for take-off, engine temperature correct, oxygen working—knowing that a slip on any item would be dangerous or disastrous.

The interlocking complexity of the controls of a bomber comes as a surprise to one who is used to an automobile which is merely steered by a wheel and accelerated by stepping on a pedal. Consider what a bomber pilot must do to step on the gas. First, there are four engines and four complete sets of controls. If all is well, he can operate them in unison, but if one engine is overheated or in difficulty it is another matter. The pilot pushes the throttles forward—but that is only the beginning. The mixture must be adjusted—four controls. The supercharge "boost" for each engine must be changed for the new throttle setting. The manifold air temperature must be checked and adjusted because the thin, cold stratospheric air gets very hot during compression in the supercharger. R.p.m. must be inspected to make sure each of the automatic variable-pitch propellers is on the job. In fact, the whole procedure of throttle setting is so complicated that the pilots are asked to memorize three or four throttle settings and associated adjustments. Otherwise, the busy pilot would too often operate on inefficient combinations and he would be cheated of the full performance of his engines to a considerable degree.

Electronics has begun to relieve the pilot of his multitude of duties. Two steps have been the introduction of the electronic automatic pilot for handling the controls and the electronic turbo-regulator to run the tricky exhaust turbine superchargers. The automatic pilot relieves the strain of long flights, and it is especially useful in rough weather because its electrical muscles have more strength than a man's. Flying by autopilot consists simply of tuning three small knobs on the instrument board—for turn, climb, and bank. The famed Norden bombsight flew our large bombers electronically, as they approached the target, by means of the autopilot. Without it, accurate high-altitude bombing would have been impossible, for there is no other way to hold the plane in such stable flight.

The exhaust turbines powered the superchargers which supplied air to the carburetors. The turbines' speed depended on altitude, throttle setting, and several other factors. Change of throttle required readjustment. Incorrect adjustment meant loss of engine power or overspeed of the turbine with consequent danger of its flying to pieces and wrecking the plane.

With four electronic controllers to take over the regulation of the turbine of each engine, the bomber pilot was relieved of some distracting duties.

Electronic control of aircraft has surpassed these wartime accomplishments. At the Bikini atom-bomb tests, radio-controlled drone planes with no one aboard flew into and through the treacherous radioactive cloud to gather scientific information. The drone planes took off from the ground and were controlled for a time from a ground station. Then the control was transferred to a mother plane which flew along behind as the plane was directed into the atom-bomb cloud. In some cases, the control of the drone was passed to a ship below and then back again to the mother plane. Finally, the drone was directed back over its home field, the control passed to the ground station, and the plane landed safely.

But drone planes require a continuous human observation and control. There is a pilot who flies the plane although he does it from a distance by radio and electronics. More advanced electronic controls that can be preset to take-off, fly, and land a plane with no more human intervention than the initial pressing of a push button have been under experimental development by the Army Air Technical Service Command. Radio beams navigate the plane, but the electronic brain controlling the flight does everything else.

The plane of the future will be almost entirely automatically controlled, largely by electronic devices, if these trends continue. It is conceivable that the entire plane will be navigated and flown by some radar or Teleran method, that the multitude of instruments will be watched only by electronic eyes, and that the pilot's job will be reduced to pressing a few buttons and watching a half-dozen colored lights.

However, before the control of a giant plane and the safety of a hundred lives may be entrusted so completely to an electronic pilot, electronic components and equipment must be developed to a point where their performance is absolutely reliable. Failure, in any way, of the autopilot must be less likely than the now remote chance that the wing of a plane will fall off, or that a motor will drop out. It can be done, and work is under way to approach such perfection. To make doubly sure, a second stand-by pilot could be available to take over, as is done now with human operators. Someday, flying a monster transport airplane will require no more skill or training than that needed now to run a streamlined streetcar.

Have you ever wondered how soon it will be before you are flying your personal helicopter to market or on a shopping expedition? It will probably not be before the appearance of an inexpensive, exceedingly reliable electronic autopilot to fly the tricky windmill plane. The helicopter is several times harder to fly than an ordinary plane—it is the nature of the beast. An ordinary person will not have the time or inclination to acquire the proficiency that safety requires. But if its controls can be reduced to a few push buttons—with safety features that prevent dangerous maneuvers—then the helicopter has a chance to live up to the glowing promises made for its future.

In the field of mathematics and engineering nimble electronic brains are taking over the solution of problems too difficult or too exacting for the human mind. The first of these appeared during the war. The M-9 antiaircraft gun director was an electronic brain that by itself operated radar gear to track enemy planes. From the radar data the M-9 director then performed electronically a complicated mathematical computation to find where to shoot to hit the speeding target, and finally it automatically aimed and fired the guns by electric remote control. The human crew needed only to pass the ammunition, and initially to point out to the machine which target to shoot at. Operating against German buzz-bombs, it chalked up the remarkable score of one bomb downed on the average for every forty rounds of ammunition fired—and this against a missile as speedy as the fastest pursuit ship and considerably smaller.

When an engineer must design a radar antenna, an airplane wing, or a new bridge, there are two methods he may use. He may test his ideas with models or he may use straight mathematics. He may build a scale model of the part and test this model to find out whether his ideas really work—or if not, where the weaknesses of the design lie. But good models are expensive to build; the test equipment, such as wind tunnels for wing testing, is very expensive. Finally the model, because of its smaller size, may omit some crucial feature of the full-size structure. A full-size replica is even more expensive to build and test, but there are many times when it is the only alternative to the usually avoided straight-mathematical method.

In principle the engineer may test his ideas with nothing more than a set of mathematical calculations. In aircraft wing design, for instance, enough is known about the laws of behavior of airflow and interaction between the moving air and the wing surface to allow a precise mathematical formulation of the whole problem. But the carrying out of the computations necessary for solution is generally impractical. Thousands or millions of individual multiplications and additions would be required. Ordinary, manually operated keyboard computing machines take too long; the solution of single problems would last months or years. The results must usually be known long before then. Therefore models, because they give a quick solution, have been used in spite of their other disadvantages.

New lightning-fast electronic computing machines promise to change this situation radically. A 200-ton electronically coupled differential analyzer at the Massachusetts Institute of Technology has been at work on military problems during the war. The fabulous ENIAC—a name contracted from Electronic Numerical Integrator and Computer—built at the University of Pennsylvania for Army Ordnance, contains 18,000 vacuum tubes. It is at the moment the most rapid mathematical computing machine in existence, with a speed at least several hundred times that of the best human machine operator. But even before the ENIAC was completed, its inventors, J. W. Mauchly and J. P. Eckert, had conceived the design of an entirely new kind of electronic computing machine, far superior in speed and performance to the ENIAC, yet employing only a fraction of the number of vacuum tubes. So promising is this new type of machine that at least five different organizations are now actively engaged in building their versions of it, and within the next few years when the machines are completed there will indeed be a revolution in applied mathematics.

Why, you may ask, should such super machines be built? When the ENIAC can solve what would otherwise be a three-months-long computation job in three hours, why build a new machine able to do it in three minutes?

Within the answer lies a statement of the revolution in computation. To a question in engineering design asked today, an answer must be provided in a day, a week, or a month. An answer later would be useless. Until now, few mathematical problems could be made simple enough to allow rapid enough solution. Badly needed answers have thus been unobtainable. But an electronic computing machine, with the same time allowance, can handle and solve problems a thousand times more complex. With each increase in speed, the frontiers are pushed back. If a machine can do in an hour what would require a lifetime of work by a skilled mathematician, what problems could be solved in a month of night-and-day electronic machine operation!

These new electronic computers can think! At the beginning of the problem, the machine is given instructions for a solution. But it can be directed to modify these instructions during the computation and to select an alternative procedure according to the result of a previous operation. By the same principle, machines to perform repetitive logical thought processes instead of numerical calculation might be built. If ever possible, such machines could take over much tedious brain work, leaving human intellects more time for creative and imaginative thought.

The vast potentialities of electronic machines of this type have yet to be explored. Numerical computation and logical processes could be combined to give a machine that would take an engineering question, set up the equations by itself and then do the numerical computations—instead of performing only the last step. An electronic machine automatically operating a warning radar net may be the only protection against enemy V-2 rockets bringing atomic bombs to our shores. It would have a degree of vigilance, speed of perception, and accuracy of counterattack impossible with human operators. The field is far too new for us even to guess the limits of application. Watch for the appearance of these new electronic thinking engines. Their future seems most promising.

The one wartime development that holds the greatest potentialities for good or evil—as men see fit to use it—is atomic energy. And whether the use be in power plants and biological laboratories, or in driving battleships and laying waste to cities, electronic instrumentation and controls will be indispensable.

The age of atomic power opened December 2, 1942, when the first self-sustaining nuclear-reacting pile was put into operation. The place was the squash court beneath the stands of Stagg Field at the University of Chicago, and the first atomic engine was an ungainly doorknob-shaped stack of graphite blocks and hunks of uranium. In 1945, three atomic explosions—one for test and two over Japanese cities—ended a war and shocked the world into the realization that a new era had begun.

The atomic-bomb project would have been impossible without electronic contributions of the most varied sort. In particular, one single electronic instrument, the Geiger-Müller counter, saw service from the beginning to the end of the whole undertaking. This instrument responds to radiations and particles thrown off by the exploding nuclei of radioactive substances. It can actually count the individual fragments as they pass through the sensitive detecting tube. Its ability to sense the presence of radioactive materials caused it to be used in the initial scientific studies of fissionable atoms, in the prospecting for uranium ore for use in the bomb, in the refining of the ore and the separation of isotopes, in the transmutation of uranium to plutonium in the nuclear-reacting piles, in safety and health measures at every step to protect the workers, and finally in determining the aftereffects of the bomb.

The first large-scale separation of the rare and elusive uranium 235 isotope, the explosive material of the bomb, was done by means of a gigantic electromagnetic and electronic centrifuge called the calutron. For a whole year the only major source of separated U235 was a calutron separation plant, and from its output the first atomic bombs were manufactured. The gaseous-diffusion uranium separation plant, one of the largest chemical plants in existence, was almost completely controlled by automatic electronic instruments. Operation was actually said to have been better over the week ends when there were fewer human operators around to upset the delicate electronically set controls. Later, the Bikini atom-bomb tests were an electronics man's paradise (or nightmare) with possibly one of the greatest concentrations of electronic instrumentation ever assembled in one place. Every conceivable effect was measured and recorded. Air pressure, water pressure, wave action, sounds in both the air and water, light, nuclear radiations were all studied by equipment which was either radio-controlled or which turned on photoelectrically from the light of the aerial burst.

Already engineers and medical scientists are applying to peacetime uses many of the nuclear engineering results from the atomic-bomb project. The first experimental atomic-power plant is now under construction at Oak Ridge, Tennessee, with a uranium pile reactor to replace the coal-burning boiler of the conventional steam plant. Atomic generation of power will not soon displace coal where it is available. Steam and atomic generating stations will be about equally expensive to build, and both require the expensive wire distribution system. Cost of coal for fuel in a steam generating system is only about 5 percent of the cost of the power delivered to your home, and only in fuel cost can atomic energy effect a saving. However, isolated communities and regions having neither coal nor water power will be benefited, since once the atomic-energy plant is built, the small amount of uranium fuel required for operation could be easily brought in. The Navy is studying the use of atomically powered battleships, since such vessels would have virtually no fuel problem, while now battleships must be followed by a long line of oil-carrying ships to keep them supplied with fuel at their advanced bases. Small atomic-power units, for powering automobiles or supplying power to homes, do not seem likely.

In medicine, artificially radioactive material will furnish a new weapon against malignant growths and will give biological research workers a most powerful key to the secrets of the chemical and physiological action of the body. Many of the most common elements can be made artificially radioactive. When they are fed to a person, or injected, in small harmless amounts, the element can be traced in its course through the body by timing the arrival, say at a finger, of the tiny indications of radioactivity. Electronic detectors and counters are indispensable for such studies. Within a day or week the last of the radioactivity will have burned itself out with no harm done. The greatest human benefit from the two billion dollars spent in developing the atomic bomb will probably come from such medical research.

The wartime development of the atomic bomb produced comparatively little new knowledge about the foundations of the universe. The bomb was made by applying basic knowledge available in 1940—though putting this knowledge to work was a stiff piece of engineering. It was not pure science.

Now with the war over, the atom-bomb scientists intend to catch up with their lost research and to fill the gap caused by their five years' distraction. The atom-smashing engines in existence will again be turned to the investigation of the unknown. Ideas for research, stifled by the war, will soon be carried out. Many new and improved methods of atom smashing, some taking over ideas from radar and electronics, have been proposed and several show such promise that extensive work has begun on them.

Study of the tiny, hard-to-hit nucleus of the atom requires the use of fast-moving, hard-hitting particles of tremendous energy. In the same way you rap a melon with your knuckles to see if it is ripe, the physicist shoots high-speed electrons, protons, or other elementary particles at the nucleus to try to discover its internal structure. The natural disintegration of radium furnished the first investigators with high-speed particles for experiment. Soon more convenient sources for them were found in vacuum tubes built something like X-ray tubes, which could hurl atomic fragments at targets under the impulse of thousands of volts.

The Van de Graaff-type high-voltage generator made it possible to supply several million volts to the vacuum-tube accelerators. For the first time particles having energies comparable to those coming from nuclear explosions were produced artificially with ease. In the modern Van de Graaff generator a sphere inside a pressurized chamber is caused to accumulate an enormous electric charge from a moving charge-conveying belt. The pressurized gas of the chamber prevents million-volt sparks from jumping from the charged sphere to the enclosing grounded shell. Placed vertically under the sphere is a long accelerator tube down which the charged particles speed under the force of the several million volts. While it is now surpassed by other generators in ability to produce extremely high-energy particles, the Van de Graaff-type atom smasher, because of its constancy of voltage and easy control, can give precise measurements of a kind impossible with other generators.

The cyclotron, invented by E. O. Lawrence, whirls the particles in the cross field of an enormous magnet as they are brought up to speed. The particles are given a push twice each revolution by the voltage from a powerful electronic oscillator. The many pushes, of several thousand volts each, add up to a total effect of a single, several-million-volt impulse. The cyclotron has been a most important tool in atomic-bomb research and in the artificial production of isotopes. It excels in handling a dense steam of charged particles and is therefore used in laboratory studies of transmutation. Particle energies in the order of 10 million electron volts are produced by cyclotrons. A typical cyclotron such as the one at the Massachusetts Institute of Technology has a magnet weighing 75 tons and is large enough to whirl the particles in a 40-inch circle.

Still greater particle energies are produced by the betatron, invented by D. W. Kerst in 1941. While the Van de Graaff accelerator and the cyclotron are used to accelerate positively charged particles such as the proton or the deuteron (the nucleus of the heavy hydrogen atom), the betatron is restricted to the use of the negatively charged electrons. Hence its name, for electrons are often called beta particles in nuclear physics. A giant betatron built in the Research Laboratory of the General Electric Company weighs 130 tons and produces electrons with an energy of 100 million electron volts. The X rays produced by these high-energy electrons as they strike a tungsten target are by far the most powerful produced. It may be possible to induce nuclear transformations in substances by irradiation with these rays.

The present goal of the atom smashers is the production of particles having energies near a billion electron volts—though even this is far short of the incredible energies possessed by some of the cosmic rays which arrive unpredictably from space. The new engines and methods for accelerating charged bits of matter to energies greater than 200 million electron volts bear such names as "synchrotron," "microtron," "linear wave-guide accelerator," "relativistic ion accelerator," and "linear resonator accelerator." Radar techniques such as cavity resonators, pulsing, and wave guides have prominent place in several of the proposed devices. With particles of such great energy at their disposal, the investigators can duplicate in their laboratories nuclear reactions hitherto appearing only by the chance incidence of a cosmic ray, or taking place in the nuclear energy furnaces of the stars.

The understanding of the unknown mechanism of the atomic nucleus—and not the design of more devastating bombs—is the goal of the atom-smashing scientists. But the resulting advances of physics in the atomic age, the results of probings beyond the veil of the unknown, cannot even be guessed. Characteristically, the major physical discoveries of the last fifty years have surprised even the workers themselves.

The future of our civilization and the future of electronics are closely related. Our technology has demonstrated its ability to solve its problems. Not so with world politics. The shape of the world of the future depends essentially on our ability to live with other men. The atomic bomb, which ended one war, has shown clearly to the citizens and nations of the world that they have a choice between peace and co-operation on the one hand and unimaginable destruction on the other. In either event electronics will play a crucial role.

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"see" pictures and change light into electricity to give us television. In the factory they heat things from the inside out and do myriad jobs of counting, sorting and controlling articles you use every day and the machines that make them. In the hospital they give out healing rays; they search out sources of hidden pain and show them to the doctor in his fluoroscope or on X-ray plates.

Electronics: What Everyone Should Know tells us clearly and simply how and where electronics works for us behind the scenes of everyday life. The authors do not even use mathematics to make vivid just how an electronic tube operates. They explain the use of fundamental and applied electronics, devices such as your present radio, the new FM radio, computing machines, radar, electric eyes and a host of others. Anyone with an intelligent curiosity about electronics has enough background to enjoy and understand this book.

Calvin and Charlotte Davis Mooers worked with electronics as civilian scientists at the Naval Ordnance Laboratory during the war, and have been deeply versed in electronics and its manifestations for many years. With this knowledge and practical experience they combine a nice gift for writing in nontechnical terms, and they have a knack of bringing the subject home to the intelligent layman and making it alive for him. *Electronics: What Everyone Should Know* has been written with the same command of information, the same writing skill that characterize *Plastics, Astronomy* and *Aviation* in the same series.

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ar that modern applications of the basic sciences nics will be increasingly important in the postwar orld. Although most people lack time and patience to cover all ese fields in regular school or college courses, everyone does need certain basic knowledge of the established sciences and of the chnics depending on them.

The *What Everyone Should Know* books are designed to give ist what their titles promise — and a little over. Each book covers ne field. It offers an up-to-date, carefully worked out survey of its eld, sound and authoritative, but put in simple, nontechnical nguage guaranteed not to frighten off the general reader nor et to treat him like an ignoramus. Lively, interesting, the *What veryone Should Know* books supply a surprising amount of ighly useful information so pleasantly that the reader has no nse of effort.

STRONOMY: WHAT EVERYONE SHOULD KNOW, by JOHN STUART ALLEN, Director of the Division of Higher Education of the New York State Education Department, former teacher of astronomy and celestial navigation, co-author of *Atoms, Rocks and Galaxies* and author of many articles and monographs.

VIATION: WHAT EVERYONE SHOULD KNOW, by DEVON FRANCIS, formerly aviation editor for the Associated Press, now on the staff of *Popular Science Monthly,* author of many articles on aviation in at least a dozen magazines, founder, first president and executive secretary of the Aviation Writers Association, and winner in 1938 of the TWA award for the "best informed aviation writing."

LASTICS: WHAT EVERYONE SHOULD KNOW, by BERNARD WOLFE, editor of *Mechanix Illustrated,* conductor of a radio program, and author of many articles in scientific magazines as well as of a book, *How to Get a Job in Aircraft Industry.*