# ENGINEERING ELECTRONICS

BY

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*To*

KEITH HENNEY

# PREFACE

This book has been written to meet the needs of the practicing engineer who has a good foundation in electricity, but who has no specific training in electronic concepts and methods. The material in the book was originally collected for a lecture course delivered to a group of one hundred such men, members of the engineering department of the Westinghouse Lamp Company. These men, typical of many engineers in the electrical industry, were faced with an increasing number of electronic problems but found that their educational background was sufficiently out-of-date to make the going difficult.

The experience gained in the lecture course has indicated that a practical background in electronic technology should include three basic parts: (1) an understanding of electronic conduction, its capabilities, and limitations, (2) a familiarity with different types of electron tubes and their special fields of use, and (3) knowledge of circuits in which electron tubes are applied. The book has accordingly been divided into three sections: Physical Electronics, Electron Tubes, and Electron-tube Applications.

In writing the book, the author has attempted to steer a course between simple descriptions of equipment on the one hand and elaborate technicalities on the other. The practical side of the subject has been developed in a series of type problems and solutions and by lists of problems at the end of the chapters, numerical answers to which are included in Appendix IV. The mathematical treatment has been limited to high-school algebra and trigonometry, except in two cases where calculus must necessarily be used. These latter demonstrations have been confined to footnotes, where they may be studied or skipped over as the reader desires.

It is hoped that the book will serve not only for the practicing engineer but also for the student who wishes to orient himself in the field before undertaking advanced courses. For such purposes the book is adaptable to an introductory course for junior or senior college students in general electrical engineering curricula.

The author wishes to acknowledge with gratitude the assistance of Mr. Keith Henney, editor of *Electronics*, who read the manuscript and offered many valuable suggestions, and of Mr. Beverly Dudley, associate editor of the same publication, who spent many hours in reading the proofs. The author has also received many helpful suggestions from engineers of the Westinghouse Lamp Company. Data on the fundamental electron dimensions ($e$ and $e/m$) were supplied by Professors R. T. Birge of the University of California, J. A. Bearden of Johns Hopkins, and W. V. Houston of the California Institute of Technology.

Illustrations and detailed technical data have been supplied by the following companies: Allis-Chalmers Manufacturing Company, Figs. 1 and 89; General Electric Company, Figs. 77, 78, 81, 84, 87, 88, 91, 92, 97, 104, 105, and 106; RCA Manufacturing Company, Radiotron Division, Figs. 64, 65, 68, 70, 72, 73, 75, 76, 94, 98 and 125; Westinghouse Lamp Division, Westinghouse Electric and Manufacturing Company, Figs. 79, 85, 86, 90, 95, 96, 100, 101, 116, and 117; Western Electric Company, Fig. 93. The cooperation of these organizations is much appreciated.

DONALD G. FINK.

ENGLEWOOD, N. J.,
*April*, 1938.

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# INTRODUCTION

# CHAPTER I

## ELECTRONICS IN ENGINEERING—A PRELIMINARY SURVEY

Electronics is that branch of science and technology which relates to the conduction of electricity through gases or in vacuo.

—Proposed Definition, American Institute of Electrical Engineers

Electronic methods in electrical engineering have progressed, in their short history, at a pace which few other branches of applied science can equal. In 1900 no electronic device, save possibly the X-ray tube, was applied to any practical purpose. Today whole industries, including such important activities as radio broadcasting, sound motion pictures, and the world-wide communication systems, are completely dependent upon electron tubes. In research, especially in the physical sciences, electron tubes are now among the most important tools in the exploration of new fields. In industry, electron tubes have solved difficult problems of control and measurement, and, through the use of photosensitive tubes, have made automatic many manufacturing operations which formerly could not be accomplished without the human eye.

Radio receivers, by virtue of their presence in 25 million American homes, have brought into service more electron tubes than there are people in the country. Even more impressive to the imagination is the fact that electronic methods of long-distance communication now make it possible for any one of 34,000,000 telephones in 68 countries to be connected with any other. This record of achievement justifies the claim that electronics has for many years been the most active branch of electrical engineering in producing new and useful applications of electricity.

**1. Electronic Functions in Electrical Engineering.**—Electrical engineering is concerned with the generation, transmission, and utilization of electric power. In the early history of the art, electric power was generated in batteries, transmitted over short distances only, and utilized in but the simplest ways. Later it was found that messages could be sent along wires by interrupting the power flow in accordance with a prearranged code. This simple modification of the current flow led to the first large-scale commercial application of electricity, the telegraph. The telephone resulted from the ability of Bell's microphone to modify the current flow in still more complex fashion, producing current variations similar in form to the complicated sound-pressure variations formed by the human voice. In both cases—and in others too numerous to examine—the usefulness of electric energy was expanded by the process of *modifying* the basic current, that is, by producing new forms of current variation capable of performing new functions.

The success of electron tubes is an outstanding example of this principle. Electron tubes have one purpose: to modify the form of the electrical energy which passes through them, according to some prearranged plan. Their utility lies in the fact that they are the most versatile modifiers of electrical energy ever devised.

*Rectification.*—An important type of power-modification is the conversion of alternating current into direct current, the process called rectification. The alternating current supplied by power companies is unsuited to certain purposes such as charging batteries, electroplating metals, heavy-duty traction service, arc welding, telephone service, and the like, all of which require direct current. The older method of transforming the alternating current into direct current involves two rotating machines, an alternating-current motor and a direct-current generator mechanically coupled together. The electronic method makes use of rectifier tubes which perform the conversion directly. The largest electronic devices in service are the mercury-arc rectifiers (see Fig. 1) which convert alternating current into direct current for subway-train traction motors. They handle a current of five thousand amperes continuously. The inverse process of converting direct current into alternating current is of less practical importance in commercial power practice, but where necessary it may be accomplished in electronic inverter circuits.

*Frequency Conversion.*—Frequency conversion is a form of power modification which is accomplished almost exclusively by electron tubes. Power, generated commercially at 60 or 25 c.p.s.[1]

[1] For definitions and meanings of abbreviations, see the listing on p. 344.

must be converted for special purposes to alternating current of several thousand cycles per second. Such high-frequency power is used, for example, in the induction furnace, an important tool in alloy research and metallurgical processing. An electron tube, connected in an oscillating circuit, takes direct current or 60-cycle

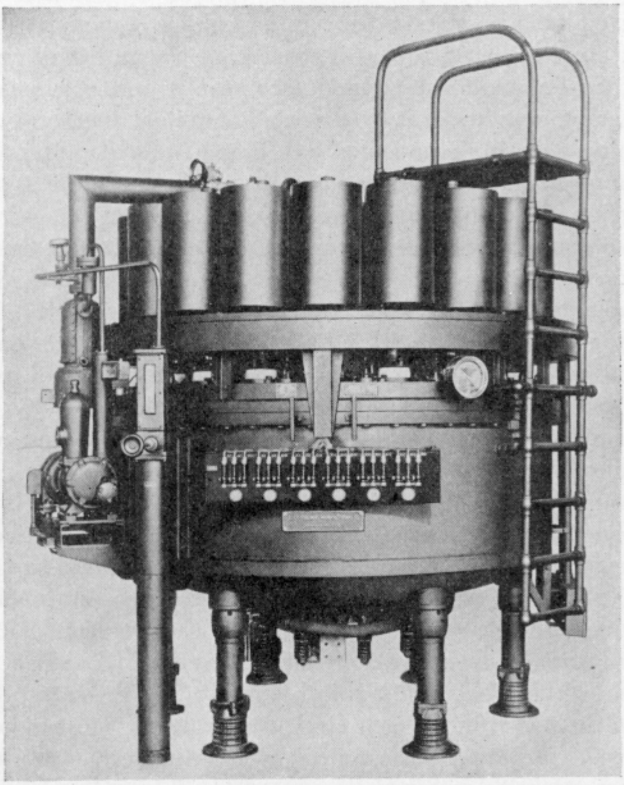

FIG. 1.—Allis-Chalmers tank rectifier, one of the largest electronic devices in service. It is approximately 9 ft. tall and will handle 3000 kw. at 625 volts.

alternating current from the power lines and converts it to alternating current of, say, 5000 c.p.s. While rotating machinery capable of generating currents of this frequency can be built, the electronic oscillator is used in preference because of its greater flexibility and economy.

Alternating current of still higher frequency, from 10,000 to 300,000,000 c.p.s., is essential in radio transmission, since it is the only type which will radiate from an antenna into space. The generation of these million-per-second currents is a job now assigned exclusively to electron tubes. In a broadcast station,[1] for example, the following electronic functions are utilized: The alternating-current power supplied from the power lines, at 60 cycles, is rectified to direct current by rectifier tubes, converted from direct current into high-frequency alternating current by oscillator tubes, increased in strength by amplifier tubes, further modified in modulator tubes in accordance with the microphone (program) currents, amplified further by very large amplifier tubes, and finally radiated from the antenna.

*Amplification.*—In addition to alternating- to direct-current conversion and frequency conversion, the electron tube serves to increase the strength of alternating currents without changing their frequencies. This process, called amplification, is the most generally useful of all electronic functions. It consists of taking power from a strong source of supply, say a battery, and modifying its form in a tube operating under the control of a weak source of power. The battery current is thereby transformed into an amplified reproduction of the control current and can be used to actuate devices which the weak control current could not affect.

*Repeated Amplification.*—In power-engineering practice, the wires over which power is transmitted are made large enough to pass the current without excessive losses of power in heating the wire. In electrical communication, however, it is not economically or technically feasible to make the wires large, because of the great number and length of the circuits. Hence most of the power in the communication current is lost in heating the wire. To prevent the power from being lost entirely, it is amplified at regular intervals along the line. Direct current, supplied locally at each amplification point, is modified by amplifier tubes which operate under the control of the weakened communication current. The modified direct current, thereby given the form of the original communication current, is sent

[1] Tubes in broadcast stations represent a considerable investment. In station WJZ, for example, the tube line-up, exclusive of those in the studio, consists of 2 type 862's ($1650 each) 2 type 892's ($325 each), 3 type 849's ($160 each), 1 type 860, 2 type 865's, 1 type 210, 6 type 857's ($275 each), 10 type 866's, 3 type 217's, 1 type 211, and 10 smaller tubes.

over the next stretch of line. After traveling some distance, it in turn becomes so weak that amplification is again necessary. The amplification is repeated over and over again, new energy being added to the line under the control of the successive "editions" of the communication current. As shown in Fig. 2, in the open-wire transcontinental-telephone circuits, the original voice energy is amplified, in 15 successive stages, a total of 1,000,000,000,000,000 times!

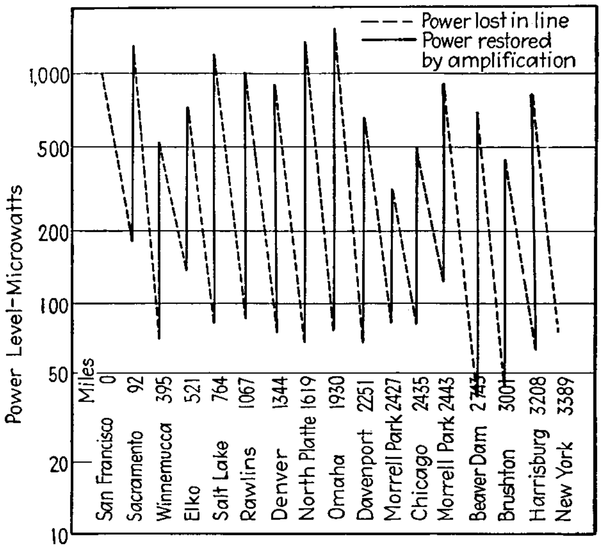


FIG. 2.—Power-level diagram of the transcontinental open-wire telephone circuit between New York and San Francisco, illustrating the use of electronic amplification in communications practice.[1]

*Control and Measurement Functions.*—In addition to its functions as a rectifier, frequency converter, and amplifier in power and communications practice, the electron tube serves a multitude of uses as a measurement and control device. Its ability to amplify fits it for the detection and measurement of extremely small electric currents and voltages. One form, the electrometer tube, can measure currents of a few hundred electrons per second, the smallest continuous flow of electricity yet detected. Electronic measurement technique is applied generally in all

[1] NANCE and JACOBS, Transmission Features of Transcontinental Telephony, *Trans. A.I.E.E.*, **45**, 1159 (1926).

scientific and engineering pursuits. One of the latest applications is in the field of biology in the measurement of the delicate currents generated by living organisms. Most of our present knowledge of the electrical action of the brain, for example, has been gained through electron-tube technique.

In the field of industrial control, electron tubes find use because of their ability to react to weak stimuli, their rapidity of response, lack of fatigue, and their flexibility of application. An electron tube can respond to a control impulse in less than a millionth of a second, and it can at the same time control many kilowatts of power.

*Photosensitive Applications.*—In a separate division of the electron-tube family are the phototubes, which are sensitive to light. The eye and the photographic emulsion, the only practical light-sensitive elements available before the advent of the phototube, are limited in many ways. The human eye responds to a limited range of colors, is insensitive, prone to fatigue, and expensive to maintain. Photographic emulsions are severely restricted by the delay and inconvenience of the developing and fixing processes. The phototube, in contrast, is highly sensitive, can be made to have a wide color response, and operates continuously, at any speed, without fatigue. It can detect instantaneously, for example, the light from a star of the fourteenth magnitude which would require several minutes' exposure to record itself on the photographic plate of a large telescope, and which is about $\frac{1}{300}$th as bright as the weakest star visible to the naked eye. In its most advanced form (the iconoscope, described on pages 206–210), the phototube performs all the essential functions of the human eye, perceiving and transmitting complete optical images.

These photosensitive electron tubes have given rise to a wholly new branch of electrical-engineering practice. The applications cover so wide a variety, from sound motion pictures to astronomical research, that it is doubtful if all the phototube uses have ever been listed. A partial list compiled[1] in 1935 contains 253 separate applications of phototubes.

*Electronic Sources of Light.*—The electronic production of light, while the oldest electronic phenomenon observed (a lightning flash properly falls within the definition of an electronic

[1] *Electronics*, January, 1935, p. 2.

phenomenon, since it is the conduction of electricity through a gas), is one of the latest branches of the field to receive concentrated attention. The mercury arc and the tubular neon lights are familiar examples, as is the newer sodium lamp. The recently developed fluorescent gas-discharge lamps may become serious challengers of the incandescent lamp as a source of general illumination. The high efficiency of the sodium lamp and its effectiveness as a source of street lighting have already given it an important position in the newer installations in that field.

**2. The Principles of Electronic Action. The Free Electron and Its Control.**—The distinguishing feature of all electron tubes is the fact that they conduct electricity not through wires, as do all other electrical devices, but through a gas or through a vacuum. The utility of this mode of current conduction is the explanation of the utility of the electron tube itself. The following chapters are devoted to the expansion of this basic concept.

*Electricity Is a Flow of Electrons.*—Wide experimental and theoretical evidence points to the fact that the ordinary electric current is in reality a flow of elementary electrical units, called electrons. These electrons are of unbelievably small size, but they possess a definite mass and other familiar characteristics.

Electrons have the property of repelling one another, the force of repulsion increasing greatly as the electrons near one another. To explain this remarkable behavior, each electron is considered to possess an *electric charge*, the charge being a numerical measure of the force of repulsion experienced between two electrons 1 cm. apart.

The ability of electrons to repel other electrons, *i.e.*, their possession of electric charge, makes it possible to transfer energy through the motion of electrons. When an electric current is generated in a generator, for example, the mechanical energy imparted to the drive shaft is converted into energy of electron motion in the armature winding. Electricity is thus basically the science of electron motion. The conduction of electricity through a wire is simply the motion of electrons along the wire.

With these basic ideas in mind we recall that the electron tube conducts electricity (*i.e.*, conducts a flow of electrons) through a gas or through a vacuum, and that the function of the tube is to modify the electron flow in some predetermined manner. The action of the electron tube in carrying out this modification process may be shown as follows: Consider a wire carrying a current whose form we wish to modify. To do so we must modify the motion of the electrons flowing along the wire. This can be accomplished only in indirect fashion, so long as the electrons are in the wire. However, if we can remove the electrons from the wire, temporarily, and then return them again, we can modify their motion directly while they are freely moving in space. The temporary removal of the electrons is accomplished by breaking the wire and connecting its two ends to electrodes inside a glass or metal container (or "tube") containing

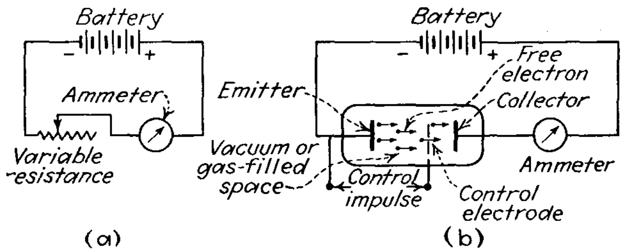


FIG. 3.—In (*a*) the current flowing from the battery may be controlled by varying the amount of resistance in the circuit. The electronic method of control (*b*), by influencing the motion of free electrons, permits more rapid changes of the current, and allows the use of extremely feeble control impulses.

a gaseous or vacuous space. If we cause the current of moving electrons to pass between the electrodes, it is possible to control their motion while they are passing through the tube. This control of the electron motion modifies the electric current flowing in the circuit, and the electronic function is thereby exercised.

It is necessary to satisfy certain obvious requirements in this process. In the first place, the electrons will not leave the first electrode and enter the space beyond without some urging. This urging process, by which electrons are freed from the electrode, is the first essential in any electron tube. In the second place, ways and means must be available for influencing the motion of the electrons while they are in their temporarily free condition before they enter the other electrode. This requirement involves a study of the electric and magnetic forces by which electron motion may be influenced. It requires study also of the speed with which the electron completes its journey ("transit time") and of the mutual reactions of the electrons on one another during the flight in space ("space charge"). It is also necessary that the electrons be collected by the second electrode and that their subsequent actions be under control; we must inquire what happens to the electrons if they are collected by the second electrode only in part. Finally, the study is incomplete until we examine the influence of the group of gas particles (if they are present in appreciable numbers) through which the electron flow takes place. We find, among other things, that in certain circumstances light is produced by the energy interchanges between the electrons and the gas particles, and that this light can be put to considerable practical use.

**3. The Terminology of Electronics. The Organization Chart.** The foregoing description of the basic electronic action has been given, for the sake of clarity, with a minimum of technical terms. To introduce the terminology of the subject we refer to the chart shown in Fig. 4, which is intended to serve also as a guide to the organization of this book.

Electronic theory springs from the main body of physics and is particularly dependent on three branches of physical knowledge: electrodynamics, atomic structure, and statistical physics. These give rise to the three basic studies of electronic theory itself: space charge, electron emission, and the gas discharge. Space charge is the study of the motions of groups of electrons in a vacuum of gas-filled space; it reveals the laws which govern the flow of free electrons and the means by which electron motion may be controlled. Electron emission is the study of the "urging process" previously referred to, *i.e.*, the methods by which electrons are made to leave metals and to enter the adjacent space. Three important methods of emission are listed: thermionic emission, caused by heating a metal surface; photoelectric emission, caused by the action of light on a surface; and secondary emission, caused by the bombardment of a surface by electrical charges. The study of the gas discharge reveals the laws governing electron motions in a gas-filled space; the resulting conduction of electricity gives rise to a side branch, the electronic production of light.

The body of electronic theory is then applied to the design and manufacture of electron tubes, of which there are four important

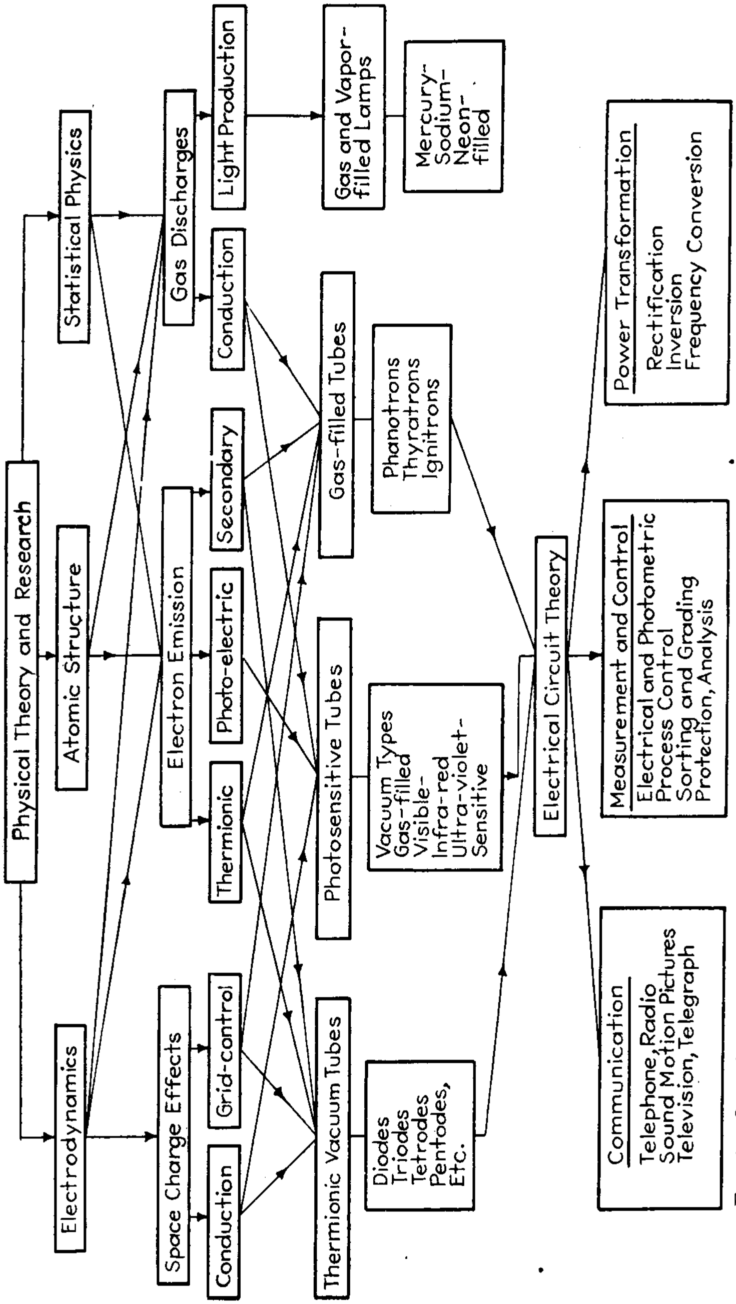


FIG. 4.—Organization of the field of electronics. The arrows indicate the interdependence of the various branches.

types: the thermionic vacuum tubes, photosensitive tubes, gas-filled conduction tubes, and gas-filled lamps. The first two types derive their names from the particular type of electron emission which is employed, but, as is revealed by the maze of crisscrossing arrows, all branches of electronic theory are applied in designing each type. In each type there are a number of special forms, each having different characteristics and applications, some of which are listed.

Electron tubes are of no value, of course, until they are connected with other electrical apparatus. Each different electron-tube application calls for a circuit connection with different types of external apparatus. The study of electron-tube applications begins, therefore, with the study of electrical-circuit theory. Electron-tube circuits are applied, as we have seen, in three major divisions: electrical communication; the control and measurement of scientific and industrial processes; and the transformation of basic power sources.

While the chart is in no sense a complete résumé of electronics, it contains the essential elements, and should serve to guide the reader in his study of the chapters which follow.