Electronics for Scientists

Principles and Experiments for Those Who Use Instruments

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ELECTRONICS FOR SCIENTISTS
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Preface

This book is a practical book for scientists and science students. It is written expressly for *chemists*, *physicists*, *engineers*, *medical researchers*, *biologists*, and other science students and research workers who have little or no background in electronics but who need to gain a working knowledge of electronic devices and circuits. The text begins with *electronic principles*, *basic circuits*, and *components*. It leads systematically into *servo systems*, *operational amplifiers*, *feedback control*, *digital circuits*, and other devices used in current laboratory research and engineering control problems. The liberal use of diagrams attests to the authors' belief that a picture can speak louder than a thousand words.

The order of presentation is laboratory-centered. There is a natural progression from the basic measurement techniques necessary to start experimentation toward the complete instruments and systems. Specific components are usually introduced in the chapter where the most common or important applications are first described. Circuits with *new and special devices* are presented as well as the widespread *transistor and vacuum-tube circuits*. Most circuit diagrams contain actual component values so that they can be used as working drawings. A selected list of references with specific comments concerning the nature of the contents is included at the end of each chapter.

The three supplements at the end of the book serve several functions. Supplement 1 introduces and gives specifications on the universal experimental system used to perform the experiments in the book, and the pictures acquaint the reader with the individual components. Supplements 2 and 3 serve primarily as review of and reference to the *basic laws* and *component characteristics* which are usually introduced in basic courses of college physics. For scientists who do not remember or have had little exposure to these basic relationships, Supplements 2 and 3 are a good starting point.

This book should be especially useful as a text for a one-semester course at the junior-senior level in various physics, chemistry, or engineering college curricula, or as a self-teaching text for scientists on the job. For those who already have a good basic training in electronics, the chapters on comparison measurements, operational amplifiers, feedback control, servo systems, and digital circuits should provide both new information and reference material, because all these topics are presented in a way that the authors believe to be unique. As explained in the introduction, the authors have also found the material in this book to provide a practical working background in electronics for both graduate and postdoctoral students, especially if combined with thorough discussions of specific systems related to individual disciplines.

There have been many people influential in the start, preparation, and completion of this book. Professor H. A. Laitinen encouraged us from the beginning, both in support of the course from which this book developed and by his enthusiasm for the experimental system that we originated. The staff of the Heath Company (Benton Harbor, Michigan), especially W. Kooy, E. B. Mullings, and A. Robertson, was responsible for taking our original system and ideas and developing them into the completely integrated system of components and laboratory instruments now available for performing the experiments. Several valuable discussions took place with Professors Harry Pardue and Robert Kerr concerning portions of the manuscript. Great appreciation goes to Professor D. Lazarus of the University of Illinois Physics Department. He read all the chapters and made many important suggestions that greatly influenced our presentation of several topics. Mr. Verle Walters contributed in many ways to the construction of the original experimental system. Julia Zvilius, Frances Watson, and Linda Leahy were all very helpful in typing and assembling various parts of the manuscript. We are especially grateful for the help and encouragement of our wives, Gay Malmstadt and Mary Enke.

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Introduction

Go into a clinical laboratory, a chemistry, biological, or soil-science laboratory—in fact, go into laboratories in all areas of science and technology—and you will find them loaded with instruments that depend upon electronic circuits for operation. Talk to the experimental personnel, the people who do the research and accumulate the data, and you learn that these scientists are using a powerful array of tools with considerable success to probe the mysteries of their specialties. But you also learn of problems! Problems of how to put a new instrument into operation, how to modify a commercial instrument for a new research problem, how to increase sensitivity, how to eliminate electrical noise, how to prevent inaccuracies because of interaction between the measurement device and the system under test, how to automate a process or analytical method.

Unless answers to these questions can be readily provided by the available scientific personnel, a research project might be stalled, a breakthrough in science or production delayed. At the University we have observed research students waste weeks and months of valuable time because of the improper use of perfectly good instruments or the use of inadequate ones. Seldom do they understand what instrument changes should be made to keep pace with the developments in their research. Reports from several industrial-research directors indicate that the same situation prevails among many scientists on the job. This is to be expected, of course, because electronics has come of age since many of them completed their formal training.

Fortunately, however, there is an increasing awareness among experimental scientists that instruments can be used more effectively and that more reliable measurements can be obtained if some basic understanding and working ability in electronics can be "picked up along the way." It is the purpose of this book to help the already trained scientist or advanced college science student to acquire this understanding and working ability.

Obviously, if unlimited time were available, a thorough program of study in an electronics department over a period of years would be desirable. However, the number of courses in most scientific curricula are already overwhelming, and the scientist at work is generally overloaded with his regular responsibilities. It was therefore a major concern to develop a course of study and experimentation that would permit a breakthrough of the "electronics barrier" in a minimum amount of time.

In the Chemistry Department at the University of Illinois many different ideas were tested with chemistry graduate students. The senior author of this book presented lectures, special seminars, and various laboratory courses over several years. It became increasingly apparent that a laboratory-oriented course was essential to provide the desired results. Finally a set of experiments evolved, together with descriptive material and a new, unique, and rapid method of connecting electronic circuits; the three proved to be an efficient and effective combination in taking scientifically trained students across the "electronics barrier"—to the point where they were working not with "magic boxes" but with scientific instruments. As would be hoped and expected, it also paved their way for further study and furnished a new awareness of how electronics might be useful in their work. It was found that this could be accomplished in 15 half days of laboratory work with at least an equivalent amount of time for study. This amounts to about one very full day per week during the regular 15-week college semester.

Many scientists throughout the country heard of our semester course and asked whether it would be possible to have a special concentrated course. Therefore a 3-week course was arranged for the summer of 1960, covering the same material as that in the semester course. All in attendance had scientific B.S., M.S., or Ph.D. degrees. Some were research group leaders with their companies; others were relatively new college graduates or Ph.D.'s. Upon completion of the course this group left no doubt that the venture was successful, and the scientists in attendance encouraged us to repeat the course. The second year there were more applicants than the course could accommodate. There are now requests by applicants to be put on waiting lists for future summer classes. Inquiries concerning both the regular and concentrated courses come from industries, colleges, and medical laboratories throughout the United States and many other countries as well. Several schools would like to set up similar courses. Some individuals in laboratories would like descriptive material, experiments, equipment, and parts to work with in their spare time on the job or at home. The many indications of interest demonstrate a need and desire for a special type of training in experimental electronics and have prompted the writing of this book.

Concentrating so much in a 3-week period does not mean that one is "getting something for nothing." Rather, an all-out effort is required. The important point is that the material can be absorbed, and absorbed effectively, in this short period of time. The schedules and responsibilities of many thousands of scientists and engineers are such that a longer period away from their regular jobs is impossible.

The authors' experience has indicated that the experiments can be performed most efficiently and the basic concepts grasped most easily by working in small laboratory sections of five or six students per instructor. As in the regular semester course, each student works at a desk complete with test equipment, parts, and tools which are for his individual use throughout a 4- to 5-hr laboratory period. With an instructor available throughout this period, the give-and-take certainly stimulates the thinking and performance of each person.

There are many who find it necessary to get such training either at home or on the job or not at all. Therefore the problems and experiments have been presented with the hope that the book could serve as a self-teaching text. The circuits could be successfully built, tested, understood, and used by a scientist or engineer working in his home or laboratory. The disadvantage of missing the discussions with instructors and other students could be compensated for by additional reading from the references supplied and by allowing somewhat longer times for the experiments.

As sketched in the following paragraphs, an electronics-instrumentation laboratory made up of relatively inexpensive units is a unique feature of the courses and is described in the book. This carefully planned and tested laboratory setup, which is described in detail, provides the possibility for efficient experimentation either for self-training at home or on the job or in an organized course.

The construction of the circuits described in this book would take much longer than the scheduled 15 half days if only conventional soldering techniques were used. Therefore, many available "breadboarding" schemes were tested to speed up the construction of the circuits. Unfortunately, all had shortcomings, primarily because they were not typical of good wiring practice and the connected circuits had characteristics considerably inferior to those with soldered joints. Therefore a scheme was devised which has subsequently proved completely satisfactory. It increases the speed of construction, testing, and component interchange in circuits at least threefold.

Parts and wires are connected point to point as in conventional practice, but spring clips permit the same parts and wires to be used over and over again, hundreds of times. The clips bind tightly so that circuit characteristics are, in general, quite similar to those with soldered joints. Component placement and the finished circuit are very similar to that of standard chassis wiring. The complete laboratory system is described in Supplement 1.

The preparation of the original experimental setup was a long and tedious job. The hand making of the parts was very time-consuming and a deterrent to others who wished to use the system. Fortunately, however, all parts and chassis are now commercially produced. All the basic experiments described in this book, including servomechanisms and operational amplifiers for computation and control, can be performed by using the commercially available kits and inexpensive instrumentation laboratory. Hundreds of other useful circuits can also be constructed with the same parts.

Many of those who have taken the course have expressed a keen desire to have a similar complete system at their work or at home and always available for rapidly testing new ideas before permanent construction is attempted. Needless to say, such a system is an excellent aid in building or modifying instruments.

The order in which topics were introduced was changed many times so that the most systematic presentation might be achieved. Discontinuities in the order were revealed by the troubles and questions of the students working in the laboratory. For 3 years now the order has remained essentially unchanged because the response of the students indicated that each experiment and its descriptive material followed logically from previous experiments and descriptive material. On the basis of this experience, it is recommended that anyone unfamiliar with electronics start at the beginning and proceed consecutively through the chapters. To do otherwise would be to risk wasting time in studying and working with the more complex circuits in the later chapters. Those who have some background in electronics may want to delve immediately into the later chapters on servomechanisms, operational amplifiers, and digital systems. For convenient reference and review on basic d-c and a-c circuits, Supplements 2 and 3 have been provided. In these sections the basic laws of electricity, such as Ohm's and Kirchhoff's laws, are presented. Resistors, capacitors, and inductors and their simple networks are discussed. Important tables are included in the Appendix.

Each chapter opens with a discussion of the important basic principles. This is followed by a section of experiments that emphasize the most important aspects of each subject. Although valuable information can be obtained by reading only the discussion sections, there is no doubt that it is by working the experiments that great strides can be made in exploring the new possibilities of electronics in one's own research.

chapter one

Electrical Measurements

The operation of electronic circuits and systems which make up most modern scientific instruments depends on correct values for the components, such as resistors and capacitors, and on the use of suitable voltages and currents of proper phase and frequency within the circuits. To test and study operational characteristics or to trouble-shoot (i.e., determine the cause of instrument failure), it is especially important to make accurate measurements of current, voltage, resistance, phase angle, and frequency. It is the purpose of the discussion and experiments in this chapter to introduce the various test instruments and show how they can be used to obtain reliable information.

Some of the test equipment is relatively simple, and the methods of operation follow directly from a few well-known basic laws of electricity. In such cases, a thorough understanding of the equipment is possible at this point. However, some test equipment, for example, the oscilloscope, is an assemblage of several more or less complex electronic circuits, many of which are the subject of study and experimentation in subsequent chapters. Therefore a detailed understanding of the oscilloscope is not possible at this time; yet it is important to learn now the general functions of its basic circuits and components and how to use it to obtain reliable measurements. With this indispensable test instrument, as well as the other meters available, it is possible to measure the most important variables in all the circuits that are to follow. Since many of the circuits to be studied are the general building blocks for the oscilloscope as well as most scientific instruments, a greater appreciation and understanding of this test instrument will develop with the completion of subsequent chapters.

1-1 Measurement of Voltage and Current

The purpose of a *voltage* measurement is to determine the *potential difference*[1] between two points in a circuit. The potential difference between any two points in a circuit is measured by connecting the two voltmeter leads to these points (see Fig. 1-1). Thus the voltmeter is connected "across" or in *parallel*[2] with the circuit whose potential is to be measured.

Because the voltmeter *resistance*[3] is not infinite and is connected between two points of unequal potential, a *current*[4] will occur in the voltage-measuring circuit. The application of the voltmeter to the test points may change the current magnitudes in the circuit enough to cause a considerable change in the potential being measured. If a voltmeter has a resistance of 60 kilohms when switched on the 3-volt scale and its leads are connected across a 10-kilohm resistor in the circuit, the potential across the combination of 10 kilohms and 60 kilohms will no longer be 2.5 volts. The parallel resistance $= (10K^* \times 60K)/(10K + 60K) = 8.6K$. The potential that the voltmeter will indicate is 10 volts $\times$ $[8.6K/(30K + 8.6K)] = 2.23$ volts. *To avoid this kind of error, a voltmeter of sufficiently high internal resistance must be used to make the measurement.* The method of determining a voltmeter's resistance is discussed in Sec. 1-2. The slide-wire potentiometer, which makes a potential measurement under conditions approaching zero current through the instrument, is discussed in Chap. 6.

[1] *Voltage* is the difference in electric pressure between two points. The *potential difference* between two points is the work required to transfer a unit quantity of electricity from one point to the other. Between any two points the voltage and the potential difference are the same and are measured in volts. Both terms are commonly used interchangeably and are abbreviated V, E, or emf, although voltage (V) usually implies that if the two points were connected in a closed circuit a flow of current would result. A potential difference (E or emf) may exist between two electrically isolated points simply because of a difference in electrostatic charge. For this reason the terms potential or potential difference are sometimes used to indicate the zero-current or open-circuit potential between two points.

[2] Circuit components are said to be arranged in *parallel* when each component has both terminals in common with the two terminals of the other components. The voltage is the same across all components connected in parallel.

[3] *Resistance* is the opposition to the flow of current offered by a device or circuit element. Resistance (R) has for units ohms, abbreviated Ω.

[4] *Current* is the rate of electric charge transfer from one point to another. Current (I or i) is measured in amperes, abbreviated A. The current in a circuit is related to the voltage and resistance by Ohm's law ($E = IR$), as explained in Supplement 1.

* When kilohms are used in calculations, the symbol K is often employed.

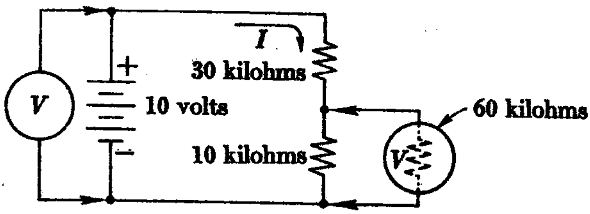

Figure 1-1 Voltage measurement.

The purpose of a current measurement is to determine the rate of electron flow in any given branch of a circuit. The usual current meter must be put in *series*[5] with the components in that branch so that the electrons flow through the meter coil (see Fig. 1-2). The circuit must be broken to connect the ammeter; therefore the ammeter becomes an essential part of the circuit being measured. Since the ammeter has some internal resistance, its insertion into the circuit may considerably decrease the current in the measured branch. Consider the effect of introducing a milliammeter which has a resistance of 100 ohms in the circuit of Fig. 1-2. The resistance in the R_3 branch will increase to 1.1 kilohms. This will cause only a small change in the potential across R_2 and R_3. The resistance of R_2 in parallel with R_3 and meter = 525 ohms. The potential across R_2 and R_3 is 1.5 volts (525/1525) = 0.517 volt. The current through the meter is then 0.517 volt/1.1 kilohms = 0.468 ma,[6] instead of the 0.5 ma that would be read if the meter had zero resistance. The determination of the resistance of a meter is discussed in the next section. This information is important

[5] Components are said to be in *series* when there is only one point of connection between them. The current through all components arranged in a simple series circuit is the same.

[6] *Milliampere*, thousandth of an ampere, is abbreviated ma.

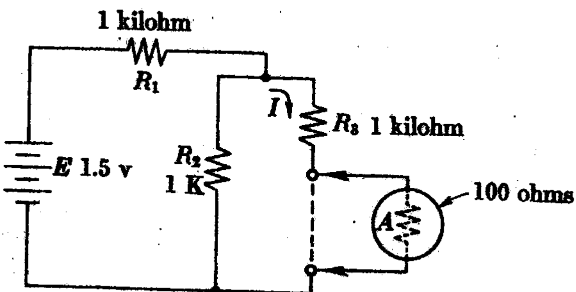

Figure 1-2 Current measurement.

because the meter resistance must be allowed for in connecting current meters into circuits.

1-2 The Moving-Coil Meter

Of all the devices (meters) that convert an electrical quantity to the physical displacement of a pointer or light beam, the moving-coil meter is by far the most common. The moving-coil meter owes its popularity to its great versatility, combined with reasonable ruggedness, accuracy, and simplicity. Discussion of other types of meters, which are used mostly in heavy-duty and special applications, will be found in the References.

The usual D'Arsonval moving-coil meter used in test instruments is shown in Fig. 1-3*a*. A coil of fine wire, wound on a rectangular aluminum frame, is mounted in the air space between the poles of a permanent horseshoe magnet. Hardened-steel pivots attached to the coil frame fit into jeweled bearings so that the coil rotates with a minimum of friction. An indicating pointer is attached to the coil assembly, and springs attached to the frame return the needle (and coil) to a fixed reference point. When electrons flow through the coil a magnetic field is developed that interacts with the magnetic field of the permanent magnet to force the coil to rotate as in an electric motor. The direction of rotation depends on the direction of electron flow in the coil. The magnitude of the pointer deflection is proportional to the rate of flow of electrons (the current). The laboratory galvanometer is a very sensitive moving-coil meter; it is discussed in Sec. 6-2. A recording galvanometer is shown in Fig. 1-3*b*. A writing stylus is used instead of a pointer. The stylus can have an ink tip, or it can have a tip that is the contact for an electro-sensitive, heat-sensitive, or pressure-sensitive paper. The roll of chart paper is usually driven by a constant-speed motor. If a writing arm of fixed length is used, the ordinate will be curved. In order to convert the curvilinear motion of the writing tip into rectilinear motion, various writing mechanisms have been devised to change the effective length of the writing arm as it moves across the chart.

The meter movement has three characteristics which are used to determine its effectiveness for a given measurement. These characteristics are sensitivity (milliamperes full scale, microamperes per centimeter, microamperes per degree, etc.), internal resistance (the d-c resistance of the coil in ohms), and accuracy (normally $\frac{1}{2}$ to 3 per cent of full scale deflection for general-purpose meters, and 0.1 to 1 per cent for laboratory types).

When the current through the meter changes value suddenly, it is desirable that the indicator move quickly to its new position with no overshoot or oscillations. This desired behavior is accomplished by *damping* or braking the meter movement. Some meters have a damper built in; others, particularly galvanometers, need to be damped by adjusting the re-