AN INTRODUCTION TO ELECTRONICS FOR PHYSIOLOGICAL WORKERS

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FOREWORD

In writing this short account, I have attempted to fill the gap between the elementary textbooks of radio and the more advanced monographs dealing with specific applications of electronics to biological research. The elementary radio books, while starting from simple premises, naturally include much that is entirely irrelevant to electrophysiology, and equally, and more seriously, omit, or touch only lightly on, aspects of the utmost importance ; the more advanced accounts, while describing specific apparatus, do not always explain the fundamental operation in sufficient detail to enable anyone not already acquainted with the subject to adapt the apparatus to their particular requirements. In the following pages I have therefore tried, while starting, as far as possible, at the beginning, to give an account of basic electronic theory with the emphasis placed according to the relevance of each matter to the biologist's viewpoint. Unfortunately those parts of most importance are not necessarily the most simple, and in fact involve quite advanced techniques. By starting with simple ideas, and providing copious cross-references, it is hoped that the basic principles of some of the more complex circuits commonly used in physiology have been made clear.

This is not a book for those who hope, in an idle hour, to 'pick up' something about electronics, but aims to provide an introduction to the subject for those graduate students and others who wish to use electrophysiological techniques, and who should be prepared to do so with some understanding. It has been borne in mind throughout that the practical applications of the subject will be the main interest, and so quantitative treatment, together with worked examples, has been given wherever possible. In this way it is hoped that the book will not only help in an understanding of the way in which circuits function, but indicate the range of applications, and the directions in which published circuits may be modified to suit individual needs.

I. C. W.

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CONTENTS

Chapter 1

SOME FUNDAMENTALS

Conductors and Insulators.—Conduction of the electric current depends on the relative movement of electric charges. Those media which allow comparatively free movement of such charges are called conductors, while those that do not are termed insulators. There is, of course, no sharp distinction between the two, one class merging gradually into the other. On account of its small size and high mobility, currents are carried most readily by the free electron. Media which have large numbers of loosely bound electrons (such as the metals) are good conductors. That class of conductors known as the electrolytes depend for their conductivity on the migration of charged ions (atoms or groups of atoms which have either more or less than their normal complement of electrons) through the solvent medium. Since such ions are very large compared with the electron, they are moved much less readily and so do not behave as such good conductors.

Although the current is carried by the migration of charges, a distinction must be made between the velocity of the current and that of the individual charges themselves. The distinction is somewhat analogous to that between the velocity of the pulse wave and of the blood, in the circulatory system. Although the velocity of the current is extremely high, the migration of any particular electron is only at the rate of a few centimetres per second, and that of an ion very much slower. If a truck is run into the end of a long line of trucks in a shunting yard, a corresponding truck is rapidly ejected from the far end (the current flows). It requires the process to be continued for a much longer time before the original truck itself emerges at the far end. It is only when the current is conducted in a vacuum that the rate of electron migration approaches the current velocity.

Resistance.—The opposition which a medium offers to the passage of a steady current is measured in terms of its resistance. In order to compare the resistive effects of different materials the resistance of a centimetre cube of the material is taken and is termed the *resistivity*. (It will be obvious that the resistance depends on the shape of the conductor as well as the amount of material. A long, thin wire has a much higher resistance than a short, fat bar of the same volume.) Resistivity has the dimensions of ohms cms. Resistivities of some typical conductors and insulators are given in Table I.

TABLE I

Material	Resistivity (ohms cms.)
Copper	$1{\cdot}7 \times 10^{-6}$
Carbon	5000×10^{-6}
Iron	10×10^{-6}
Mercury	96×10^{-6}
Nichrome	100×10^{-6}
Silver	$1{\cdot}6 \times 10^{-6}$
Fibre	10^{10}
Glass	$10^{12} - 10^{13}$
Ebonite	$10^{15} - 10^{18}$
Mica	$10^{13} - 10^{17}$
Paraffin wax	$10^{16} - 10^{18}$
Shellac	10^{16}
Distilled water	5×10^{5}
Ethyl alcohol	3×10^{5}
NaCl 0·001%	5×10^{4}
NaCl 1%	70
NaCl 5%	15

The conductivity of 'good conductors', such as the metals, is seen to be about 10^{20} times that of the class of 'insulators'. Electrolytes occupy an intermediate position. Note that the presence of moisture will very much reduce the effectiveness of an insulator, especially if traces of dissolved salts are present. This is true whether the moisture is *absorbed* by the insulator, or merely presents a surface leakage path.

Ohm's Law.—In order to drive a current through a conductor, a potential difference must be applied between its ends, and to maintain a given current the potential difference must be greater in proportion the greater the resistance. Conversely, when a current is flowing through a conductor there will be a potential difference across its ends proportional to its resistance. These relationships are expressed in the formula

$$E = IR \quad \text{or} \quad I = \frac{E}{R},$$

where E = potential difference in volts, I = the current in amperes, and R = the resistance in ohms. This constitutes Ohm's Law. Not all substances exhibit this linear relationship between voltage and current, but all the common conductors and most electrolytes (within certain limits) do so. A number of electronic devices which conduct currents do not obey this law, a fact which is extremely useful for certain circuits.

The energy which is employed in driving the current against the opposition of the resistance in the circuit is dissipated by collision between the moving charges and the molecules of the medium, and appears as heat. The *power* dissipated in this way is proportional to the resistance and to the square of the current, and is measured in watts if I is in amperes and R in ohms. Thus

$$\text{Power } W = I^2R \text{ watts.}$$

A resistance therefore must always be chosen of a suitable rating to dissipate, without reaching an unduly high temperature, the heat produced by the current which is to flow in it.

Resistances in Combination.—When two resistors are joined in series (Fig. 1, 1a) so that the same current flows

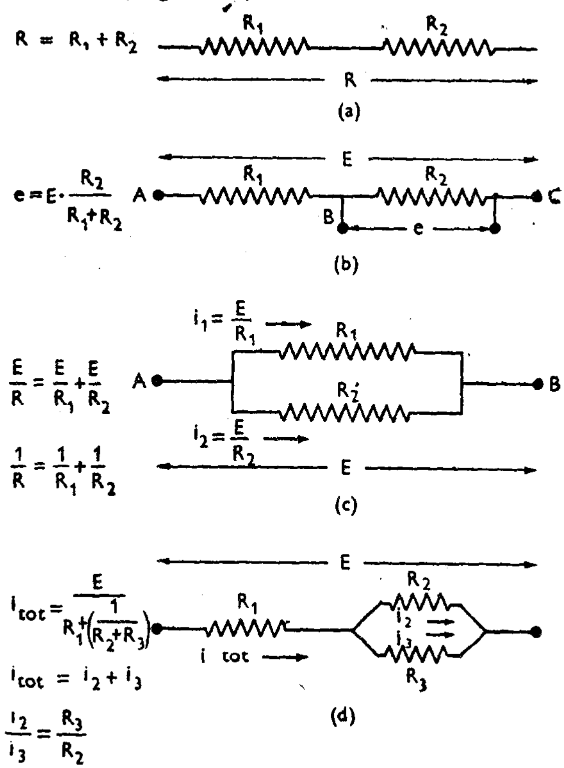

FIG. 1, 1

through each, it is fairly obvious that the total resistance is the sum of the individual resistances :

$$R_s = R_1 + R_2 + R_3 \ . \ . \ . + R_n.$$

By applying Ohm's Law it is readily seen that the voltage across each individual resistor in the chain bears the same proportion to the whole voltage as the resistance of that resistor does to the total resistance. Resistance chains thus form convenient potential dividers. In Fig. 1, 1b, if a voltage E is applied across AC the voltage e across BC is

$$e = E\frac{R_2}{R_1 + R_2}.$$

The case of resistors in parallel is slightly more complex. Consider the resistors R_1 and R_2 connected as in Fig. 1, 1c. Let a voltage E be applied between the points A and B. Applying Ohm's Law we see that this voltage will drive a current E/R_1 through R_1 and a current E/R_2 through R_2. The total current between A and B is thus $E/R_1 + E/R_2$. But this total current is equal to the total voltage E divided by the total effective resistance which we may call R. Therefore, we have

$$\frac{E}{R} = \frac{E}{R_1} + \frac{E}{R_2} \quad \text{or} \quad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

Generally, $1/R = 1/R_1 + 1/R_2 + 1/R_3 + \ldots 1/R_n$.

In dealing with more complex networks of resistors it is well to bear in mind that the sum of currents flowing away from any given junction must be algebraically zero, and that the current will divide itself in inverse proportion to the relative resistance of the different pathways (Fig. 1, 1d).

Direct and Alternating Currents.—The current produced by a primary cell or an accumulator flows always in the same direction. The current produced by a simple dynamo, however, varies continuously and reverses direction periodically. It is possible to change such a current into a direct one (d.c.) by means of a commutator on the machine itself, but owing to the much greater convenience of handling an alternating current (a.c.) it is usually distributed as such. As will be apparent later, a.c. signals are much more readily handled electronically than d.c. signals and the properties of alternating currents are of great importance. Strictly speaking, current of any waveform which changes direction periodically constitutes an alternating current, but since most generators produce a.c. whose waveform is approximately sinusoidal, and since any periodic waveform can be regarded as composed of a series of harmonically related sine waves (Fourier's Theorem), we usually consider particularly this current form.

A sine wave can be regarded as being generated by the projection on a straight line, of a point rotating round

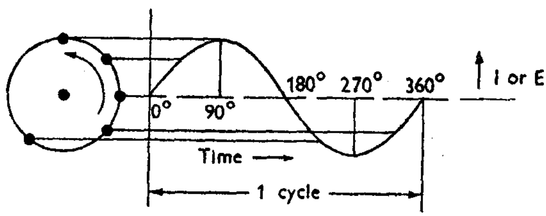

FIG. 1, 2

a circle at a uniform rate (Fig. 1, 2). One complete revolution of the circle corresponds to a whole cycle, and the number of cycles in a given time interval — usually one second — is called the Frequency. The time of one cycle is called the Period. Subdivisions of a cycle are sometimes made in fractions of a period, e.g. one-quarter period, but it is more usual to divide the cycle into parts in accordance with the angle through which the generating point has moved. Thus starting from an arbitrary zero, the current has risen to a positive maximum after the point has rotated through 90°. It falls to zero again at 180°, goes through the negative maximum at 270°, and completes the cycle at 360°. It is thus possible to refer accurately to corresponding points on two different waves.

Current and Voltage Measurements.—With direct currents there is little difficulty in measuring the value of the current and voltage, since both these are constant. In the case of an alternating current, however, the value is continually changing from instant to instant and periodically reversing direction so that the mean over one cycle is zero. Inspection of Fig. 1, 3 suggests an obvious possibility, that of measuring the height from a positive to a negative peak, or from the zero position to either peak. The former is known as the 'peak-to-peak' value and the latter as the 'peak' value

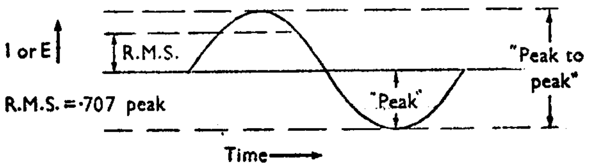

Fig. 1, 3

of the voltage or current. The peak value is the value most easily measured, for example, on an oscillograph trace, and readily enables one alternating current or voltage to be compared with another. It is also an essential value to know for assessing component ratings — for example, the breakdown voltage of an insulator — since the peak voltage is the highest it must stand. Similarly, a valve rating may be limited by the peak current.

For certain purposes, however, we may want to compare the current, not with another alternating current, but with a direct current. To do this we may take advantage of the relation previously given between current, and power dissipated (heat production) in a resistance. Since the power depends on the square of the current, it is immaterial whether that current is positive or negative. If we take the value of the current at any instant during the cycle and square it, the result will be a measure of the power dissipation in a resistance during that instant.

If we do this for every instant during the cycle, add the results, and find a mean value for this square, we shall have a value of I^2 such that the dissipation would have been the same had I^2 remained constant throughout the cycle — in other words, had it been a direct current. If we take the square root, then I is the equivalent direct current which would dissipate the same amount of power in a resistance. On account of its derivation, this value is called the 'root mean square' or r.m.s. value of the current. Most a.c. meters are calibrated to read r.m.s. values. For a sinusoidal waveform the r.m.s. current or

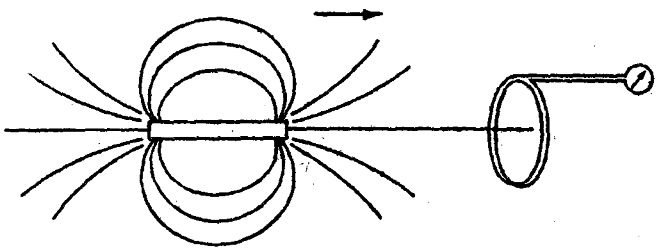

Fig. 1, 4

voltage is 0·707 of the peak value; care should be taken to distinguish between the two when reading or giving a.c. figures.

Electromagnetic Induction.—If a magnet be moved relatively to a closed loop of wire so that the lines of the magnetic field 'cut' the wire, then a current is induced in the loop and is maintained as long as the relative motion continues, Fig. 1, 4. This current is driven by the 'induced electromotive force'. The magnitude of this induced e.m.f. depends on the *rate* at which the lines of the magnetic field cut the loop. This rate can be increased by increasing the rate of relative movement, by increasing the strength of the field (so that the lines are closer), or by increasing the number of turns in the loop. The principle of induction is the basis of the simple dynamo already mentioned. A loop rotating at constant speed in a uniform field (Fig. 1, 5) gives rise to a sinusoidal alternating current, the current being maximal when the wire is moving across the lines of force — and therefore cutting them rapidly, and minimal when it is moving along the lines; also the current is positive or negative according to the direction in which the wire is cutting the field.

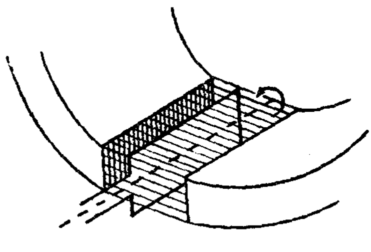

FIG. 1, 5

The relative directions of current, magnetic field, and direction of motion of the conductor, are given in the so-called 'left-hand rule' (Fig. 1, 6). If the thumb and first two fingers of the left hand are arranged so that each is at

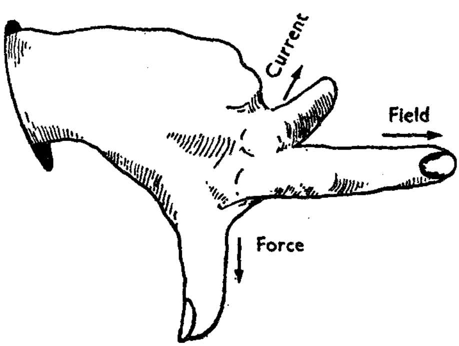

FIG. 1, 6

right angles to the other two, then if the first finger represents the direction of the magnetic field, and the second finger the direction of the current flow, the thumb represents the direction in which the resulting force would tend to move the conductor. Magnetic fields can be used also to deflect electron streams, which are effectively current conductors.

It is well known that there is a magnetic field associated with steady current flow in a stationary conductor. This is the principle of the electromagnet as seen in the electric bell, time-marker, and many other devices. When the wire carrying the current is in the form of a coil the magnetic field strength depends on the 'ampere-turns', that is, on the product of the strength of the current and the number of turns of wire in the coil. If we move the magnetic field of this coil relatively to a second coil, then there will be an induced e.m.f. in the second coil, just as there was in the experiment with a moving bar magnet. But in order to change the magnetic field relative to the second coil B it is not essential to move the first coil A physically. The same effect can be achieved by varying the current in coil A, thereby changing the magnetic field associated with it and causing the lines of force to move. In doing so they cut the coil B and induce an e.m.f. in it. Thus if two coils are wound in close proximity, varying the current in one will produce a corresponding current flow in the other. This is the principle of the induction coil and the transformer. If the current applied to one coil of a transformer (the primary) is a sinusoidal alternating one of given frequency, a current of similar frequency and waveform will flow in the other coil (the secondary). Herein lies the basis of one of the most useful properties of alternating currents — the ease with which they can be transferred magnetically between two circuits which are not in electrical contact with each other, and also the way in which voltages and currents may be 'transformed' in the process.

The voltages across the coils of a transformer are proportional to the relative numbers of turns in the coils. There is no gain of *power* in a transformer, and, if the transformer is an 'ideal' one, no loss of power either. In any real transformer there is always some slight loss, but to a first approximation, the power derived from the