Experiments With Semiconductor Devices

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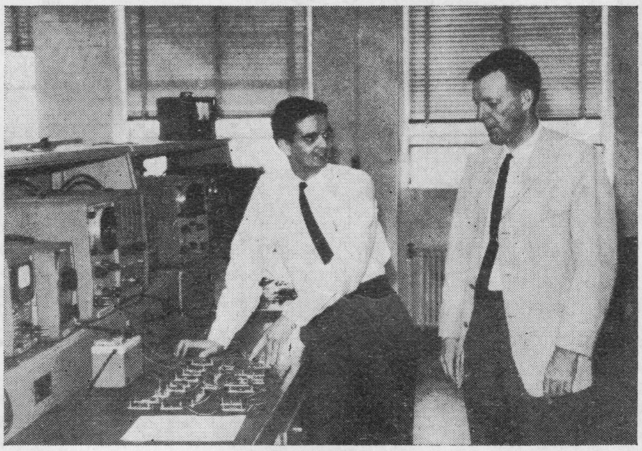

Herman B. Ross, Jr. and R. E. Alley, Jr.

THIS article describes experiments employing semiconductor diodes and/or transistors which illustrate some of the applications of these devices described in a previous article in *The Physics Teacher*.[1] In order to keep the cost of necessary equipment as low as possible, the experiments have been designed to employ a single type of diode and a single type of transistor, and the number of different circuit elements has been kept as small as is consistent with the desirability of obtaining realistic circuit performance.

In the rectifier and clipping circuits we have used a step-down transformer to supply the input voltage from the 115 volt power line, thereby eliminating hazards associated with working directly with the ac line. The clipper circuits, consequently, have low voltage outputs and the direct voltage outputs of the rectifiers are low. However, except for the fact that the voltage drops across the diodes may be detectable in comparison with the output voltages, the principles are illustrated as well at low as at high voltages. The recommended diodes have peak inverse voltage ratings of 400 volts; therefore, they may, if one desires, be used in experiments involving higher input voltages.

In working with alternating voltages we assume that the power line voltage and the output of a variable frequency oscillator vary sinusoidally with time according to the equation

$$e = E_m \sin 2 \pi ft$$

Therefore, if we plot e as a function of time, we obtain a curve which has maximum positive and negative values E_m and which repeats with a frequency f cycles per second (cps). The *period* T is the time required for one complete cycle and is equal to $1/f$ seconds. An alternating voltage applied to the terminals of a resistor R ohms will cause a current

$$i = (E_m/R) \sin 2 \pi ft = I_m \sin 2 \pi ft$$

[1] References are placed at the end of this article.

While a sinusoidal voltage or current may be described by stating its maximum value and its frequency, it turns out to be more practical to specify effective or root-mean-square (rms) values instead of maximum values. The rms value of a voltage (or current) is the numerical value of the steady direct voltage (or current) that would produce the same average heating effect in a given resistor as the alternating voltage or current. In what follows, we shall be concerned with maximum, rms, and peak-to-peak values of periodic currents and voltages. For sinusoidal variations the maximum value is related to the rms value by $E_m = \sqrt{2}\, E_{rms}$. A similar equation applies for current.

The experiments described here require, in addition to the components listed for each experiment, an audio frequency oscillator, a cathode ray oscilloscope (CRO), and a meter having high internal resistance which will be used for measuring direct voltages. The oscillator should be capable of supplying both a sinusoidal wave and a rectangular (commonly called square) wave at frequencies from about 10 cps up to at least 100,000 cps (100 kilocycles/sec, or kcps). The CRO should have a five inch diameter tube and should have provision for calibrating the vertical deflection so that the instrument may be used as an ac voltmeter. It should have vertical sensitivity of 25 millivolts per cm on its most sensitive range. The frequency range need not be greater than zero to 450 kcps. A combination volt-ohm-milliammeter will serve satisfactorily as the dc voltmeter. A combination ac/dc vacuum tube voltmeter is useful, but should be considered a luxury rather than a necessity. Where limited funds are available, it is better to spend the money for a better oscillator and oscilloscope rather than to try to economize on these items in order to purchase the vacuum tube voltmeter. It is convenient, but not necessary to have a variable (0 to 30 volts) low direct voltage power supply which operates from the ac power

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line. This supply can replace the 9 volt battery in the transistor experiments and it provides the possibility of extending the experiments beyond those described here. All these items of equipment are available already wired or in kit form from several sources.

For those not familiar with electronics components, it may be mentioned that resistors used in electronics circuits are usually manufactured with a tolerance of ± 10%. Resistance values normally available enable one to obtain any desired value of resistance within the 10% limit. Resistance values specified in our circuits are standard values. Thus, although a 2,000 ohm resistor might be satisfactory in some circuit, this is not a standard value; therefore, one having 2,200 ohms, a standard value, is specified.

In all the circuits which we shall consider (and, indeed in most electronics circuits) there is a common connection between the *input* voltage and the *output* voltage. This common connection is generally referred to as "ground" and is indicated by the symbol ⏚. The input voltages and the output voltages will then be the voltages of some points in the circuit with respect to ground. Whenever we refer to the voltage of some point in one of our circuits, we shall mean its voltage with respect to ground, unless a specific statement is made to the contrary.

In our discussions and in our circuit diagrams we shall use the following commonly employed conventions.

A. *Resistors:* For resistors of less than 1000 ohms we shall follow the numerical value of the resistance by the capital Greek letter omega (Ω). Thus a 520 ohm resistor will be designated as 520Ω.

For resistors of 1000 ohms or more we shall use the capital letter K to represent thousands of ohms. For example a 220,000 ohm resistor will be designated 220K.

B. *Capacitors:* Capacitor values will be specified in microfarads (10^{-6} farad) or in picofarads (10^{-12} farad). The abbreviation for microfarads will be mfd, and that for picofarads will be pfd. For example, a 25 microfarad capacitor will be written 25 mfd and a 200 picofarad capacitor will be written 200 pfd. [The picofarad was adopted as a unit fairly recently. Those who are familiar with the older designation will recognize that the picofarad is identical with the micromicrofarad (mmfd).]

C. *Frequency:* For frequencies below 1000 cycles per second we shall use the abbreviation cps, while frequencies of 1000 cycles per second and above will be expressed in kilocycles per second, kcps.

EXPERIMENT NUMBER 1—RECTIFIERS

In the previous article,[1] we discussed the use of diodes as rectifiers and showed diagrams for half-wave and full-wave circuits. In this experiment we specify values of components and we describe the use of simple filters to smooth the waveform of the rectifier output. We also discuss bridge type rectifiers.

PART A. Half-Wave Rectifier

The circuit is shown in Fig. 1. Alternating voltage is supplied by a transformer which gives approximately 25 volts across its secondary (points *b-b'*) and half this value between the center tap *d* and either end. We use half the secondary, so the input to our rectifier is approximately 12.5 volts rms. As has already been described, diode D_1 conducts during the half of each ac cycle, making *b* positive with respect to *d*. The output voltage (across points *a-a'*) then has the form shown in Fig. 1b. This may be observed with the CRO. By using the CRO as a voltmeter,[2] and by connecting our dc voltmeter across *a-a'*, we find the peak value of the half sine wave and the direct voltage* indicated in Fig. 1b. (The values quoted are those actually measured on a circuit in our laboratory, where the power line voltage is 117 volts. Differences among components and variations in power line voltage may give slightly different values for other experimenters.) The average current in R_1 is calculated by direct application of Ohm's law.

The simplest type of filter for smoothing the rectifier output consists of a capacitor connected in parallel with R_1. Figure 2 shows the rectifier with a 1 microfarad (10^{-6} farad) capacitor added. Figure 2b shows the output voltage. The half sine waves have been spread out and the ripple voltage (the time-varying part of the output) has a spread from top to bottom of 16 volts as measured with the CRO. The average voltage has been increased as indicated in the figure. The action of the capacitor is explained as follows.

When the diode conducts, the capacitor is charged to a potential difference equal to the peak value of the half sine wave shown in Fig. 1b. As the voltage at *a-a'* begins to decrease from its maximum value, C_1 begins to discharge through R_1 at a rate which depends upon the *time constant,* $\tau = R_1C_1$, of the combination. The capacitor voltage, therefore, decreases, and at some value of the decreasing half sine wave voltage, the voltage across the capacitor will be greater than the voltage at *b-d*. When this occurs, a reverse bias appears on the diode, and it stops conducting. The capacitor C_1 continues to discharge through R_1 until the voltage of the next positive half cycle from the rectifier exceeds the capacitor voltage. Then the diode

* The dc voltmeter reads the average value of the time-varying voltage. The average value is equal to the area of one complete cycle of the time varying wave divided by the time for one cycle (the period).

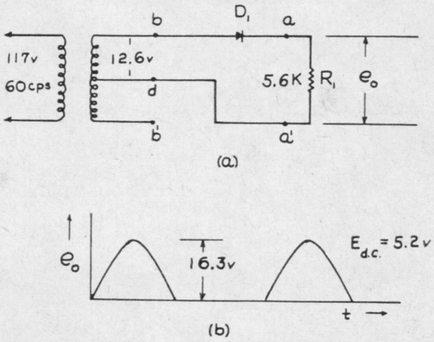


Figure 1. (a) Half-wave rectifier without filter. (b) Output voltage.

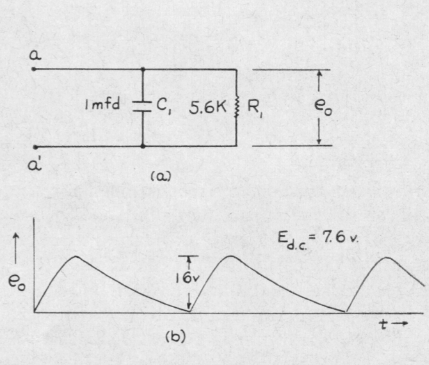
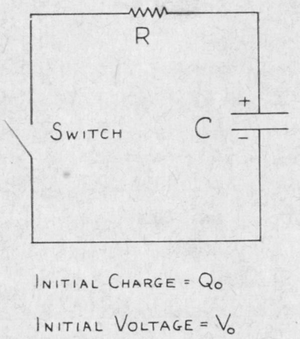


Figure 2. (a) Single capacitor filter. (b) Output voltage when supplied from half-wave rectifier.

begins conducting again, and C_1 recharges to the peak value of the rectifier output. The waveform and the direct voltage at *a-a'* depend upon the relative values of τ and of the period T of the ac input. The constant† τ represents the time required for the capacitor voltage to decrease to $1/\epsilon$, or 37%, of its initial value. Approximately, the capacitor voltage decreases linearly with time. For 60 cps, $T = 0.0167$ sec. If τ is short compared with T, the capacitor will lose most of its charge between input pulses and its voltage will therefore drop almost to zero. Then the filter will have little effect upon the rectifier output. Such is the case with $C_1 = 1$ mfd and $R_1 = 5.6$ thousand ohms (5.6K), because τ is only 0.0056 second. We observe the effect of changing τ by replacing R_1 by $R_3 = 100\text{K}$. Observation of the output voltage with the CRO will show a much smaller ripple voltage and measurement with the voltmeter will show a larger value of average output voltage. We see then that the half-wave rectifier with a single capacitor filter works best when the resistance is high and the *load current* is correspondingly low. If R is infinite, the output voltage is constant and equal to the peak of the ac input, but no current is supplied. Since the *input resistance* of the CRO is very high (millions of ohms) this condition may be observed by removing R.

† Consider the circuit shown in the figure. The switch is initially open and there is a charge Q_o, and therefore a voltage $V_o = Q_o/C$ on the capacitor. We wish to find an expression for the charge, q, on the capacitor as a function of time, t, after the switch is closed at $t = 0$.



After the switch is closed, Kirchhoff's second law applied around the circuit gives, since $i = dq/dt$,

$$R\,(dq/dt) + q/C = 0.$$

This equation may be solved by separating the variables:

$$dq/q = -(1/RC)\,dt.$$

Integration gives,

$$\ln q = -(1/RC)t + K$$

where K is the constant of integration. If $K_2 = \ln K$ we may write

$$q = K_2 e^{-(1/RC)t}.$$

The constant K_2 is evaluated by substituting the initial conditions, that is, $q = Q_o$ when $t = 0$. Such substitution gives $K_2 = Q_o$, and so

$$q = Q_o e^{-(t/RC)}.$$

When $t = RC$, then $q = Q_o/e = Q_o/2.72$ or approximately $0.37Q_o$. The time RC, which is commonly referred to as the *time constant,* is the time required for the charge on the capacitor to fall to 37% of its initial value when it discharges through a resistor R. Note that in the above equations, R is in ohms and C is in farads.

Since the voltage on the capacitor is $v = q/C$, the product RC also represents the time required for the voltage across the capacitor to fall to 37% of its initial value.

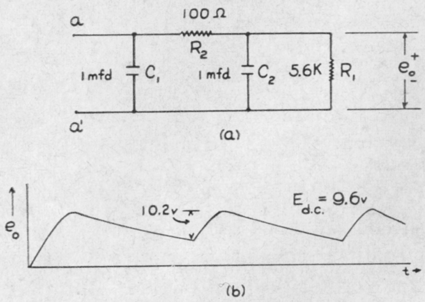


Figure 3. (a) C-R-C filter. (b) Output voltage when supplied from half-wave rectifier.

Figure 3 shows a more satisfactory filter circuit. We use two identical capacitors, C_1 and C_2, with a low value of resistance, R_2, in series between the two capacitors. Measurements with the CRO and the voltmeter give the results shown in Fig. 3b. Even a qualitative analysis of this circuit is too complicated to consider here. However, removal of R_2 from the circuit of Fig. 3a will demonstrate that the inclusion of R_2 results in much greater improvement in performance than is realized by placing C_1 and C_2 in parallel and omitting R_2. If R_2 is in place, and a larger resistor $R_3 = 100\text{K}$ is substituted for R_1 further decrease in ripple and increase in average voltage are observed.

PART B. Full-Wave Rectifier

In Fig. 4a, we use both halves of the transformer secondary and add diode D_2. Then D_1 and D_2 conduct on alternate halves of the ac cycle and the direction of the current in R_1 is always from a to a'. The output is as shown in Fig. 4b. Addition of C_1 to form a filter results in greater improvement of the output than was the case for the half-wave rectifier, because now the time between peaks of the rectifier output is $T/2$, and there is less time for discharge of the capacitor. Results for this filter are shown in Fig. 5b. If the second capacitor and R_2 are added as shown in Fig. 6,

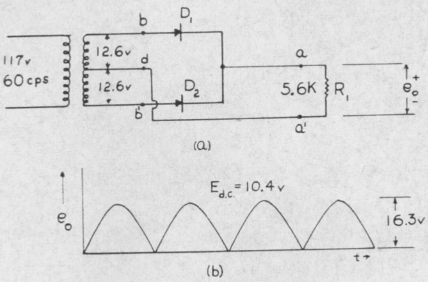


Figure 4. (a) Full-wave rectifier without filter. (b) Output voltage.

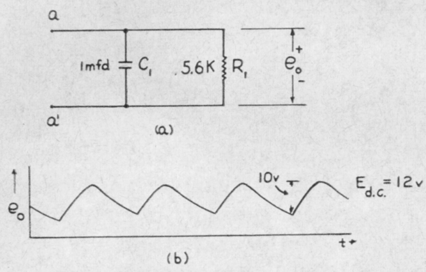


Figure 5. (a) Single capacitor filter. (b) Output voltage when supplied from full-wave rectifier.

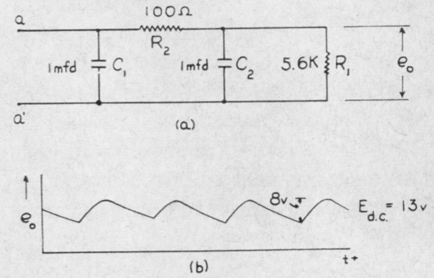


Figure 6. (a) C-R-C filter. (b) Output voltage when supplied from full-wave rectifier.

the output is further improved as illustrated in Fig. 6b. For each of these filters, replacement of R_1 by the larger resistor $R_3 = 100\text{K}$ provides still further improvement in waveform and direct voltage.

It is instructive to make comparisons between the half-wave and the full-wave rectifier by connecting the CRO and the voltmeter across the output and then changing the circuit from full-wave to half-wave by opening the connection between point b' and diode D_2 in Fig. 4a. This may be done safely without disconnecting the ac power in our circuit because it operates at low voltage. However, were we using a high voltage transformer such as is employed to provide plate voltage to vacuum tubes, this would not be safe. One should then either include a switch at point b', or disconnect the circuit from the power line before handling the connection.

PART C. Bridge Rectifier

In this circuit, shown in Fig. 7a, we again use only half the secondary transformer winding. However, by using four diodes we obtain full-wave rectification. If we follow through the circuit, we see that when point b is positive with respect to d, there is forward voltage on diodes D_2 and D_4 and thus there is a current path through D_2, R_1 and D_4 to point d. When d is positive with respect to b, D_1 and D_3 conduct, and the current through R_1 is again from a to a'. Observations at a-a' with the CRO and the voltmeter give the results shown in Fig. 7b. These are somewhat less than the values for the full-wave output of Part B, because there now are two diodes in series with R_1 and there is a small voltage drop in each. If we use the same two filter circuits as were used in the previous experiment, we obtain essentially the same results as with the full-wave rectifier of Fig. 4, with slightly smaller average voltages because now there are two diodes in series. The single capacitor gives a peak-to-peak ripple of 10 volts and $E_{dc} = 11.3$ volts. The two-capacitor filter of Fig. 6 gives 8 volts peak-to-peak ripple and $E_{dc} = 12.3$ volts.

It is apparent, of course, that higher input alternating voltages will provide correspondingly higher direct voltage outputs. For example, the half-wave rectifier and the bridge rectifier may be supplied directly from the 115 volt power line without the use of transformers. Still higher direct output voltages may be obtained by use of a step-up transformer and two diodes. The diodes and the filter capacitors must, of course, have the appropriate voltage ratings.

It is apparent that if a step-up transformer is not used, the direct output voltages of both the half-wave and the bridge circuits are limited by the amplitude of the ac line voltage. With either circuit, the maximum direct voltage obtainable is the peak value of the line voltage, i.e., about 160 volts, and this value can be obtained only with vanishingly small load current.

If a transformer is to be used to increase the output voltage then the circuit of Part B (Fig. 4a) has the

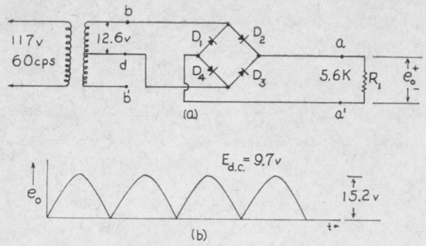


Figure 7. (a) Bridge-type full-wave rectifier. (b) Output voltage.

advantage of providing full-wave rectification using only two diodes. In our experiment we used a step-down transformer and we were able to illustrate the principle of the rectifier while avoiding high voltages which might prove hazardous to the inexperienced student. Suppose, however, we use a step-up transformer with a 1 to 7 turns ratio. Then the rms voltage between terminals b-b' in Fig. 4a would be, with 115 volts rms input, about 800 volts, and there would be 400 volts rms from b to d and from b' to d. The maximum values of these voltages would be $\sqrt{2} \times 400$ or approximately 560 volts. If we use diodes having PIV well in excess of 560 volts, we can build a full-wave rectifier which, without filtering, will give an average voltage of about 250 volts. If we then use the two capacitor filter we may raise the direct voltage appreciably and reduce the ripple substantially. The capacitors must, of course, be designed to work properly at 560 volts. In this example we might use capacitors which have a standard rating of 600 volts. They probably would be of the electrolytic type, and would have to be placed in the circuit with proper regard for the polarity markings on their cases.

We have avoided the use of inductors (coils of wire wound on iron cores) because of their expense and size. However, for rectifiers which are to supply large currents at constant voltage and low ripple the best type of filter uses one or more inductors as shown in Fig. 8. Depending upon specific applications, one may have either an inductor or a capacitor as the first circuit element in the filter. Always, the capacitors are connected in parallel (that is, between the positive and negative leads) while the inductors are placed in series with the positive lead. (See Fig. 15 of reference 2.)

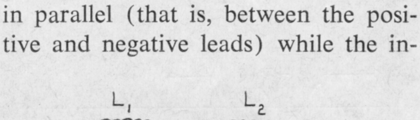


Figure 8. L-C filter used to supply large loads.

EXPERIMENT NUMBER 2— VOLTAGE DOUBLER, TRIPLER AND QUADRUPLER CIRCUIT

Sometimes it is necessary to obtain a very high voltage which will not be required to supply an appreciable amount of current. An example is the accelerating voltage for the electron gun of a cathode ray tube.

Figure 9 shows a circuit which will provide two, three, and four times the maximum value of the sinusoidal input voltage. Again, we use half the secondary of our transformer, along with four diodes and four 200 volt capacitors. Let us analyze the operation of this circuit.

The alternating voltage between a and a' has a peak value of 18 volts. When voltage is first applied to the circuit and when point a is negative with respect to a', D_1 conducts and C_1 charges, acquiring a potential difference of 18 volts with the polarity indicated. When the polarity at a-a' reverses, D_2 conducts, and C_1 and C_3 are in series across the transformer. Some of the charge on C_1 is transferred to C_3. On the next half cycle (a negative with respect to a') D_1 conducts and charge is added to C_1, raising its potential difference back to 18 volts. Because of the charge on C_3, D_3 is now forward biased and conducts and some charge is transferred from C_3 to C_2. When the polarity again reverses, D_2 and D_4 conduct, charge is added to C_3 and some charge from C_2 flows to C_4. After several cycles of alternating voltage, all capacitors are fully charged, and all diodes are non-conducting because the forward voltage on none of them ever rises above zero. When all capacitors are fully charged, the potential difference across C_1 is E_m, or 18 volts in this case. All other capacitors have potential differences of $2E_m$, with polarities as indicated. We see that if we take point a' as our reference or

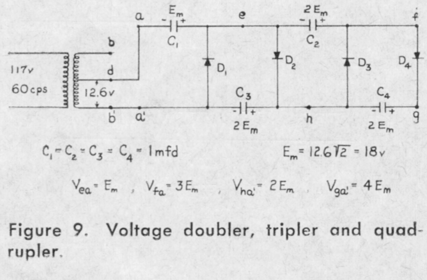


Figure 9. Voltage doubler, tripler and quadrupler.

ground point, then $V_{ga'} = 4E_m$ and $V_{ha'} = 2E_m$, and we have a voltage doubler and a voltage quadrupler. If point a is the reference point, then $V_{fa} = 3E_m$, and we have a voltage tripler. Since points a and a' are on the secondary winding of a transformer, it is permissible to ground either point (but not both simultaneously). This circuit will not, however, give voltages $2E_m$, $3E_m$ and $4E_m$ all referred to the same point. Addition of more diodes and capacitors will make it possible to obtain any integral multiple of E_m.

If the circuit of Fig. 9 were supplied directly from the power line, E_m would be approximately 160 volts, and the other voltages would be approximately 320, 480, and 640. Higher values could be obtained by use of a step-up transformer to supply the input voltage. Of course, all the diodes must be capable of withstanding the inverse voltages to which they will be subjected, and the capacitors must be designed for the high voltages which may appear across them.

EXPERIMENT NUMBER 3—DIODE CLIPPER CIRCUITS

In the previous article we discussed the use of diodes as clippers, that is, as devices to limit the voltage appearing across the load. In this experiment we shall set up two clipper circuits and examine their operation. We recall that clipping action requires the use of batteries or some sources of direct voltage in order to provide reverse bias on the diodes and thereby to determine the voltage level at which clipping occurs. In order to reduce the number of batteries required, we shall perform our experiment with a very low amplitude of alternating voltage input. We obtain the alternating voltage by placing a voltage divider across half the secondary of our step-down transformer. As shown in Fig. 10, the voltage divider consists of a 750 ohm and a 220 ohm resistor in series. By means of this combination, the peak voltage supplied to the clipping circuit is reduced to (220/970) × (18) or approximately 4.15 volts. This is the value of V_s in Fig. 10. This voltage divider action may be checked by using the CRO as a voltmeter and measuring the peak values at d-b' and at e-b'.

To show clipping of only the positive half cycle of V_s, we connect a diode D_1 and a 1.5 volt battery so that the battery provides a reverse bias on D_1, as shown in Fig. 10. The 2.2K resistor is included to limit the current when the diode conducts. Now as V_s rises toward its positive peak value, D_1 remains nonconducting and e_o follows the sinusoidal increase in V_s. When V_s reaches 1.5 volts, D_1 conducts, and e_o is determined by the bias battery voltage E_1. The output voltage remains fixed at this value until V_s falls below E_1. Then D_1 stops conducting, and the output voltage again follows V_s. The negative half cycle of V_s is unaffected by D_1, and so e_o follows V_s. If we observe e_o with our calibrated CRO we can see the clipped waveform and also measure the voltage amplitudes for the positive and negative half cycles. The results are shown in Fig. 10b. If we measure the voltage E_1 we find that clipping occurs at a voltage somewhat greater than E_1. This is explained by the fact that there is a voltage drop in the diode when it is conducting, and this adds in series with E_1 to determine the actual clipping level. If higher values of V_s and E_1 were used, the drop across D_1, which has a fixed value, would be negligible in comparison with E_1 and the difference between E_1 and the clipping level would be too small to be detected.

If a second diode D_2 and a second battery E_2 are added to the circuit with polarities as shown in Fig. 11a, then both the top and bottom of V_s will be clipped, and the result will be a wave having approximately trapezoidal shape with peak-to-peak voltage of approximately 4.4 volts. If E_2 is increased to 3 volts, then there will be asymmetrical clipping, with the top of the wave clipped at about 2.2 volts and the bottom at about 3.5 volts. [See Fig. 11b] Examination of e with the CRO will show clearly that the flat portion of the positive half of the output lasts for a larger fraction of the ac cycle than does the flat portion of the negative half. An interesting exercise is to measure with the CRO the fraction of the cycle during which the output is constant. Since we know that V_s is sinusoidal and since we know its maximum value, such a measurement enables us to calculate the clipping level.

Let us now remove the voltage divider from the transformer secondary and supply our symmetrical clipping circuit of Fig. 11 from points d-b' on the transformer. The peak value of the input to the clipper is then approximately 18 volts. The clipping level, however, is unchanged at approximately 2.2 volts positive and negative. The result is that we are now clipping the input wave at values which are nearer the points at which the input wave passes through zero. Near zero volts, the sine wave is almost linear and so if we clip near zero, our output wave will be almost exactly trapezoidal. This effect can be observed with the CRO connected across e_o. If the amplitude of the input voltage to the clipping circuit is increased still further by using the points b-b' as the voltage source, then the sides of the trapezoid become almost vertical, and the output has the appearance of a square wave. One method of obtaining a square wave is, therefore, to clip an alternating voltage of large amplitude at a very low voltage level. The obvious disadvantage of this method of obtaining a square wave is that the square wave has a very small amplitude. In Experiment 4 we shall describe another way of producing a square wave which may have much greater amplitude, and whose frequency may be different from that of the ac line.

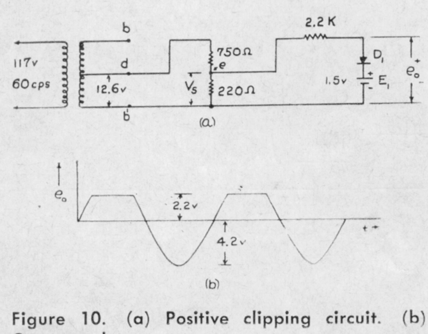


Figure 10. (a) Positive clipping circuit. (b) Output voltage.

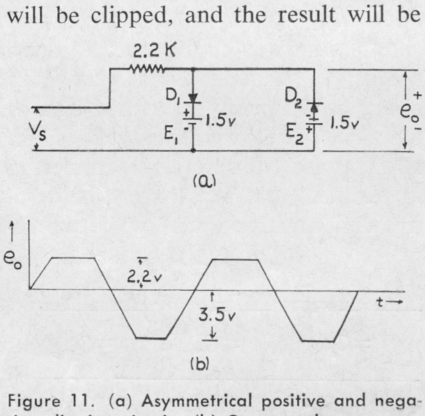
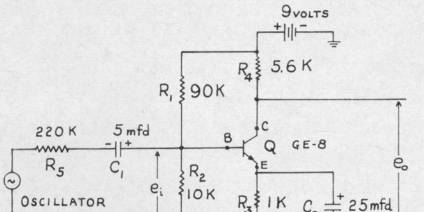


Figure 11. (a) Asymmetrical positive and negative clipping circuit. (b) Output voltage.

EXPERIMENT NUMBER 4—SINGLE STAGE TRANSISTOR AMPLIFIER

In the previous article,[1] we discussed the use of the transistor as a voltage amplifier, and showed a simple diagram for a common emitter circuit (Fig. 15 of previous article). We also discussed the location of the quiescent operating point, indicating that it should be so chosen as to make it possible for the amplifier to operate over a reasonable range of input signal without being driven into a non-linear region of its collector characteristic. In this experiment we shall examine the operation of a transistor amplifier which is designed to meet these requirements. It is a characteristic of transistors that they are quite sensitive to temperature changes, and unless some provision is made to compensate for such changes, the operating point may move close to the edge of, or completely out of, the region of linear operation. This, of course, destroys the effectiveness of the device as a linear amplifier (i.e., an amplifier which gives an output voltage proportional to the input). It is necessary, therefore, to provide means for stabilizing the operating point, and the simple circuit described in the previous article must be modified to accomplish this. There are several ways in which stabilization may be achieved. One common method is shown in the circuit of Fig. 12 where we use a common-emitter amplifier employing a GE8 germanium n-p-n transistor. This transistor is an inexpensive general purpose type which has a fairly



CAPACITORS ARE ELECTROLYTIC. OBSERVE POLARITY MARKINGS IN CONNECTING

Figure 12. Single stage transistor amplifier.

wide range of applications. In Fig. 12, stabilization is achieved through the use of resistors R_1, R_2, and R_3. The effectiveness of stabilization is expressed in terms of the *stability factor* S which is related to the three resistors and to the beta of the transistor by the equation

$$S = (1+\beta)\frac{1+(R_3/R_a)}{1+(1+\beta)(R_3/R_a)}$$

where R_a is the effective resistance found by combining R_1 and R_2 in parallel. The beta of a transistor may be defined in terms of the incremental change in current supplied to the base, Δi_b, and the corresponding incremental change in the current, Δi_c, in the collector circuit, $\beta = \Delta i_c/\Delta i_b$. The desirable situation is to have S as small as possible. However, the quiescent operating point (reference 2, page 62) of the transistor also depends upon some of the quantities involved in the expression for S, and so it is necessary to arrive at a satisfactory compromise which will give both adequate stability and a satisfactory operating point. The values of the resistors in Fig. 12 have been selected to achieve this double purpose.

In Fig. 12 the 9-volt battery supplies the operating voltage for the transistor. Since the GE8 is an n-p-n transistor, the positive end of the battery is connected through resistor R_4 to the collector (point C in Fig. 12). Thus, the collector-emitter junction is reverse biased. The combination of resistors R_1, R_2 and R_3 provide the forward bias required for the base-emitter junction. The signal to be amplified is supplied by the audio frequency oscillator. We saw in the previous discussion that for satisfactory operation the input current to the transistor base must be very small. The large resistor R_5 is connected in series with the oscillator in order that the input current may be adjusted to a satisfactory value. The capacitor C_1 must be included so that there will be no path for direct current through the oscillator. The purpose of the capacitor C_2 is to provide a low impedance path for alternating current around resistor R_3. If C_2 were not provided, there would, when a signal is applied to the input, be an alternating current in R_3. This would produce an alternating voltage across R_3 which would have the effect of reducing the overall voltage amplification of the stage.

The important characteristics of an amplifier are its voltage gain, A, defined as the ratio of output alternating voltage (e_o) to input alternating voltage (e_i); its frequency responses, which describes the way in which the voltage gain varies with the frequency of the voltage to be amplified; and its linearity, which describes the fidelity with which the output voltage reproduces the time dependence of the input voltage. Sometimes we are also interested in the relative phase of the output and input voltages—this generally is described by stating the angle through which the phase of the input voltage is shifted in the amplification process.

Let us now perform some experiments to determine the characteristics of the amplifier of Fig. 12. If the response is to be linear, it is necessary to keep the amplitude of the input voltage small. We begin by setting the oscillator for a frequency of 1000 cps. Using the CRO as a voltmeter we adjust the oscillator output for 3 volts peak to peak. Next we use the CRO as a voltmeter to measure e_i, the voltage between transistor base and ground. This is the input voltage to the amplifier. Now we connect the CRO between the collector of the transistor and ground and measure the output voltage e_o. The ratio of these is the voltage gain, A. The input voltage specified above is small enough so that the amplifier should be operating linearly. However, as a check on the linearity of the amplifier we use the CRO to observe the waveform of the output. While visual observation of the waveform is not an entirely satisfactory method for checking for distortion, we can at least be sure that no obvious change in wave shape has occurred.

Our next step is to take data from which to plot a frequency response curve. To do this, we set the oscillator frequency for 10 cps and use the CRO to measure e_i and e_o. From these values, we calculate A. We then adjust the oscillator to 50 cps and repeat the measurement of A. We continue the measurements, using the following frequencies: 100, 500, 1000, 2000, 5000, 10,000, 12,000, 15,000, 20,000, 50,000, and 100,000 cps. The final step is to plot the calculated values of gain as functions of frequency. The accepted method of presenting the information is to use semi-logarithmic graph paper, plotting the frequency on the logarithmic scale and the voltage gain on the vertical scale. The frequency range used will cover four cycles of logarithmic paper. If such paper is not available, we may use the A-scale of a 6-inch slide rule to lay off appropriate distances on the horizontal axis, or we may find the base 10 logarithm of each frequency and plot it on the horizontal axis.

When plotted as described above, our voltage gain data will give a curve as shown in Fig. 13. We observe that the gain is low at 10 cps, but rises rapidly with frequency, reaching its maximum value at about 200 cps. The

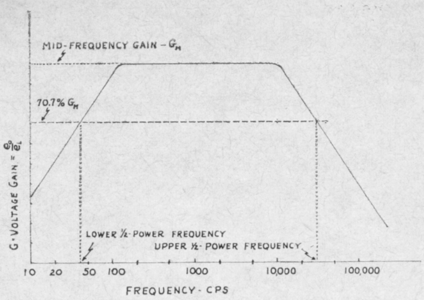


Figure 13. Frequency response of single stage amplifier.

gain then remains constant over a relatively wide frequency range up to about 10,000 cps. At this frequency the gain begins to decrease and at 100,000 cps it has fallen to a small fraction of its maximum value. The frequency range over which the gain is constant is called the mid-frequency range; the two ends of the curve are the low and high frequency ranges respectively. An important characteristic of the frequency response curve is the location of the "half-power frequencies," defined as the low and high frequencies at which the gain is 70.7% of the mid-frequency gain. From our graph in Fig. 13, we see that for the amplifier of Fig. 12, the mid-frequency gain is approximately 100, and the lower and upper half-power frequencies are approximately 40 cps and 30 kcps respectively.

The term "half-power frequency" originated as follows: If a voltage E volts is supplied to a resistor R ohms, the power dissipated (transformed into heating) in the resistor is $P = E^2/R$ watts. If R is held constant and if E is reduced to some value E' such that the corresponding power is $P' = P/2$, then it follows that $E' = E/\sqrt{2} = 0.707E$. Since in our experiment e_i is constant, the voltage gain e_o/e_i is 0.707 or 70.7% of its maximum value when $e_o = 70.7\%$ of its maximum value $(e_o)_{max}$. The frequencies at which the gain is 70.7% of its maximum value are thus the half-power frequencies.

The data quoted above are the result of experiments on one GE8 transistor. Transistors of the same type vary considerably in individual characteristics, particularly in the current gain, beta. Therefore, the data presented here should be considered as typical, but one should not expect that experiments with another GE8 transistor will give the same numerical results. However, the circuit of Fig. 12 is so designed that any GE8 transistor should work properly with the component values indicated there.

It is of interest to observe what happens as the input voltage to the amplifier is increased. We set the oscillator for 1000 cps and connect the CRO to observe the waveform of the output voltage. As we gradually increase the oscillator output voltage, we observe that the amplifier output wave becomes distorted, flattening at the top and bottom. If the input voltage is increased to a high enough value, the output voltage will have the appearance of a square wave. When this type of distortion occurs, the amplifier is said to be "overdriven." We see that overdriving an amplifier provides a method of producing approximately square waves.

It was stated earlier that capacitor C_2 in Fig. 12 serves to increase the voltage gain of the amplifier. This statement may be verified by readjusting the oscillator output to the value used in obtaining the frequency response curve, setting the frequency for 1000 cps, and disconnecting C_2. The voltage gain will decrease. Removal of C_2 results in introducing "negative feedback" into the amplifier —that is, the current change which produces the output voltage is, by passing through R_3 in Fig. 12, causing a change in emitter voltage which partially counteracts the amplifying effect of the circuit. If we repeat our measurements to obtain a new frequency response curve with C_2 disconnected, we find that the mid-frequency gain has been reduced to about 10 but the bandwidth of the amplifier has increased. The upper ½-power frequency is about 150 kcps and the lower ½-power frequency is less than 5 cps. This illustrates a general principle, namely, the reduction of the gain of an amplifier increases its bandwidth, while increase in gain reduces the bandwidth.

We may use the amplifier of Fig. 12 to illustrate "square-wave testing." Fourier showed that, with certain restrictions which are of no concern here, any periodic function of time having frequency f_o may be represented as the sum of a series of sinusoidal functions of time whose frequencies are nf_o, where n is an integer. A typical term in a *Fourier series* has an amplitude A_n and a phase angle θ_n which depend upon the shape and amplitude of the original periodic function. The typical term would be written, $A_n \sin(2\pi n f_o + \theta_n)$. The Fourier series which represents a periodic rectangular wave of amplitude B and frequency f is

$$\frac{4B}{\pi}[\sin 2\pi ft + \tfrac{1}{3}\sin 3(2\pi ft) + \tfrac{1}{5}\sin 5(2\pi ft) + \tfrac{1}{7}\sin 7(2\pi ft) + ---]$$

In this series, the phase angles are all zero, only odd values of n appear, and for a typical term, $A_n = (4B/n\pi)$. The first term in the series is the *fundamental;* the other terms are *harmonics.*

If now a periodic rectangular wave (commonly referred to as a square wave) of frequency f is applied to the input of an amplifier, the output of the amplifier will be approximately a square wave provided the bandwidth of the amplifier is great enough so that it will pass without attenuation a sufficiently large number of terms of the Fourier series representation of the square wave. (The phases of the components of the output are also important, but within the mid-frequency range an audio amplifier will cause the same phase shift [180°] for all frequencies.) By plotting the individual terms in the series and adding them graphically, we can show that if the frequency $15f$ lies below the upper half-power frequency of the amplifier, the amplifier will give a reasonably good reproduction of the square wave input. If, therefore, we supply a square wave of small enough amplitude so that it does not overdrive the amplifier, then an examination of the amplifier output will give some information about the amplifier bandwidth. Thus, if an amplifier gives an essentially undistorted output with a 100 cps square wave input, we know that the upper ½-power frequency is at least 1500 cps. Let us apply square wave input of 100 cps to the amplifier of Fig. 12. According to our data plotted in Fig. 13 the upper ½-power frequency is about 20,000 cps. Therefore, we would expect the output of our amplifier to be an undistorted 100 cps square wave. This turns out to be the case. However, if the input frequency is increased to 1000 cps, the output begins to show signs of distortion, and as the input square wave frequency is increased further, the output rapidly loses its rectangular shape.

EXPERIMENT NUMBER 5—TWO STAGE CAPACITOR-COUPLED AMPLIFIER

Frequently, greater voltage gain is required than may be obtained from a single amplifier state. Then two or more stages are connected in *cascade,* with the output of one stage being used as the input to the next stage. An important consideration in designing such an amplifier is the method by which the two stages are connected together. Since there is a direct voltage between points *C* and ground of the amplifier of Fig. 12, it is not satisfactory merely to connect a wire from point *C* to the base of the next transistor, because we would then be applying this direct voltage to the base of the second transistor and it would be difficult, if not impossible, to achieve a satisfactory quiescent operating point. We could include a battery in series between collector and base, with a value of voltage and a polarity such that it compensates for the direct voltage at the collector. There are, however, other more satisfactory methods of coupling the two stages. One of these is to use a transformer, thereby isolating the two stages. A simpler and generally more desirable type of coupling employs a capacitor, shown as C_3 in Fig. 14. This capacitor is chosen so as to act as a low impedance path for alternating currents between points *a* and *b* but at the same time it isolates the base of the second transistor from the direct voltage on the first collector.

In Fig. 14 we have two amplifier stages each identical with that in Fig. 12, connected in cascade by capacitor C_3. If C_3 is disconnected at point *a,* and the output of stage number 1 measured between *a* and ground, we will obtain the same frequency and gain characteristics as we found for the circuit of Fig. 12. Similarly, stage 2 alone has characteristics similar to those of Fig. 12. One might expect, therefore, that since each stage has a voltage gain of approximately 100, the two cascaded stages would show an overall voltage gain of $(100)^2$ or 10,000. Examination of Fig. 14, however, shows that this should not be true. The gain measurements of Fig. 12 were taken with no *load* on the amplifier, that is with no circuit elements connected between the collector and ground. In the cascaded circuit, however, the first stage is effectively loaded by the *input resistance* of the second stage. Usually the result of loading an amplifier stage is to decrease its gain, and this is the case here. If we measure the gain between the input e_i and point *a* in Fig. 14, we find that the gain of the first stage is now about 20 instead of 100. The second stage, however, has no load upon it, and so its gain will be about 100 as before. The overall gain then should be of the order of $100 \times 20 = 2{,}000$.

Let us take data for a frequency response curve for the two stage amplifier. The first thing we must recognize is that the input voltage e_i must be lower than it was for the measurements on the single stage amplifier; otherwise, the output voltage of stage 1, when applied to stage 2, will constitute too large an input voltage for this stage, with the result that stage 2 will produce a distorted, practically

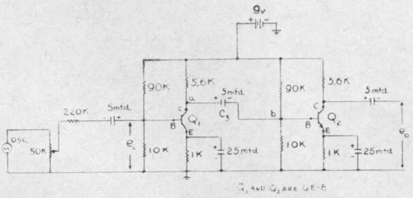


Figure 14. Two-stage resistance capacitance coupled transistor amplifier.

square wave output. In order to avoid overdriving stage 2, therefore, we reduce e_i to about 0.002 volt, peak-to-peak. Since the oscillator output cannot be adjusted directly to such a low value of output voltage, we use a variable resistor as shown in Fig. 14.

With an input frequency of 1000 cps, we measure an output, e_o, of 4 volts. The voltage gain is, therefore, $A = 4/0.002 = 2000$. If we again measure gain at different frequencies and plot our data as before, we obtain a frequency response having steeper increasing and decreasing slopes than those of the corresponding curve for a single stage. We also detect a small increase in the lower ½-power frequency and a small decrease in the upper ½-power frequency. Thus, the effect of connecting two identical stages in cascade is to decrease the overall bandwidth, while at the same time to increase the overall gain. As with the single stage, we find that overdriving by supplying a large input signal can result in an output which is a very close approximation to a square wave. Furthermore, square wave testing of this amplifier will, since the bandwidths are comparable, give about the same results as those obtained with the single stage.

In the procedure described above, it is necessary to set e_i to a very small value (0.002 volt). If the CRO is not sensitive enough for measurement of such a low voltage, the following alternative procedure will give reasonably accurate gain *vs* frequency curve.

Replace the 5 mfd capacitor C_1 by a 25 mfd capacitor. Then C_1 will be practically a short circuit compared with the 220K resistor, and if the oscillator voltage is held constant as the frequency changes, then e_i will also be practically constant. Now set the oscillator for 1 kcps and for an output voltage of 1 volt peak-to-peak. Observe e_o with the CRO and adjust the 50K potentiometer so that a sinusoidal output waveform is obtained. Now if the oscillator frequency is varied with its output voltage held constant, there will be a constant, though unknown, value of e_i. Measure the output voltage for the prescribed frequency range. In the mid-frequency range e_i will be constant, and will have its maximum value. Now if we divide each measured value of e_i by this maximum value of e_i, we obtain data from which we may plot a *normalized* frequency response curve in which the output voltage (for the same input voltage) at any frequency is expressed as a fraction of the mid-frequency output voltage. Such a curve has exactly the same shape as the curve of voltage gain *vs* frequency, and from it one may determine the half-power frequencies, simply by noting at what frequencies the output voltage is 70.7% of the mid-frequency output voltage.

EXPERIMENT NUMBER 6—THE WIEN BRIDGE OSCILLATOR

We have seen in experiments 4 and 5 that we may employ transistors in circuits which will act as voltage amplifiers. In those circuits we supplied a small voltage to the amplifier input, and as a result of the amplifier action of the circuit, we obtained a much larger output voltage. By restricting the amplitude of the input voltage, we obtained an output waveform identical with that of the input. In the mid-frequency range, a single stage amplifier produces a constant 180° phase shift between input and output. Two stages produce 360°

phase shift, and this, of course, corresponds to no phase shift. We conclude, then, that for the amplifier of experiment 5, the input and output voltages are in phase in the mid-frequency range. We may check the validity of this conclusion by using the CRO to compare the phases of the two voltages (see reference 2).

If, by some means not yet specified, we take a sample of the output voltage of the two-stage amplifier and supply it to the amplifier input in place of the oscillator voltage, we have a situation in which the amplifier is supplying its own input voltage. If the fraction of the output voltage fed back to the input is such that its amplitude is equal to the amplitude of the voltage originally supplied by the external oscillator, the amplifier will operate as an oscillator without external excitation. The two-stage amplifier has thus been converted into an oscillator. If, however, such an arrangement is to produce a useful oscillator, some provision must be made for controlling the frequency and waveform of the output voltage.

Let us imagine that we have a circuit consisting of resistors and capacitors (this will be referred to as the RC network) which has two input terminals and two output terminals. If variable resistors and capacitors are used, the RC circuit may be designed so that it will produce a change in phase between a sinusoidal voltage supplied at its INPUT terminals and the sinusoidal voltage which appears at its OUTPUT terminals. Over some range of frequency, the R's and C's may be so adjusted that the output and input voltages are exactly in phase for one particular frequency, but are not in phase for any other frequency. Furthermore, the RC circuit may be designed to introduce *attenuation,* that is, it may be designed so that its output voltage is any desired fraction, less than unity, of the input voltage.

In Fig. 15, we represent the RC circuit and the two-stage amplifier by rectangles, and we show connections such that the RC circuit receives its input from the amplifier output and supplies its output to the amplifier input. A diagram such as Fig. 15 is called a *block diagram.* Block diagrams are often used when one wishes to show the interconnections among two or more circuits without complicating the drawing by showing the details of the individual circuits. Now the amplifier output is in phase with its input for all frequencies in the mid-frequency range. When the amplifier output signal passes through the RC network it will, in general, be shifted in phase. However, depending upon the adjustments of the R's and C's, there will be one frequency for which the phase shift through the RC circuit is zero and there is now only one frequency in the mid-frequency range of the amplifier for which the input and output of the amplifier are in phase. If the RC network attenuation is adjusted so that just the proper amplitude of voltage is supplied to the amplifier, then the whole circuit will perform as an oscillator *at the frequency of zero phase shift,* and will give an output voltage which is sinusoidal. Since the frequency of zero phase shift depends upon the adjustment of the R's and C's in the RC network, we have a variable frequency sinusoidal oscillator.

Figure 16 shows the details of such an oscillator which employs the two-stage amplifier of experiment 5. The RC network consists of the circuit elements at the left of the drawing which are enclosed in broken lines. The 470K resistor R_3 has been chosen for satisfactory operation of this particular circuit. Observe that an additional 100 ohm resistor, R_5, has been added in the emitter circuit of the first transistor. This resistor, without a capacitor in parallel, introduces "negative feedback," thus reducing the overall gain of the two-stage amplifier. The variable resistor, R_4, determines the fraction of the output voltage of the amplifier which is returned to the input. Its correct setting is that for which the output of the oscillator, as observed with the CRO at e_o is sinusoidal. (R_4 is the same variable resistor used in Fig. 14 to obtain the very low input voltage required for the two-stage amplifier. In Fig. 16, only two connections are made to R_4—one at the moving contact and the other at one end of the resistance wire. Adjustment of the moving contact changes the resistance between points *a* and *b* in Fig. 16.)

Frequency control of the oscillator is achieved through adjustment of the two resistors, R_1 and R_2, and the two capacitors, C_1 and C_2. Usually, the R's are equal and the C's are equal. When these equalities exist, the frequency, f, of the oscillator may be calculated from

$$f = \frac{1}{2\pi RC} \text{ cps}$$

where R is in *ohms* and C is in *farads.* If we employ variable capacitors arranged mechanically so that both C's may be varied simultaneously by the same amount (i.e., if we use *ganged* capacitors), we can change the frequency continuously. Similarly, simultaneous variation of the two R's will change the frequency.

In the experiment, we shall not use variable capacitors or resistors, but we shall change the C's by substituting different fixed values of capacitance. We shall not, therefore, obtain a continuously variable frequency output, but rather several fixed frequencies which depend upon the values of the C's.

Let us first use $R_1 = R_2 = R = 100$ K and $C_1 = C_2 = C = 200$ pfd. From the formula we calculate a frequency of 7.96 kcps. After aujusting R_4 for the best waveform as observed with the CRO, we measure the frequency of our experimental oscillator by comparing it with the commercial oscillator, using the procedure described in reference 2. In our laboratory, the measured frequency was 8.6 kcps. The difference, of less than 10%, between observed and calculated frequencies is attributed to the fact that the components in our circuit may vary by as much as $\pm 10\%$. If we replace the C's by others having values of 300 pfd, the calculated and observed frequencies are 5.3 kcps and 5.6 kcps respectively. This closer agreement is accidental and merely means that the circuit elements were closer to their nominal values in this

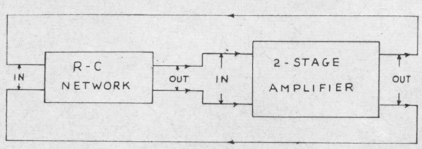


Figure 15. Block diagram of RC network connected to two-stage amplifier.

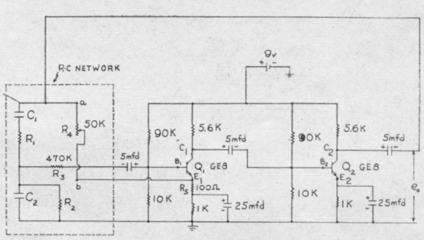


Figure 16. Wien bridge oscillator.

case than in the previous one. We may observe the effect of changing the R's by keeping $C_1 = C_2 = 300$ pfd and making $R_1 = R_2 = 200K$. We would then expect the frequency to be half that observed with the preceding combination of R's and C's. We may continue substituting different values of resistances and capacitances and obtain a wide range of output frequencies. There are, however, upper and lower limits to the values of the R's and the C's which may be used if one is to obtain a satisfactory waveform. We may also examine the effects of using unequal values for R_1 and R_2 and for C_1 and C_2. The formula for frequency will no longer be valid, however.

If you examine its circuit diagram, you probably will find that your commercial oscillator uses the circuit demonstrated in this experiment. A pair of mechanically ganged capacitors provides continuously variable frequency control over each of several frequency ranges. A particular range is selected by means of a switch which selects one of several pairs of identical resistors which correspond to R_1 and R_2 in Fig. 16. Your oscillator contains additional circuit elements to provide frequency stability and constant output with changes in temperature or power line supply voltage. It also has an amplifier whose *gain* (amplification) may be varied in order that the voltage output of the oscillator may be changed. Square waves may be obtained by increasing the voltage fed to the amplifier and thus overdriving it.

The Wien bridge is a popular circuit for general purpose oscillators in the frequency range up to several hundred kcps. There are other designs which provide these frequencies, but they are not generally as easily controlled, nor do they give as good an output waveform. At "radio frequencies" and higher, the Wien bridge is not applicable; oscillators are employed whose frequencies are determined by combinations of inductance and capacitance.

EXPERIMENT NUMBER 7— THE FREE-RUNNING MULTIVIBRATOR (MVBR)

In some applications it is desirable to have a periodic voltage whose wave form is rectangular. We have seen that an approximation to such a *square wave* may be obtained by clipping a sinusoidal voltage wave, or by overdriving a linear amplifier whose input is a sinusoidal voltage. Now we consider a circuit which is designed to provide a square wave output of variable frequency.

We employ two identical transistors in the circuit shown in Fig. 17. If we refer to the collector characteristic of a transistor (Fig. 16 in the previous article), we see that there are two limiting conditions of operation of the device. In one case, when there is zero base current, the transistor is not conducting and the collector current consists of only a very small leakage current. The transistor is *cut off*, there is practically no current in the resistor which connects the transistor's collector to the voltage supply, and therefore in the OFF condition there is a voltage, V_C, at the collector which is essentially equal to the supply voltage. The other limiting condition of operation is that in which the transistor is in *saturation*; the base current is high, the base voltage is very slightly positive with respect to the emitter, the transistor is carrying maximum current, and the voltage at the collector is almost zero. This is designated as the ON condition. When the transistor is used in a *linear* amplifier, precautions are taken to insure that the transistor never approaches either the OFF or the ON condition.

In the free-running multivibrator, the transistors are made to operate in either the ON or the OFF condition, and we make use of the change in collector voltage of a transistor when it is suddenly switched from the ON to the OFF condition and after a predetermined length of time, switched from OFF to ON again. At a given instant, only one transistor is conducting, and it is in the condition of saturation. The second transistor is in the OFF condition. The interconnections between the transistors in Fig. 17a are such that neither transistor can remain permanently ON or permanently OFF. If we observe the voltage at the collector of either transistor, we find that this voltage changes periodically from a value equal to that of the supply voltage (when the transistor is OFF) to practically zero (when the transistor is ON). If these changes occur abruptly, then the collector voltage has an approximately rectangular waveform.

We now describe the operation of the circuit of Fig. 17a. Observe that

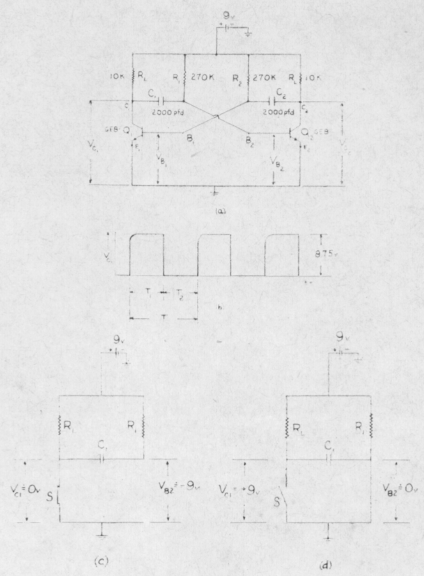


Figure 17. (a) Free-running transistor multivibrator. (b) Observed waveform of voltage at collector of Q_1. (c) Circuit involving C_1 just after Q_1 becomes fully conducting. (d) Circuit involving C_1 just before Q_1 begins to conduct.

in this circuit resistors of equal size (R_L) connect each collector to the supply voltage, which in Fig. 17a is the 9-volt battery. The collector of Q_2 is connected to the base of Q_1 through capacitor C_2, and there is a corresponding connection from the collector of Q_1 to the base of Q_2 through C_1. The base of Q_1 (and therefore one side of capacitor C_2) is connected back to the battery through R_2. The base of Q_2 (and one side of C_1) is similarly connected through R_1.

We assume that the MVBR has been operating long enough to reach a steady state, and we begin consideration of its operation just before Q_1 begins to conduct. At that instant, the portion of the circuit involving C_1 and R_1 may be represented by the circuit shown in Fig. 17d. Switch S corresponds to Q_1 which is not conducting, and is therefore an open circuit. There is a potential difference of 9 volts across C_1, because Q_2 is conducting, and its base (point B_2) is at zero volts. When Q_1 begins to conduct, it very quickly reaches a condition of saturation. This means that voltage V_{C1} very quickly drops from +9 volts to zero volts. This corresponds to closing the switch in Fig. 17d. This causes the left-hand plate of C_1 to drop from +9 volts to zero volts. But there is a charge of the polarity shown in Fig. 17d on C_1, therefore even after switch S closes there is still a 9 volt potential difference between the plates of C_1. This potential difference can change only if positive charge is supplied from the battery to the right-hand plate of C_1, and this charge must flow through the high resistance R_1. Therefore, immediately after V_{C1} drops from +9 volts to zero, the potential difference across C_1 is maintained temporarily at 9 volts, and this means that point B_2 drops from zero volts to −9 volts. The situation immediately after Q_1 begins to conduct and V_{C1} drops to zero is shown in Fig. 17c. Now B_2 is at a much lower voltage than the emitter of Q_2 and therefore Q_2 turns OFF. However, this is not a permanent condition, because the right-hand plate of C_1 is receiving positive charge from the battery through R_1 at a rate which depends upon the time constant R_1C_1. Therefore, the voltage V_{B2} immediately begins to rise toward zero. When V_{B2} reaches approximately zero volts, Q_2 begins to conduct and quickly goes into a condition of saturation. Thus, when Q_2 turns ON, its collector voltage V_{C2} drops quickly to practically zero. This sudden drop of 9 volts is transferred by C_2 to the base of Q_1, causing V_{B1} to drop to approximately −9 volts and thereby causing Q_1 to turn OFF. Now the left-hand plate of C_2 begins to receive positive charge from the battery through R_2. Therefore V_{B1} immediately begins increasing from −9 volts toward zero volts and after a time determined by the product R_2C_2, the base of Q_1 reaches approximately zero volts and Q_1 turns ON.

The process is thus a repetitive one, with conduction automatically switching between Q_1 and Q_2 at rates which depend upon R_1C_1 and R_2C_2. The voltage at each collector will have an approximately rectangular waveshape. If $C_1 = C_2$ and $R_1 = R_2$, then the ON and OFF times will be the same for both transistors, and the output waveform at either collector will be as shown in Fig. 18a. If R_1C_1 is not equal to R_2C_2, then the ON and OFF times for the two transistors will be unequal, and the voltage waveforms at the two collectors will be as shown in Fig. 18b. Usually design considerations make it desirable for $R_1 = R_2$ and changes in ON and OFF times are effected through changes in C_1 and C_2.

Our experiment uses the circuit of Fig. 17a. To start, we make $C_1 = C_2$. The output voltages observed with the CRO at the two collectors will then appear identical, although, as should be clear from the above explanation,

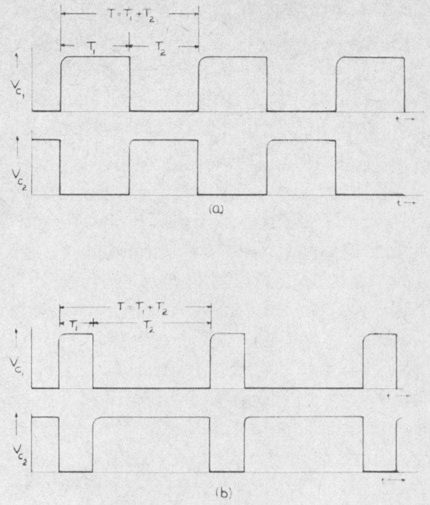


Figure 18. Waveforms of collector voltages of multivibrator. (a) Equal ON-OFF times. (b) Unequal ON-OFF times.

they are actually 180° out of phase. With our equipment, we cannot observe this phase difference. We can measure the frequency of the rectangular output wave by using the calibrated time base of our CRO to measure the period T of a complete cycle. If T is in seconds, then the frequency is $f = 1/T$ cps.

Next we keep $C_1 = 2000$ pfd but change C_2 to 3000 pfd. We see that T has increased. It is also now obvious that V_{C1} and V_{C2} are 180° out of phase, since if the high voltage part of V_{C1} lasts for a longer time than its low voltage part, exactly the reverse will be true for V_{C2}. By making C_1 much greater than C_2, we obtain an output V_{C1} consisting of very short positive pulses separated by relatively long time intervals, while V_{C2} will consist of long positive pulses separated by short intervals. The minimum pulse length is governed by the fact that there are minimum values of R and of the C's for which the circuit will operate, and by the product R_LC which determines how quickly the collector voltage of a transistor can rise to its maximum value. (See Fig. 19, described below.)

Figure 19 shows the collector and base voltages of the transistors as functions of time for one complete cycle when C_1 is not equal to C_2. T_1 and T_2 represent, respectively, the times during which Q_1 and Q_2 are ON. Then $T = T_1 + T_2$. T_1 and T_2 may be calculated from

$$T_1 = R_2C_2(ln2) \qquad T_2 = R_1C_1(ln2)$$

Usually $R_1 = R_2 = R$, then

$$T = T_1 + T_2 = R(C_1 + C_2)ln2$$

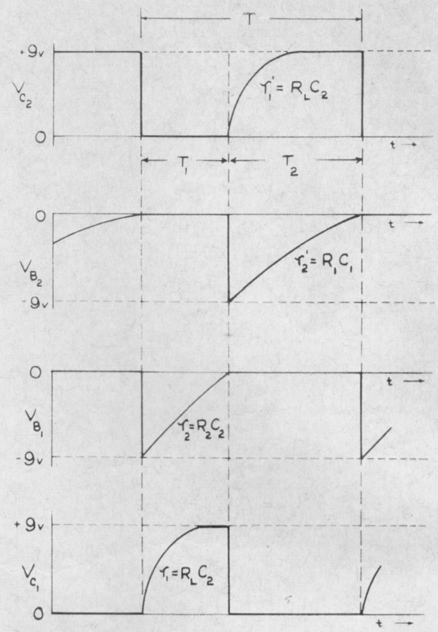


Figure 19. Time relationships of collector and base voltages in multivibrator. (Time constants τ_1 and τ_1' exaggerated.)

In our laboratory, with the values of R's and C's shown in Fig. 17a, we obtained a measured period of 740 microseconds (1 microsecond $= 10^{-6}$ second). Calculation, using the above equation gives 748 microseconds. This is unusually good agreement, considering the manufacturing tolerance of the components, and one should not expect that he will obtain such results with another circuit. The output waveform is shown in Fig. 17b. With a 9 volt battery supply, the amplitude of our square wave was 8.75 volts.

Careful examination of the output waveforms at the two collectors will show that, as indicated in exaggerated fashion in Fig. 19, the voltages at the two collectors do not have exactly vertical sides when they are increasing. There is some rounding of the corners, caused by the fact that, when either transistor is switched OFF, the rate of increase of its collector voltage is affected by the rate at which the voltage on the capacitor connected to that collector can change. The time required for change in voltage on C_1 depends upon (but is not equal to) R_LC_1; similarly, for C_2 the time depends upon C_2R_L. Although these products are usually small compared with RC_1 and RC_2, they nevertheless impose restrictions upon the rate of change of collector voltages and cause them to have definite *rise times.* For short pulses, this may represent a distinct limitation.

If we are willing to accept some

decrease in amplitude of the output voltage we may realize great improvement in waveform by the use of a simple clipping circuit as shown in Fig. 20a. By reducing the output amplitude from 8.75 volts to 6.5 volts we obtain output pulses which have practically vertical sides, so the output voltage is much more nearly a square wave than the voltage (Fig. 17b) obtained directly from the MVBR.

The MVBR output has various applications. It may be used in square wave testing of amplifiers, it can serve to control other circuits by turning them on or off, and it may be used in conjunction with a simple *RC* series circuit to produce very short voltage pulses. We shall investigate this last application in the next experiment.

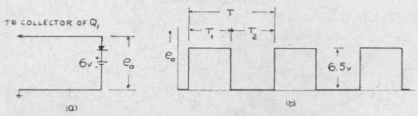


Figure 20. (a) Clipping circuit for multivibrator output voltage. (b) Output voltage.

EXPERIMENT NUMBER 8—PEAKING CIRCUIT

Consider the circuit shown in Fig. 21a. If we apply Kirchhoff's second law to this circuit, we have

$$e_{\text{in}} = \frac{q}{C} + Ri.$$

If *R* and *C* are so chosen that the voltage (V_R) across *R* is a small fraction of e_{in} then, approximately,

$$e_{\text{in}} = \frac{q}{C}$$

and therefore,

$$\frac{de_{\text{in}}}{dt} = \frac{1}{C}\frac{dq}{dt} = \frac{i}{C}$$

or $$i = C\,(de_{\text{in}}/dt) = \frac{dq}{dt}.$$

But $V_R = iR$ and so

$$e_o = V_R = RC\,(de_{\text{in}}/dt).$$

By proper choice of *R* and *C*, therefore, we obtain a *differentiating circuit,* where e_o is proportional to (de_{in}/dt). Since the voltage across the capacitor (V_C) is inversely proportional to *C* and since V_R is proportional to *R*, the condition we have imposed implies a very small value of the product *RC*. A more complete analysis shows that for good differentiation the product *RC* (which has the dimensions of seconds) must be much smaller than *T*, the period of e_{in}.

In Fig. 21a, *R* and *C* have been so chosen as to satisfy the condition

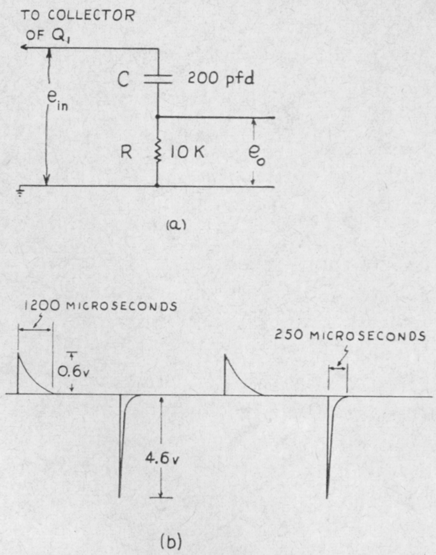


Figure 21. (a) Differentiating circuit. (b) Output with multivibrator output voltage applied.

$RC \ll T$, where e_{in} is the square wave output of the MVBR as shown in Fig. 17b. If the edges of the square wave were exactly vertical, the derivative would consist of a series of very short pulses, positive when the square wave rises and negative when the square wave decreases. In the limiting case, the pulse heights would be equal to the height of the square wave and each pulse would last for zero time. Because our circuit is only an approximate differentiator, and because the edges of the square wave are not truly vertical, there will be some departure from the ideal output in our experimental circuit.

Fig. 21b shows the results obtained when the waveform of Fig. 17b is applied to the circuit of Fig. 21a with the values of *R* and *C* indicated there. The positive pulses have amplitudes of about 0.6 volt and last for approximately 1200 microseconds while the negative pulses are much higher and narrower, rising to about 4.6 volts and lasting for only 250 microseconds. The differences between positive and negative pulses are explained by reference to Fig. 17b. The rounding of the leading edge of the output from the MVBR means that the rate of rise of these "square" voltage waves is not as great as their rate of fall. Furthermore, the leading edge requires a longer time to reach its final value than does the trailing edge. If we insert the clipping circuit of Fig. 20a between the MVBR and the differentiating circuit, there results a definite improvement in the positive output pulses, because now the leading edge of the input wave is more nearly rectangular in shape.

EXPERIMENT NUMBER 9—LINEAR SWEEP GENERATOR

The discussion of the oscilloscope in reference 2 explains the necessity of applying to the horizontal deflection plates of the cathode ray tube a voltage which increases linearly with time. That paper describes some circuits which will produce close approximations to such a voltage. In a good CRO considerable care is exercised in the design of a circuit which will give an extremely linear sawtooth voltage in order that the sweep may serve as an accurate means for measuring time. In radar, where the distance of an object is determined by observing the time between the emission of a short pulse of electromagnetic energy and the return of the echo from the object, linearity of sweep is obviously of great importance for accurate range determination.

Figure 2 of reference 2 shows a circuit in which a capacitor *C*, connected in series with a resistor *R*, is charged from a source of constant voltage, *E*. A gas tube is connected across the capacitor, and when the voltage across *C* reaches the firing potential of the gas tube, the tube conducts and *C* discharges rapidly. The resistor limits the current to a value lower than that required to maintain conduction in the gas tube, and so when the voltage across the capacitor has dropped to a sufficiently low value, the gas tube stops conducting and the capacitor begins to charge again. The increase in voltage across *C* is actually exponential, but if one considers a small enough segment of the curve, an exponential approximates a straight line, and so this arrangement produces an almost linear sweep voltage.

Consider now what happens if we replace the constant voltage source by a constant current source. After time *t*, the voltage V_c on an initially uncharged capacitor is $V_c = q/C$, where *q* is the charge which has been supplied and *C* is the capacitance. If the charge is supplied by a constant current I, then $q = It$, the capacitor voltage is, therefore, $V_c = It/C$, and V_c is exactly proportional to time. (Consistent units in these relations are volts, coulombs, amperes, farads, and seconds.) In Fig. 2 of reference 2, one could obtain a constant charging current by use of a pentode vacuum tube. In its usual operating range, the pentode has a constant plate current, and if this current is supplied to charge the capacitor, then V_c is a linear function of time.

When a transistor is operating with a common base connection, its collector current is constant and is proportional to the base current. If this current is used to charge a capacitor, the voltage on the capacitor will increase linearly with time. Transistors operate at low voltages and a gas tube is not usually a satisfactory means for effecting the sudden discharge of the capacitor, because the capacitor voltage will not reach a sufficiently high value to cause the gas tube to conduct. If we wish to take advantage of the constant charging current supplied by a transistor, we must employ some device other than a gas tube to provide the discharge path. One useful device is the unijunction transistor. Its construction and principle of operation are described in the following paragraph.[3]

A bar of n-type silicon, which is doped so that its resistance is several thousand ohms, has non-rectifying contacts attached at each end. (A problem which sometimes arises with semiconductor materials is that of attaching metallic contacts to the semiconductor. Care must be exercised to make sure that the bond between the metal and the semiconductor is such that the polarity of the voltage across the bond has no effect upon the conducting properties of the bond. A connection which meets this requirement is called *non-rectifying* or *ohmic*.) One end of the silicon bar is designated base-1 ($B1$) and the other end is designated base-2 ($B2$). By an alloying process, a small section of the bar near $B2$ is made p-type, so there is a rectifying junction between the p-type material, designated the emitter, E, and the silicon bar. The construction of the device is illustrated in Fig. 22. $B1$ is grounded, and a positive voltage V_{bb} is applied at $B2$. When there is no emitter voltage, the silicon bar has a uniform resistance throughout its length, and it acts as a voltage divider, with a fraction δ of V_{bb} appearing between E and $B1$. If V_E, the emitter voltage, is less than δV_{bb} the emitter diode is reverse biased and there will be only a small leakage current at the emitter. If V_E is greater than δV_{bb}, the emitter diode conducts, and holes are injected into the bar. The holes move down toward $B1$ and cause an increase in electron density in the region between E and $B1$. There results a decrease in resistance between E and $B1$. Furthermore, as the emitter current I_E increases, V_E decreases. The result is a rapid increase in current and practically a short circuit between E and $B1$. Figure 22b shows an equivalent circuit for a unijunction transistor. R_1 is shown as variable, because R_1 changes with emitter current. For a typical device, R_1 may vary from 4.5K with $I_E = 0$, to 40 ohms with $I_E = 50$ milliamperes. The condition of high current and low resistance from E to $B1$ continues as long as V_E is greater than δV_{bb}. If V_E decreases to a small enough value, then the emitter junction becomes reverse biased again, and conduction between E and $B1$ virtually ceases.

Now we consider Fig. 23a which shows an n-p-n transistor, Q, and a unijunction transistor, U, connected to form a linear sweep generator. When V_{cc} is applied, the base current I_B of Q is constant. Since the collector current I_C of Q is equal to beta times I_B, the collector current is also constant. The collector current charges the capacitor C at a constant rate; therefore, V_c increases linearly with time. As V_c increases, point M rises toward a maximum value of 9 volts. Point M is connected to the emitter of U, and at some value V_1, of V_c, depending upon V_{bb}, U begins to conduct between E and $B1$, providing almost a short circuit between its emitter and ground. Thus, C rapidly loses charge through the low resistance of U in series with R_4, and V_c drops quickly to a voltage V_2, at which the emitter of U becomes back biased. Then U stops conducting, and C begins charging up again through transistor Q.

Figure 23b shows the waveform of voltage across C (between point M and ground). If we apply this voltage to the CRO and adjust the CRO amplifiers properly, it is possible to align the increasing part of this voltage wave with the intersections of the vertical and horizontal lines on the face of the cathode ray tube, as illustrated in Fig. 23c. This shows that V_c is indeed increasing linearly with time. We observe some curvature at the minima of V_c. This curvature results from the fact that there is some resistance R (R_4 plus the resistance between E and $B1$ of U) in series with C when it discharges. The discharge circuit thus has a small time constant $\tau = RC$, and V_c approaches V_2 exponentially rather than reaching this value instantaneously.

The amplitude ($V_1 - V_2$) of the sawtooth wave depends upon V_{bb}, since this voltage determines the value of V_E at which U becomes conducting, and the value of V_E at which the emitter becomes back biased. Increase in V_{bb} will increase V_1 more than it will increase V_2, therefore, a larger value of V_{bb} will result in increased amplitude of the sawtooth wave.

The period T of the output voltage wave depends directly upon the charging current I_C and this in turn depends upon the base current I_B in Q. Since the base current is controlled by R_1, we may change T by varying R_1. In our laboratory, adjustment of

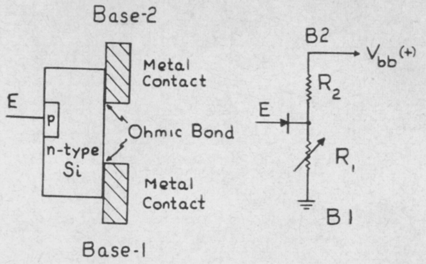


Figure 22. (a) Schematic diagram of unijunction transistor. (b) Equivalent circuit of unijunction transistor.

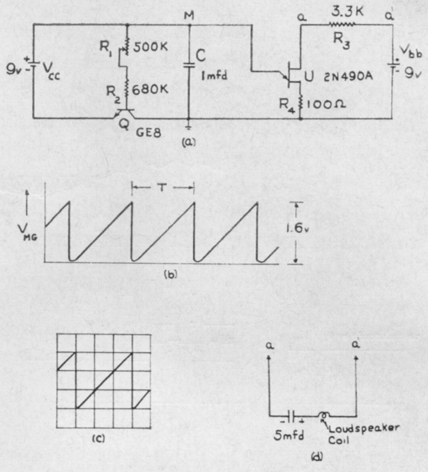


Figure 23. (a) Sawtooth generator circuit. (b) Output voltage. (c) Alignment with CRO grid to check linearity. (d) Method for connecting loudspeaker.

R_1 resulted in a continuous variation of T from 1.35 to 4.5 milliseconds. If R_1 is made too large, oscillations cease, because the base current of Q has been made so small that the collector current, which provides the charging current for C, is essentially zero. If the sum $(R_1 + R_2)$ is too small, then the base current is sufficient to drive Q into a non-linear operating region, and the charging current for C is no longer constant.

An interesting experiment is to use the waveform of Fig. 23b to supply the sweep of the CRO. Set the CRO controls so that the internal sweep generator is not in use. Then the output of the *horizontal amplifier* contained in the CRO is connected to the horizontal deflection plates of the cathode ray tube. (This is the same adjustment of the CRO as is made when one wishes to observe Lissajous figures.) If we now supply the output V_c of Fig. 23a to the horizontal amplifier input of the CRO, a horizontal line will appear on the screen, just as if the internal sweep were being used. If we apply a sine wave of voltage to the vertical input of the CRO and adjust its frequency to that of our sweep voltage (between 200 and 750 cps, depending upon the setting of R_1 in Fig. 23a) we observe a sine wave on the cathode ray tube. This wave is undistorted, and this is a further indication that the increasing part of V_c is a linear function of time.

We observe two effects when the internal sweep of the CRO is not employed. One of these is the *return trace,* a line representing the sudden drop in voltage at the end of each cycle of the sawtooth wave. The return trace does not appear when the internal sweep of the CRO is used, because a *blanking voltage* is applied to the electron gun, stopping the flow of electrons from the gun during the time required for the return trace. A second effect which occurs when we use the external sawtooth generator is the tendency of the sine wave which appears on the face of the cathode ray tube to drift at random to the right or left. No adjustment of the sine wave oscillator will produce a permanently stationary pattern. The drift results from the absence of a *synchronizing signal* for the sweep voltage. Small changes in temperature or in V_1 or V_2 will cause corresponding small changes in T. When the *internal sweep* is used, a synchronizing signal locks the beginning of each sweep to some fixed frequency and thus provides an exactly constant value of T. Such a synchronizing voltage could be provided for the circuit of Fig. 23a by the use of additional circuit elements. (Lack of synchronization also makes it impossible to obtain a stationary Lissajous figure from two independent voltage sources. The pattern will rotate slowly as small changes in frequency occur in one or both input voltages.)

Another interesting and simple experiment consists in connecting a small loudspeaker, *in series with a 5 mfd capacitor to block the direct current,* across points *a-a′* in Fig. 23a. (See Fig. 23d.) Then, an audible signal may be heard; the pitch (frequency) of this audible signal may be changed by changing the value of the resistor R_1.

REFERENCES

1. R. E. Alley, Jr., *Semiconductors and Semiconductor Devices,* The Physics Teacher, **3**, 55 (1965).

2. F. E. Christensen, *The Oscilloscope and How It May Be Used,* The Physics Teacher, **1**, 172 (1963).

3. *"Transistor Manual,"* General Electric Company, Semiconductor Products Division, Syracuse, N. Y. 1965.

For additional references for further reading, see the bibliography accompanying reference 1.

The Bell Telephone Laboratories has recently published a book by Siegfried S. Meyers entitled *Experiments with Conductors and Semiconductors,* which describes a dozen relatively simple experiments. The book can be obtained in limited quantities from the local telephone business offices or purchased from Edward Stern & Company, Independence Mall, Philadelphia, Pa. 19105. Price $0.35.

APPENDIX—EQUIPMENT REQUIRED FOR THE EXPERIMENTS

A. INSTRUMENTS

Many manufacturers offer test instruments which are suitable for use in the experiments described here. It is impossible to list all sources; therefore, we shall simply specify the characteristics required of each instrument and indicate the approximate price range of each. Many suppliers advertise in *The Physics Teacher,* and all four of the instruments listed may be obtained from at least one of these manufacturers. Teachers should write to manufacturers for catalogs and prices of their products. The three necessary instruments (oscilloscope, oscillator and volt-ohm-milliammeter) and the low voltage dc power supply are all available as kits which are to be assembled by the purchaser. The kits are usually less expensive than the ready-to-use instruments, and if one follows the very detailed instructions carefully, he should have an instrument which will perform satisfactorily.

1. *Oscillator:*
   - Sinusoidal output frequency range: 10 cps to 600 kcps
   - Square wave frequency range: 10 cps to 25 kcps
   - Output voltage: 0.1 volt to 10 volts r.m.s.
   - (The frequency and the output voltage should both be continuously variable over the specified ranges.)
   - Price range: $80.00 for a kit up to $250.00 for some factory-wired models.
   - Note: All manufacturers do not offer combination sine and square wave oscillators. A fairly satisfactory variable frequency square wave oscillator may be obtained by building an amplifier as described in Experiment 4 and overdriving it with the sine wave oscillator. This will give a reasonably good square wave output up to a frequency of about 25 kcps.
2. *Oscilloscope:*
   - Cathode ray tube diameter: 5 inches
   - Frequency range of vertical amplifier: dc up to 450 kcps
   - Vertical amplifier sensitivity: 0.025 volt r.m.s. per inch
   - The vertical amplifier should have a provision for calibration so that the CRO may be used as a voltmeter for ac.
   - Price range: $90.00 for a kit, up to several hundred dollars for a factory-wired model.
3. *Volt-Ohm-Milliammeter:*
   - Resistance on direct voltage ranges: 20,000 ohms per volt
   - Resistance on alternating voltage ranges: 5,000 ohms per volt
   - Alternating and direct voltage ranges: Several ranges should be provided ranging from 1.5 volts full scale to at least 500 volts full scale.
   - Price range: $25.00 for a kit up to as much as $100.00 for factory-wired models, depending in part upon the accuracy of calibration.
4. *Low Direct Voltage Power Supply:*
   - Output voltage: 0 to 30 volts continuously variable
   - Output current: at least 200 milliamperes at 30 volts
   - Price range: $25.00 for a kit up to $125.00 for a factory-wired model.

B. COMPONENTS

The following list includes all the components required for performing the nine experiments described in this paper. The minimum number of each component is specified. Since they are relatively inexpensive, it is desirable to have on hand a few spares of each value of resistor and capacitor, as well as two spare transistors and two spare diodes. It is generally not advisable to stock up on batteries, since their shelf lives are limited. Except for the transistors, which should be General Electric GE8 n-p-n, the particular brand of component is not important.

The components are available from various supply companies. Surplus property may also be a good source of some items.

1. *Resistors:* These should be of the composition type, which are the cheapest and quite satisfactory, and should have a rating of 1 watt. Individual units cost about $0.15 each regardless of resistance; however, they may be bought in quantity in assorted sizes, the unit cost depending upon the total number purchased.

Quantity	Resistance	Quantity	Resistance
1	100 ohms	2	5.6 K
1	220 ohms	2	10 K
1	680 ohms	2	90 K
1	750 ohms	3	220 K
2	1 K	2	270 K
1	2.2 K	1	470 K
1	3.3 K	1	1 megohm

2. *Potentiometers:* These may be 2 watt or 4 watt devices. The various types of taper in the windings which are specified in catalogs are of no significance in our applications. These units cost about $1.00 each. Two are required: one of 50 K total resistance and one of 500 K total resistance.

3. *Capacitors:* The 5 mfd and the 25 mfd capacitors should be *electrolytic*. The 0.05 mfd and the 1.0 mfd capacitors may be paper, or more likely, mylar. The capacitors in the picofarad range may be ceramic or mica. (The voltage ratings of these will probably be much in excess of the minimum specified below.)

Number	Capacitance	Minimum voltage	Unit price
1	0.05 mfd	200	$0.15
4	1.0 mfd	200	0.65
3	5.0 mfd	25	0.85
2	25.0 mfd	25	1.00
2	200 pfd	100	0.15
2	300 pfd	100	0.15
3	2000 pfd	100	0.15
2	3000 pfd	100	0.15

4. *Transformer:* This is of the type usually listed in the catalogs as a filament transformer. It should have a 115-volt primary and a *center-tapped* secondary which will give approximately 12.5 volts from center terminal to either end. A current rating of 1 ampere in the secondary winding is adequate. Price is about $3.00.

5. *Batteries:* If a low voltage power supply is purchased, then it may replace one of the 9-volt batteries. In the list below, Burgess type numbers are given. However, these are specified only in order to indicate the physical size of the battery. Equivalent batteries of other manufacturers are satisfactory.

Quantity	Burgess No.	Volts	Price
2	2N6	9	$1.30
2	Type 2	1.5	0.25
1	(use 2 type 2)	3.0	
1	C6X	6.0	0.70

Note: Various types of snap connectors or metal holders are available for making connection to the batteries. It is possible to make solder connections, but great care must be exercised to avoid overheating and thereby ruining or shortening the life of the dry cells.

6. *Transistors:* Four GE-8 n-p-n transistors are required. The price is $1.20 each.

7. *Diodes:* Four diodes are required. The cheapest are the silicon "top hat" type which cost about $1.00 each. They should have a rating of 400 volts peak inverse voltage and should be able to carry a continuous current of about 750 milliamperes.

8. *Unijunction Transistor:* This is required for the sweep generator in experiment 9. It is the most expensive of all the components. The type number is 2N490A. The price is $8.35. One of these is required.

C. METHODS FOR INTERCONNECTING CIRCUIT ELEMENTS

Since it is necessary to be able to change connections in the individual circuits as well as to use the same components for constructing several different circuits, it is desirable to have some means of interconnecting the circuit elements without making use of solder. (Soldering is not recommended for connecting semiconductor devices, in any case, because it is quite easy to damage them by overheating.) Most instructors who have charge of electronics laboratories have developed their own methods for simple and rapid interconnection of circuit elements or else they make use of one of the commercially available systems. If you are near a college or university, you will find it helpful to seek advice from the physics or electrical engineering faculty members who are responsible for the electronics courses.

In our laboratory, we use equipment manufactured by Science-Electronics, Inc., 195 Massachusetts Ave., Cambridge 39, Mass. Other companies which we know of which supply such equipment are Hickock Teaching Systems, 545 Technology Square, Cambridge, Mass., and Phillips Advance Control Co., 59 West Washington Street, Joliet, Illinois. You should request catalogs and price information from these companies. They will describe the equipment, and may suggest ideas for developing your own scheme of circuit connection.

One word of advice is in order with regard to connecting transistors. Transistor sockets are generally unsatisfactory. It is desirable to connect each transistor and diode permanently to some type of base, either a slab of plastic into which terminals have been inserted, or, more simply, a terminal strip. Be sure, with the GE8 transistors and with the unijunction transistor properly to identify and mark the leads so that you will connect them correctly in the circuits. It is also a good idea to mark the polarity of the diodes after they have been mounted.